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PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

September 1979

NOTICE

The mention of trade names or commercial products in this publication is for illustrative purposes only and does not constitute endorsement or recommendation for use by the USEPA.

FOREWORD

The formation of the United States Environmental Protection Agency marked a new era of environmental awareness in America. This Agency's goals are national in scope and encompass broad responsibility in the areas of air and water pollution, solid wastes, pesticides, and radiation. A vital part of EPA's national pollution control effort is the constant development and dissemination of new technology.

It is now clear that only the most effective design and operation of pollution control facilities using the latest available techniques will be adequate to ensure continued protection of the nation's waters. It is essential that this new technology be incorporated into the contemporary design of pollution control facilities to achieve maximum benefit of our expenditures.

The purpose of this manual is to provide the engineering community and related industry with a new source of information to be used in the planning, design, and operation of present and future wastewater pollution control facilities. It is recognized that there are a number of design manuals and manuals of standard practice, such as those published by the Water Pollution Control Federation, available in the field, and that each of these adequately describes and interprets current engineering practices as related to traditional plant design. It is the intent of this manual to supplement this existing body of knowledge by describing new treatment methods and by discussing the application of new techniques for more effectively removing a broad spectrum of contaminants from wastewater.

Much of the information presented is based on the evaluation and operation of pilot, demonstration, and full-scale plants. The design criteria thus generated represent typical values. These values should be used as a guide and should be tempered with sound engineering judgment based on a complete analysis of the specific application.

This manual is one of several available from Technology Transfer to describe technological advances and new information. Future editions will be issued as warranted by advancing state-of-the-art to include new data as they become available and to revise design criteria as additional full-scale operational information as generated.

ABSTRACT

The purpose of this manual is to present a contemporary review of sludge processing technology, with particular emphasis on design methodology. This is a revision of a manual originally published in October 1974.

The revised edition incorporates chapters on design approach, disinfection, composting, transport, storage, sidestream treatment, and instrumentation. Other sections have been considerably expanded.

Design examples are used throughout the manual to illustrate design principles.

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Chapter 1. Purpose and Scope

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CHAPTER 1

PURPOSE AND SCOPE

1.1 Purpose

The purpose of this manual is to present an up-to-date review of design information on all applicable technologies available for treatment and disposal of municipal wastewater solids. Wastewater solids include grit, scum, screenings, primary sludges, biological sludges, chemical sludges, and septage.

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) and the Clean Water Act Amendments of 1977 (Public Law 95-217) require levels of municipal wastewater treatment sufficient to meet the congressional mandate of cleaning up the nation's waterways. Through the USEPA Construction Grants Program, financial incentives have been provided to assist publicly owned treatment works (POTWs) in meeting these requirements. Federal and state requirements impact both effluent quality and treatment alternatives, utilization, and disposal of wastewater solids.

The tasks associated with managing municipal wastewater solids are neither simple nor cheap. In providing higher levels or additional treatment of wastewaters, greater volumes of wastewater solids are produced. The combination of greater volumes of sludges, mixtures of various sludges, and more restrictive management requirements have complicated the solids management options available to the design engineer. These facts require both the design engineer and the operations personnel to give serious consideration to the interdependence of both the liquid and solids portions of the treatment facility. The need for sound wastewater solids management is significant. Typically, solids processing and disposal costs can account for 20 to 40 percent of the total operating and maintenance cost of a treatment facility (1). Thus, there is strong incentive to utilize the most appropriate and cost-effective alternatives available.

This manual supersedes the USEPA _Process Design Manual for Sludge Treatment and Disposal_, EPA 11-74-006, published in 1974. Since 1974, new wastewater solids processing techniques have developed, existing techniques have matured, and operating experience and data are available. Current legislation, solids management requirements, and advances in sludge treatment and disposal technologies warrant this revision.

1.2 Scope

This manual has been prepared for use by professionals engaged in the design and approval of municipal wastewater solids treatment and disposal systems. Design information presented includes:

- Origins, quantities, and characteristics of municipal wastewater treatment plant solids;
- Process descriptions, including theory and appropriate design criteria;
- Energy requirements;
- Public health and environmental considerations;
- Cost and performance data; and
- Design examples.

Some material is not included because it has been presented elsewhere. A section on sanitary landfills has been omitted because an EPA manual of this subject has been published recently (2). The treatment of land utilization is abbreviated because an EPA Design Seminar publication is available (3).

1.3 Process Classification

The manual is divided into 19 chapters, with 15 chapters devoted to sludge processes. Additional chapters cover general considerations, design approach, and sludge properties. Figure 1-1 depicts the basic classification by process. It should be noted that processes within classifications overlap to some extent. As an example, stabilization, disinfection, and disposal also take place during high temperature processing. The processes, as they appear on Figure 1-1, should be read in left-to-right sequence; they do not, however, necessarily appear in a treatment system in the order shown. Figure 1-1 is arranged to display sludge treatment and disposal options rather than to suggest any particular order of operations.

1.4 References

1. USEPA. Construction Costs for Municipal Wastewater Treatment Plants 1973-1977. Office of Water Program Operations. Washington, D.C. January 1978.

2. USEPA. Process Design Manual: Municipal Sludge Landfills. Environmental Research Information Center, Office of Solid Waste, Cincinnati, Ohio 45268. EPA-625/1-78-010, SW-705. October 1978.

3. USEPA. "Principals and Design Criteria for Sewage Sludge Application on Land." Sludge Treatment and Disposal Part 2. Technology Transfer, Cincinnati, Ohio 45268. EPA-625/4-78-012. October 1978.

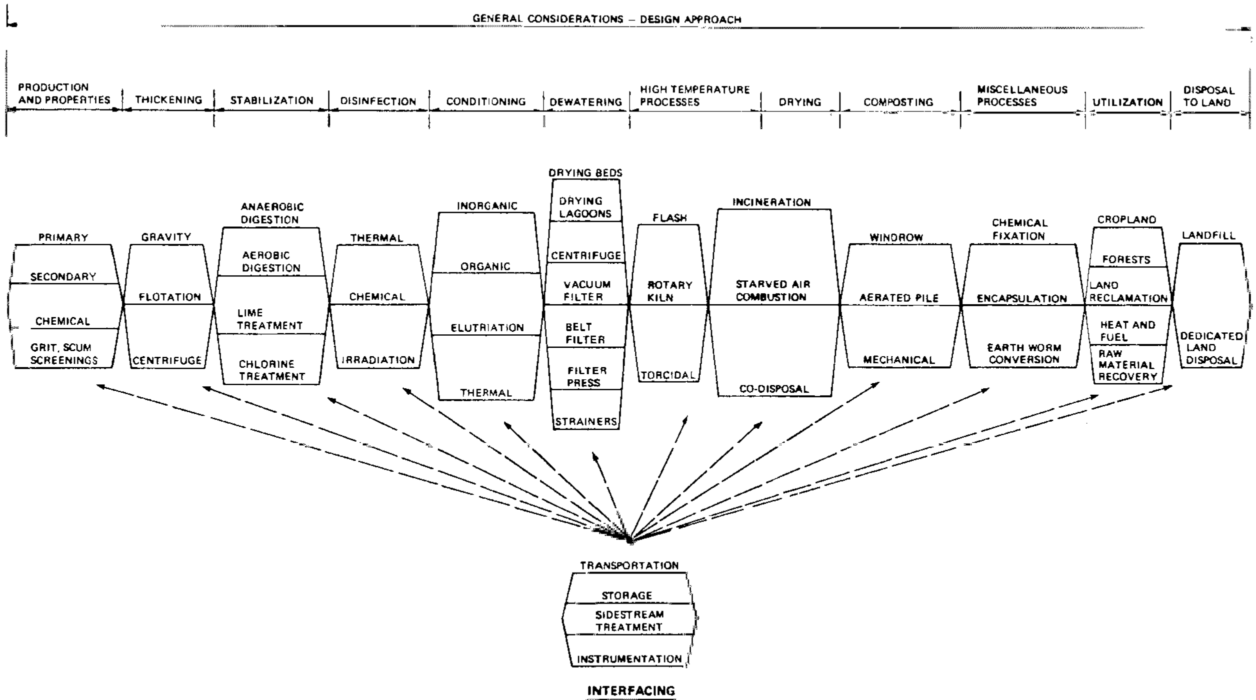

FIGURE 1-1

CLASSIFICATION OF TREATMENT AND DISPOSAL OPTIONS

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Chapter 2. General Considerations

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CHAPTER 2

GENERAL CONSIDERATIONS

2.1 Introduction and Scope

Non-technical factors can heavily influence the planning, design, construction, and operation of solids management systems, and these non-technical considerations must be faced from the day a project is conceived. Non-technical factors include legal and regulatory considerations, as well as other issues, such as public participation.

2.2 Legal and Regulatory Considerations

The thrust of this section is to describe the intent and effects of federal legislation and to provide a reference list which features the most current criteria. Where state and local requirements may be involved, they are so noted.

2.2.1 Effect of Effluent Discharge Limitations on Wastewater Solids Management

The Federal Water Pollution Control Act of 1972 (PL 92-500) established levels of treatment, deadlines for meeting these levels, and penalties for violators. For plants discharging to surface waters, effluent requirements are expressed in permits issued by the National Pollutant Discharge Elimination System (NPDES). NPDES permits have generally mandated the upgrading of existing treatment plants or the construction of new plants to provide higher levels of treatment and reliability.

The law, while providing direction toward the goal of a cleaner environment, has created problems for designers and operators of wastewater treatment plants. Higher level treatment generally means a greater mass and volume of solids to be managed. Solids treatment systems not only must handle more material but must do so more effectively. Solids not captured therein are returned to the wastewater treatment process and can potentially degrade effluent quality and defeat the very purpose of the law. Thus, stricter discharge limits have had the effect of making solids treatment and disposal more important, more difficult, and more expensive.

2.2.2 Restrictions on Wastewater Solids Treatment

Wastewater solids must be managed so that laws and regulations are not violated. Air emissions' limits and nuisance prohibitions are of particular importance.

2.2.2.1 Air Emissions Limits

The Clean Air Act Amendments of 1970 (PL 91-604) and 1977 (PL 95-95) contain provisions for regulating point source emissions, for example, emissions from incinerators. USEPA has promulgated several regulations in response to this legislation. The most restrictive are the New Source Review regulations (40 CFR 51-18) and Prevention of Significant Deterioration (40 CFR 52-21) regulations. New Source Review (NSR) regulations apply in areas where allowable levels for any pollutant are exceeded. The regulations affect any new source which, after installation of an air pollution control device, could emit >50 tons per year (45 t/yr) of the offending pollutant (controlled emission) or which could emit >100 tons per year (91 t/yr) of the offending pollutant were there no pollution control device or were the existing device to fail (uncontrolled emission). These sources are prohibited unless their emissions can be compensated for by the reduction of emissions from other sources within the same area. This compensation clause is known as the Emissions Offset Policy. Relaxation of the Emissions Offset Policy is being considered for certain categories of resource recovery projects. Presently, few urban areas exceeding 200,000 population meet all national air quality standards. Therefore, NSR regulations will apply to almost all urban plants, particularly larger ones.

Prevention of Significant Deterioration (PSD) regulations apply primarily to areas which are presently meeting air quality standards. They affect 28 major stationary source categories with potential uncontrolled emissions exceeding 100 tons per year (91 t/yr) and any other source with potential uncontrolled emissions of over 250 tons per year (227 t/yr). Such sources are allowed provided they use Best Available Control Technology (BACT) to treat gaseous discharges and provided the emissions of specified pollutants do not increase at rates greater than set forth by regulatory schedules.

The Clean Air Act also requires "state implementation plans" (SIPs) to regulate all significant point sources, including new sources. SIPs generally limit emissions, establish emissions offset policies, require reporting, and establish penalties and administrative procedures. State or regional boards usually administer the permit system.

Historically, air emissions limits have affected incinerators more than other wastewater solids treatment processes. However, air emission limits can affect any solids treatment system.

Examples include sludge drying processes and the burning of gases from anaerobic digesters either by flaring or in internal combustion engines. USEPA has already issued New Source Performance Standards for sludge incineration (40 CFR 60-150) and "Amendments to National Emission Standards" (40 CFR 61-52). These establish particulate air pollution emission standards and limit mercury emissions from incinerators and dryers of wastewater treatment plant solids. Chapter 11 contains further information on air pollution regulations.

2.2.2.2 Nuisances

Courts have ordered municipalities to pay damages or cease operation when wastewater solids treatment processes have been proven to be the source of nuisances such as noise and odor. In some cases, judgments have resulted in the permanent shutdown of plants containing expensive equipment. Since most NPDES permits specify that treatment plant operations be nuisance free, this is a goal which designers and operators must strive to achieve.

2.2.2.3 State and Local Requirements

When state and local requirements are more stringent than federal regulations, the state and local conditions govern. Air Pollution Criteria are the most striking example of this. The criteria are particularly restrictive in California, where local nitrogen oxide (NO_x) regulations may require that new stationary reciprocating engines above a certain size be equipped with catalytic converters (1). As another instance of local controls, deed restrictions and local ordinances effectively prevent sludges produced at the Easterly Plant in Cleveland, Ohio, from being processed on the plant site (2).

2.2.3 Laws and Regulations Governing Wastewater Solids Utilization and Disposal

2.2.3.1 Federal Water Pollution Control Act

The Clean Water Act of 1977 (PL 95-217) contains two major provisions for wastewater solids utilization and disposal. Section 405 requires USEPA to issue guidelines and regulations for the disposal and reuse of wastewater solids. Guidelines and regulations to be issued in the next few years are expected to limit the quantity and kinds of toxic materials reaching the general public by setting limits on the quantity and quality of sludge distributed for public use or applied to lands where crops are grown for human consumption. The methods by which sludge is applied to land are expected to be controlled to meet aesthetic requirements, and groundwater protection will probably be required at wastewater solids disposal sites. The degree of stabilization or disinfection for sludge is expected to be specified, along with monitoring and reporting requirements and design criteria. The guidelines and regulations will probably rely on the fact that wastewater solids may endanger the public and the environment if not properly managed, and that requisites for use must be stricter than those for disposal.

The other major provision is intended to encourage sludge utilization. This provision, Section 307, requires pretreatment of industrial wastes if such wastes inhibit wastewater treatment or sludge utilization. This should increase the potential for sludge reuse.

2.2.3.2 Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) of 1976 (PL 94-580) requires that solid wastes be utilized or disposed of in a safe and environmentally acceptable manner. Wastewater solids are included by definition in provisions relating to solid waste management. USEPA is currently developing guidelines and criteria to implement the provisions of this act. These guidelines and criteria will fall into three general categories: (a) treatment and disposal of potentially hazardous solid wastes (wastewater solids are expected to be excluded from this category in most if not all cases); (b) criteria and standards for solid waste disposal facilities; and (c) criteria defining the limits for solid waste application to agricultural lands. USEPA will issue the guidelines and criteria that relate to municipal sludge management under joint authority of RCRA and Section 405 of the Clean Water Act.

2.2.3.3 Toxic Substances Control Act

The Toxic Substances Control Act of 1976 (PL 94-469) authorizes USEPA to obtain production and test data from industry on selected chemical substances and to regulate them where they pose an unreasonable risk to the environment. This act, in combination with other federal legislation cited (PL 95-217 and PL 94-580), should help reduce the amount of pollutants discharged to the municipal system from manufacturing processes. Of particular significance to wastewater solids utilization is the fact that the act prohibits the production of polychlorinated biphenyls (PCBs) after January 1979 and the commercial distribution of PCBs after July 1979. PCBs can be concentrated in wastewater sludges and are a chemical constituent of concern in meeting proposed utilization criteria. Sludge PCB levels should decrease once PCBs no longer enter the waste treatment system.

2.2.3.4 Marine Protection, Research and Sanctuaries Act

Several large cities, including New York and Philadelphia, as well as some smaller cities in the New York - New Jersey area, dispose of wastewater solids by barging them to the ocean. The 1977 amendments to the Marine Protection, Research, and Sanctuaries Act of 1972, as well as other laws and regulations prohibit disposal of "sewage sludge" by barging after December 31, 1981. In addition, no federal construction funds are available for wastewater solids treatment and disposal systems that include any type of ocean disposal, either by barge or pipeline. Therefore, no further coverage of ocean disposal will be made in this manual.

2.2.3.5 Environmental Policy Acts

The National Environmental Policy Act of 1969 requires that the federal government consider environmental effects of many actions. Municipal wastewater treatment systems, including solids treatment, utilization, and disposal systems are covered by this act because of their potential effect on the environment and because they are funded by federal construction grants. Most states have similar policy acts. The acts, which require reports and hearings, assure that the environmental consequences of proposed operations are considered, and also provide the designer with a useful forum to develop public response (see Section 2.3.6). They do, however, usually lengthen the facility planning and design process.

2.2.3.6 State and Local Reuse and Disposal Requirements

While most states and municipalities follow federal guidelines, many may formulate more restrictive measures. For example, localities that apply sludge to land on which food crops are grown may wish to analyze their sludges more frequently than required by federal guidelines or limit sludge application rates more severely. Many state and local regulatory agencies are presently awaiting the issuance of federal guidelines before finalizing their requirements.

2.2.4 The Comprehensive Nature of Section 405 of the Clean Water Act

As indicated, Section 405 of the Clean Water Act of 1977 (PL 95-217) requires USEPA to promulgate regulations governing the issuance of permits for the disposal of sewage sludge relative to Section 402 NPDES permits and to develop and publish from time to time regulations providing guidelines for the disposal and utilization of sludge. These regulations are to identify uses for sludge, specify factors to be taken into account in determining the measures and practices applicable to each such use or disposal (including publication of information on costs) and identify concentrations of pollutants which interfere with each such use or disposal.

This broad authority to issue regulations covering different sludge management practices has been viewed as a mechanism to allow USEPA to bring together all of the regulations that have been or will be issued under various legislative authorities for controlling municipal sludge management at a single location in the Code of Federal Regulations, under the joint authority of Section 405. Therefore, regulations on air emission controls will be issued under the joint authority of Section 405 of the Clean Water Act and various sections of the Clean Air Act; regulations on land disposal and land application under joint authority with the Resource Conservation and Recovery Act; regulations on ocean disposal under joint authority with the Marine Protection, Research and Sanctuaries Act, and so forth. Regulations covering practices not influenced by other authorities (for example, home use, give-away or sale of sludge derived products) could be issued solely under the broad authority of Section 405.

Thus, all regulations related to management of municipal wastewater solids will be issued, administered, and enforced under the umbrella of Section 405. Sludge management facilities and practices will therefore be approved or disapproved along with NPDES permits.

2.3 Other Non-Technical Factors Affecting Wastewater Solids Management

2.3.1 Availability of Construction Funds

Construction of municipal wastewater solids treatment and disposal facilities is usually financed with public money. Currently, federal funds are used to pay for 75 percent of grant-eligible construction costs. State contributions vary. In addition, PL 95-217 gives projects using innovative and alternative technologies, for example, sludge utilization and energy recovery, a 15 percent advantage in cost-effectiveness comparisons over projects using conventional technology. They are also given a 10 percent bonus (to 85 percent) on federal construction grants (3). Innovative technologies can also be replaced with 100 percent funding if they fail within two years. Thus, federal and state grant fund requirements may influence to a considerable degree the sludge management system chosen and the way a system is designed. Cost-effective design, careful and conservative cost estimating, and clear explanations to decision-makers of the rationale for selected treatment and disposal systems will assist greatly in obtaining federal and state construction funds.

Design engineers should refer to the USEPA Construction Grants Manual for federal grant requirements (4). In many states these requirements are supplemented by state regulations.

Occasionally, a governmental agency may declare certain features of a design to be ineligible for grant funding. Sometimes these declarations are in direct contradiction with the design engineer's opinion regarding their necessity. The designer should be aware of these potential conflicts of opinion and submit full documentation and justification along with the request for funding. The design year for full loading, special loading allowances, system reliability requirements, and facility flexibility allowances are important parts of this documentation.

2.3.2 Special Funding Requirements

The designer must be aware of special conditions associated with federal and state grant funding, such as "buy American" provisions, "or equal" clauses, affirmative action in employment, and special auditing and cost control requirements.

Competitive bidding is required for public works construction contracts. Equipment specifications for these contracts must be carefully written to assure that the resulting installation satisfies the treatment and disposal requirements at minimum life cycle costs. Where the designer knows of no equal to a specific needed item, he should document the need for such equipment and assure compliance with funding restrictions prior to putting the specification out to public bid. USEPA has recognized the designer's need to achieve better control over the equipment to be used for wastewater treatment systems and is proposing to issue regulations which allow prequalification of critical equipment items.

2.3.3 Time Span of Decisions

Frequently, several years elapse from the choice of a specific process to the operation of that process. This time is usually spent in the necessary work of completing environmental hearings, detailed designs and regulatory reviews, and arranging for funding, construction, and start-up. Furthermore, most facilities must be operated for close to life expectancy to avoid waste of construction funds. During this extended time span, technology may improve, new laws may be passed, new regulations may be issued, and economic factors may change. The engineer must consider these possibilities for change in decision making. He should favor processes that are sufficiently flexible to remain useful in the face of changing technology, regulations, economics, and sludge characteristics.

2.3.4 Uncertainties

The selection of a specific process normally hinges on its cost in comparison with the cost of competing processes. Uncertainties make cost comparisons difficult. For example, consider two competing processes, one labor-intensive, the other requiring expensive chemicals. There are uncertainties as to how many man-hours will be needed per ton of sludge, what chemical additions will be required, and what future cost trends will be. It is often difficult to predict whether labor or chemicals will be more severely affected by inflation. Labor productivity also must be predicted. Given these uncertainties, it may be necessary to say that "Process A is probably more cost-effective," rather than "Process A is more cost-effective." Cost uncertainties are usually greater for processes that are not widely used. There are also uncertainties in the quality of solids that will be produced. For instance, if incineration is selected on the basis of previous dewatering unit production of a cake with 35 percent solids, but only 20 percent solids is actually obtained, then the cost of incineration may become excessive.

Experience at Kenosha, Wisconsin, where one of the first filter presses for sludge in the United States was installed, illustrates the difficulties of making accurate cost estimates. Pilot testing indicated that an optimal lime dose would be equal to 12 percent of the sewage solids fed. In addition a ferric chloride dose equal to 3 percent of the sewage solids fed was required. Full-scale operating experience, however, indicates a 17 percent lime dose is required; therefore, lime costs are 40 percent greater than anticipated. Also, in this plant, only part-time operator attention was anticipated, because the units were fully automated. In practice, full time operation is required. Maintenance costs, assumed to be nominal, have instead been significant, averaging about $3 per ton of dry solids (5).

Whenever possible, the engineer should investigate full-scale working systems to determine actual operating conditions and operating and maintenance costs. If there is insufficient full-scale operating experience to estimate these conditions and costs with confidence, the design engineer must make liberal allowances for uncertainties.

2.3.5 The Design Team

Many factors are important in selecting and designing sludge treatment and disposal processes, for example, capital costs, operating strategies, and environmental effects. Different individuals have different perspectives on wastewater solids management. These individuals should be heard. Therefore, a "design team" concept is helpful. The design team should include:

- Those involved in the day-to-day design effort; that is, the design staff.

- An advisory committee composed of those who are not involved in the day-to-day design effort but who must operate and administer the wastewater solids management system or whose services are required to implement the design; for example, treatment plant operators, public works directors, grant administrators, regulatory officials, engineering reviewers including value engineers, and special consultants. The advisory committee serves in a policy-making and review role.

The advisory committee should be made aware, through clear and accurate reporting, of all aspects of sludge management alternatives, including the design staff's evaluations and recommendations.

The design staff should expect criticism and guidance from the advisory committee. If a proposal or criticism appears to have merit, it should be evaluated with respect to its effect on the solids treatment and disposal scheme. If it does not, the consequences of incorporating it into the design should be clearly explained.

A better project will be achieved by an early exchange of views. While responding to criticism may cause delays early in the project, delays are small in terms of both time and cost compared with those that would be experienced were dissatisfaction to surface late in the project.

2.3.6 Public Involvement

Public involvement in environmental decision making is not only wise, it is mandatory. The National Environmental Policy Act of 1969, the Clean Water Act of 1977 (PL 95-217), and the Resource Conservation and Recovery Act of 1976 (PL 94-580) all require public involvement mechanisms and activities. Acceptance of the project by residents of the community and a working relationship between the public and the design team is essential. Experience has shown that programs are more easily accepted if the public understands what they are.

The relationship between the design staff and the public is similar in many ways to that between the design staff and the advisory committee. The public also serves in a policy-making and review role; it should be made aware of all aspects of sludge management alternatives and should provide criticism and guidance to the design staff. A means of educating the public and creating a dialog between the public and the design staff must be established. Mechanisms for accomplishing this are the mass media, bulletins, public hearings, and presentations to interested groups.

Special efforts should be made to involve groups and individuals who, from past experience, have demonstrated an interest in environmental affairs or those who are likely to be directly affected by the proposed project. Developing a list of interested persons and organizations for formal and informal notifications and contacts is a good way to ensure public participation. The group might consist of:

- Local elected officials.
- State and local government agencies, including planning commissions, councils of government, and individual agencies.
- State and local public works personnel.
- Conservation/environmental groups.
- Business and industrial groups, including Chambers of Commerce and selected trade and industrial associations.
- Property owners and users of proposed sites and neighboring areas.
- Service clubs and civic organizations, including the League of Women Voters.
- Media, including newspapers, radio, and television.

Public participation programs are discussed in detail in two recent publications (6,7).

2.3.7 Social and Political Factors Affecting Waste Export

For metropolitan areas, potential sludge disposal studies generally include land disposal in some form by export to low population open space. Even if these spaces are located in the same political jurisdiction, local opposition towards accepting the wastes of "others" is often intense. If the proposed export is to another political jurisdiction, the opposing forces are generally so great as to effectively preclude this option.

It is often hoped that such opposition can be overcome by public participation and education. However, the social and political factors at work have been demonstrated to be remarkably immune to such efforts.

These comments are not intended to preclude export options but as a caution to designers not to be so swayed by the economic and technical advantages of such plans that inadequate attention is given to alternatives which have a greater possibility of being implemented.

2.4 References

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PROCESS DESIGN MANUAL FOR SLUDGE TREATMENT AND DISPOSAL

Chapter 3. Design Approach

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CHAPTER 3

DESIGN APPROACH

3.1 Introduction and Scope

This chapter presents a methodology for the design of wastewater solids management systems. Topics discussed include systems approach, process selection logic, mass balance calculations, concept of sizing equipment, contingency planning, and other general design considerations such as energy conservation and cost-effective analysis.

3.2 Systems Approach

Overall wastewater treatment plant performance is the sum of the combined performances of the plant's linked components. The actions of one component affect the performance of all the others. For example:

- Materials not captured in solids treatment processes will be returned in the sidestreams to the wastewater treatment system as a recirculating load. This load may cause a degradation in effluent quality, an increase in wastewater treatment costs, and process upsets.

- Failure to remove and to treat solids at the same rate as they are produced within the wastewater treatment system will eventually cause effluent degradation and may increase wastewater treatment operating costs.

- Hydraulic overloads resulting from inadequate solids thickening can cause downstream solids treatment processes (such as, anaerobic digestion) to operate less effectively.

- The addition of chemicals to the wastewater treatment process for purposes of nutrient and suspended solids removal will increase the quantity and alter the characteristics of solids which must be treated and disposed.

It is important to understand the relationship between process parameters and the performance of processes, for example, how thickener feed rate affects thickener performance. It is equally important to understand how individual processes affect one another when combined into a system, for instance, how the performance of the thickener affects digestion and dewatering. Interactions between the processes in a system are described in this chapter.

3.3 The Logic of Process Selection

Wastewater treatment and wastewater solids and disposal systems must be put together so as to assure the most efficient utilization of resources such as, money, materials, energy, and work force in meeting treatment requirements. Logic dictates what the process elements must be and the order in which they go together.

A methodical process of selection must be followed in choosing a resource-efficient and environmentally sound system from the myriad of treatment and disposal options available. The basic selection mechanism used in this manual is the "principle of successive elimination," an iterative procedure in which less effective options are progressively culled from the list of candidate systems until, only the most suitable system or systems for the particular site remain.

The concept of a "treatment train" has been propounded as a result of a systems approach to problem solving. However, this concept is useful only if all components of the train are considered. This includes not only sludge treatment and disposal components, but wastewater treatment options and other critical linkages such as sludge transportation, storage, and side stream treatment. The successful devlopment of a treatment train from a collection of individual components depends on a rigorous system selection procedure, or logic. For large plants, system selection is complex and a methodical approach is required. Progressive and concurrent documentation of the procedure is mandatory in that it prevents a cursory dismissal of options. For smaller plants (that is, <1 MGD) the system choices are often necessarily more obvious and the selection procedure is usually shorter and less complex.

The general sequence of events in system selection is:

1. Selecting relevant criteria.

2. Identifying options.

3. Narrowing the list of candidate systems.

4. Selecting a system.

3.3.1 Identification of Relevant Criteria

Criteria for system selection must be pinpointed prior to system synthesis. A listing of potential criteria for consideration is shown on Figure 3-1. The list is not necessarily complete and planners may find other criteria which they wish to include. The relative importance of each criterion will vary from site to site. For example, reliability may be most important at one site, whereas minimizing costs may be paramount at another. Criteria deemed relevant for each site in question are subsequently used in the system selection procedure (see Section 3.3.3).

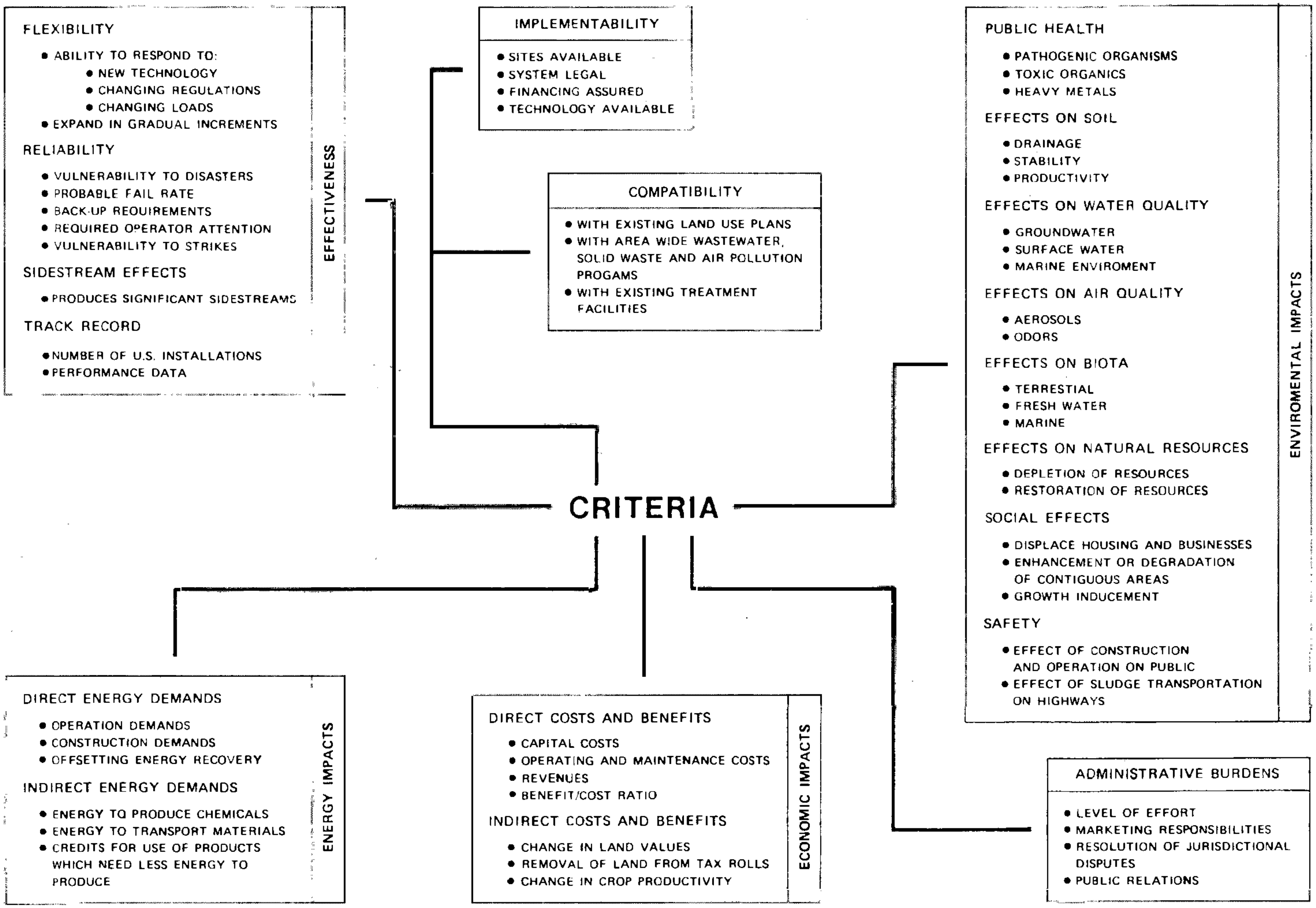

FIGURE 3-1

CRITERIA FOR SYSTEM SELECTION

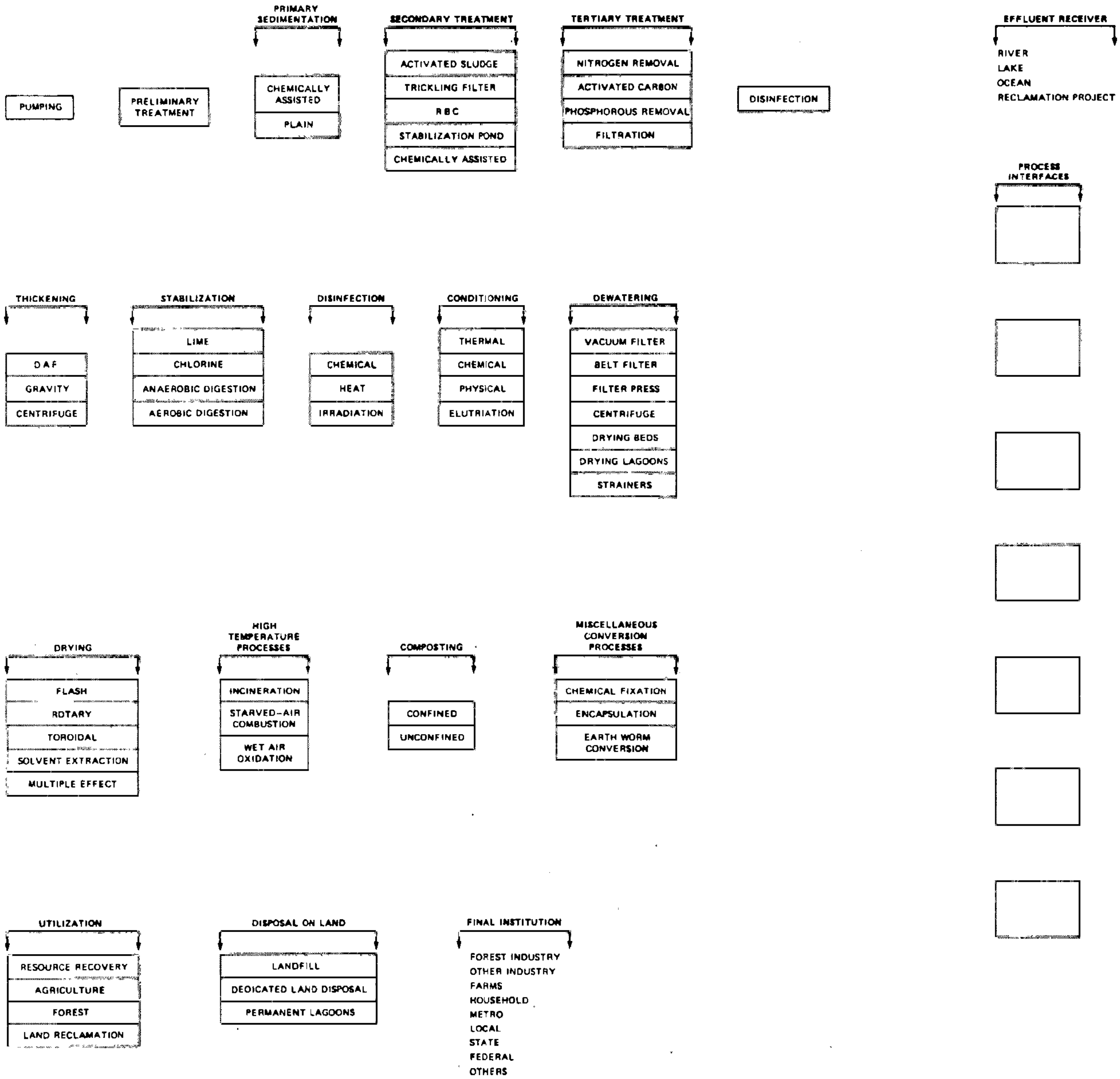

FIGURE 3-2

COMPONENTS FOR SYSTEM SYNTHESIS

3.3.2 Identification of System Options

Candidate systems are synthesized from an array of components, such as these shown on Figure 3-2. Wastewater and solids management components are listed as a reminder that all components of the train must be considered. Figure 3-3 illustrates how Figure 3-2 can be used to develop a specific flow sheet. Process streams can be drawn on copies of the master drawing. Relevant information such as solids concentrations and mass flow rates can be entered directly on the flow sheet, if desired. The advantages of using arrays such as Figure 3-2 are that nearly all potential options are identified and process streams are clearly displayed.

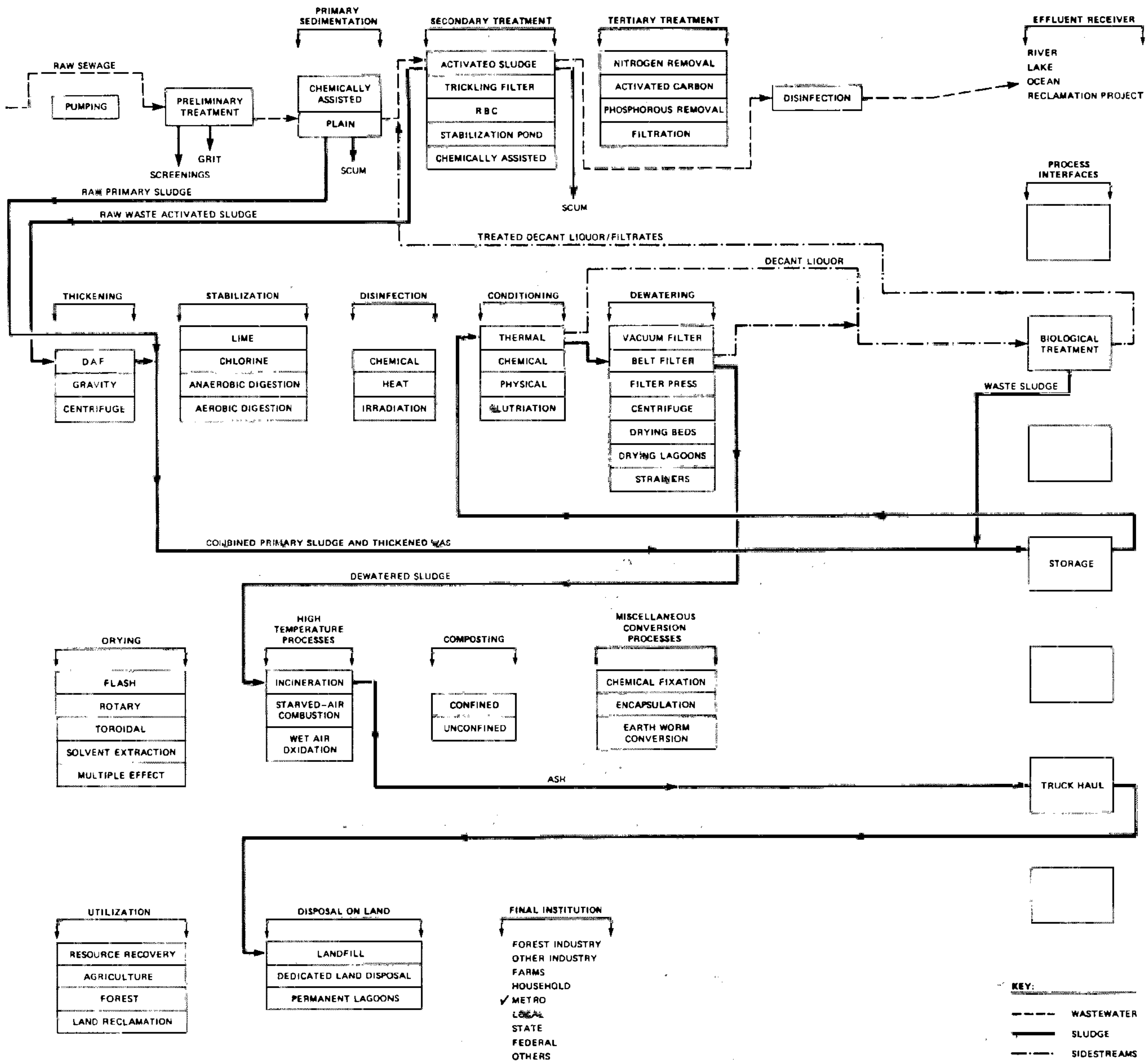

FIGURE 3-3

FLOWSHEET DEVELOPED FROM COMPONENTS FOR SYSTEM SYNTHESIS

3.3.3 System Selection Procedure

The process selection procedure consists of (1) developing treatment/disposal systems which are compatible with one another and appear to satisfy local relevant criteria, and (2) choosing the best system or systems by progressive elimination of weaker candidates. Related to these are the concepts of base and secondary alternatives.

3.3.3.1 Base and Secondary Alternatives

A base alternative is defined as a wastewater solids management system which, during evaluation, appears able to provide reliable treatment and disposal at all times under all circumstances for sludges. It therefore meets the prime criterion of reliability.

It must also satisfy the following seven conditions:

1. It must be legally acceptable.

2. Sites for processing and disposal operations must be readily available.

3. Environmental and health risks must be sufficiently low to satisfy the public and all agencies having jurisdiction.

4. It must be competitive with cost to other alternatives on a first-round analysis.

5. The necessary equipment and material must be readily available.

6. The contractor must be able to begin construction immediately following design and have the system operational almost immediately after construction.

7. Financing of the system must be straightforward and assured.

A secondary alternative is defined as a wastewater solids management system which does not meet the prime criterion of reliability, that is, the system cannot accept all of the sludge under all circumstances all of the time. This does not mean secondary alternatives are without value; they may in fact be used to great advantage in tandem with base alternatives and may in fact accept a greater quantity of sludge than the base alternative. As an example, a city's horticultural market may be insufficiently developed to accept all of the city's sludge all of the time; therefore, horticulture cannot be considered a base disposal alternative. However, it may cost less to release the sludge to horticulture than to dispose of it by means of city's base disposal alternative, for example, landfilling. The city should therefore make every effort to dispose of as many solids as possible via horticulture, the secondary alternative. However, should the secondary alternative fail or be interrupted for any reason, the sludge going to the secondary system must be readily and quickly diverted back to the base alternative, which must remain fully operational and thus immediately capable of receiving the entire sludge flow.

3.3.3.2 Choosing a Base Alternative: First Cut

The purpose of the first cut is to rapidly and with minimum effort produce a list of candidate base alternatives which are technically feasible and reasonably cost-effective. The alternatives must be environmentally acceptable and implementable in the time frame of the project. Analyses are qualitative at this stage. The first cut involves determination of:

1. Practical base disposal options.

2. Practical base solids treatment systems.

3. Practical treatment/disposal combinations.

Determination of Practical Base Disposal Options

The method of solids disposal usually controls the selection of solids treatment systems and not vice versa. Thus, the system selection procedure normally begins when the solids disposal option is specified.

In the first cut, feasible base disposal alternatives and relevant criteria are set up in matrix form. An example is shown in Table 3-1. Feasible alternatives are those which appear to be suitable for the situation at hand. Obviously inapplicable alternatives would not be included in this matrix. Only those criteria which the planner see's as critical for the site at hand should be considered in this first cut. Other, less critical criteria can be considered in subsequent iterations, where more in-depth investigation is needed for each of the candidate processes.

For the hypothetical situation described in Table 3-1, nine utilization/disposal options are considered feasible and are set up for evaluation. The criteria most important to the site are judged to be reliability, environmental impacts, site availability and cost. Base disposal alternatives are judged to be practical only if they satisfy all the relevant criteria. In Table 3-1, utilization of sludge on private agricultural land is an unacceptable base disposal alternative. Reasons for this might be insufficient acreage or a lack of assurance that the farmers would accept all of the sludge. Alternatives which would seem to satisfy relevant criteria for base disposal alternatives are utilization on public agricultural land, landfill, and dedicated land disposal. Before considering these, however, one must determine what combinations of solids treatment processes make sense for the site in question.

TABLE 3-1

EXAMPLE OF INITIAL SCREENING MATRIX FOR BASE SLUDGE DISPOSAL OPTIONS

Utilization/disposal options	Relevant criteria				
	Reliability	Environmental impacts	Site availability	Cost	Acceptable for base alternative
Bag-market as fertilizer	O[a]	X[b]	X	X	O
Agricultural land (private)	O	X	X	X	O
Agricultural land (public)	X	X	X	X	X
Forested land (private)	O	X	O	O	O
Forested land (public)	X	X	O	O	O
Give to citizens (horticulture)	O	X	X	X	O
Combine with commercial topsoil	O	X	X	X	O
Dedicated land disposal	X	X	X	X	X
Landfill	X	X	X	X	X

[a]O = unacceptable.
[b]X = acceptable.

Determine Practical Base Treatment Systems

Table 3-2 illustrates process compatibility matrix for treatment alternatives. Incompatible processes and processes which are not applicable in given locations are eliminated. The combination of drying beds and mechanical dewatering, for example, is considered incompatible because both dewatering and drying take place on the drying bed; mechanical dewatering is not needed. On the other hand, the combination of incineration and mechanical dewatering of unstabilized sludge is generally compatible, but for the hypothetical case investigated is ruled out because of air pollution considerations. After first-cut analysis, seven base treatment options are considered feasible and are further evaluated.

Determine Practical Base Treatment/Disposal Combinations

Practical base treatment and disposal combinations are then combined in a matrix, which is subjected to further culling. Table 3-3 shows the matrix of base treatment/disposal combinations made by bringing forward the base disposal and treatment options from Tables 3-1 and 3-2. Incompatible combinations and systems ruled out by local constraints are then eliminated. For example, undewatered wastewater solids are not generally disposed of in landfills. An example of local constraints is the ruling out of applying lime stabilized sludge on agricultural lands because of already high soil pH.

TABLE 3-2

EXAMPLE OF PROCESS COMPATIBILITY MATRIX

	Digestion options		Undigested sludge options				
	Anaerobically or aerobically digested		Not stabilized		Lime stabilized	Thermally conditioned	Wet air oxidation
Final processing step	Mechanically dewatered	Not dewatered	Mechanically dewatered	Not dewatered	Mechanically dewatered	Mechanically dewatered	Mechanically dewatered
No further processing	X[a]	X	O[b]	O	X	Ø[c]	Ø
Drying beds	O	X	O	O	O	O	O
Heat dry	X	O	O	O	O	O	Ø
Pyrolysis	O	O	Ø	O	O	Ø	O
Incineration	O	O	Ø	O	O	Ø	O
Compost	X	O	X	O	O	O	O

[a]X = generally compatible.
[b]O = generally not compatible.
[c]Ø = generally compatible, but ruled out by local constraints.

TABLE 3-3

EXAMPLE OF TREATMENT/DISPOSAL COMPATIBILITY MATRIX

	Treatment options						
	Digested sludge options					Undigested sludge options	
Viable local disposal options	Mechanically dewatered	Mechanically dewatered, heat dry	Mechanically dewatered, compost	Not mechanically dewatered	Not mechanically dewatered, drying beds	Mechanically dewatered, composted	Lime stabilized, mechanically dewatered
Agricultural land (public)	X[a]	X	X	X	X	X	Ø[b]
Landfill	X	X	O[c]	O	X	X	X
Dedicated land disposal	X	X	O	X	X	X	Ø

[a]X - generally compatible.
[b]Ø - generally compatible, but ruled out by local considerations.
[c]O - generally not compatible.

The number of candidate base treatment/disposal systems is thus reduced. For the hypothetical case of Table 3-3, sixteen systems remain for further evaluation.

3.3.3.3 Choosing a Base Alternative: Second Cut

The purpose of second-cut analyses is to further reduce the list of candidate systems. Analyses are more quantitative than in the first cut, but the level of effort used to investigate each option is not yet intensive. Information used in the second cut is general and readily available, for instance, equipment cost curves which are not site-specific, areawide evaluation of soils, geology, hydrology, topography and land use, and general energy costs.

One approach is to set up a numerical rating system for the remaining candidate systems, such as that shown in Table 3-4. The list of criteria to be considered may be expanded beyond those critical criteria used in first cut analyses to encompass the full range of criteria listed on Figure 3-1, or any fraction of it. This follows the principle that as the list of candidate process narrows, each will be analyzed in greater detail.

TABLE 3-4

EXAMPLE OF NUMERICAL RATING SYSTEM FOR ALTERNATIVES ANALYSIS

		Ratings of alternatives										
		Alternative 1		Alternative 2		Alternative 3		Alternative 4		. . . .	Alternative n	
Categories and criteria	Relative weight[a]	AR[b]	WR[c]	AR	WR	AR	WR	AR	WR		AR	WR
Effectiveness												
- Flexibility	3	4	12	6	18	9	27	5	15	. . . .	6	18
- Reliability	5	3	15	5	25	5	25	2	10	. . . .	2	10
- Sidestream effects	3	10	30	9	27	5	15	6	18	. . . .	7	21
- Track record	2	5	10	7	14	4	8	9	18	. . . .	6	12
Compatibility												
- With existing land use plans	2	8	16	8	16	8	16	7	14	. . . .	4	8
- With areawide wastewater, solid waste and air pollution programs	3	3	9	6	18	3	9	5	15	. . . .	7	21
- With existing treatment facilities	4	5	20	5	20	6	24	8	32	. . . .	3	12
Economic impacts												
- Net direct costs	4	7	28	8	32	8	32	9	36	. . . .	7	28
- Net indirect costs	1	8	8	9	9	6	6	3	33	. . . .	8	8
Environmental impacts												
- Public health	5	7	35	6	30	4	20	6	30	. . . .	7	35
.	.	.	.	.	.	.	.	.	.	. . . .	.	.
.	.	.	.	.	.	.	.	.	.	. . . .	.	.
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.	.	.	.	.	.	.	.	.	.	. . . .	.	.
Administrative burdens												
- Level of effort	1	4	4	6	6	5	5	7	7	. . . .	4	4
- Marketing responsibilities	2	5	10	5	10	4	8	7	14	. . . .	9	18
- Resolution of jurisdictional disputes	1	3	3	4	4	4	4	4	4	. . . .	2	2
- Public relations	2	4	8	2	4	5	10	5	10	. . . .	3	6
Total weighted alternative rating[d]	-	-	1,576	-	1,430	-	963	-	840	. . . .	-	1,317

[a]Relative importance of criteria as perceived by reviewer; scale, 0 to 5; no importance rated zero, most important rated 5.

[b]Alternative rating. Rates the alternatives according to their anticipated performance with respect to the various criteria; scale 0 to 10; least favorable rated zero, most favorable rated 10.

[c]Weighted rating. Relative weight for each criteria multiplied by alternative rating.

[d]Sum of weighted ratings for each alternative.

In the second cut, subjective judgments are combined with technical measurements. Numerical values are assigned to all criteria for all alternative systems. The planner's perception of the relative importance of each criterion is indicated on a rating scale, say of 0 to 5, with highest ratings given to criteria the planner considers to be of greatest importance, and the lowest to those of least important. For example, if reliability is highly valued for the site in question, reliability may be assigned a relative weight of 5.

Next, each alternative system is rated according to its anticipated performance with respect to the various criteria, again by using a rating scale, say 0 to 10. An alternative which rates favorably is given high scores; one which rates less favorably is given lesser scores. For example, an alternative which is not dependable may be rated at 2 with respect to reliability.

The relative weight is then multiplied by the alternative rating to produce a weighted rating for each criteria/alternative combination. For the examples described in the previous two paragraphs, the weighted rating for the alternative in question with respect to reliability is 5 x 2 = 10.

Finally, the weighted ratings are summed for each alternative to produce a total or overall rating. Systems with lowest overall ratings are eliminated, with higher rated systems carried forward for further evaluations. In the example shown in Table 3-4, Alternatives 3 and 4 are eliminated and Alternatives 1, 2, and n are carried forward.

3.3.3.4 Third Cut

The third cut uses the same methodology as the second, but the number of alternatives remaining is more limited; typically to a maximum of 3 to 5--and the analysis is more detailed. Information may include:

- Analyses of potential sludge disposal sites (soils, geology, and groundwater).
- Local surveys to determine marketability of sludge and sludge by-products.
- Possible effects of industrial source control/ pretreatment programs on process viability and quality of sludge for disposal.
- Data oriented literature search.
- Detailed analysis of effect of candidate systems on the environment (air, water, land).

- Information developed from site-specific pilot work.
- Mass balances.
- Energy analyses.
- Detailed cost analyses.

3.3.3.5 Subsequent Cuts

Subsequent cuts are even more detailed. Analyses are repeated until the optimum base treatment/disposal alternative is defined.

3.3.4 Parallel Elements

By means of the procedure discussed above, a base alternative is selected. However, the optimum system may include more than just this base alternative. A number of parallel elements may be involved which provide flexibility, reliability, and operating advantages. For example, the base alternative for the system depicted on Figure 3-4 is thickening, anaerobic digestion, storage in facultative sludge lagoons, and spreading of liquid sludge on agricultural land. Parallel elements cosnsist of the application of liquid sludge on forest land and drying beds followed by distribution for horticultural purposes. If horticultural and forest land outlets were each large enough to accept all of the sludge under all circumstances and at all times, three base alternatives are then available. If not, the forest land and drying beds/horticulture applications would be considered secondary alternatives.

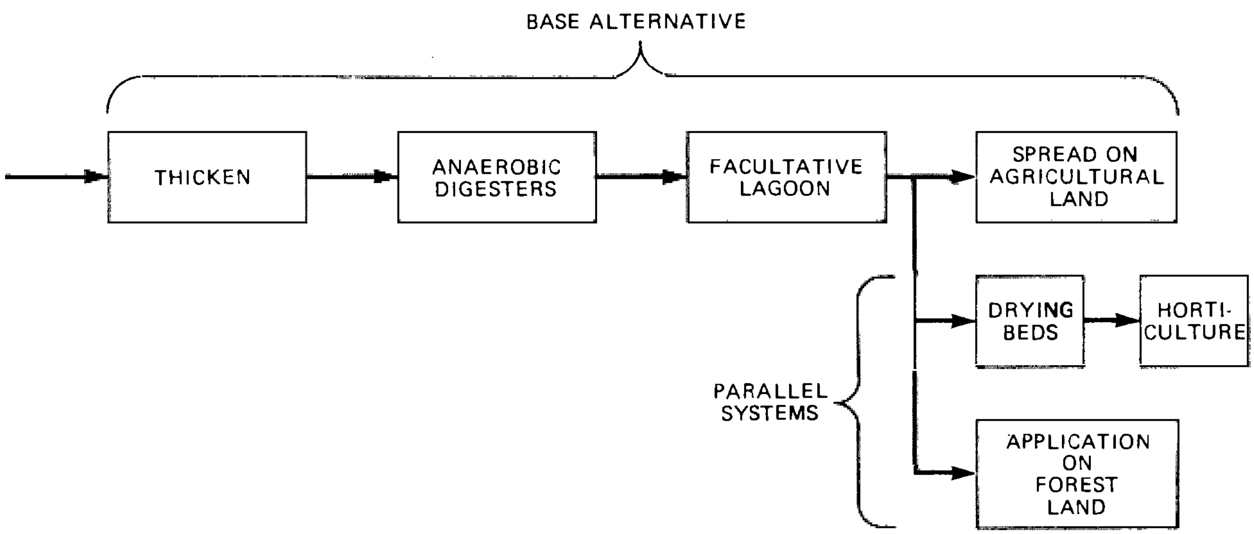


FIGURE 3-4

PARALLEL ELEMENTS

The concept of providing for more than one base alternative may at first seem contradictory but a given base alternative might not always be reliable because unpredictable events might occur. For example, new owners of farmland may decide they do not wish to accept sludge, or a disaster or strike could interrupt one method of transporting sludge to its ultimate destination. To minimize risks, therefore municipalities may wish to provide more than one base alternative. The selection procedure presented in Section 3.3.3 has the advantage of clearly depicting which is the second or even third most desirable base alternative.

Parallel base alternatives are more common in large systems, which are generally located in urban areas where land is scarce than in small plants, which are usually located in rural areas where land is more plentiful and temporary storage and disposal options therefore more numerous. Large plants may maintain two or three base alternatives to ensure solids disposal. Since this may increase the cost of operation, it leads to the observation that very large systems do not necessarily benefit from economies of scale when it comes to wastewater solids disposal.

3.3.5 Process Selection at Eugene, Oregon

Eugene, a city of 100,000 people, is located at the southern end of the agricultural Willamette Valley in Western Oregon. The Metropolitan Wastewater Management Commission (MWMC) was formed in 1977 to implement the findings of a facility planning effort which called for the construction of a regional sewage treatment plant. The plant, to be constructed on the site of the existing Eugene plant, will serve the whole metropolitan area. This area is composed of the cities of Eugene, Springfield, and urbanized portions of Lane County.

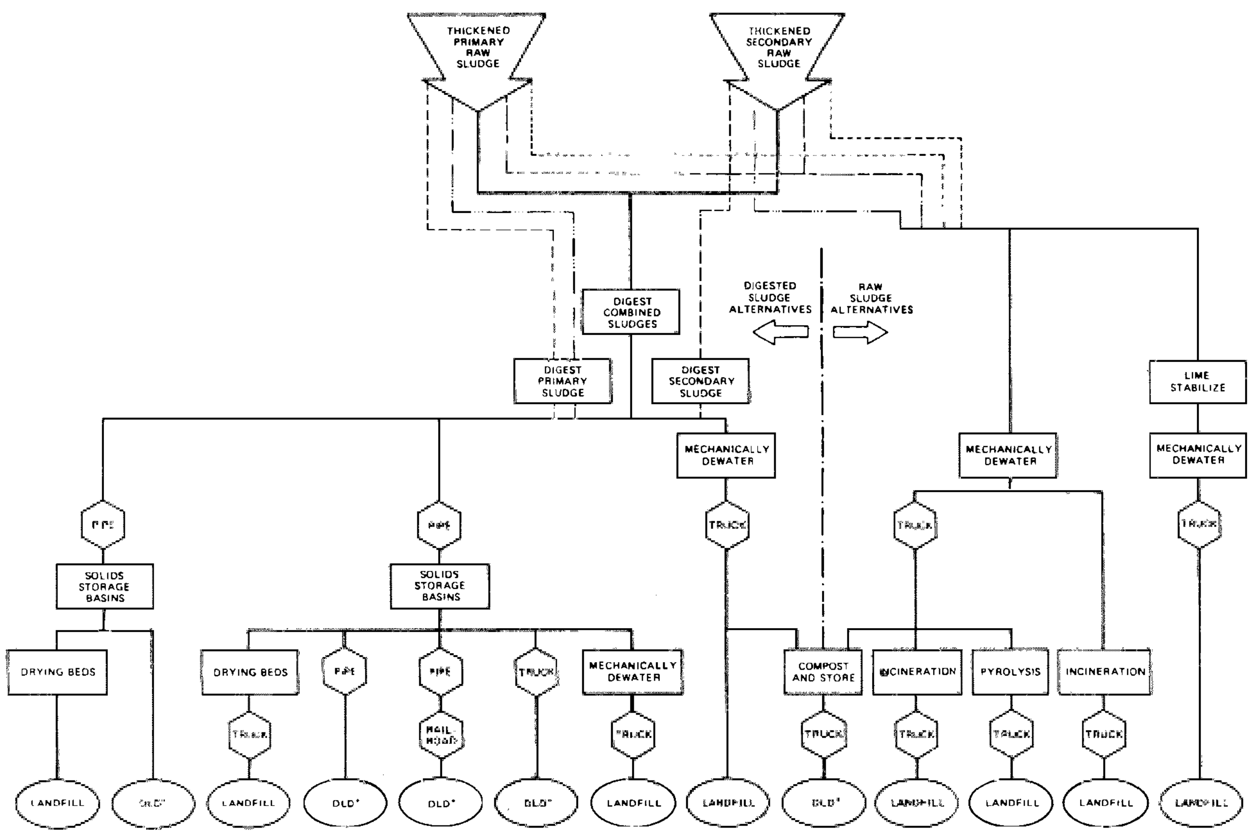
Regionalization and upgrading of the plant to meet a 10/10 summer effluent standard for BOD_5 and suspended solids prior to discharge to the Willamette River, means that sludge quantities are dramatically increased. The plant is to serve a population of 277,000 by the year 2000. Design average dry weather flow is 49 MGD (2.15 m^3/s), wet weather flow is 70 MGD (3.07 m^3/s), and peak wet weather flow is 175 MGD (7.67 m^3/s).

The plant will use an activated sludge process, with flexibility for operation in plug, step, contact stabilization, or complete mix modes. Provision is also made for the addition of mechanical flocculators in the secondary clarifiers and tertiary filtration if either or both prove desirable at a later date.

It was decided early that sludge thickening would be economical, regardless of the sludge management system which would eventually be used. Consequently, two existing thickeners, one gravity and one flotation, will be retained for thickening primary sludge, waste-activated sludge, or a combination of the two.

A key provision in the selection of a suitable sludge management system was that the system be fully operational by the time the wastewater treatment system is started up. This seemingly straightforward condition was complicated by the fact that planning for the sludge system did not start until design of the wastewater treatment plant was already under way. This meant that the sludge management system would be forced to fit into an already developed plan for the wastewater treatment facility (which is by no means unusual).

As a first cut, sludge disposal options were immediately developed and screened for acceptability as part of a base alternative, using a matrix similar to that developed in Table 3-1. Practical treatment systems were identified from a process compatibility matrix similar to Table 3-2. Practical disposal/processing combinations were then developed in a matrix form (as in Table 3-3). Physically incompatible or otherwise unsuitable combinations were eliminated in this matrix. A flowsheet was then prepared for the remaining options, with necessary intermediate storage and transport requirements added in. The flowsheet of alternatives for Eugene second cut analysis is shown on Figure 3-5.



*DLD - DEDICATED LAND DISPOSAL

FIGURE 3-5

CANDIDATE BASE ALTERNATIVES FOR EUGENE-SPRINGFIELD

It is worth noting that utilization on agricultural land could not be considered as a base alternative despite the large agricultural acreage north of Eugene and the fact that the new regional plant is on the north side of the city. It would have been a requisite that MWMC own sufficient farmland (2,000 to 3,000 acres) to accept all of the sludge generated. The cost of purchasing such acreage was deemed unacceptably high; furthermore, there was opposition to converting private land to public land. Thus agricultural utilization was not considered further in the search for a base alternative.

The second cut analysis was more quantitative. Information used was general and readily available. For example, costs were taken from current cost curves, and certain environmental impacts were assessed from projects with similar disposal systems and soil/groundwater conditions. With numerical data established for each criterion, a rating table was produced similar to that of Table 3-4. The data were developed by the project engineers, but the ratings were analyzed extensively by the Citizens Participation Committee (CPC) on sludge management which had been recruited from the population at large at the very beginning of the project. The committee was composed of various vested interest groups, representatives of government agencies and private unaffiliated citizens who were interested in the project.

Systems with the lowest total ratings were then eliminated. Incineration was found to be unacceptable primarily because it would impact the already limited dilution capacity available during the summer in the trapped valley airshed of Eugene; pyrolysis was eliminated primarily because of its perceived inability to meet the construction deadline for plant start-up; and lime stabilization with disposal to landfill was eliminated primarily on a cost-effective basis. At the end of the second cut analysis, all alternatives which could accommodate raw sludges were eliminated, since, as indicated, most raw sludge options (incineration, pyrolysis, lime stabilization) were not viable and there was a strong desire to make use of existing digesters. A decision was made to combine primary and secondary sludge in order to avoid the cost and problems of constructing and operating separate systems for each.

The same methodology used in the second cut was used in the third; however, data used in the analysis were more site specific, so that economic and environmental comparisons could be better refined. As examples:

- Actual routes were selected to off-site facilities; river crossings were defined, and decisions were made on routing pipes under bridges or jacking under freeways.
- For disposal at the local sanitary landfill, estimates were made of (1) the contribution of the sludge to landfill leachate production and subsequent marginal leachate treatment costs to be passed back from the

Lane County Solid Waste Division to MWMC, and (2) the actual net volume of landfill required for sludge disposal, allowing for sludge consolidation.

- For dedicated land disposal, seasonal water tables and detailed groundwater migration patterns, as well as private well locations and depths were determined.

- Estimates were made of comparative nitrate loadings which would eventually reach the Willamette River from treated landfill leachate discharge; from groundwater migration from dedicated land disposal; and from filtrates from mechanical sludge dewatering (which is subsequently discharged with the effluent).

- Transportation modes were analyzed in detail and costed for various sludge solids concentrations and transport routes and distances.

These detailed analyses still left a number of viable base alternatives. At this point, other less tangible factors were considered. These were (1) that the chosen base alternative(s) be compatible with desired secondary alternatives, and (2) that flexibility and reliability be provided through the use of parallel systems. After intensive screening, it was decided that two base alternatives would be used: spreading of liquid sludge on dedicated land and open-air drying followed by landfill disposal. Both alternatives included force main transport of digested sludge from the regional treatment plant to a remote sludge management site, where the sludge was to be stored in facultative sludge lagoons. Liquid sludge would be spread on dedicated land at the sludge management site. Dried sludge would be trucked to landfill. Operations associated with disposal (spreading, drying, and landfilling) would be carried out during dry weather. These systems provide the desired flexibility and reliability and are compatible with preferred secondary alternatives.

Several variations of sludge utilization on land were adopted as secondary alternatives, since there was a strong feeling that sludge should be used beneficially. The alternatives of particular interest to the Eugene-Springfield area included agricultural use on private farm land, use for ornamental horticulture, in nurseries and public parks, and use in a mixture with commercial topsoils in landscaping. Sludge would be provided to these outlets as the market demands. Variable demand is particularly important in Oregon's Willamette Valley, where prolonged winter rainfall and summer harvesting schedules control the timing of agricultural sludge use.

The flowsheet for the Eugene system is shown on Figure 3-6.

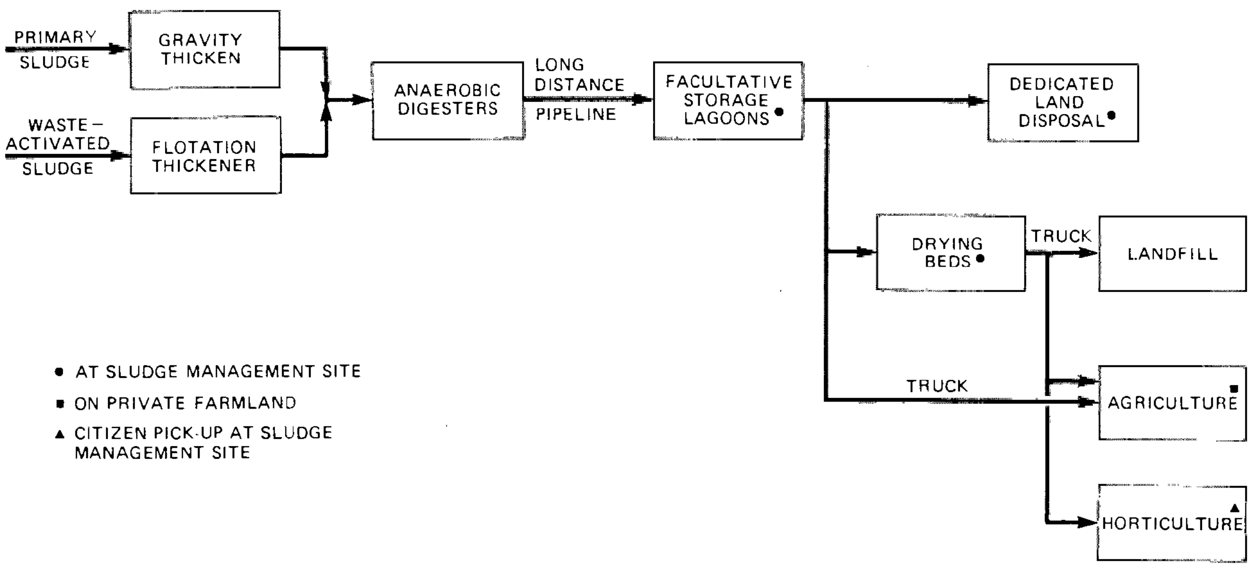


FIGURE 3-6

FLOWSHEET FOR THE EUGENE-SPRINGFIELD SLUDGE MANAGEMENT SYSTEM

The ability to use base facilities and equipment for desired secondary alternatives was a major consideration in selecting the base system. In Eugene, the force main, sludge lagoons, and application equipment to be used for dedicated land disposal of the liquid sludge are also required for agricultural use. Trucks to transport liquid sludge from the sludge management site to agricultural sites will, however, be an additional expense for the secondary alternatives.

It is hoped that eventually all sludge can be utilized on land. As indicated, however, in Table 3-5, full agricultural utilization of sludge is estimated to be more costly than either of the pure disposal options. This is because more equipment is needed to transport sludge to and spread it on the agricultral sites than is needed for the pure disposal options. Thus, as of 1979, any system which even partially incorporates agricultural utilization will be more costly than pure disposal options. This could change if the farmers can be persuaded to pay for the sludge.

TABLE 3-5

ESTIMATED COSTS OF ALTERNATIVES FOR EUGENE-SPRINGFIELD

Sludge form	Alternative	Total annual cost, million dollars
Liquid	Dedicated land disposal only	1.03
	Agricultural utilization only	1.53
Dried	Landfill only	1.14
	Agricultural utilization only	1.32

At the time this manual was written (1979), MWMC was involved in public hearings aimed at selecting a suitable sludge management site.

3.4 The Quantitative Flow Diagram

Overall system performance is the sum of the combined performances of the system's linked processes. This is nowhere more clearly expressed than on a Quantitative Flow Diagram (QFD). The QFD is used to estimate loadings to the various wastewater treatment, solids treatment, and solids disposal processes. The QFD is the starting point for understanding process interactions and is nothing more than a materials balance. Although balances can be struck for components like nitrogen, phosphorus and chemical oxygen demand, the most useful balances are those for suspended solids. The QFDs to be presented here are for suspended solids. Each flowsheet has its own unique set of balance equations. In the following pages, mass balances for a specific, rather simple flowsheet are derived, thus illustrating the technique. The mass balance equations are then summarized in tabular form. Mass balance equations for a more complex and more common flowsheet are later presented, without derivation. Two worked QFDs are presented as examples. The intent is to demonstrate the usefulness of the method.

3.4.1 Example: QFD for a Chemically Assisted Primary Treatment Plant

The flowsheet for a chemically assisted primary wastewater treatment plant with anaerobic digestion and mechanical dewatering of the sludge is shown on Figure 3-7. In this example chemicals are added to enhance the sedimentation process. Sidestreams from the digester and dewatering units are recycled to the primary sedimentation basin. The calculation is carried out in a step-by-step procedure:

1. Draw the flowsheet (as on Figure 3-7).

2. Identify all streams. For example, stream A contains raw sewage solids plus chemical solids generated by dosing the sewage with chemicals. Let the mass flow rate of solids in Stream A be equal to A lb per day.

3. For each processing unit, identify the relationship of entering and leaving streams to one another in terms of mass. For example, for the primary sedimentation tank, let the ratio of solids in the tank underflow (E) to entering solids (A + M) be equal to X_E. X_E is actually

an indicator of solids separation efficiency. The general form in which such relationships are expressed is:

$$X_\Theta = \frac{\text{mass of solids in stream } \Theta}{\text{mass of solids entering the unit}}$$

For example, $X_P = \frac{P}{K + S}$, $X_J = \frac{J}{E}$. The processing unit's performance is specified when a value is assigned to X_Θ.

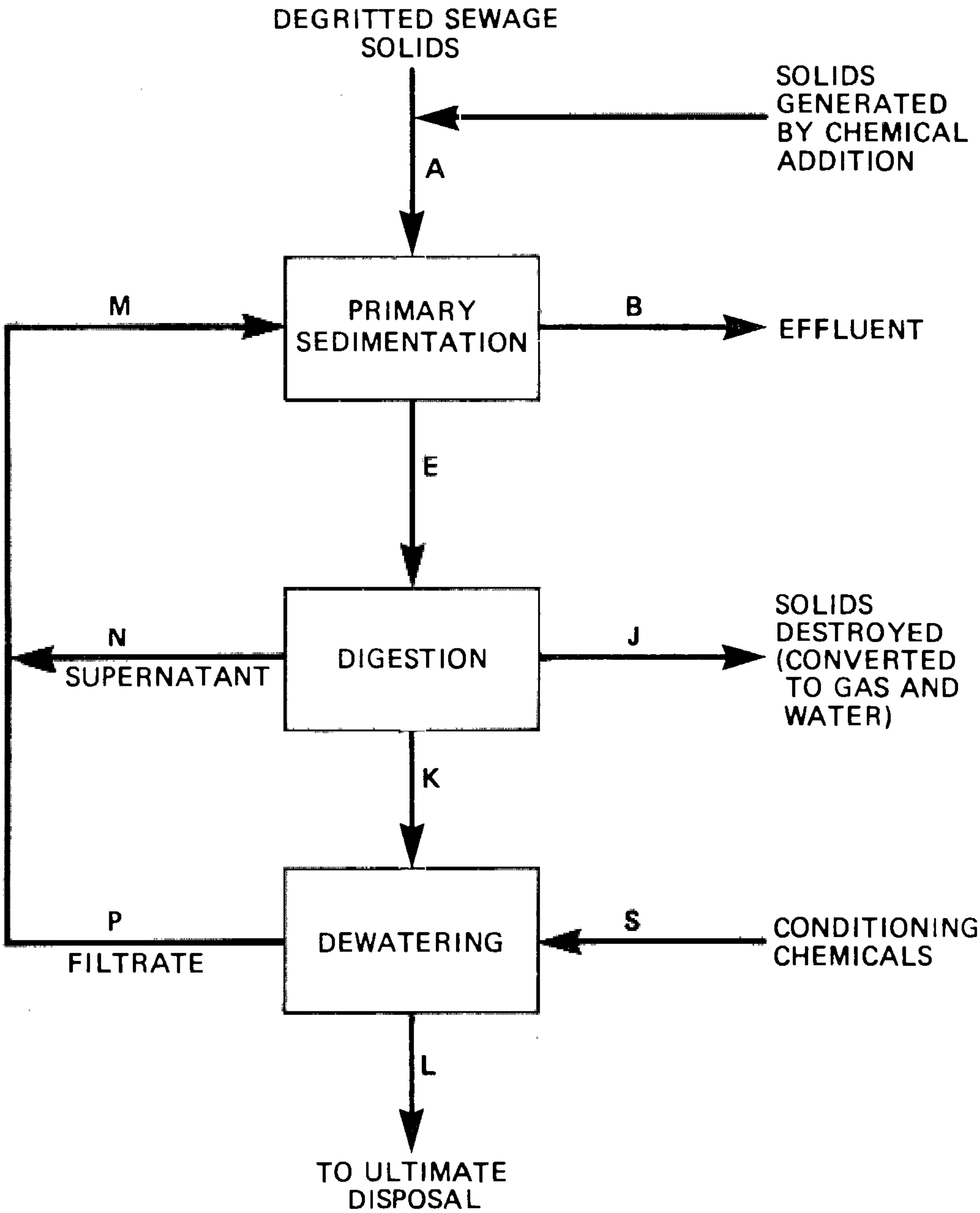


FIGURE 3-7

BLANK QFD FOR CHEMICALLY-ASSISTED
PRIMARY PLANT

4. Combine the mass balance relationships so as to reduce them to one equation describing a specific stream in terms of given or known quantities. In the calculation to be presented, expressions will be manipulated until E, the primary solids underflow rate, can be expressed in terms of A, X_E, X_J, X_N, X_P, and X_S, quantities which the designer would know or assume from plant influent surveys, knowledge of water chemistry and an understanding of the general solids separation/destruction efficiencies of the processing involved. The calculation is carried out as follows:

   a. Define M by solids balances on streams around the primary sedimentation tank:

   $$X_E = \frac{E}{A + M} \qquad (3\text{-}1)$$

   Therefore,

   $$M = \frac{E}{X_E} - A \qquad (3\text{-}2)$$

   b. Define M by balances on recycle streams:

   $$M = N + P \qquad (3\text{-}3)$$

   $$N = X_N E \qquad (3\text{-}4)$$

   $$P = X_P(S + K) \qquad (3\text{-}5)$$

   $$S = X_S K \qquad (3\text{-}6)$$

   Therefore,

   $$P = X_P(1 + X_S)K \qquad (3\text{-}7)$$

   $$K + J + N = E \qquad (3\text{-}8)$$

   Therefore,

   $$K = E - J - N = E - X_J E - X_N E = E(1 - X_J - X_N) \qquad (3\text{-}9)$$

   and

   $$P = X_P E(1 - X_J - X_N)(1 + X_S) \qquad (3\text{-}10)$$

   Therefore,

   $$M = E[X_N + X_P(1 - X_J - X_N)(1 + X_S)] \qquad (3\text{-}11)$$

c. Equate equations (3-2) and (3-11) to eliminate M:

$$\frac{E}{X_E} - A = E[X_N + X_P(1 - X_J - X_N)(1 + X_S)]$$

$$E = \frac{A}{\frac{1}{X_E} - X_N - X_P(1- X_J - X_N)(1 + X_S)} \qquad (3\text{-}12)$$

E is now expressed in terms of assumed or known influent solids loadings and solids separation/ destruction efficiencies.

Once the equation for E is derived, equations for other streams follow rapidly; in fact, most have already been derived. These are summarized in Table 3-6.

TABLE 3-6

MASS BALANCE EQUATIONS FOR FLOWSHEET OF FIGURE 3-7

$$E = \frac{A}{\frac{1}{X_E} - X_N - X_P\ (1-X_J-X_N)(1 + X_S)}$$

$$M = \frac{E}{X_E} - A$$

$$B = (1-X_E)(A + M)$$

$$J = X_J E$$

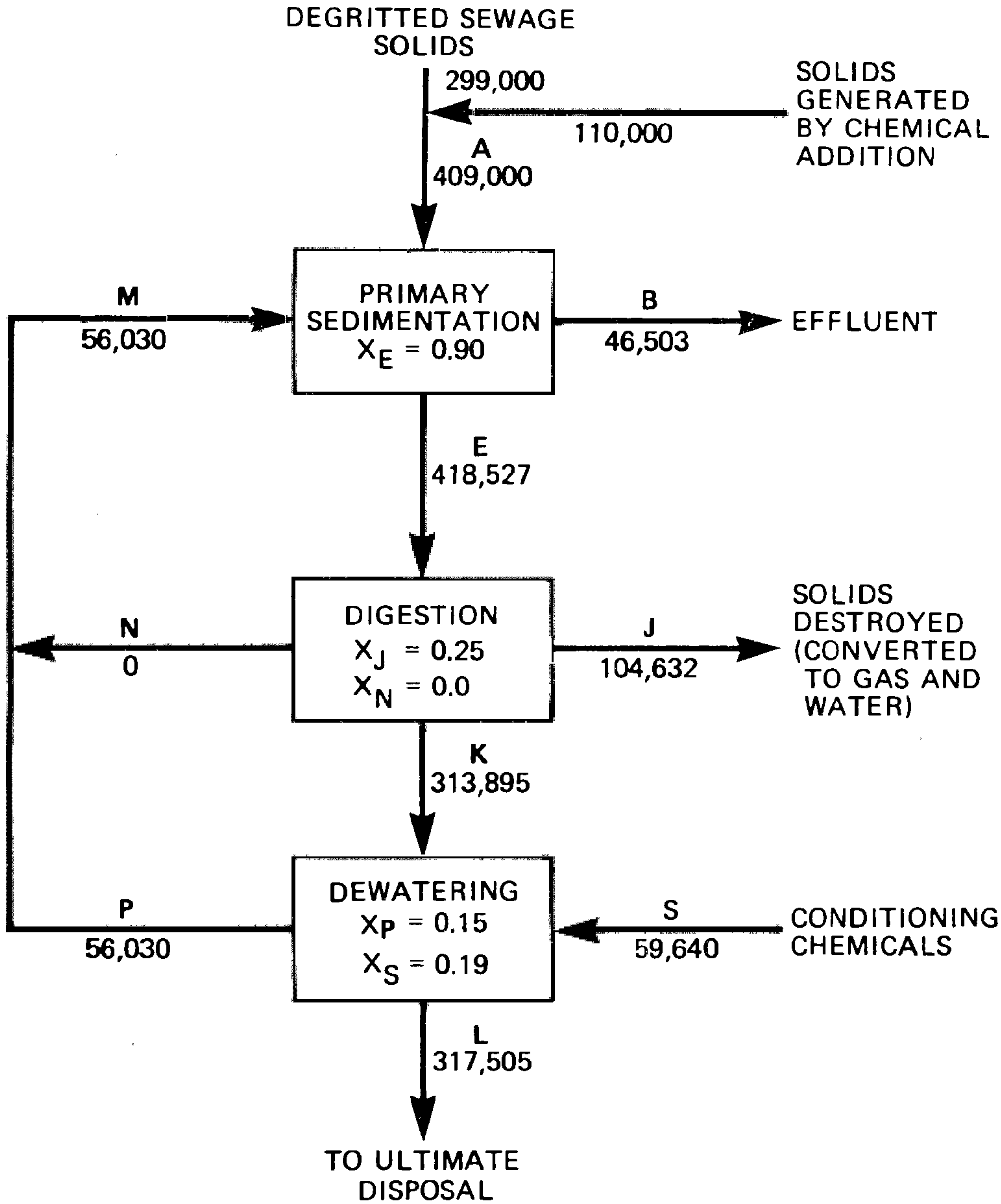
$$N = X_N E$$

$$K = E(1-X_J-X_N)$$

$$S = X_S K$$

$$P = X_P\ (1 + X_S)K$$

$$L = K\ (1 + X_S)(1-X_P)$$



ALL QUANTITIES ARE EXPRESSED IN POUNDS PER DAY

1 lb/day = 0.454 kg/day

FIGURE 3-8

QFD FOR CHEMICALLY-ASSISTED PRIMARY PLANT

Figure 3-8 is a worked example in which all solids flow rates are calculated. For this example the following information was provided:

a. Based on estimates from facility planning studies, average influent suspended solids loading is 299,000 pounds per day (136 t/day). Alum is added to the degritted raw sewage to increase capture. The chemical solids generated as the result of alum addition is estimated at 110,000 pounds per day (50 t/day). The latter figure is derived from pilot work at Seattle, Washington, where the ratio of new solids generated/solids in untreated raw sewage was 0.37/1 when alum ($Al_2(SO_4)_3 \cdot 14H_2O$) additions of 110 to 125 mg/l were added to raw wastewater (1). Therefore, A = 299,000 (1 + 0.37) = 409,000 pounds per day (185 t/day).

b. Primary sedimentation solids capture is 90 percent of the sum of sewage solids, chemical solids and recycle solids which enter the basin. Note that solids capture as usually computed (sewage solids basis only) is only 84.4 percent, i.e.,

$$\left(1 - \frac{\text{effluent suspended solids}}{\text{influent sewage solids}}\right) 100$$

$$= \left(1 - \frac{46,503}{299,000}\right) 100 = 84.4 \text{ percent}$$

c. Twenty-five percent of the suspended solids fed to the digestion system are destroyed, i.e., converted to gas or water (X_J = 0.25). The number assumed is somewhat less than the usual value used (0.30-0.40), since the biodegradable fraction of digester feed in this instance is low because of the large proportion of chemical solids present.

d. Digesters are not supernated (X_N = 0.0).

e. Solids capture in the dewatering units is 85 percent (X_P = 0.15).

f. Conditioning chemicals are 19 percent by weight of digested sludge fed to the dewatering units (X_S = 0.19).

When all loadings are expressed quantitatively and superimposed on the flowsheet, the designer can begin to develop a feel for the process. The effects of recycle loading and individual process efficiencies on overall process performance can be assessed by manipulation of the variables. Calculations can be done very rapidly when the mass balance equations (presented in Table 3-6) are set up for solution on a computer or a programmable calculator.

The investigator must exercise judgment in estimating the various process efficiencies (X_θ). For example, one should assume reduced efficiencies for primary sedimentation if recyle streams contribute large quantities of solids to the sedimentation tank, since recycled solids tend to be less easily removed than fresh solids from the sewer system. Their mere presence in the recycle stream is an indication of the difficulties in separating them.

3.4.2 Example: QFD for Secondary Plant with Filtration

The example just worked was relatively simple. Figure 3-9 shows a more complex system--secondary aerobic biological treatment followed by filtration. Mass balance equations for this system are summarized in Table 3-7. For this flowsheet the following information must be specified.

a. Influent solids (A).

b. Effluent solids (Q), that is, overall suspended solids removal must be specified.

c. X_E, X_G, X_J, X_N, X_R, and X_S are straightforward assumptions about the degree of solids removal, addition or destruction.

d. X_D, which describes the net solids destruction reduction or the net solids synthesis in the biological system, must be estimated from yield data (see Section 4.3.2.4). A positive X_D signifies net solids destruction. A negative X_D signifies net solids growth. In this example 8 percent of the solids entering the biological process are assumed destroyed, i.e., converted to gas or liquified.

Note that alternative processing schemes can be evaluated simply by manipulating appropriate variables. For example:

a. Filtration can be eliminated by setting X_R to zero.

b. Thickening can be eliminated by setting X_G to zero.

c. Digestion can be eliminated by setting X_J to zero.

d. Dewatering can be eliminated by setting X_P to zero.

e. A system without primary sedimentation can be simulated by setting X_E equal to approximately zero, e.g., 1×10^{-8}. X_E cannot be set equal to exactly zero, since division by X_E produces indeterminate solutions when computing E.

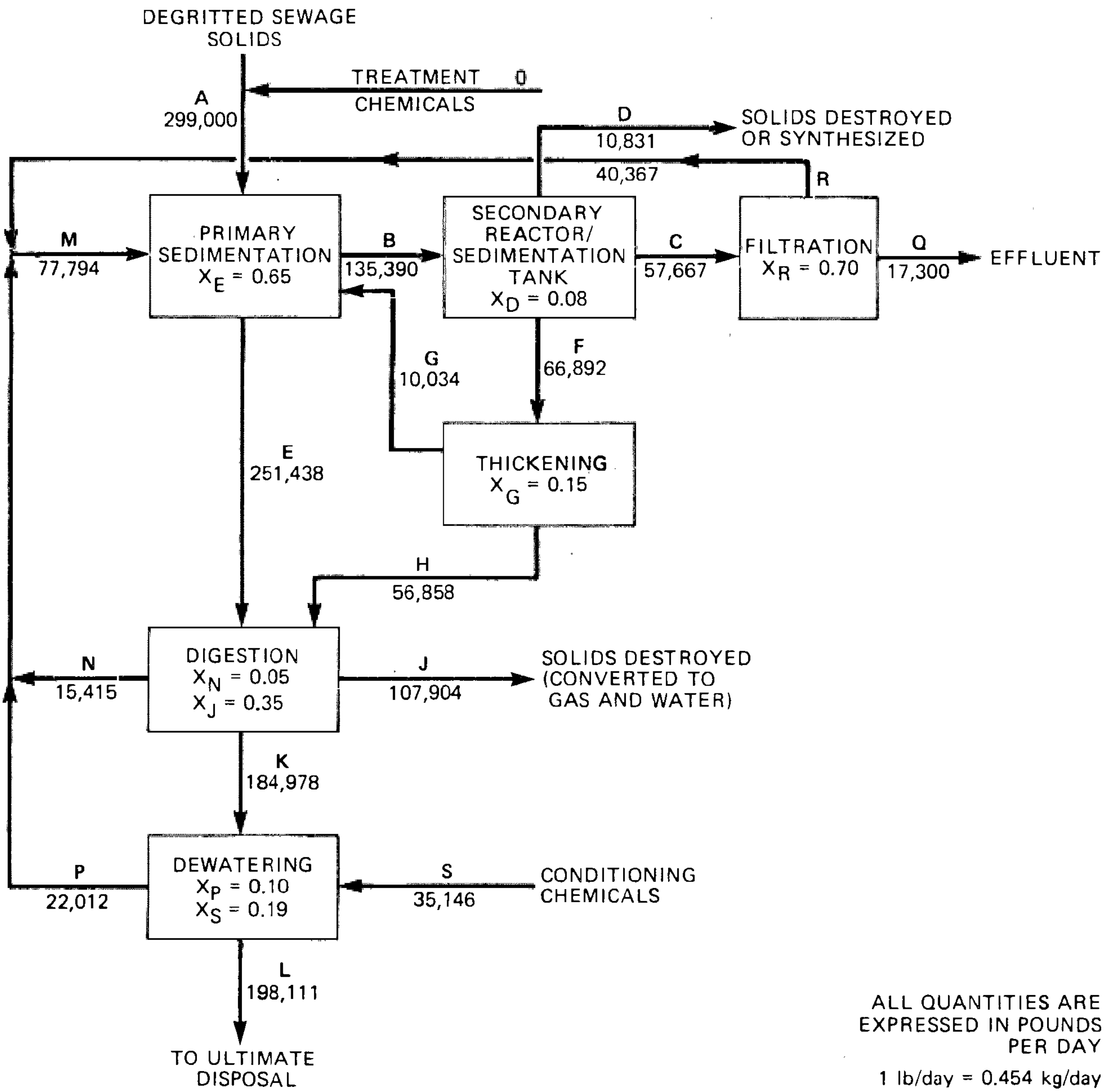


FIGURE 3-9

QFD FOR SECONDARY PLANT WITH FILTRATION

A set of different mass balance equations must be derived if flow paths between processing units are altered. For example the equations of Table 3-7 do not describe operations in which the dilute stream from thickener (stream G) is returned to the biological system instead of the primary sedimentation tank.

TABLE 3-7

MASS BALANCE EQUATIONS FOR FLOWSHEET OF FIGURE 3-9

$$E = \frac{A - \left(\frac{Q}{1 - X}\right)(\gamma - X_R)}{\frac{1}{X_E} - \alpha - \beta\ (\gamma)}$$

Where $\alpha = X_P\ (1 - X_J - X_N)(1 + X_S) + X_N$

$$\beta = \frac{(1 - X_E)(1 - X_D)}{X_E}$$

$$\gamma = X_G + \alpha\ (1 - X_G)$$

$$B = \frac{(1 - X_E)E}{X_E}$$

$$C = \frac{\Omega}{1 - X_R}$$

$$D = X_D B$$

$$F = \beta\ E - \frac{\Omega}{1 - X_R}$$

$$G = X_G F$$

$$H = (1 - X_G)F$$

$$J = X_J\ (E + H)$$

$$K = (1 - X_J - X_N)(E + H)$$

$$L = K\ (1 + X_S)(1 - X_P)$$

$$M = \frac{E}{X_E} - G - A$$

$$N = X_N\ (E + H)$$

$$P = X_P\ (1 + X_S)K$$

$$R = \frac{X_R}{1 - X_R} Q$$

$$S = X_S K$$

3.5 Sizing of Equipment

The QFD described in the previous section can be an important aid to a designer in predicting long-term (i.e., average) solids loadings on sludge treatment components. This allows the designer to establish such factors as operating costs and quantities of sludge for ultimate disposal. However, it does not establish the solids loading which each equipment item must be capable of processing. A particular component should be sized to handle the most rigorous loading conditions it is expected to encounter. This loading is usually not determined by applying steady-state models (e.g., QFD calculations) to peak plant loads. Because of storage and plant scheduling considerations, the rate of solids reaching any particular piece of equipment does not usually rise and fall in direct proportion to the rate of solids arriving at the plant headworks. Consider a system similar in configuration to that shown on Figure 3-9. If maximum solids loads at the headworks (Stream A) are twice the average value, it does not necessarily follow that at that instant maximum dewatering loads (Stream K) are twice the average dewatering load.

To pursue this further, consider the design of a centrifuge intended to dewater anaerobically digested primary and secondary sludge at a small treatment plant. The flow scheme is similar to that shown on Figure 3-9. The plant is staffed on only one shift per day, seven days per week. The digesters are complete-mix units equipped with floating covers. Because of the floating covers, digester volume can vary. Secondary sludge is wasted from the activated sludge systems to a dissolved air flotation thickener prior to digestion whenever operators are available to operate the thickener.

As indicated, the average loadings to the centrifuge can be defined by the QFD, but computation of the necessary centrifuge capacity requires analysis of both the load dampening effect of the storage in the digesters and the plant operating schedule. During periods of peak plant solids loadings, loads to the dewatering units may be attenuated by storing portions of the peak loadings within the digester. This can be done by either mechanism 1 or mechanism 2 below, acting either singly or in concert.

1. Digester volume is increased by allowing the digester floating cover to rise.

2. Solids are allowed to concentrate and thus accumulate within the digester (See Chapter 15, Section 15.2.2.2 for example of storage by mechanism 2).

The effect of both mechanisms 1 and 2 is storage within the digester of part of the load which would otherwise go to the centrifuge. Thus peak dewatering loads will not be 2.5 times the average when peak solids mass withdrawn from primary and secondary sedimentation tanks are 2.5 times the average, but something less, for example, only 1.4 times the average value. The degree of load dampening is a direct function of the size and operating configuration of the digester.

Since the centrifuge will only operate when attended, the "design" loading must account for this factor. The centrifuge must be either capable of processing, during one shift, all the sludge which must be extracted from the digester during the peak day (for example, 1.4 times average quantity) or the operators must dewater sludge for longer than one shift per day. A judgment would be needed at this point whether to pay for increased equipment capacity or operator overtime to handle the peak loads. With no operator overtime, the "design" centrifuge capacity would have to be 1.4 x 24/8 = 4.2 times the average daily digested sludge production to account for both the effect of sludge peaking, storage volume and only one operations shift per day.

Note that the dissolved air flotation thickener would need to be designed for 24/8 x 2.5 = 7.5 times the average daily rate of waste activated sludge production if it is assumed no upstream storage is available for dampening thickener loadings, the thickener itself has no storage capacity, and the thickener is only operated one shift per day.

The foregoing example shows the influence of solids peaking, storage volume and operating strategy on the selection of design loadings for a particular sludge handling process. Several other factors are important in selecting the capacity a unit must have, including:

- Uncertainties. When systems are designed without the benefits of pilot or full-scale testing, actual sludge quantities and characteristics as well as efficiencies of the sludge handling system components may not be known with certainty. The degree and potential significance of the uncertainties must be considered when developing design criteria. This usually has the effect of introducing a safety factor into the design so that reliable performance can be obtained no matter what conditions are encountered in the full-scale application. The magnitude of the safety factor must be determined by the designer, based on his judgement and experience.

- Equipment reliability. Greater capacity or parallel units must be specified if there is reason to believe that downtime for any particular units will be high.

- Sensitivity of downstream components. If losses in efficiency of a particular sludge handling component at peak loading conditions would cause problems for downstream processes, this upstream process should be designed conservatively. Conversely, if reduced efficiency could be tolerated, design need not be so conservative.

3.6 Contingency Planning

As indicated previously, flexibility to cope with unforeseen problems is highly desirable in any wastewater solids management system. Such problems and possible solutions include:

- Equipment breakdowns. Downtime may be minimized by having maintenance people on call, by advance purchase of key spare parts, by providing parallel processing units and by making use of storage.

- Solids disposal problems. These may include closures of landfills, unwillingness of current users to further utilize sludge, failure of a process to provide a sludge suitable for utilization, strikes by sludge transporters, and inability to dispose of sludge due to inclement weather. Disposal problems can be reduced by providing long-term storage and/or more than one disposal alternative.

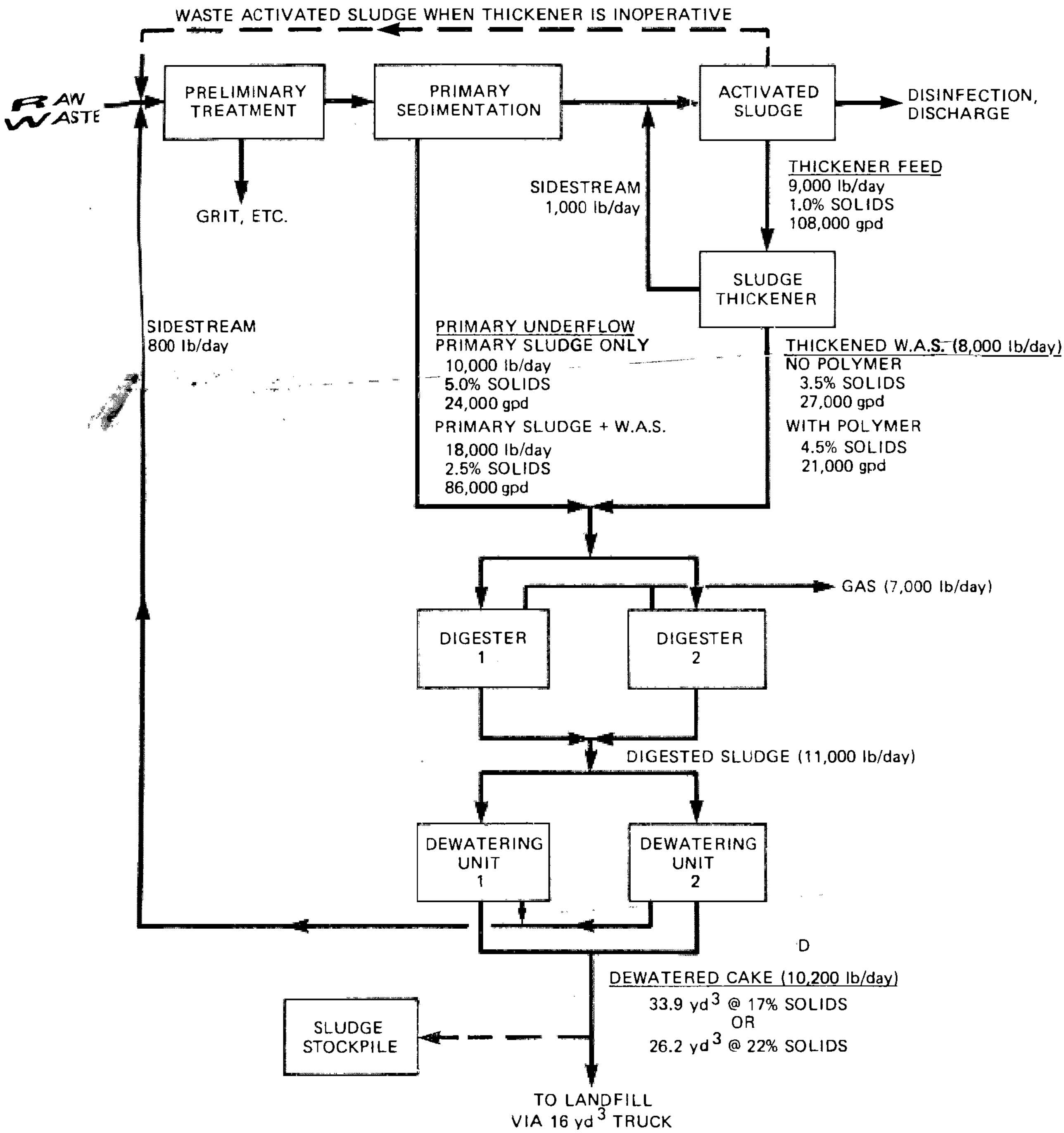
- Sludge production greater than expected. In some instances this may be dealt with by operating for more hours per week than normal or by using chemicals to modify sludge characteristics, thus increasing solids processing capacity.

Because of these factors, it is desirable to have more than one process for sludge treatment and disposal. Often it is possible to add considerable flexibility with modest investment. Backup or alternative wastewater solids treatment processes often have higher operating costs per ton of sludge processed than the primary processes. This is acceptable if the alternative process is not frequently needed and can be provided at minimum capital cost.

3.6.1 Example of Contingency Planning for Breakdowns

Assume the plant is a 10 MGD activated sludge facility with sludge thickening, anaerobic digestion, and digested sludge dewatering as shown on Figure 3-10. Pertinent design details include:

1. The waste activated sludge (WAS) thickener can be operated with or without polymers. If polymers are used, a more concentrated sludge can be produced. WAS can be diverted to the headworks if the WAS thickener is removed from service.



1 lb/day = 0.454 Kg /day

1 gpd = 0.00378 m^3/day

1 yd^3 = 0.765 m^3

FIGURE 3-10

CONTINGENCY PLANNING EXAMPLE

2. Two complete-mix digesters with floating covers are provided. Each digester has a net volume of 610,000 gallons (2,310 m^3) at minimum cover height. Net volume at maximum cover height is 740,000 gallons (2,803 m^3), thus total digester storage volume is 2 (740,000-610,000) = 260,000 gallons (984 m^3). The digesters are not supernated.

3. Two dewatering units are provided. Each unit, when fed at 90 gpm (40.8 m^3/hr) can produce a 22 percent solids cake. When the dewatering units are fed at 110 gpm (49.9 m^3/hr) a 17 percent solids cake is produced. The units are fed at 90 gpm (40.8 m^3/hr) unless conditions dictate otherwise. The bulk density of each cake is 65.5 pounds per cubic foot (1,050 kg/m^3).

4. The cake is trucked to ultimate disposal. Each truck holds 16 cubic yards (12 m^3) of cake.

5. A dewatered sludge storage area of capacity 750 cubic yards (574 m^3) is available.

6. Weekends are 2.7 days long (from 5 p.m. Friday to 8 a.m. Monday).

<u>Case A</u>. All units available:

1. Digester detention time $= \frac{2\ (610{,}000\ \text{gal})}{(24{,}000 + 27{,}000)\ \text{gpd}}$ = 24 days.

2. Dewatering operation:

   a. Weekly sludge feed = 7 (24,000 + 27,000 gpd) = 357,000 gallons (1,350 m^3).

   b. Hourly throughput = 2 x (90 gpm) (60 min/hr) = 10,800 gal per hr (40.8 m^3/hr).

   c. Operation is carried out over $\frac{357{,}000\ \text{gal}}{10{,}800\ \text{gal/hr}}$ = 33 hours per week.

   d. 26.2 cubic yards (20.0 m^3) of 22 percent solids sludge cake is produced each day.

3. If dewatering is not operated over the weekend, then 51,000 gpd (2.7 days) = 138,000 gal (522 m^3) of digested sludge must be stored in the digesters during this period. Available storage which can be obtained by letting the floating cover rise is 260,000 gallons (983 m^3). Therefore digester storage capacity is adequate for weekend storage, including long (3.7 day) weekends.

4. Truckloads required to haul dewatered cake = $\frac{26.2 \text{ yd}^3/\text{day}}{16 \text{ yd}^3/\text{truck}}$ = 1.6 truckloads per day (11 per week).

In summary, the dewatering operation can be carried out in a normal 5-day, 8-hour-per-day week. Time is available for start-up and shutdown and for providing good supervision. Digester detention time is more than adequate for good digestion.

Case B. Thickener is out of service. All other units are available. Waste activated sludge is diverted to the plant headworks and is subsequently removed in the primary sedimentation tank.

1. Digester detention time = $\frac{2\ (610{,}000 \text{ gal})}{86{,}000 \text{ gpd}}$ = 14 days; short, but tolerable.

2. Dewatering operation:

   a. Weekly sludge feed = 7 (86,000 gpd) = 602,000 gal (2280 m^3).

   b. Hourly throughput. At 90 gallons per minute, throughput is 10,800 gallons per hr (40.8 m^3/hr). At 110 gallons per minute, throughput is 13,200 gallons per hr (49.9 m^3/hr).

   c. Operating hours required. At 90 gallons per minute (40.8 m^3/hr), required operating hours = $\frac{602{,}000 \text{ gal}}{10{,}800 \text{ gph}}$ = 56 hours per week. This requires substantial overtime or a second shift. At 110 gallons per minute (49.9 m^3/hr), required operating hours = $\frac{602{,}000 \text{ gal}}{13{,}200 \text{ gph}}$ = 46 hours per week. This reduces the amount of overtime required.

   d. If the dewatering units operate at 90 gallons per minute (40.8 m^3/hr), 26.2 cubic yards per day (20.0 m^3/day) of 22 percent cake is produced. Operation at 110 gallons per minute (49.9 m^3/hr) produces 33.9 cubic yards per day (25.9 m^3/day) of a 17 percent solids sludge cake.

3. If dewatering units are not run on weekends, 86,000 gal/day x 2.7 days = 232,000 gallons (878 m^3) must be stored in the digesters. Digester storage capacity is adequate for normal weekends, but not long weekends.

4. For 22 percent cake, 11 truckloads per week are required. For 17 percent cake, 15 truckloads per week are required.

In summary, loss of the thickener reduces digester detention time, increases required dewatering unit operating time and the amount of trucking required for disposal of cake. The operation can be managed, but with more difficulty. This example also illustrates the value of the thickener.

Case C. One digester is out of service. All other units are operating:

1. Digester detention time $= \frac{610{,}000 \text{ gal}}{24{,}000 + 27{,}000 \text{ gpd}} = 12$ days. This is only marginally adequate. By using polymers in the thickener, assume waste activated sludge thickness is increased from 3.5 to 4.5 percent. Detention time is increased to $\frac{610{,}000 \text{ gal}}{24{,}000 + 21{,}000 \text{ gpd}} = 14$ days, still short, but an improvement.

2. Dewatering operation. This is not greatly affected by loss of the digester. It can still be operated with a single shift and a 22 percent cake can can be produced.

3. Weekend storage. Without polymer addition to the thickener, required storage volume is 2.7 days x 51,000 gpd = 138,000 gallons (522 m^3). One digester (130,000 gallons or 492 m^3) has inadequate storage and a dewatering machine must be run part of the weekend. If polymer is used, required storage = 2.7 x 45,000 = 122,000 gallons (462 m^3). One digester is marginally adequate for storage.

4. Eleven (11) truckloads per week are required to transport the sludge cake.

In summary loss of a digester can be compensated for by using polymer in the thickener.

Case D. One dewatering machine is out of service. All other units are available.

1. Digestion is not affected.

2. Dewatering operation. Try the following alternatives:

   a. Feed rate 90 gallons per minute (40.8 m^3/hr). Required operating time $= \frac{51{,}000 \text{ gpd}}{90 \text{ gpm } (60 \text{ min/hr})} = 9.4$ hours per day, every day, excluding start-up and shutdown time.

   b. Feed rate is 110 gallons per minute. Required operating time $= \frac{51{,}000 \text{ gpd}}{110 \text{ gpm } (60 \text{ min/hr})} = 7.8$ hours/day, every day, excluding start-up and shutdown time.

c. Try adding polymers to thickener and maintaining a 110 gallons per minute feed rate to the dewatering units. Required operating time = $\frac{45,000 \text{ gpd}}{110 \text{ gpm } (60 \text{ min/hr})}$ = 6.8 hours per day, every day, excluding start-up and shutdown times.

3. Weekend digester storage is not an issue as dewatering units must be run seven days a week.

4. Eleven (11) truckloads are required to transport 22 percent cake, 15 truckloads are required for 17 percent cake.

In summary, loss of one dewatering unit will require operation of the remaining unit for seven days a week. overtime costs will be high.

Case E. Truck strike lasting a month. Assuming 22 percent cake, sludge, accumulates at about 25 cubic yards (19 m^3) a day. The sludge storage area stockpile must, therefore, be able to store about 25 (30) = 750 cubic yards (570 m^3) of sludge to avoid major problems due to the strike. Odors from the stockpile could be a problem.

Conclusion: The system as designed should be able to handle contingencies.

3.7 Other General Design Considerations

3.7.1 Site Variations

Characteristics such as size and location of the plant and solids disposal sites strongly influence the nature and cost of treatment and disposal systems.

- Disposal may often be accomplished on land, thus eliminating expensive dewatering, provided adequately sized sites are within reasonable distances from the treatment plant. However, dewatering is usually required if the amount of land available for sludge disposal is limited or if the sludge must be trucked long distances for disposal. Sufficient land also permits long-term storage in faculative lagoons, which can also provide some inexpensive disinfection.

- Zoning regulations are different for different sites.

- Locations near waterways and railroads provide opportunities for barge and rail transportation of sludges and supplies.

- Structures are less costly if foundation conditions are good. Quite often, however, wastewater treatment plants are located in valley bottoms, tidelands, or reclaimed landfills where expensive foundations are required.

- Costs for labor, electricity, freight on chemicals, and trucking can vary markedly from one region to another.

Because of these variations, the best alternative for one site is often not the best at another site. Also, reported capital and operating costs from one site must be carefully adjusted before being used at another site.

3.7.2 Energy Conservation

As fossil fuel supplies become more scarce and more expensive, energy conservation becomes increasingly important. The designer should employ energy-efficient processes and recover energy from sludges and sludge by-products, where practical.

The following points should be considered in the design of energy-utilization processes:

- Energy from high temperature sources is generally more useful than energy derived from low temperature sources, since it can be put to a wider variety of uses.

- The evaporation of water in dryers and furnaces, consumes large amounts of energy. Such processes should therefore be provided with a well-dewatered sludge. Inert materials such as, chemicals or ash used to condition sludge for dewatering are, however, also energy consumers.

- Energy required for digestion and thermal conditioning is minimized where thickening is used to reduce the water content of process feed sludges.

- Trucking energy can be reduced if haul distances are short and the sludge is well-dewatered.

- Energy is required for the manufacture and transportation of chemicals. Therefore, chemicals should be added in minimum amounts that are consistent with good operation. Whenever possible chemicals should be employed which require the least energy to produce and transport.

- Costs saved by reducing peak energy demands can be subtantial. In some instances, a treatment plant's electrical bills are largely determined by peak energy loadings, as opposed to total energy consumed. The designer should actively seek solutions to reduce peak energy demand. Energy recovered from sludge and sludge-derived fuel can be used for this purpose.

- Motors should be accurately sized. Motors are most efficient when operated near capacity. However, motors in wastewater treatment plants are frequently operated far below capacity.

- Where anaerobic digester gas is utilized, gas storage should be provided to minimize wastage.

- Recycle loads from solids treatment processes should be minimized. Recycled loads increase the power and chemical requirements of wastewater treatment processes.

The designer should always keep in mind, however, that true economy is not found by minimizing specific uses of energy, but by minimizing overall costs.

Energy recovery is discussed in Chapter 18. Energy costs for many of the sludge treatment and disposal options are contained in chapters describing those options. A 1978 publication (2) contains more detailed guidance on making energy-effective analyses as well as a great deal of information on primary energy consumption, the electricity and fuel consumed directly at the treatment plant and secondary energy consumption, the energy required to manufacture chemicals used in sludge treatment.

3.7.3 Cost-Effective Analyses

One of the decisive factors in process selection is cost. Cost analyses must be carried out so that all alternatives are evaluated on an equivalent basis. EPA has issued guidelines for cost-effective analyses (3). Monetary costs may be calculated in terms of present worth values or equivalent annual values over a defined planning period. Capital and operating and maintenance costs must be considered in the evaluation. Indirect costs should be included such as loss of property taxes when private land is acquired and incremental costs which the wastewater treatment facility must bear when sidestreams are returned to them. Credits for such items as crops and recovered energy should be taken where appropriate. The discount rate to be used in the analysis is established annually by the Water Resources Council. All construction cost data is referenced to a specific location and year using cost indices such as the Engineering News-Record Construction Cost Index, the EPA Sewage Treatment Plant Index, or the EPA Sewer Construction Cost Index. Inflation in costs and wages are not considered in the analyses, since it is assumed all prices will tend to change over time by the same percentage.

Cost-effective analysis for sludge treatment and disposal systems has been discussed in somewhat greater detail in a 1979 publication (4). Present worth and equivalent annual value calculations are discussed in References 5 and 6, among others.

TABLE 3-8

SOLID PROPERTIES CHECKLIST

1. Origin and type
2. Quantity
3. Concentrations
4. Chemical composition and biological properties including biodegradability
5. Specific gravity
6. Rheological properties (e.g., viscosity)
7. Settling properties
8. Dewatering properties
9. Fuel value
10. Suitability for utilization or disposal without further processing

TABLE 3-9

PROCESS DESIGN CHECKLIST

1. Description of process
   Details of works, schematic drawing, logical location in overall sludge treatment flowsheet.
2. Process Theory
3. Current status
   Number of suppliers; usage in USA; good and bad experience and potential for avoiding problems; advantages and disadvantages with respect to competing processes.
4. Design criteria
   Process loadings (solids and hydraulic); pilot scale investigations (when to make them, methods, costs, limitations); special considerations (solids origin).
5. Instrumentation specific to the process.
6. Operational considerations: Flexibility.
7. Energy impacts
   Primary and secondary requirements.
   Potential for energy recovery.
8. Actual performance data and case histories.
9. Public health and environmental impacts.
10. Solids production and properties.
11. Sidestream production and properties.
12. Cost information
    Construction/operation (tie to ENR and EPA Construction Cost Indexes); constraints (site-specific). Break down costs by category (labor, electricity, etc.) so that adjustments can be made for different conditions.

3.7.4 Checklists

The following checklists provide information a designer must have to design wastewater solids treatment and disposal systems. Three checklists are provided.

1. A Solids Properties Checklist appears in Table 3-8. This checklist summarizes required information concerning raw solids entering the solids treatment system and solids produced in the various processes and operations.

2. A Process Design Checklist appears on Table 3-9. This checklist describes information necessary to select and design sludge treatment and disposal processes.

3. A Public Health and Environmental Impact Checklist appears in Table 3-10. This checklist summarizes key interactions that must be resolved between proposed process and the surrounding environment.

TABLE 3-10

PUBLIC HEALTH AND ENVIRONMENTAL IMPACT CHECKLIST

1. Control of vectors (bacteria, parasites, virus, flies, rats)
2. Odor
3. Air pollution
4. Groundwater contamination
5. Surface water contamination (by run-off)
6. Soils contamination
7. Land use
8. Social-economic
9. Utilization (sludge or byproducts used beneficially)
10. Occupational safety
11. Risk of accidents involving the public
12. Control of potentially hazardous substances
13. Effects on biota including transfer and accumulation of pollutants in the food chain
14. Use of material resources

Designers should refer frequently to these checklists to assure that all relevant topics are given proper consideration during planning stages and system design. An extensive series of checklists dealing with wastewater solids management has also been prepared for EPA (4). The checklists are intended to serve as aids for the review of facility plans, for preparation of designs and specifications and the writing of operations and maintenance manuals.

3.8 References

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3. Federal Register. "Cost-Effectiveness Analyses." 40 CFR 35-Appendix A. September 1975.

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6. Peters, M.S. and Timmerhaus, K.D. Plant Design and Economics for Chemical Engineers. New York. McGraw-Hill Book Co. 1962.

EPA 625/1-79-011

PROCESS DESIGN MANUAL FOR SLUDGE TREATMENT AND DISPOSAL

Chapter 4. Wastewater Solids Production and Solids

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 4

WASTEWATER SOLIDS PRODUCTION AND CHARACTERIZATION

4.1 Introduction

This chapter principally discusses the quantities and properties of sludges produced by primary biological and chemical wastewater treatment processes. Screenings, grit, scum, septage, and other miscellaneous wastewater solids, including the sludge produced in the treatment of combined sewer overflows, are discussed briefly.

4.2 Primary Sludge

Most wastewater treatment plants use primary sedimentation to remove readily settleable solids from raw wastewater. In a typical plant with primary sedimentation and a conventional activated sludge process for secondary treatment, the dry weight of primary sludge solids is roughly 50 percent of that for the total sludge solids. For several reasons, primary sludge is usually easier to manage than biological and chemical sludges. First, primary sludge is readily thickened by gravity, either within a primary sedimentation tank or within a separate gravity thickener. In comparison with biological and many chemical sludges, primary sludge with low conditioning requirements can be mechanically dewatered rapidly. Further, the dewatering device will produce a drier cake and give better solids capture than it would for most biological and chemical sludges.

4.2.1 Primary Sludge Production

4.2.1.1 Basic Procedures for Estimating Primary Sludge Production

Primary sludge production is typically within the range of 800 to 2,500 pounds per million gallons (100 to 300 mg/l) of wastewater. A basic approach to estimating primary sludge production for a particular plant is by computing the quantity of total suspended solids (TSS) entering the primary sedimentation tank and assuming an efficiency of removal. When site-specific data are not available for influent TSS, estimates of 0.15 to 0.24 pound per capita per day (0.07 to 0.11 kg/capita/day) are commonly used (1). Removal efficiency of TSS in the primary sedimentation tank is usually in the 50 to 65 percent range (2). An efficiency of 60 percent is frequently used for estimating purposes, subject to the following conditions:

- That the sludge is produced in treatment of a domestic wastewater without major industrial loads.

- That the sludge contains no chemical coagulants or flocculents.

- That no other sludges--for example, trickling filter sludge--have been added to the influent wastewater.

- That the sludge contains no major sidestreams from sludge processing.

As an example, if a designer estimates the TSS entering the primary clarifier as 0.20 pound per capita per day (0.09 kg/capita/day, and the removal efficiency of the clarifier as 60 percent, the estimated primary sludge production is 0.12 pound per capita per day (0.054 kg/capita/day).

If relevant data are available on influent wastewater suspended solids concentrations, such data should, of course, be used for design purposes. Estimates of TSS removal efficiency in primary sedimentation tanks may be refined by use of operating records from in-service tanks or by laboratory testing. The "Standard Methods" dry weight test for settleable matter estimates under ideal conditions the amount of sludge produced in an ideal sedimentation tank (3). Sludge production will be slightly lower in actual sedimentation tanks.

4.2.1.2 Industrial Waste Effect

Suspended solids removal efficiency in primary sedimentation depends to a large extent on the nature of the solids. It is difficult to generalize about the effect that industrial suspended solids can have on removal efficiency, but an example illustrates that the effect can sometimes be dramatic. At North Kansas City, Missouri, a municipal plant serves residential customers and numerous major industries, including food processing, paint manufacturing, soft-drink bottling, paper manufacturing, and grain storage and milling. Raw wastewater entering the plant had a 15-day average suspended solids concentration of 1,140 mg/l that was attributable to the industries. Primary sedimentation removed 90 percent of these solids. The quantity of primary sludge was, therefore, about 8,000 pounds per million gallons (1,000 mg/l) of wastewater treated. This value is several times the normal one for domestic wastewater. On two of the 15 days, removal exceeded 14,000 pounds per million gallons (1,700 mg/l) (4).

4.2.1.3 Ground Garbage Effect

Home garbage grinders can significantly increase the suspended solids load on a wastewater treatment plant. These solids are largely settleable. Estimates of the increased primary sludge resulting from the use of garbage grinders range from 25 percent to over 50 percent (1,5,6).

4.2.1.4 Other Sludges and Sidestreams

Operating experience shows clearly that the amount of sludge withdrawn from the primary sedimentation tank is greatly increased when sludge treatment process sidestreams such as digester supernatant, elutriate, and filtrates or centrates and other sludges like waste-activated are recycled to the primary sedimentation tank. Quantifying the solids entering and leaving the primary clarifier by all streams is an important tool for estimating primary sludge production when recycled sludges and sludge process sidestreams contribute large quantities of solids.

4.2.1.5 Chemical Precipitation and Coagulation

When chemicals are added to the raw wastewater for removal of phosphorus or coagulation of nonsettleable solids, large quantities of chemical precipitates are formed. The quantity of chemical solids produced in chemical treatment of wastewater depends upon the type and amount of chemical(s) added, chemical constituents in the wastewater, and performance of the coagulation and clarification processes. It is difficult to predict accurately the quantity of chemical solids that will be produced. Classical jar tests are favored as a means for estimating chemical sludge quantities. The quantities of suspended solids and chemical solids removed in a hypothetical primary sedimentation tank that is processing wastewater which has been treated by lime, aluminum sulfate or ferric chloride addition are estimated in Table 4-1.

4.2.1.6 Peak Loads

Peak rates of primary sludge production can be several times the average. Peak solids production levels also vary from one plant to another. Four studies of primary sludge production rates are summarized and presented here.

At Ames, Iowa, (9) the wastewater is basically of domestic origin. A university contributes about 30 percent of the volumetric and mass loads. Storm runoff is collected and kept separate from the domestic wastewater. For 21 years of record, the suspended solids loads in the peak month of each year were divided by the yearly average. The average of these ratios was 1.37. The average for comparison of peak days and peak months over ten years of record was 1.59. Thus, in a typical year, the maximum daily flow would be about 1.37 x 1.59, or 2.2 times the average. The maximum day's sludge production was, therefore, expected to follow a similar pattern and was estimated to be 2.2 times the average value.

TABLE 4-1

PREDICTED QUANTITIES OF SUSPENDED SOLIDS AND CHEMICAL SOLIDS REMOVED IN A HYPOTHETICAL PRIMARY SEDIMENTATION TANK (7,8)

Sludge type	No chemical addition[b]	Chemical addition[a]		
		Lime[c]	Alum[d]	Iron[e]
Suspended solids, lb/mg	1,041	1,562	1,562	1,562
Chemical solids, lb/mg	-	2,082	362	462
Total sludge production, lb/mg (kg/cu m)	1,041 (0.13)	3,644 (0.44)	1,924 (0.23)	2,024 (0.24)

[a]Assumes 10 mg/l influent phosphorus concentration (as P) with 80 percent removed by chemical precipitation.

[b]Assumes 50 percent removal of 250 mg/l influent TSS in primary sedimentation.

[c]125 mg/l $Ca(OH)_2$ added to raise pH to 9.5.

[d]154 mg/l $Al_2(SO_4)_3 \cdot 14\ H_2O$ added.

[e]84 mg/l $FeCl_3$ added.

Note: Assumes no recycle streams (for example, recycle of waste-activated sludge to primary sedimentation, digester supernatant, etc.).

Secondary solids production would be cut from 833 lb/mg without chemical addition to 312 lb/mg with chemical addition in this hypothetical plant.

A study conducted in 1936 used data from Chicago, Cleveland, Columbus, Syracuse, Rochester, and several other large American cities (10) to show a typical relationship between peak raw sewage solids loads entering a plant and duration of time that these peaks persist. This relationship is shown graphically on Figure 4-1. The curve is appropriate for large cities with a number of combined sewers on flat grades. The peaks occur at least partly because solids deposited in the sewers at low flows are flushed out by storm flows.

Data were collected over a five-year period from the West Point plant at Seattle, Washington and used in a 1977 study (11). Peak primary sludge loads of four- to ten-day durations were compared with average loads. The duration of four days was selected because it appeared to be highly significant to digester operations at this plant, and because loads tended to drop after about four days of heavy loading. The highest four-day primary sludge production was more than four times the normal production from the plant's service area. Main contributors to the peak load were:

- Solids deposits in the sewers. These deposits were resuspended during high flows and carried to the treatment plant. The computer-operated storage system, which minimizes combined sewer overflows, apparently contributed to solids deposition/reentrainment.

- Storm inflow. Measurements of TSS in storm drainage fluctuate widely but often show over 200 mg/l suspended solids. A large portion of the West Point service area contains combined sewers.

- Sludge conditioning and dewatering. Problems in these processes have caused the sidestreams to contain more solids than usual.

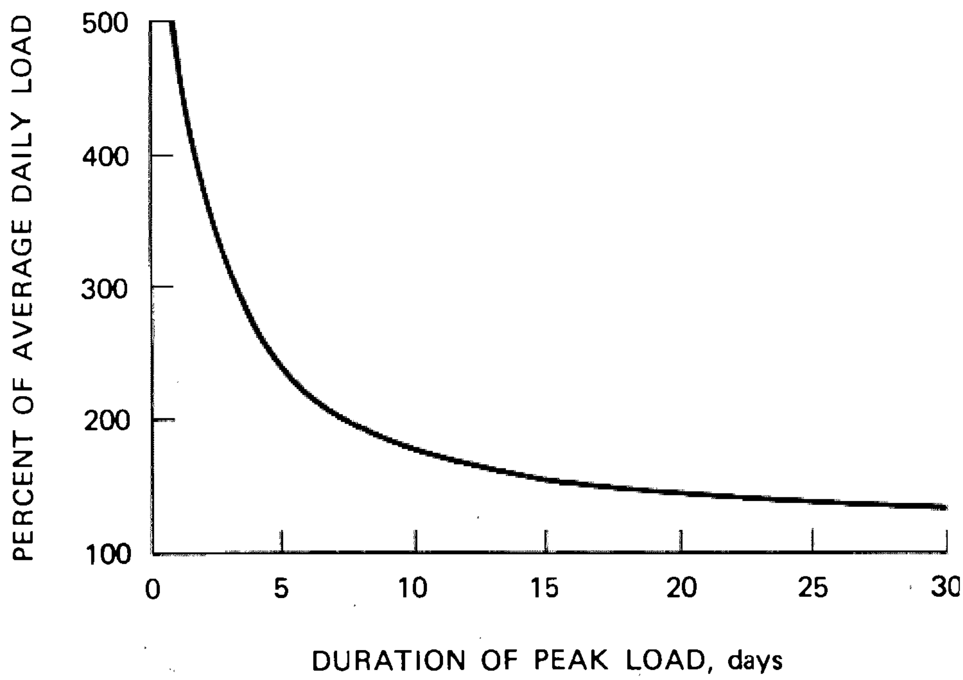
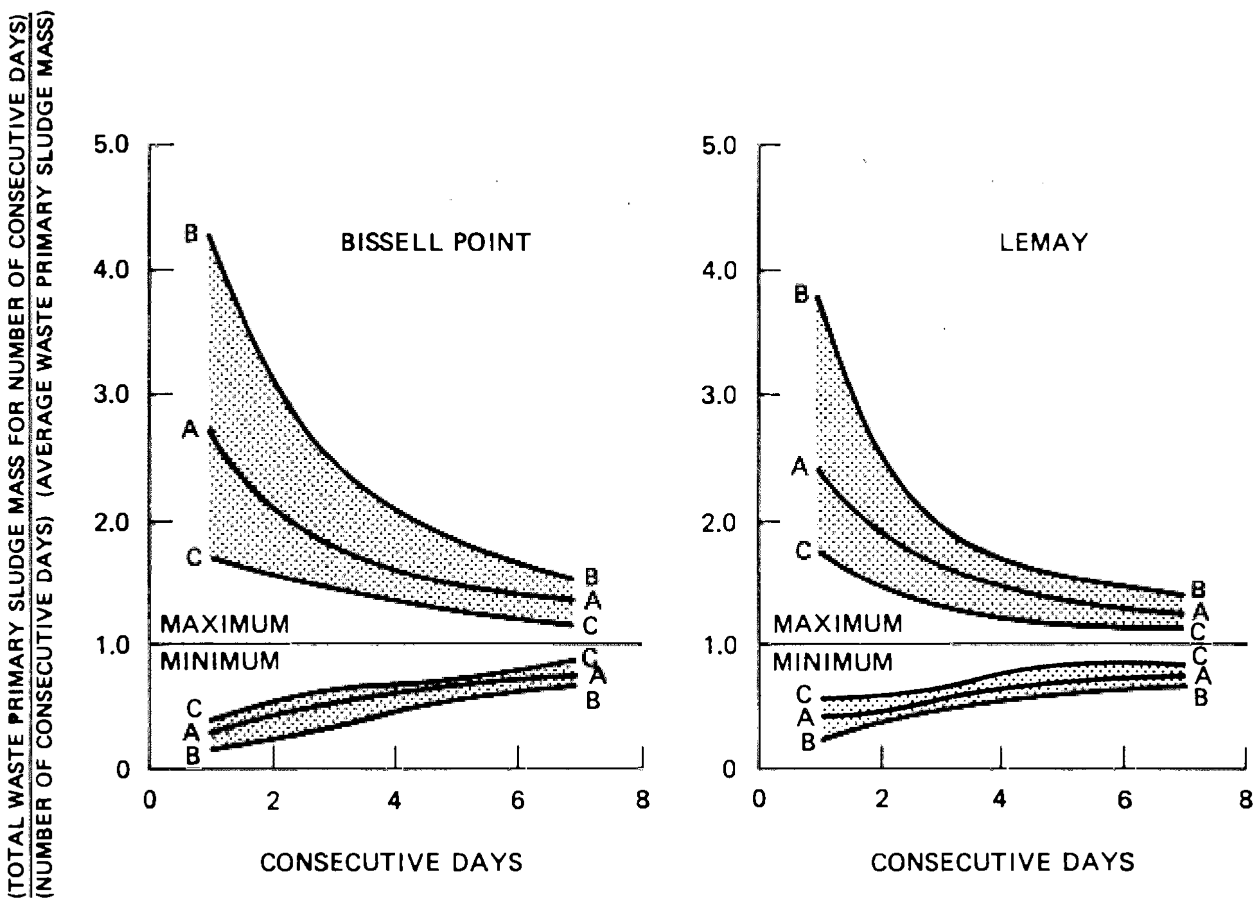


FIGURE 4-1

TYPICAL RELATIONSHIP BETWEEN PEAK SOLIDS LOADING AND DURATION OF PEAK FOR SOME LARGE AMERICAN CITIES (10)

The fourth study, done in 1974, discussed two plants in St. Louis, Missouri (12). The graphs shown on Figure 4-2 illustrate the variation in daily waste primary sludge production as a fraction of the average waste primary sludge production with duration of that production rate for the eight months that data were taken. Both of these plants have significant industrial loads, and both serve large areas of combined storm and sanitary sewers.



KEY: A – A AVERAGE OF RESULTS OF EIGHT MONTHS
B – B MOST EXTREME RESULTS RECORDED IN ALL OF THE EIGHT MONTHS
C – C RESULTS FROM THE LEAST EXTREME OF THE EIGHT MONTHS

FIGURE 4-2

PEAK SLUDGE LOADS, ST. LOUIS STUDY (12)

4.2.2 Concentration Properties

Most primary sludges can be concentrated readily within the primary sedimentation tanks. Several authors claim that a five to six percent solids concentration is attainable when sludge is pumped from well-designed primary sedimentation tanks (2,10,13, 14). However, values both higher and lower than the five to six percent range are common. Conditions that influence primary sludge concentration include:

- If wastewater is not degritted before it enters the sedimentation tanks, the grit may be removed by passing the raw primary sludge through cyclonic separators. However, these separators do not function properly with sludge concentrations above one percent (15).

- If the sludge contains large amounts of fine nonvolatile solids, such as silt, from storm inflow, a concentration of well over six percent may sometimes be attained (11,16).

- Industrial loads may strongly affect primary sludge concentration. For example, at a plant receiving soil discharged from a tomato canning operation, a primary sludge with a 17 percent solids concentration, of which 40 percent is volatile, was recorded. Normal primary sludge at this plant had a solids concentration of from five to six percent solids (60 to 70 percent volatile) (17).

- Primary sludge may float when buoyed up by gas bubbles generated under anaerobic conditions. Conditions favoring gas formation include: warm temperatures; solids deposits within sewers; strong septic wastes; long detention times for wastewater solids in the sedimentation tanks; lack of adequate prechlorination; and recirculating sludge liquors (18). To prevent the septic conditions that favor gas formation, it may be necessary to strictly limit the storage time of sludge in the sedimentation tanks. This is done by increasing the frequency and rate of primary sludge pumping (19).

- If biological sludges are mixed with the wastewater, a lower primary sludge concentration will generally result.

4.2.3 Composition and Characteristics

Table 4-2 lists a number of primary sludge characteristics. In many cases, ranges and/or "typical" values are given. In the absence of recirculating sludge process sidestreams, the percent of volatile solids in the primary sludge should approximate the percent volatile suspended solids in the influent wastewater. A volatile solids content below about 70 percent usually indicates the presence of storm water inflow, sludge processing sidestreams, a large amount of grit, sludge from a water filtration plant that was discharged to the sanitary sewer, low volatile solids from industrial waste, or wastewater solids that have a long detention time in the sewers.

TABLE 4-2

PRIMARY SLUDGE CHARACTERISTICS

Characteristic	Range of values	Typical value	Comments	Reference
pH	5 - 8	6	-	1
Volatile acids, mg/l as acetic acid	200 - 2,000	500	-	1
Heating value, Btu/lb (kJ/kg)	6,800 - 10,000	-	Depends upon volatile content, and sludge composition, reported values are on a dry weight basis.	1
		10,285	Sludge 74 percent volatile.	1
		7,600	Sludge 65 percent volatile.	20
Specific gravity of individual solid particles	-	1.4	Increases with increased grit, silt, etc.	1
Bulk specific gravity (wet)	-	1.02	Increases with sludge thickness and with specific gravity of solids.	1
		1.07	Strong sewage from a system of combined storm and sanitary sewers.	21
BOD_5/VSS ratio	0.5 - 1.1	-	-	22
COD/VSS ratio	1.2 - 1.6	-	-	22
Organic N/VSS ratio	0.05 - 0.06	-	-	22
Volatile content, percent by weight of dry solids	64 - 93	77	Value obtained with no sludge recycle, good degritting; 42 samples, standard deviation 5.	22
	60 - 80	65		
	-	40	Low value caused by severe storm inflow.	11
	-	40	Low value caused by industrial waste.	17
Cellulose, percent by weight of dry solids	8 - 15	10	-	1
	-	3.8	-	23
Hemicellulose, percent by weight of dry solids	-	3.2	-	23
Lignin, percent by weight of dry solids	-	5.8	-	23
Grease and fat, percent by weight of dry solids	6 - 30	-	Ether soluble	1
	7 - 35	-	Ether extract	23
Protein, percent by weight of dry solids	20 - 30	25	-	1
	22 - 28	-		23
Nitrogen, percent by weight of dry solids	1.5 - 4	2.5	Expressed as N	1
Phosphorus, percent by weight of dry solids	0.8 - 2.8	1.6	Expressed as P_2O_5. Divide values as P_2O_5 by 2.29 to obtain values as P.	1
Potash, percent by weight of	0 - 1	0.4	Expressed as K_2O. Divide values as K_2O by 1.20 to obtain values as K.	1

1 Btu/lb = 2.32 kJ/kg

Primary sludge always contains some grit, even when the wastewater has been processed through degritting. Where screenings are comminuted and returned to the wastewater flow, the fragmented screenings appear in the primary sludge. Smaller plastic and rubber items that pass through screens also appear in the primary sludge.

Primary sludge typically contains over 100 different anaerobic and facultative species of bacteria (24). Sulfate-reducing and oxidizing bacteria, worm and fly eggs, and pathogenic microorganisms are typically present.

4.3 Biological Sludges

4.3.1 General Characteristics

Biological sludges are produced by treatment processes such as activated sludge, trickling filters, and rotating biological contactors. Quantities and characteristics of biological sludges vary with the metabolic and growth rates of the various microorganisms present in the sludge. The quantity and quality of sludge produced by the biological process is intermediate between that produced in no-primary systems and that produced in full-primary systems in cases when fine screens or primary sedimentation tanks with high overflow rates are used. Biological sludge containing debris such as grit, plastics, paper, and fibers will be produced at plants lacking primary treatment. Plants with primary sedimentation normally produce a fairly pure biological sludge. The concentrations and, therefore, the volumes of waste biological sludge are greatly affected by the method of operation of the clarifiers. Biological sludges are generally more difficult to thicken and dewater than primary sludge and most chemical sludges.

4.3.2 Activated Sludge

4.3.2.1 Processes Included

Activated sludge has numerous variations: extended aeration; oxidation ditch; pure oxygen, mechanical aeration, diffused aeration; plug flow; contact stabilization, complete mix, step feed, nitrifying activated sludge; etc (2). This manual does not discuss lagoons in which algal growth is important or lagoons that tend to accumulate wastewater solids or biological solids. These methods, however, can be used for predicting activated sludge production in highly loaded aerated lagoons where the bacteria are maintained in solution.

4.3.2.2 Computing Activated Sludge Production - Dry Weight Basis

The quantity of waste-activated sludge (WAS) is affected by two parameters: the dry weight of the sludge and the concentration of the sludge. This section describes how the dry weight of activated sludge production may be predicted.

Basic Predictive Equations

The most important variables in predicting waste-activated sludge production are the amounts of organics removed in the process, the mass of microorganisms in the system, the biologically inert suspended solids in the influent to the biological process, and the loss of suspended solids to the effluent.

These variables can be assembled into two simple and useful equations:

$$P_X = (Y)(s_r) - (k_d)(M) \qquad (4\text{-}1)$$

$$WAS_T = P_X + I_{NV} - E_T \qquad (4\text{-}2)$$

where:

P_X = net growth of biological solids (expressed as volatile suspended solids [VSS]), lb/day or kg/day;

Y = gross yield coefficient, lb/lb or kg/kg;

s_r = substrate (for example, BOD_5) removed, lb/day or kg/day;

k_d = decay coefficient, day^{-1};

M = system inventory of microbial solids (VSS) microorganisms, lb or kg;

WAS_T = waste-activated sludge production, lb/day or kg/day;

I_{NV} = non-volatile suspended solids fed to the process, lb/day or kg/day;

E_T = effluent suspended solids, lb/day or kg/day.

These equations, as stated or with slight variations, have been widely used. Equation 4-1 dates back to 1951 (25). However, different terms and symbols have been used by various authors in expressing Equations 4-1 and 4-2. Table 4-3 summarizes some of the terminology that has evolved. The technical literature reflects some inconsistency in terminology with the term "M." Test results reported by various authors and presented in Table 4-3 were derived on the basis of "M" defined as mixed liquor VSS only.

To use Equation 4-1, it is necessary to obtain values of Y and k_d. While Table 4-4 summarizes several reported values for these parameters, it is best to determine Y and k_d on an individual waste stream whenever possible.

TABLE 4-3

ALTERNATE NAMES AND SYMBOLS FOR EQUATION (4-1)

As used in this chapter			Other symbols for similar quantities	Other common names for similar quantities
Symbol	Name	Dimensions		
P_x	Biological solids production	$\frac{Mass}{Time}$	ΔX_V, dX/dt, A, S, dM/dt, R_g	Accumulation, net growth, excess microorganisms production
Y	Gross yield coefficient[a]	$\frac{Mass}{Mass}$	a, K_s, c	Yield coefficient, synthesis coefficient, growth-yield coefficient
s_r	Substrate removal	$\frac{Mass}{Time}$	dF/dt, S, B, Fi, R	Food, utilization, load
k_d	Decay constant	$\frac{1}{Time}$	b, K_d, K_e	Endogenous respiration, maintenance energy, auto-oxidation
M	Microbial solids inventory	Mass	S, X, X_v	Microbial mass, solids under aeration, solids inventory, mixed liquor solids

[a]The letter Y has also been used for the net yield coefficient P_x/s_r. The net yield coefficient is quite different from the gross yield coefficient.

To use Equation 4-2, it is necessary to estimate I_{NV}, non-volatile influent solids, and E_T, effluent suspended solids. The following are generally included within the term I_{NV}:

- Non-volatile solids in influent sewage, including recycle sludge liquors.
- Chemical precipitates--for example, aluminum phosphates--when alum is added to the activated sludge process.
- Stormwater solids that are not removed in previous processes (36).
- Normal non-volatile content of the activated sludge. In the absence of sludge liquors, chemical precipitates, and stormwater, activated sludge will be about 80 percent volatile (less in extended aeration) at most municipal treatment plants.

To compute E_T, a small value such as 10 mg/l TSS should be used.

The following sections discuss several factors that can influence the production of waste-activated sludge. Section 4.3.2.3 is a detailed example of how sludge quantities should be computed.

TABLE 4-4

VALUES OF YIELD AND DECAY COEFFICIENTS FOR COMPUTING WASTE-ACTIVATED SLUDGE

Reference	Gross yield coefficient[a]	Decay coefficient[b]	Type of wastewater	Scale of plant	Aeration	Temperature, °C	Sludge age, days[c]	BOD_5 removal calculation
25	0.5	0.055	Primary effluent	Bench	Air	19 - 22	2.8 - 22	Influent
26	0.70	0.04	Primary effluent	Pilot	Oxygen	Not stated	1 - 4	Influent minus effluent
26, 27	0.67	0.06	Primary effluent	Full	Air	18 - 27	1.2 - 8	Influent minus effluent
28, 29	0.73	0.075	Primary effluent	Pilot	Air	10 - 16	1 - 12	Influent minus effluent
30	0.94	0.14	Primary effluent (wastewater includes dewatering liquors)	Pilot	Air	15 - 20	0.5 - 8	Influent minus soluble effluent
31	0.73	0.06	Primary effluent	Pilot	Oxygen	18 - 22	2.5 - 17	Influent minus effluent
32	0.5	Not calculated (negligible)	Primary effluent (military base)	Pilot	Air	0 - 7	Long[d]	Influent
12	0.74	0.04	Primary effluent (much industry)	Pilot	Oxygen	17 - 25	2.1 - 5	Influent minus soluble effluent
30	1.57	0.07	Raw degritted including dewatering liquors	Pilot	Air	15 - 20	0.6 - 3	Influent minus soluble effluent
33	1.825	0.20	Raw degritted	Bench	Air	4 - 20	1 - 3	Soluble influent minus soluble effluent
34	0.65	0.043	Raw degritted	Bench	Air	20 - 21	11 and up[d]	Influent minus effluent
34	0.70	0.048	Raw degritted	Bench	Air	20 - 21	Long[d]	Influent minus effluent
34	0.54	0.014	Raw degritted	Full	Air	Not stated	Long[d]	Influent minus effluent
35	1.1	0.09	Raw	Full	Air	Not stated	1.1 -2.4	Influent minus effluent

[a] Gross yield coefficient Y, lb (kg) VSS/lb (kg) BOD_5.

[b] Decay coefficient k_d, days^{-1}.

[c] Mean cell residence time or sludge age θ_m, measured as mass of mixed liquor VSS divided by biological solids production P_x. Note that coefficients may be somewhat different if total system inventory of VSS (mixed liquor VSS plus VSS in clarifiers) is used rather than just mixed liquor VSS.

[d] Extended aeration.

Note: All values in this table are for an equation of the type $P_x = Ys_r - k_dM$ (equation 4-1).

Effect of Sludge Age and F/M Ratio

Equation (4-1) can be rearranged to show the effect of the sludge age (θ_m).

$$P_x = \frac{(Y)(s_r)}{1 + (k_d)(\theta_m)} \qquad (4-3)$$

where $\theta_m = \frac{M}{P_x}$ = sludge age, days.

Similarly, Equation 4-1 can be rearranged to show the effect of the food-to-microorganism ratio (F/M):

$$Px = (Y)(s_r) - \frac{(k_d)(s_r)}{(C_2)(F/M)} \qquad (4\text{-}4)$$

where:

C_2 = coefficient to match units of s_r and "F" in F/M; if s_r is BOD_5 removed (influent minus effluent), then C_2 is BOD_5 removal efficiency, about 0.9;

F/M = food-to-microorganism ratio;

$$= \frac{BOD_5 \text{ applied daily}}{\text{VSS (mass) in system}} .$$

As θ_m increases and F/M decreases, the biological solids production P_x decreases. Sludge handling is expensive, and costs can be reduced by using high values of θ_m or low values of F/M. However, there are offsetting cost factors, such as increases in the aeration tank volume needed, oxygen requirements for the aerobic biological system, etc. Also, as seasons change, so may the optimum θ_m and F/M for maximum wastewater treatment efficiency. Therefore, it is desirable to be able to operate across a range of conditions. Obviously, trial-and-error calculations are required to determine the least costly system.

Effect of Nitrification

Nitrification is the bio-oxidation of ammonia nitrogen and organic nitrogen to the nitrite and nitrate forms. Compared with processes that are designed for carbonaceous (BOD_5, COD) oxidation only, stable nitrification processes operate at long sludge ages (θ_m) and low food-to-microorganism ratios (F/M). Also, nitrification processes are often preceded by other processes that remove much of the BOD_5 and SS. As a result, activated sludge in a nitrification mode generally produces less waste-activated sludge than conventional activated sludge processes. However, there is an additional component to nitrification sludge, the net yield of nitrifying bacteria, Y_N. This may be estimated at 0.15 pounds SS per pound of total Kjeldahl nitrogen (organic plus ammonia) removed (37). Y_N varies with temperature, pH, dissolved oxygen, and cell residence time. However, detailed measurements of Y_N are not ordinarily required for sludge facility design because the yield of nitrifying bacteria is small. For example, if Y_N is 0.15 and if the nitrifying process removes an ammonia nitrogen concentration of 20 mg/l and an organic nitrogen concentration of 10 mg/l then nitrification would add 0.15 x (20+10) = 4.5 milligrams of nitrifying bacteria per liter of wastewater (38 pounds per million gallons). These quantities are small compared to other sludges. In single-stage nitrification processes, the sludge production figures must also include the solids produced from the carbonaceous oxidation, computed at the θ_m and F/M of the nitrifying system.

Effect of Feed Composition

The type of wastewater that is fed to the activated sludge process has a major influence on the gross yield (Y) and decay (k_d) coefficients. Many industrial wastes contain large amounts of soluble BOD_5 but small amounts of suspended or colloidal solids. These wastes normally have lower Y coefficients than are obtained with domestic primary effluent. On the other hand, wastes with large amounts of solids, relative to BOD_5, either have higher Y coefficients or require adjustments to reflect the influent inert solids. Even among soluble wastes, different compositions will cause different yields.

Effect of Dissolved Oxygen Concentration

Various dissolved oxygen (DO) levels have been maintained in investigations of activated sludge processes. Very low DO concentrations--for example, 0.5 mg/l--in conventional activated sludge systems do appear to cause increased solids production, even when other factors are held constant (38). However, there is vigorous disagreement concerning solids production at higher DO levels. Some investigators state that use of pure oxygen instead of air reduces sludge production. This is attributed to the high DO levels attained through the use of pure oxygen (39,40). Other investigators in recent well-controlled investigations have concluded that if at least 2.0 mg/l DO is maintained in air-activated sludge systems, then air and oxygen systems produce the same yield at equivalent conditions (such as food-to-microorganism ratio) (41, 42).

Effect of Temperature

The coefficients Y (gross yield) and k_d (decay) are related to biological activity and, therefore, may vary due to temperature of the wastewater. This variation has not been well documented in pilot studies and process investigations. One study obtained no significant difference due to temperature over the range 39° to 68°F (4°to 20°C)(33). However, others have observed significant differences within the same temperature range. Sometimes a simple exponential ("Arrhenius") equation is used for temperature corrections to Y and k_d. For instance, it has been stated that chemical and biochemical rates double with an 18°F (10°C) rise in temperature. Exponential equations have been found to be accurate for pure cultures of bacteria, but are quite inaccurate when applied to Y and k_d for the mixed cultures found in real activated sludges (43, 44).

For the design engineer, the following guidelines are recommended until such time as process investigations and research efforts in this area provide more consistent and reliable information:

- Wastewater temperatures in the range of from 59° to 72°F (15° to 22°C) may be considered to be a base case. Most of the available data are from this range. Within this range, there is no need to make temperature corrections. Any variations in process coefficients across this temperature range are likely to be small in comparison to uncertainties caused by other factors.

- If wastewater temperatures are in the range of from 50° to 59°F (10° to 15°C), the same k_d value as for 59° to 75°F (15° to 22°C) should be used, but the Y value should be increased by 26 percent. This is based on experiments that compared systems at 52°F (11°C) and 70°F (21°C). In these tests, k_d was the same, but Y was 26 percent higher. (On a COD basis, Y was found to be 0.48 at 38°F [11°C] and 0.38 at 56°F [21°C]) (45).

- If wastewater temperatures are below 50°F (10°C), increased sludge production should be expected (46), but the amount of increase cannot be accurately predicted from available data. Under such conditions, there is a need for pilot-scale process investigations.

- If wastewater temperatures are above 72°F (22°C), values of the process coefficients from the range 59° to 72°F (15° to 22°C) may be used for design. The resulting design may be somewhat conservative.

Effect of Feed Pattern

Various feed patterns for the activated sludge process include contact stabilization, step feeding, conventional plug-flow, and complete-mix. For design purposes, it appears to be best to ignore the feed pattern when estimating solids production.

Computing Peak Rate of Waste-Activated Sludge Production

Peak solids production occurs because of unfavorable combinations of the elements in Equations 4-1, 4-3, and 4-4, presented previously:

$$P_x = (Y)(s_r) - (k_d)(M) \qquad (4\text{-}1)$$

$$P_x = \frac{(Y)(s_r)}{1 + (k_d)(\theta_m)} \qquad (4\text{-}3)$$

$$P_x = (Y)(s_r) - \frac{(k_d)(s_r)}{(C_2)(F/M)} \quad (4\text{-}4)$$

All of these equations predict that solids production (P_x) increases with increases in s_r and F/M and decreases with increases in the mass of organisms and θ_m. Also P_x increases if the gross yield coefficient (Y) increases or if the decay coefficient (k_d) decreases. Each of these factors that tend to increase P_x will occur, within limits, in practice. To compute peak solids production, the following conditions should be assumed:

- Peak substrate removal (s_r). If high efficiency of biological wastewater treatment is maintained at peak pollutant loading, then s_r represents organics removal at maximum load. If s_r is computed on a BOD_5 removal basis, then the maximum BOD_5 removal should be used. The duration of peak solids production will match the duration of the peak load. Data have been published for several plants showing variations in BOD_5 loads (12,47,48,49).

- Minimum value of θ_m or maximum F/M. This allows the operator to select θ_m or F/M to obtain the best possible effluent. The design average condition may be F/M = 0.3, but an operator may obtain better results at F/M = 0.5 for some specific conditions at a particular treatment plant.

- Maximum likely value of Y.

- Minimum likely value of k_d.

Also, a temperature allowance should be made if wastewater temperatures below 59°F (15°C) may occur during peak loads.

Solids inventory reductions are an additional type of non-steady state condition that the designer should anticipate. It is occasionally necessary for treatment plant operators to reduce the mass of microorganisms (M) in the liquid treatment process by wasting activated sludge. Wasting activated sludges helps the operator to maintain a constant F/M in the face of reduced BOD_5 loadings. The wastewater-BOD_5 load can drop rapidly if a treatment plant serves vacation areas or industries. Wasting activated sludge also allows the operator to take aeration tanks, clarifiers, etc., out of service to limit solids on clarifiers, and to prevent major loss of solids to the effluent and to inhibit the growth of undesirable microorganisms such as scum-causing actinomycetes (50). Further, by reducing M, the operator can more readily optimize bioflocculation, thereby minimizing effluent solids, and can control air or oxygen requirements.

To accomplish the desired inventory reduction, solids handling facilities must have the capacity to accept the wasted solids. For wastewater treatment plants without major known BOD_5 and SS loading variations, allowance should be made in designing solids processing facilities for the wasting of an additional two percent of M per day and lasting up to two weeks. Such plants include those serving stable domestic populations. Industrial loads would be either small or unusually stable.

For plants with major seasonal variations in loads, allowance should be made for wasting an additional five percent of M per day and lasting for up to two weeks. Such plants serve resort areas, college towns, etc. A similar allowance should be made for plants that practice nitrification during only part of the year. Lastly, for plants with major weekday-to-weekend variations of over 2 to 1 in BOD_5 load, and medium or high food-to-microorganism ratios of over 0.3 during the high loads, allowance should be made for a one-day sludge wasting of up to 25 percent of M. The plant should also be able to handle wasting of five percent of M per day and lasting for two weeks. Plants in this category serve major industrial systems, large office complexes, schools, and ski areas.

Since inventory reductions are not generally practiced during peak loading periods, these above-discussed capacity allowances should be added to average solids production. The maximum rate of waste-activated sludge production is determined by whichever is greater: production during peak loading or the sum of average production plus inventory reduction allowances.

Occasionally, sludge is wasted in a pattern so that M increases at some times and decreases at others. An example of such a pattern is the withdrawal of WAS only during the daytime. The Tapia, California, Water Reclamation Plant uses this pattern to obtain good process control (51). Use of such patterns will, of course, increase the maximum rate at which WAS must be removed.

Measurements of Sludge Yield Coefficients

Pilot studies and full-scale operating records can provide better data for establishing sludge production design criteria than any general compilation of data from other locations. Measurements of the sludge yield coefficients are of two basic types. First, both the gross yield Y and the decay k_d may be determined. Second, observed net yields alone may be used.

Equations 4-1, 4-3, and 4-4 are used when the food-to-microorganism ratio F/M and the sludge age, θ_m, may be expected to vary in the prototype plant. To use these equations, it is necessary to determine the two sludge yield coefficients, Y and k_d. To establish these two coefficients, solids production must be measured under at least two different conditions of F/M and θ_m. Equation 4-1 can be rearranged slightly to Equation 4-5:

$$\frac{P_x}{M} = Y\left(\frac{s_r}{M}\right) - k_d \qquad (4\text{-}5)$$

where:

P_x/M = net growth rate = $1/\theta_m$ days^{-1},

$$s_r/M = \frac{\text{lb(kg) BOD}_5\text{ removed per day}}{\text{lb (kg) VSS}} .$$

This equation provides a basic straight-line relationship between P_x/M and s_r/M. For each condition of operation, P_x/M and s_r/M are calculated and plotted, and a straight line is drawn through the points. The slope of the line is the yield coefficient (Y), and the intercept represents the decay coefficient (kd). (See Figure 4-3.)

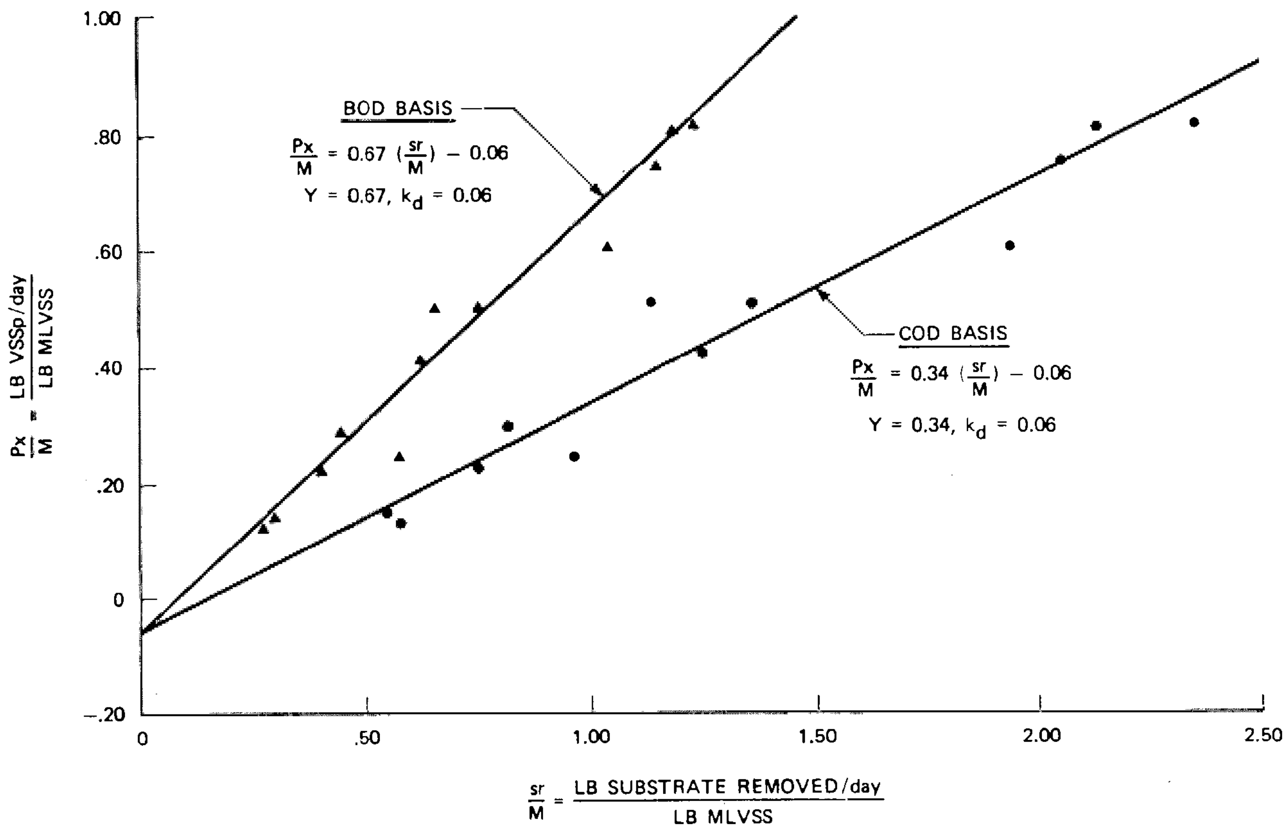


FIGURE 4-3

NET GROWTH RATE CURVES (27)

If the design conditions of s_r/M or θ_m are known and if solids production can be measured under these conditions, then it is not necessary to determine both Y and k_d. Instead, a simple observed net yield may be calculated. Equations 4-1 and 4-3 are easily rearranged to show:

$$Y_{obs} = \frac{P_x}{s_r} = Y - kd/(sr/M) = \frac{Y}{1 + (k_d)(\theta_m)} \qquad (4\text{-}6)$$

where:

Y_{obs} = net yield coefficient,

$$= \frac{\text{lb(kg) VSS produced}}{\text{lb(kg) substrate (for example, } BOD_5\text{) removed}}$$

Net yield coefficients are often reported in the literature. They are directly applicable only under the conditions of s_r/M and θ_m that occurred during the experiments; they are meaningless unless s_r/M or θ_m are measured also. For gathering data from pilot plants or existing plants for use in establishing sludge yield coefficients, several precautions should be exercised. Either automatic dissolved oxygen (DO) control should be used in the test or ample air or oxygen should be provided to ensure that the mixed liquor DO concentration is over 2 mg/l at all times. Data from widely differing temperatures should not be plotted on the same graph to determine Y and k_d. Instead, data from each temperature range should be used to determine Y and k_d for that range. Each condition of s_r/M or θ_m should be maintained long enough to obtain stable operation. To assure system stability, a period of time equal to three times the sludge age should elapse between tests. The designer should use the term I_{NV} in Equation 4-2 to correct the effect of sidestreams. The percent volatile content of the solids produced should be recorded. This will be useful in computing the total solids in the sludge.

4.3.2.3 Example: Determination of Biological Sludge Production

This example illustrates the use of yield factors and decay factors. Figure 4-4 shows a flow diagram for a hypothetical plant. The problem is to prepare an initial estimate of the loading to the waste-activated sludge thickener. Table 4-5 contains information required for this calculation, including average and maximum day loadings and activated sludge operating characteristics. It is assumed that the thickener in this example will have to handle the maximum-day waste-activated sludge production. Peak loadings of shorter duration than the maximum day production will be handled by storing the added suspended solids in the aeration basins. For the purposes of this example, the sludge treatment processes such as digestion, dewatering, disinfection, thermal conditioning, and chemical conditioning have not been identified. Depending upon the selection and design of the sludge treatment processes, the recycle loads from such processes could have a significant effect upon the quantities of waste-activated sludge and primary sludge that must be processed. When they are known, the degradable organics (BOD) and non-volatile fractions of the recycle streams should be added to the substrate removal (s_r) and non-volatile suspended solids (I_{NV}) factors. Subsequent calculations in Equations 4-1 and 4-2 are for the purposes of obtaining a sludge mass balance, which includes the effect of recycle streams.

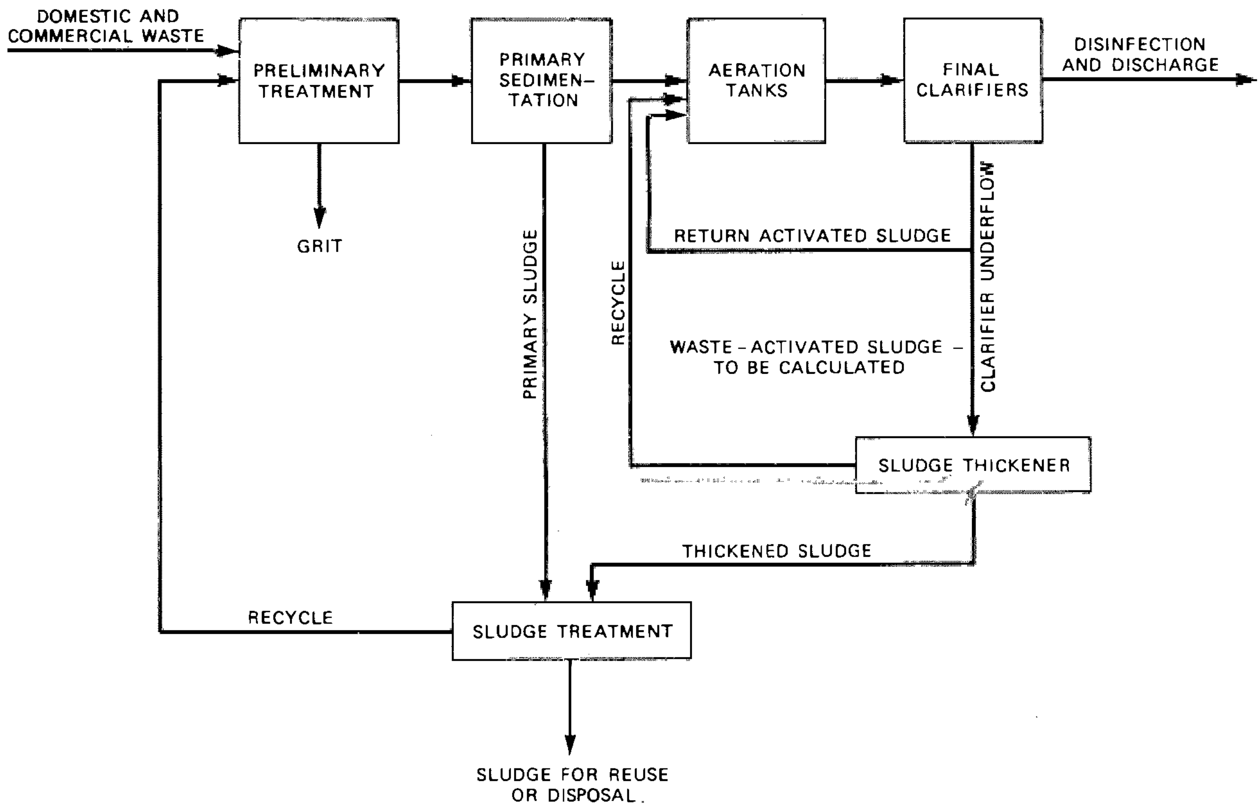


FIGURE 4-4

SCHEMATIC FOR SLUDGE QUANTITY EXAMPLE

Step 1. Determine BOD_5 load to the activated sludge process.

Average day BOD_5 load:

$$5.0 \text{ MGD} \times \frac{8.34 \text{ lb/MG}}{1 \text{ mg/l}} \times 190 \text{ mg/l} \times (1 - 0.35) = 5{,}150 \text{ lb/day}$$

Maximum day BOD_5 load (similar calculation):

$$9.5 \text{ MGD} \times \frac{8.34 \text{ lb/MG}}{1 \text{ mg/l}} \times 160 \text{ mg/l} \times (1 - 0.25) = 9{,}510 \text{ lb/day}$$

TABLE 4-5

DESIGN DATA FOR SLUDGE PRODUCTION EXAMPLE

Description	Value	Description	Value
Influent flow, mgd (m^3/day)		Sludge thickener capture efficiency	
Average day	5.0 (18,900)		
Maximum day	9.5 (36,000)	Average, percent	95
		Maximum day, percent	85
Influent BOD_5, mg/l			
Average day	190	Food-to-microorganism ratio[a]	
Maximum day	160		
		Average	0.3
Influent suspended solids, mg/l		Maximum	0.5
Average day	240	Temperature of wastewater	
Maximum day	190	Average, degrees F (degrees C)	65 (18)
BOD_5 removal in primary sedimentation, percent		Minimum, degrees F (degrees C)	50 (10)
Average day	35		
Maximum day	25	Dissolved oxygen in aeration tanks	
Suspended solids removal in primary sedimentation		Average, mg/l	2.5
		Minimum, mg/l	2.0
Average day	65	Control: automatic	-
Maximum day	50		
		Effluent limitations, 30-day average	
		BOD_5, mg/l	30
		Suspended solids, mg/l	30
		Usable test data for solids production	None[b]

[a] $\frac{\text{lb (kg) } BOD_5 \text{ applied daily}}{\text{lb (kg) mixed liquor VSS}}$

[b] Data from other plants must be used.

1 mgd = 3,785 m^3/day

Note: Maximum day influent BOD_5 and suspended solids concentrations reflect a dilution from average day data due to the higher flow.

Step 2. Determine M, the mass of microorganisms.

$$\text{Average:} \quad F/M = \frac{BOD_5 \text{ applied/day}}{\text{VSS in system}} = 0.3$$

$$M = \frac{5{,}150}{0.3} = 17{,}170 \text{ pounds VSS}$$

Maximum day: F/M = 0.5

$$M = \frac{9,510}{0.5} = 19,020 \text{ pounds VSS}$$

Step 3. Determine Y, the gross yield coefficient, and k_d, the decay coefficient. No test data are available for this waste, so estimates must be made from tests on other wastes. For average conditions, use Los Angeles data from Table 4-4 (27): Y = 0.67 pound (kg) VSS formed per pound (kg) BOD_5 removed; $k_d = 0.06 \text{ day}^{-1}$.

For maximum conditions, use minimum temperature of 36°F (10°C), which produces the maximum Y value. Use the correction from Section 4.3.2.2, which increases Y by 26 percent.

$Y_{max} = 0.67 \times 1.26 = 0.84$; do not adjust k_d

Step 4. Determine s_r (substrate removal) in units to match Y.

Average daily substrate removal:

BOD_5 applied	5,150 lb/day
Effluent BOD_5 (assume 10 mg/l* BOD_5 in effluent)	- 420 lb/day
	4,730 lb BOD_5 removed/day

Maximum daily substrate removal:

BOD_5 applied	9,510 lb/day
Effluent BOD_5 (assume 10 mg/l* BOD_5 in effluent)	- 790 lb/day
	8,720 lb/BOD_5 removed/day

Step 5. Determine P_x, the biological solids production. Use Equation 4-1 from 4.3.2.2:

$$P_x = (Y)(s_r) - (k_d)(M)$$

Average:

$$0.67 \frac{\text{lb VSS produced}}{\text{lb BOD}_5\text{ removed}} \; 4,730 \; \frac{\text{lb BOD}_5\text{ removed}}{\text{day}}$$

$$- (0.06 \text{ day}^{-1}) (17,170 \text{ lb VSS}) = 2,140 \text{ lb VSS produced/day}$$

---

*Allow 10 mg/l for effluent BOD_5, even though the plant is permitted to discharge 30 mg/l. Activated sludge plants can often attain 10 mg/l effluent BOD_5. Sludge capacity should be provided for the sludge produced under such conditions.

Maximum day, similar calculation:

$$(0.84)(8{,}720) - (0.06)(19{,}020) = 6{,}184 \text{ lb VSS produced/day}$$

Step 6. Compute I_{NV} (non-volatile suspended solids fed to the activated sludge process).

Average daily input of non-volatile suspended solids:

$$5.0 \text{ MGD} \times \frac{8.34 \text{ lb/MG}}{1 \text{ mg/l}} \times 240 \text{ mg/l} \times (1 - 0.65)(0.25^*)$$

$$= 880 \text{ lb/day}$$

Maximum daily input of non-volatile suspended solids:

$$9.5 \text{ MGD} \times \frac{8.34 \text{ lb/MG}}{1 \text{ mg/l}} \times 190 \text{ mg/l} \times (1 - 0.50)(0.25^*)$$

$$= 1{,}800 \text{ lb/day}$$

Step 7. Compute E_T (effluent suspended solids).

Average:

$$5.0 \text{ MGD} \times \frac{8.34 \text{ lb/MG}}{1 \text{ mg/l}} \times 10 \text{ mg/l} = 420 \text{ lb/day}$$

Maximum day:

$$9.5 \text{ MGD} \times \frac{8.34 \text{ lb/MG}}{1 \text{ mg/l}} \times 10 \text{ mg/l} = 790 \text{ lb/day}$$

Step 8. Compute waste-activated sludge (WAS_T) production:

From Equation (4-2);

$$WAS_T = P_X + I_{NV} - E_T$$

$$WAS_T = 2{,}140 + 880 - 420 = 2{,}600 \text{ lb TSS/day}$$
(1,180 kg/day)

Maximum day:

$$WAS_T\ 6,184 + 1,880 - 790 = 7,274 \text{ lb TSS/day} \quad (3,302 \text{ kg/day})$$

Step 9. Compute inventory reduction allowance.

Inventory reduction allowance = (0.02)(17,170) = 343 lb/day (156 kg/day)

In the present case, the inventory reduction allowance can be small. Allow two percent of M per day. The 343 lb/day computed here is much smaller than the difference between the average and maximum waste-activated sludge production (Step 8); therefore, if capacity is provided for maximum solids production, then there will be ample capacity for inventory reduction. It is not necessary to reduce inventory during peak loads.

4.3.2.4 Interaction of Yield Calculations and the Quantitative Flow Diagram (QFD)

The example just presented demonstrates a technique for calculating solids production on a once-through basis; that is, any solids associated with recycle streams were not considered in the calculation. The QFD considers the effects of recycle streams. Before the QFD can be constructed for biological treatment processes, an estimate of net solids destruction or synthesis must first be made. The relationship between solids entering and leaving the biological unit is established via the parameter X_D, which is defined as net solids destruction per unit of solids entering the biological unit. The data and calculations from the previous design example allow an initial estimate of X_D to be made.

For the average flow:

1. Solids leaving the biological unit = $P_X + I_{NV}$ = 2,140 + 880 = 3,020 pounds per day

2. Solids entering the biological unit are equal to solids in the primary effluent, which can be calculated from the data on Table 4-4. Primary effluent solids = (1 - 0.65) (240)(8.34)(5.0) = 3,503 pounds per day.

3. Net solids destruction = solids in - solids out = 3,503 - 3,020 = 483 pounds per day (219 kg/day).

4. $X_D = \frac{483}{3,503} = 0.138$

For maximum day flows:

1. Solids leaving the biological unit = 6,184 + 1,880 = 8,064 pounds per day (3,661 kg/day).

2. Solids entering the biological unit = (1 - 0.50)(190) (8.34)(9.5) = 7,527 pounds per day (3,147 kg/day).

3. Net solids destruction = 8,064 - 7,527 = 537 pounds per day (244 kg/day).

4. $X_{D_{max}} = \frac{537}{7,527} = 0.07$

Once X_D is known, the QFD calculation can be undertaken. After the QFD calculation is completed, the designer may wish to make new estimates of P_X and I_{NV}, based on information derived from the QFD calculation. For example, if the QFD calculation shows that recycle loads are substantial, then the designer may wish to modify estimates of s_r and I_{NV} and calculate new values of P_X and I_{NV}, as indicated in Section 3.4.

4.3.2.5 Concentration of Waste-Activated Sludge

The volume of sludge produced by the process is directly proportional to the dry weight and inversely proportional to the thickness or solids concentration in the waste sludge stream. Values for waste-activated sludge concentration can vary, in practice, across a range from 1,000 to 30,000 mg/l SS (0.1 to 3 percent SS).

An important variable that can affect waste-activated sludge concentration is the method of sludge wasting. A number of different methods are illustrated in Figure 4-5. Sludge solids may be wasted from the clarifier underflow. It has been argued that wasting solids from the mixed liquor should improve control of the process (2,35). In this case, waste sludge is removed from the activated sludge process at the same concentration as the mixed liquor suspended solids, about 0.1 to 0.4 percent. This low concentration can be a disadvantage because a large volume of mixed liquor must be removed to obtain a given wastage on a dry weight basis. The most common arrangement involves sludge wasting from the clarifier underflow, because the concentration of sludge there is higher than in the mixed liquor. Subsequent discussions in this section are based on sludge wasting from the clarifier underflow.

Estimating Waste-Activated Sludge Concentration

The two primary factors that affect waste-activated sludge concentration are the settleability of the sludge and the solids loading rate to the sedimentation tank. These two factors have

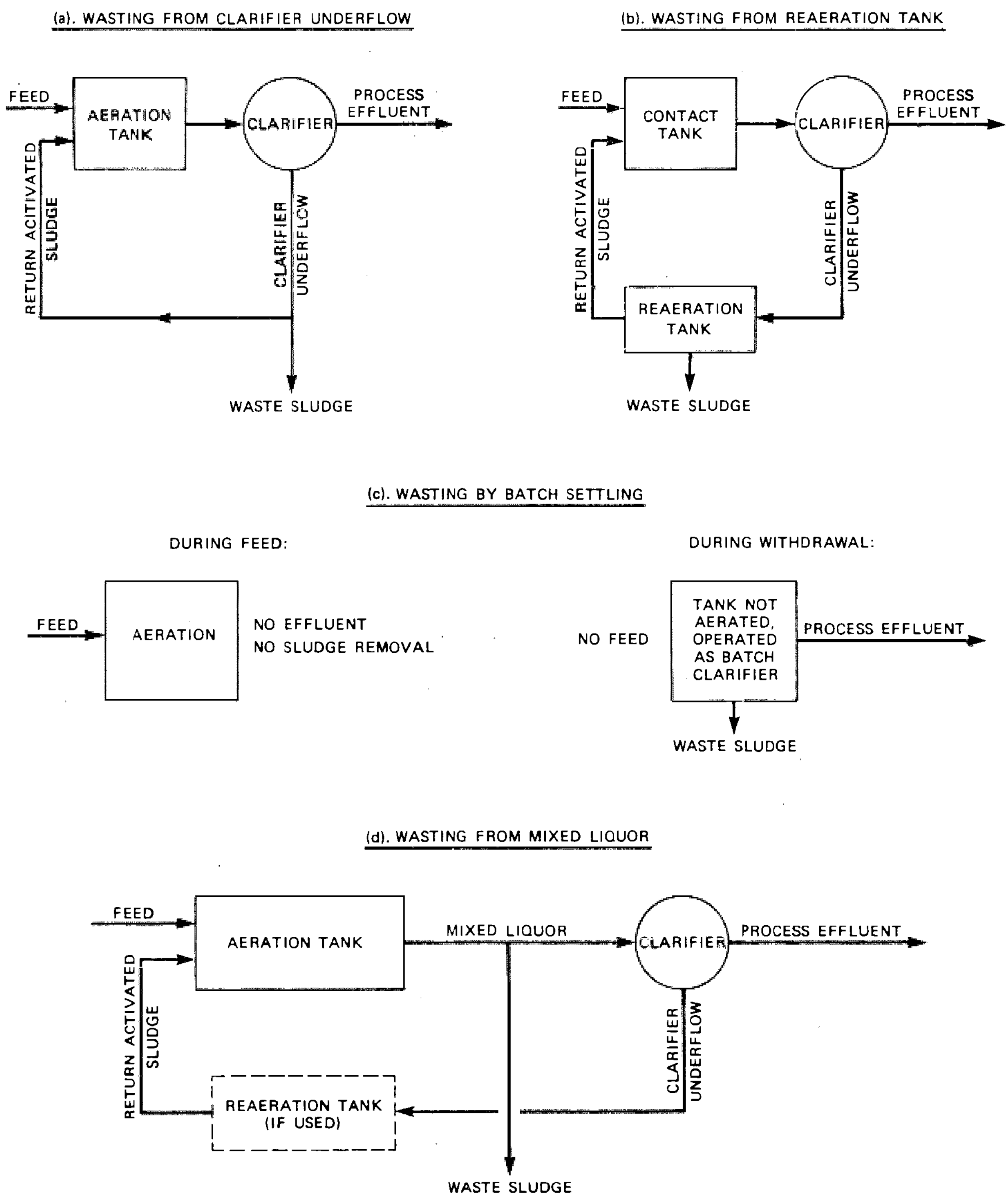


FIGURE 4-5

SLUDGE WASTING METHODS

been considered in detail in the development of solids flux procedures for predicting the clarifier underflow concentration of activated sludge (52).

Factors Affecting Underflow Concentration

Various factors that affect sludge settleability and the clarifier sludge loading rate include:

- Biological characteristics of the sludge. These characteristics may be partially controlled by maintenance of a particular mean sludge age or F/M. High concentrations of filamentous organisms can sometimes occur in activated sludge. Reduction of these organisms through sludge age or F/M control helps to produce more concentrated clarifier underflow.

- Temperature. As wastewater temperatures are reduced, the maximum attainable clarifier underflow sludge concentration (c_u) is also reduced as a result of increased water density. Also, temperature can affect the setting properties of the sludge.

- Solids flux. The solids flux is the solids load from the mixed liquor divided by the clarifier area (for example, pounds per day per square foot). Higher rates of solids flux require that clarifiers be operated at lower solids concentration.

- Limits of sludge collection equipment. Because of the pseudo-plastic and viscous nature of waste-activated sludge, some of the available sludge collectors and pumps are not capable of smooth, reliable operation when c_u exceeds about 5,000 mg/l.

- Heavy suspended solids in the sludge. If raw wastewater, instead of primary sedimentation tank effluent, is fed to the activated sludge process, higher c_u values usually result. Chemicals added to the wastewater for phosphorus and suspended solids removal may similarly affect c_u. However, such additional solids will also increase the solids load to the clarifiers.

4.3.2.6 Other Properties of Activated Sludge

Table 4-6 contains several reported measurements of the composition and properties of activated sludge solids. Comparing Table 4-6 with that of Table 4-2 for primary sludge, activated sludge contains higher amounts of nitrogen, phosphorus, and protein; the grease, fats, and cellulose amounts, and specific gravity are lower.

TABLE 4-6

ACTIVATED SLUDGE CHARACTERISTICS

Characteristic	Range of values	Typical value	Comments	Reference
pH	6.5 - 8	-	Can be less in high purity oxygen systems or if anaerobic decomposition begins.	53, 54
		5.5	Baltimore, Maryland	55
Heating value, Btu/lb (kJ/kg)	-	6,540 (15,200)	Increases with percent volatile content	56
Specific gravity of individual solid particles	-	1.08		
Bulk specific gravity	-	$1.0 + 7 \times 10^{-8} \times C$	C is suspended solids concentration, in mg/l.	57
Color	-	Brown	Some grayish sludge has been noted. Activated sludge becomes black upon anaerobic decomposition.	-
COD/VSS ratio	-	2.17		58
Carbon/nitrogen ratio	-	12.9	Baltimore, Maryland	55
	-	6.6	Jasper, Indiana	55
	-	14.6	Richmond, Indiana	55
	-	5.7	Southwest plant, Chicago, Illinois	55
	-	3.5	Milwaukee, Wisconsin (heat dried)	55
Organic carbon, percent by weight of dry solids	17 - 41	-	Zurich, Switzerland	28
	23 - 44	-	Four plants	55
Nitrogen, percent by weight of dry solids (expressed as N)	4.7 - 6.7	-	Zurich, Switzerland	28
	-	5.6	Chicago, Illinois	59
	2.4 - 5.0	-	Four plants	55
	-	6.0	Milwaukee, Wisconsin	59
Phosphorus, percent by weight of dry solids as P_2O_5 (divide by 2.29 to obtain phosphorus as P)	3.0 - 3.7	-	Zurich, Switzerland	28
	-	7.0	Chicago, Illinois	59
	2.8 - 11	-	Four plants	55
	-	4.0	Milwaukee, Wisconsin	59
Potassium, percent by weight of dry solids as K_2O (divide by 1.20 to obtain potassium as K)	0.5 - 0.7	-	Zurich, Switzerland	28
	-	0.56	Chicago, Illinois	59
	-	0.41	Milwaukee, Wisconsin	59
Volatile solids, percent by weight of dry solids (percent ash is 100 minus percent volatile)	61 - 75	-	Zurich, Switzerland	28
	-	63		58
	62 - 75	-		60
	59 - 70	-	Four plants	55
	-	76	Renton, Washington (Seattle Metro), 1976 average	-
		88	San Ramon, California (Valley Community Services District), 1975 average	-
Volatile solids (continued)	-	81	Central plant, Sacramento County, California, July 1977 - June 1978 average	-
Grease and fat, percent by weight of dry solids	5 - 12	-	Ether extract	61
Cellulose, percent by weight of dry solids		7	Includes lignin	60
Protein, percent by weight of dry solids	32 - 41	-	-	61

Several types of microorganisms are present in large numbers in activated sludge. Floc-forming (zoogleal) bacteria include species of Zoogloea, Pseudomonas, Arthrobacter, and Alcaligenes.

Activated sludge also contains filamentous microorganisms such as Sphaerotilus, Thiothrix, Bacillus, and Beggiatoa (62). Various protozoa are present, including ciliates and flagellates.

4.3.3 Trickling Filters

Trickling filters are widely used in municipal wastewater treatment. This section covers trickling filters that are used with clarifiers. When a clarifier is not used, the trickling filter effluent is usually fed to an activated sludge process. Refer to Section 4.3.5 for such combinations.

4.3.3.1 Computing Trickling Filter Sludge Production - Dry Weight Basis

Trickling filter microorganisms are biochemically similar to microorganisms that predominate in activated sludge systems. Consequently, solids production from trickling filters and from activated sludge systems is roughly similar when compared on the basis of pounds of solids produced per pound of substrate removed. There are differences between the two systems, however, with respect to solids production prediction methodology and the pattern of sludge wasting. Attempts have been made to develop solids production models consistent with biological theory (47,63,64). However, presently (1979), empirical methods are usually used for design purposes. Table 4-7 presents sludge yields observed at several treatment plants and from one long-term pilot study. These data are primarily based on heavily loaded filters.

Equations that relate the production of suspended material in a trickling filter can be developed in a form similar to that used in predicting activated sludge production. The main difference lies in the term used to define the quantity of microorganisms in the system. In long-term studies of trickling filter performance, Merrill (64) assumed that the total mass of microorganisms present in the system was proportional to the media surface area. The resulting equation for volatile solids production was:

$$P_x = Y'(s_r) - K'_d(A_m) \qquad (4\text{-}7)$$

where:

P_x = net growth of biological solids (VSS), pounds per day or kg per day;

Y' = gross yield coefficient, pound per pound or kg/kg;

k'_d = decay coefficient, day^{-1};

S_r = substrate (for example, BOD_5) removed, pounds per day or kg/day = BOD_5 in minus soluble effluent BOD_5;

A_m = total media surface area in reactor, square feet or sq m.

TABLE 4-7

TRICKLING FILTER SOLIDS PRODUCTION

Plant	Unit solids production[a]					Solids percent volatile	BOD_5 load[g]	Media	Reference
	Total BOD_5 basis[b]	IT-ES BOD_5 basis[c]	IT-ES COD basis[d]	SS basis[e]	VSS basis[f]				
Stockton, California[h]								Plastic, 27 ft^2/ft^3	65
Average of 13 months	0.74	0.67	0.43	1.00	0.94	77	27		
Highest month	1.01 (5/76)	0.92 (5/76, 7/76)	0.60 (7/76)	1.17 (6/76, 1/77)	1.08 (10/76)	86 (8/76, 11/76)	73 (8/76)		
Lowest month	0.49 (1/77)	0.48 (1/77)	0.30 (1/77)	0.61 (3/76)	0.60 (3/77)	64 (3/76, 6/76)	15 (6/76)		
Sacramento, California[h]								Plastic	66
9 noncanning months									
Average	-	-	-	1.01	1.00	78	-		
Highest month	-	-	-	1.09	1.09	83	-		
3 canning months									
Average	-	-	-	1.20	1.24	76	-		
Dallas, Texas	0.42	-	-	-	-	-	-	Rock	67
Dallas, Texas	0.65	-	-	-	-	-	-	Rock	67
Livermore, California	1.10[i]	-	-	1.39	1.51	84	57	Rock 2 to 4 in.	68
San Pablo, California	-	-	-	1.39	-	-	199	Plastic, 29 ft^2/ft^3	37
Seattle, Washington[j]	-	0.8-0.9	-	1.0	-	-	30-250	Plastic, various	64

[a] Solids production includes both waste sludge (clarifier underflow) and clarifier effluent solids.

[b] Pounds volatile suspended solids (VSS) per pound BOD_5 removed (same as kg/kg). BOD_5 removal based on total (suspended plus dissolved) measurements.

[c] Pounds VSS per pound BOD_5 removed. BOD_5 removal based on influent total minus effluent soluble (IT-ES) measurements.

[d] Pounds VSS per pound chemical oxygen demand (COD) removed. COD removal based on influent total minus effluent soluble measurements.

[e] Pounds total suspended solids (SS) produced per pounds SS applied.

[f] Pounds VSS produced per pound VSS applied.

[g] Pounds total BOD_5 applied per day per 1,000 cubic feet of media.

[h] Stockton and Sacramento plants have heavy industrial loads about August to October from fruit and vegetable canneries.

[i] Roughing filter. For BOD_5 basis, BOD_5 removal was computed by $BOD_{5,in}$ minus (0.5 times unsettled $BOD_{5,out}$). 1971 average data.

[j] Pilot studies. SS basis was found to describe data well over a wide range of loadings. Wastewater included some industrial load and recycle liquors from dewatering digested sludge.

The production of trickling filter sludge requiring subsequent sludge handling may be expressed:

$$WTFS = P_X + I_{NV} - E_T \quad (4\text{-}8)$$

where:

WTFS = waste trickling filter sludge production, pounds per day or kg/day;

I_{NV} = non-volatile suspended solids fed to the process, pounds per day or kg/day;

E_T = effluent suspended solids, pounds per day or kg/day.

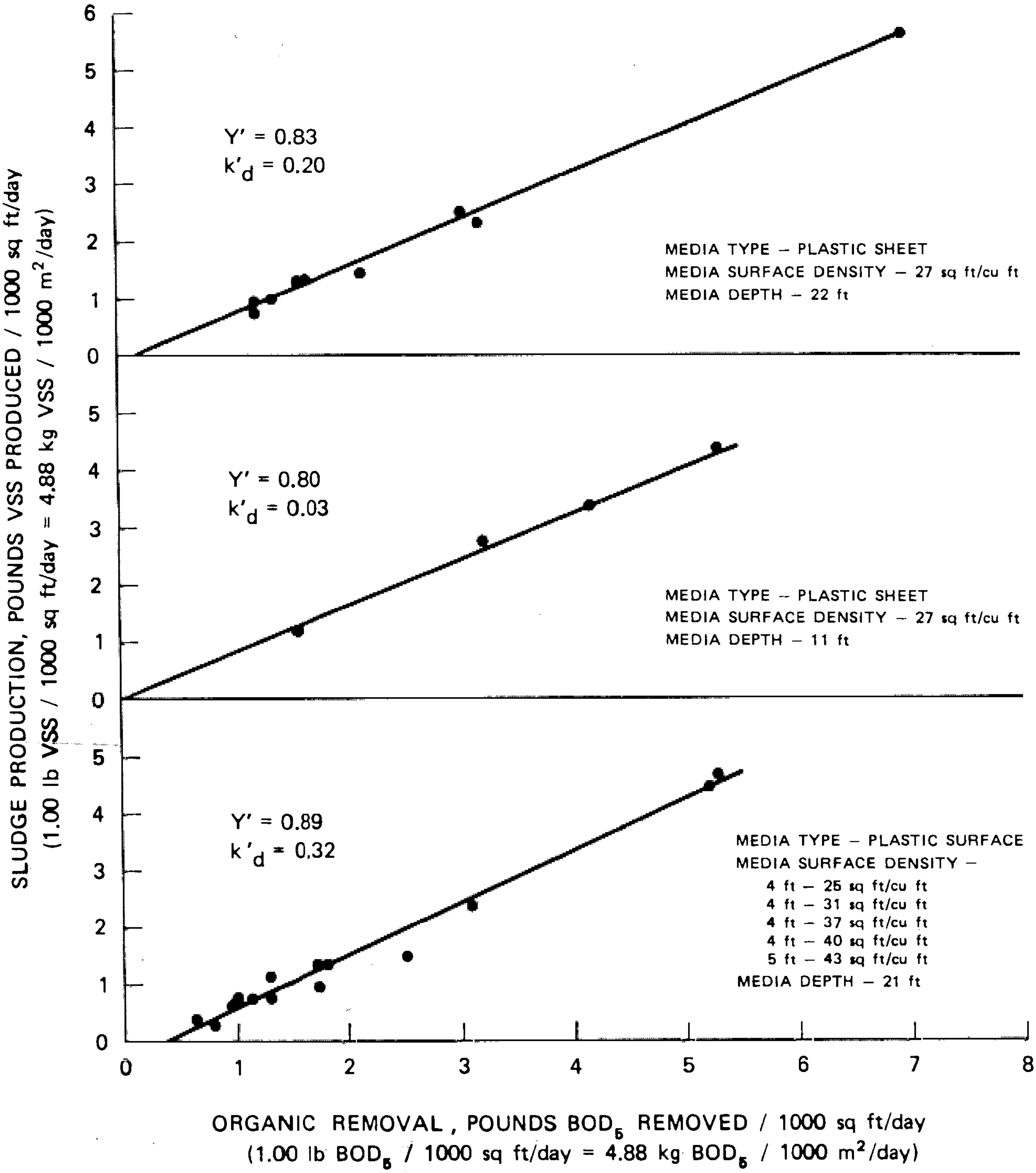
The coefficients Y' and k_d' for Equation 4-7 are obtained for a particular system by computing the slope and intercept of a line of best fit through plotted data points for $\frac{P_x}{A_m}$ vs $\frac{s_r}{A_m}$. VSS production data for three different trickling filter media designs are given on Figure 4-6.

Nitrification in trickling filters causes a synthesis of nitrifying bacteria. As in activated sludge, however, the quantity is small. A value of 25 pounds per million gallons (3 mg/l) has been suggested for design purposes (67). This quantity must be added to the other solids produced by the trickling filter.

It is known that temperature and loading rate affect sludge production: "The quantity of excess sludge produced in a low-rate trickling filter is much lower than that reported for high-rate filters or for the activated sludge process. The lower rate of solids accumulation may be attributable to the grazing activities of protozoa. The activity of the protozoa is reduced considerably at low temperatures (47)." However, there are few data to quantify these variations.

Peak sludge loads are produced by trickling filters. These may be due to variations in influent load, rapid climatic changes, and/or biochemical factors that cause unusually large amounts of biomass to peel off from the media. The term "sloughing" is used by some authorities to include steady state as well as peak solids discharges. Others restrict the term "sloughing" to unusually large discharges. In any case, peak solids loads must be considered. Table 4-8 shows some variations due to both unusual biomass discharges and to variations in influent load. Table 4-9, on the other hand, shows the biomass discharge alone. Each of the three events in Table 4-9 "occurred during periods of light organic loadings (30 to 50 pounds BOD_5 per 1,000 cubic feet per day [0.49 to 0.81 kg/m^3/day]) which had been preceded by periods in which exceptionally heavy organic loadings (215 to 235 pounds BOD_5 per 1,000 cubic feet per day [3.48 to 3.81 kg/m^3/day]) had been applied on a sustained basis (4-14 days)" (64). Table 4-9 shows that effluent solids were much greater than influent solids. This is quite different from average conditions, under which effluent solids were about equal to the influent solids.

In low-rate filters especially, there are seasonal variations in solids production. "Slime tends to accumulate in the trickling filter during winter operation and the filter tends to unload the slime in the spring when the activity of the microorganisms is once again increased" (47).



(1.00 ft = 0.30m)
(1.00 sq ft / cu ft = 3.28 m^2/m^3)

FIGURE 4-6

VSS PRODUCTION DATA FOR THREE TRICKLING MEDIA DESIGNS (64)

TABLE 4-8

DAILY VARIATIONS IN TRICKLING FILTER EFFLUENT, STOCKTON, CALIFORNIA (65)

Period	Number of samples[a]	Average TSS, mg/l	Coefficient of variation[b]	Five percent ratio[c]
March-July 1976	57	144	0.28	1.5
August-September 1976[d]	26	187	0.33	1.6
November 1976 - March 1977	51	149	0.31	1.7

[a]Samples are trickling filter effluent (before sedimentation), total suspended solids, 24-hour refrigerated composites. Flow variations within each sample population were small; that is, ratios in this table represent mass variations as well as concentration variations.

[b]Standard deviation divided by average.

[c]Ratio of individual sample concentration to average concentration that is exceeded by 5 percent of the samples.

[d]Heavy industrial load in August and September from fruit and vegetable canneries.

TABLE 4-9

DESCRIPTION OF SLOUGHING EVENTS (65)

Period	Duration, days	Suspended solids, mg/l		Flow, gpm/sq ft		Applied loading,[c] lb BOD_5/1,000 cu ft/day	Media specific surface, sq ft/cu ft
		Influent	Effluent	Influent[a]	Recycle[b]		
October 22-26, 1976	5	114	256	0.44	2.06	33	27[d]
August 5-6, 1977	2	132	289	0.63	1.56	50	27[d]
July 31-August 5, 1977	6	147	222	0.63	1.56	50	Graded[e]

[a]Influent wastewater flow divided by plan area of filter.

[b]Recycle flow (from trickling filter effluent) divided by plan area of filter.

[c]Based on influent flow.

[d]Plastic sheet media, 22 ft deep.

[e]Plastic sheet media, 22 ft deep; specific surface ranged from 25 sq ft/cu ft at the top of the filter to 43 sq ft/cu ft at the bottom.

1 gpm/sq ft = 2.46 $m^3/hr/m^2$
1 lb BOD_5/1,000 cu ft/day = 0.0162 $kg/m^3/day$

The amount of solids requiring sludge treatment depends on sedimentation performance, which is usually 50 to 90 percent removal of suspended solids. Sedimentation performance is improved by careful design, light loads, tube settlers, and coagulation and flocculation (19,64).

4.3.3.2 Concentration of Trickling Filter Sludge

Trickling filter sludge loadings on the secondary sedimentation tank are typically low--5 to 10 percent of observed solids loads to activated sludge sedimentation tanks. Trickling filter sludge also has better thickening properties than activated sludge. Consequently, trickling filter sludge can be withdrawn at a much higher concentration than waste-activated sludge. Concentration data are summarized in Table 4-10.

TABLE 4-10

CONCENTRATION OF TRICKLING FILTER SLUDGE WITHDRAWN FROM FINAL CLARIFIERS

Type of sludge	Percent dry solids	Comments	Reference
Trickling filter, alone	5 - 10	Depends on solids residence time in trickling filter	69
	7		13
	7	Low-rate trickling filter	70
	3	High-rate trickling filter	70
	3 - 4		71
	4 - 7		2
Trickling filter, combined with raw primary	3 - 6		2,69

The solids flux method for predicting sludge concentration may be used with trickling filter sludge (52). This method requires measurement of initial solids settling velocity versus solids concentration. Such relationships have been reported for at least one trickling filter process (64).

4.3.3.3 Properties - Trickling Filter Sludge

Table 4-11 contains a few analyses of trickling filter sludge properties. The microbial population that inhabits a trickling filter is complex and includes many species of algae, bacteria, fungi, protozoa, worms, snails, and insects. Filter flies and their larvae are often present in large numbers around trickling filters.

4.3.4 Sludge from Rotating Biological Reactors

Rotating biological reactors (RBRs) are used for the same basic purposes as activated sludge and trickling filters: to remove BOD_5 and suspended solids and, where necessary, to nitrify. The RBR process uses a tank in which wastewater, typically primary effluent, contacts plastic media in the shape of large discs. Bacteria grow on the discs. The discs rotate slowly on horizontal shafts; the bacteria are alternately submerged in the wastewater and exposed to air. Excess bacteria slough from the discs into the wastewater. After contacting the bacteria, the wastewater flows to a sedimentation tank, where the excess bacteria and other wastewater solids are removed. These removed solids are RBR sludge. RBR sludge is roughly similar in quantity by dry weight, nutrient content, and other characteristics, to trickling filter sludge.

TABLE 4-11

TRICKLING FILTER SLUDGE COMPOSITION

Property	Value	Comments	Reference
Volatile content, percent of total solids	64 - 86	See Table 4-7	-
Nitrogen, percent of total solids	1.5 - 5	Depends on length of storage of sludge in filter.	69
	2.9		71
	2.0		13
Phosphorus as P_2O_5, percent of total solids	2.8		71
	1.2		13
Fats, percent of total solids	6	Ether soluble.	13
Grease, percent of total solids	0.03	Test slime grown in primary effluent.	72
Specific gravity of individual solid particles	1.52		73
	1.33		2
Bulk specific gravity (wet)	1.02		13
	1.025		2
Color	Grayish brown		13
	Black		64

A small body of published data is available on RBR sludge production rate from full-scale municipal installations. At Peewaukee, Wisconsin, total suspended solids production has been reported to be 0.62 to 0.82 pounds of total suspended solids per pound BOD_5 (0.62 to 0.82 kg TSS/kg) removed. The final sedimentation tank removed 70 to 83 percent of these solids as sludge. The biological sludge alone had a concentration of 1.5 to 5.0 percent solids. Other investigations of municipal and industrial waste applications have concluded that sludge production for the RBR process amounts to 0.4 to 0.5 pound of total suspended solids per pound of BOD_5 (0.4 to 0.5 kg TSS/kg BOD_5) removed (74,75,76).

4.3.5 Coupled Attached-Suspended Growth Sludges

There are several installations of coupled attached and suspended growth processes in the United States. These dual processes are usually installed where nitrification is required or where strong wastes must be treated. The attached growth reactor is a trickling filter or a rotating biological reactor. Its role is to reduce the load on the suspended growth process. The suspended growth process uses an aeration tank and a final clarifier. Flow recirculation is usually practiced around the attached growth reactor. Several reports describe these processes and note that the sludge is similar to activated sludge, both in quantity and in characteristics (5,67,68,77,78). The sludge characterized in Table 4-12 contains some particles of dense solids from the attached growth reactor. These particles may improve the thickening characteristics of the sludge (78).

TABLE 4-12

SLUDGE FROM COMBINED ATTACHED-SUSPENDED GROWTH PROCESSES

Process	Location	Solids production lb TSS produced/ lb BOD_5 removed	Percent volatile	Primary sludge mixed with biological sludge: Percent solids	Primary sludge mixed with biological sludge: Percent volatile
Roughing filter plus nitrifying activated sludge	Livermore, California (68)	0.98	Not stated	3.3	84
Roughing filter plus nitrifying activated sludge	San Pablo, California (37)	1.47	78.2	Not stated	Not stated

4.3.6 Denitrification Sludge

Denitrification is a biological process for the removal of nitrate from wastewater. An electron donor, carbon in primary effluent or methanol, is added to the nitrate-bearing wastewater. Denitrifying bacteria extract energy for growth from the reaction of nitrate with the electron donor:

Nitrate + Electron donor (reduced state) $\longrightarrow$

Nitrogen gas + Oxidized electron donor + Energy

Denitrification has been extensively studied, and a few denitrification processes have been built into municipal plants. Denitrifying bacteria can grow either in a suspended growth system similar to activated sludge or in an attached growth system similar to a trickling filter. Sludge production for ordinary nitrified domestic waste is roughly 300 pounds per million gallons (30 mg/l) of wastewater treated (37).

4.4 Chemical Sludges

4.4.1 Introduction

Chemicals are widely used in wastewater treatment to precipitate and remove phosphorus, and in some cases, to improve suspended solids removal. At all such facilities, chemical sludges are formed. A few plants apply chemicals to secondary effluent and use tertiary clarifiers to remove the chemical precipitates. An example of this arrangement is the plant at South Lake Tahoe, California. However, it is more common to add the chemicals to the raw wastewater or to a biological process. Thus, chemical precipitates are usually mixed with either primary sludge solids or biological sludge solids.

The discussion below is brief because the subject of chemical sludges and their characteristics is discussed in detail elsewhere (79-82). A 1979 publication provides considerable background information on theoretical rates of chemical sludge production, as well as actual operating data from wastewater treatment plants employing chemicals for removal of phosphorus (7). Also, production of chemical sludges in primary sedimentation is discussed in Section 4.2.2.5.

4.4.2 Computing Chemical Sludge Production - Dry Weight Basis

Chemicals can greatly increase sludge production. The amount of increase depends on the chemicals used and the addition rates. There is no simple relationship between the mass of the chemical added and the mass of sludge produced. It is beyond the scope of this manual to describe in detail the chemistry associated with the chemicals used in treating wastewater, and the various solids-producing reactions that can occur. However, several types of precipitates that are produced and must be considered in measuring the total sludge production are listed below:

- Phosphate precipitates. Examples are $AlPO_4$ or $Al(H_2PO_4)(OH)_2$ with aluminum salts, $FePO_4$ with iron salts, and $Ca_3(PO_4)_2$ with lime (79,82,83).

- Carbonate precipitates. This is significant with lime, which forms calcium carbonate, $CaCO_3$. If two-stage recarbonation is used, a recarbonation sludge of nearly pure $CaCO_3$ is formed (84).

- Hydroxide precipitates. With iron and aluminum salts, excess salt forms a hydroxide, $Fe(OH)_3$ or $Al(OH)_3$. With lime, magnesium hydroxide, $Mg(OH)_2$, may form; the magnesium comes from the influent wastewater, from the lime, or from magnesium salts.

- Inert solids from the chemicals. This item is most significant with lime. If a quicklime is 92 percent CaO, the remaining eight percent may be mostly inert solids that appear in the sludge. Many chemicals supplied in dry form may contain significant amounts of inert solids.

- Polymer solids. Polymers may be used as primary coagulants and to improve the performance of other coagulants. The polymers themselves contribute little to total mass, but they can greatly improve clarifier efficiency with a concomitant increase in sludge production.

- Suspended solids from the wastewater. Addition of any chemical to a wastewater treatment process affects process efficiency. The change in sludge production must be considered.

Quantities of the various precipitates in chemical sludges are determined by such conditions as pH, mixing, reaction time, water composition, and opportunity for flocculation.

Chemical sludge production, like the production of other sludges, varies from day to day. The variation depends strongly on chemical dosage and on wastewater flows. If the chemical dosage is about constant in terms of milligrams per liter of wastewater, chemical solids production will still vary, since flows fluctuate from day to day. Changes in wastewater chemistry may also affect the production of chemical sludge. For example, stormwater inflow typically has a lower alkalinity than ordinary wastewater. During storms, the production of chemical sludge will be different from production in dry weather.

4.4.3 Properties of Chemical Sludges

Chemical sludge properties are affected mainly by the precipitated compounds and by the other wastewater solids. For example, a lime primary sludge will probably dewater better than a lime sludge containing substantial amounts of waste-activated sludge solids (80). Generally speaking, lime addition results in a sludge that thickens and dewaters better than the same sludge without chemicals. When iron or aluminum salts are added to raw wastewater, the primary sludge does not thicken or dewater as well as non-chemical sludge. Iron sludges dewater slightly more easily than aluminum sludges (79). When aluminum salts are added to activated sludge, the sludge may thicken much better than non-chemical activated sludge (85,86). Anionic polymers can often improve the thickening and dewatering properties of chemical sludges.

For efficient chemical usage, feed rates must be adjusted to match changes in wastewater flow and composition.

4.4.4 Handling Chemical Sludges

Most of the common sludge treatment processes can be used with chemical sludges: thickening, stabilization by digestion, incineration, etc. This section summarizes information on stabilization and also on recovery of chemicals and by-products.

4.4.4.1 Stabilization

Lime sludges may be stabilized by a small additional dose of lime. Lime stabilization may also be used for aluminum and iron sludges. The lime improves dewatering of these sludges by acting as a conditioning agent. Chapter 6 discusses lime stabilization of chemical sludges. Dewatered lime-stabilized sludges can usually be buried in sanitary landfills.

Digestion of mixed biological-chemical sludges is generally feasible. Pure chemical sludge will not digest. Studies done in 1974 and 1978, however, note significant reductions in digestibility as chemicals were added to sludge; the studies investigated the addition of aluminum, iron, and polymer (87,88).

4.4.4.2 Chemical and By-product Recovery

Where lime use results in calcium carbonate formation, it may be feasible to recover lime by recalcination. Tertiary lime treatment, as practiced at the South Lake Tahoe, California, plant is well suited to lime recovery; a recalcination process has been operated there for several years. Where lime is added to raw wastewater, lime recovery is more difficult but still possible. Lime recovery does not reclaim all of the calcium, as some is always lost with the phosphate, silica, and other materials that must be removed from the system. Lime recovery reduces but does not eliminate the amount of residue for disposal. Feasibility of lime recovery depends on plant size, amount of calcium carbonate formed, cost of new lime, and cost of sludge disposal (81,82).

4.5 Elemental Analysis of Various Sludges

As a rule, almost anything can be found in sludge. This section describes trace elements in all types of sludge. Data on concentrations of the 74 elements found in wastewater sludge are included in References 89-95.

4.5.1 Controlling Trace Elements

It is a basic principle of chemistry that elements are not created or destroyed but chemically recombined. Therefore, the mass of each element entering a treatment plant fixes the mass that either accumulates within the plant or leaves it. The mass leaving the plant does so in gaseous emissions, effluent, a special concentrated stream, or sludge. Extracting toxic elements from sludge appears to be impractical; source control is the most practical way to reduce toxicants.

Trace elements are present in industrial process waste, industrial waste spills, domestic water supply, feces and urine, and detergents. Additional trace elements are derived from:

- Chemicals in photographic solutions, paints, hobby plating supplies, dyes, and pesticides used in households and commercial enterprises.

- Storm inflow (this is particularly true for lead from gasoline anti-knock compounds).

- Corrosion of water piping, which contributes zinc, cadmium, copper, and lead (96).

- Chemicals used in wastewater treatment, sludge conditioning, etc. Table 4-13 shows an analysis of ferric chloride, which is an industrial by-product (pickle liquor) of wastewater solids treatment.

TABLE 4-13

METALS IN FERRIC CHLORIDE SOLUTIONS (97)

Constituent	Concentration, mg/l[a]
Cadmium	2 - 3.5
Chromium	10 - 70
Copper	44 - 14,200
Iron	146,000 - 188,000
Nickel	92 - 6,200
Lead	6 - 90
Silver	2
Zinc	400 - 2,150

[a]Three different liquid sources were analyzed (43 percent $FeCl_3$).

The quantity of toxic pollutants may be significantly reduced by source control. At Los Angeles County, metal finishing industries were a major source of cadmium, chromium, copper, lead, nickel, and zinc. A source control program was developed in cooperation with the local Metal Finisher's Association. This program was quite successful, as shown in Table 4-14, by the general downward trend in wastewater concentrations over time.

TABLE 4-14

PROGRESS IN SOURCE CONTROL OF TOXIC POLLUTANTS (98)

Wastewater pollutant	Concentration in mg/l in influent wastewater					
	January-June 1975	July-December 1975	January-June 1976	July-September 1976	October-December 1976	January 1977
Cadmium	0.037	0.031	0.029	0.033	0.027	0.019
Chromium	0.70	0.73	0.78	0.61	0.47	0.43
Copper	0.45	0.45	0.45	0.33	0.34	0.30
Lead	0.40	0.31	0.34	0.28	0.32	0.34
Nickel	0.31	0.33	0.35	0.34	0.27	0.21
Zinc	1.55	1.48	1.37	1.41	1.29	1.17

Note: Data for Joint Water Pollution Control Plant, Los Angeles County, California; weekly composite samples. (13).

Occasionally, elements can be converted from a highly toxic form to a less toxic form in wastewater treatment. Chromium is a good example of this. In its hexavalent form, it is highly toxic, but may be converted to the less toxic trivalent form in secondary treatment.

4.5.2 Site-Specific Analysis

The elemental compositions of various sludges differ from one another. If sludges are to be reused, they should be analyzed for a number of elements. The importance of site-specific analysis of sludges varies with the size of the project, regulatory requirements, industrial activity, and the type of reuse desired. A sampling program should recognize that:

- One plant's sludge may have 100 times or more of a certain element than another plant's.

- There may be major variations between samples at the same plant. A single grab sample may produce misleading results. Careful attention to sampling and statistical procedures will tend to reduce the uncertainty. A detailed report on such procedures is available (99).

- Estimates of trace element sludge contamination based on wastewater analysis are usually less useful than estimates based on sludge testing. However, if an element can be measured in the influent wastewater and if flow rates are known, then a mass load (lb or kg per day) may be computed. For purposes of estimating sludge contamination, it is reasonable to assume that large trace amounts of cadmium, copper, and zinc appear in the sludge. Analyses of sludge and supernatant samples from a facultative sludge lagoon have shown that there is a tendency for nickel and lead to be gradually released from the sludge to the liquid phase (97).

- Sludge samples should be analyzed for percent solids and percent volatile as well as for trace elements.

4.5.3 Cadmium

Because it is often found in amounts that limit sludge reuse as a soil conditioner, cadmium is a critical element. If sludge containing cadmium is applied to agricultural cropland, some cadmium may enter the food chain. It has been argued, with much controversy, that the normal human dietary intake of cadmium is already high in comparison to human tolerance limits and that sources of additional cadmium should be strictly limited (100,101). Table 4-15 summarizes reports on cadmium in sludge.

Chapter 18 includes a discussion of the control of sludge application rates for the purpose of limiting cadmium levels in soil and crops. Additional information on this subject is provided in reference 90.

TABLE 4-15

CADMIUM IN SLUDGE

		Concentration, mg/dry kg					
Type of sludge	Location	Mean	Standard deviation	Median	Range	Number of samples	Reference
Digested	12 U.S. cities	89	72	65	6.8 - 200	12	89
Heat dried	4 U.S. cities	150	200	67	15 - 440	4	89
Anaerobic	Various U.S.	106	-	16	3 - 3,410	98	90
"Other"	Various U.S.	70	-	14	4 - 520	57	90
Not stated	42 cities in England, Wales	-	-	<200	<200 - 1,500 (7 >200)	42	91
Incinerator ash	Palo Alto, California	84	-	-	68 - 99	2	92
Digested	Chicago (Calumet)	-	-	-	10 - 35	-	93
Digested waste-activated	Chicago (West-Southwest)	340	-	-	-	43	102
Dewatered digested primary	Seattle (West Point)	48	-	-	-	100 approximate	94
Digested	Cincinnati (Millcreek)	130[a]	1.51[b]	-	-	25	95
Raw	Several U.S. cities	30	15	20	-	20	95
Digested	About 25 U.S. cities	75	104	31	9 - 550	80	95
Raw primary	Los Angeles (Hyperion)[c]	39	-	-	-	-	103
Mesophilic digested	Los Angeles (Hyperion)[c]	140	-	-	-	-	103
Thermophilic digested	Los Angeles (Hyperion)[c]	120	-	-	-	-	103
Waste-activated	Los Angeles (Hyperion)[c]	110	-	-	-	-	103
Anaerobically digested chemical and waste-activated (3.9 percent average solids)	Chatham, Ontario[c]	2.6	1.4	1.8	0 - 10	225	99
Anaerobically digested chemical and waste-activated (3.2 percent)	Simcoe, Ontario[c]	78	5	72	66 - 110	198	99
Anaerobically digested chemical and waste-activated (4.2 percent)	Tillsonburg, Ontario[c]	9	1	9	7 - 12	40	99
Raw primary	Sacramento, California (Northeast)	2.8	1.1	2.6	1.4 - 4.2	5[d]	97
Raw primary	Sacramento (Rancho Cordova)	3.0	1.4	2.6	1.2 - 4.5	5[d]	97
Raw primary	Sacramento (Natomas)	3.5	1.1	3.6	2.2 - 5.1	5[d]	97
Raw primary and biofilter	Sacramento (Highland Estates)	4.1	1.3	3.8	2.8 - 5.9	5[d]	97
Raw primary and biofilter	Sacramento (County Sanitation District 6)	3.6	3.3	2.5	1.0 - 9.1	5[d]	97
Raw primary and biofilter	Sacramento (Meadowview)	3.1	1.0	2.6	2.3 - 4.4	5[d]	97

[a]Geometric mean.

[b]Spread factor for use with geometric mean.

[c]Concentrations reported on wet weight basis and converted to dry weight basis.

[d]Weekly composites of daily samples.

TABLE 4-15

CADMIUM IN SLUDGE (CONTINUED)

Type of sludge	Location	Concentration, mg/dry kg Mean	Standard deviation	Median	Range	Number of samples	Reference
Raw primary and bio-filter	Sacramento (City Main)	10.5	2.0	11	7.6 - 13	5[d]	97
Waste activated	Sacramento (Arden)	5.4	2.6	6.7	2.3 - 7.7	5[d]	97
Raw primary and waste-activated	Sacramento (Rio Linda)	9.7	2.9	9.1	6.2 - 14	5[d]	97
Raw primary	Sacramento (County Central)	29	28	12	8.3 - 72	5[d]	97
Anaerobically digested ferric chloride	North Toronto, Ontario	29	9	-	-	60	104
Anaerobically digested chemical (mostly alum)	Point Edward, Ontario	8.5	1.9	-	-	61	104
Anaerobically digested lime	Newmarket, Ontario	7.5	4.2	-	-	59	104
Anaerobically digested ferric chloride	Sarnia, Ontario	76	21	-	-	40	104

[a]Geometric mean.
[b]Spread factor for use with geometric mean.
[c]Concentrations reported on wet weight basis and converted to dry weight basis.
[d]Weekly composites of daily samples.

4.5.4 Increased Concentration During Processing

Toxic elements often are non-volatile solids that remain in sludge after volatile solids have been removed. Removal of volatile solids such as organic matter increases the concentration of non-volatile components, expressed on a dry weight basis. Table 4-16 shows this effect for four metals at one plant. This increased concentration may be important if sludge reuse is desired and if regulations limit reuse for sludge that contains contaminants that exceed certain concentrations.

TABLE 4-16

INCREASED METALS CONCENTRATION DURING PROCESSING

Element	Concentration, mg/kg dry weight: Raw primary sludge (79 percent volatile)	Anaerobically digested sludge (68 percent volatile)	Lagooned sludge (56 percent volatile)
Chromium	110	160	220
Copper	200	340	450
Nickel	46	63	65
Zinc	620	930	1,400
Number of samples	(5)	(2)	(30)

Note: 1977 data, Sacramento County Central treatment plant, California. Anaerobic digesters also receive thickened waste-activated sludge (metals content not measured).

4.6 Trace Organic Compounds in Sludge

Several of the trace organic compounds found in sludge, for example, polychlorinated biphenyls (PCBs), are toxic, slow to decompose and widely distributed in the environment. Table 4-17 quantifies the amount of Aroclor 1254, a common PCB, found in sludge. Three other PCBs, Aroclors 1242, 1248, and 1260, have also been found in sludge (105,107,108). In 1970, the production of PCBs for several end uses was halted in the United States and was completely phased out in 1977. As of 1979, imports of PCBs are prohibited except for a few special purposes. It is anticipated that these measures will help to reduce PCB levels in sludge. However, products containing PCBs are still in use, and these chemicals are widely distributed, so that several years may elapse before PCBs become undetectable in sludge.

TABLE 4-17

AROCLOR (PCB) 1254 MEASUREMENTS IN SLUDGE

Sludge type	Location	Average concentration of samples with compound detected: Wet basis, ug/l	Dry basis, mg/kg	Number of samples	Samples with compound detected	Year of sample collection	Reference
Undigested	Hamilton, Ontario	81	-	-	-	1976	105
Undigested (with Al)	Kitchener, Ontario	110	-	-	-	1976	-
Undigested (with Ca)	Newmarket, Ontario	74	-	-	-	1976	-
Undigested (with Fe)	North Toronto, Ontario	120	-	-	-	1976	-
Raw primary	Sacramento, CA (Northeast)	50	1.6	5[a]	1	1977	97
	Sacramento, (Natomas)	60	1.5	5[a]	1	1977	-
	Sacramento (County Central)	80	1.8	5[a]	5	1977	-
Raw primary and biofilter	Sacramento, (City Main)	80	3.8	5[a]	4	1977	-
	Sacramento (County Sanitation District 6)	50	2.0	5[a]	1	1977	-
	Sacramento (Meadowview)	50	2.4	5[a]	2	1977	-
Raw primary and waste activated	Sacramento (Rio Linda)	90	3.5	5[a]	3	1977	-
Lagooned digested primary and waste activated	Sacramento (County Central)	270	4.8	30	30	1977	106
Digested	10 U.S. cities	-	3.9	10	9	1971-1972	89
Heat dried	4 U.S. cities	-	9.3	4	4	1971-1972	-

[a] Weekly composite of daily samples.

Because of their fat-soluble nature, PCBs tend to concentrate in skimmings and scum at wastewater treatment plants. The conventional procedure of introducing skimmings into the digester can cause higher concentrations of PCBs in the final sludge. Alternative disposal procedures for skimmings, such as incineration, can reduce this problem.

Table 4-18 presents data on three chlorinated hydrocarbon pesticides found in sludge from several treatment plants.

TABLE 4-18

CHLORINATED HYDROCARBON PESTICIDES IN SLUDGE (97, 106)

Compound	Sludge type	Plant	Average concentration in samples with compound detected, mg/dry kg	Total samples	Samples with compound detected
Hexachlorobenzene	Waste-activated	Arden	0.8	5[a]	1
Hexachlorobenzene	Raw primary	County Central	0.4	5[a]	2
Lindane	Waste-activated	Arden	1.0	5[a]	1
	Raw primary	Northeast	0.6	5[a]	1
Technical-grade chlordane	Raw primary	Northeast	2.6	5[a]	1
	Raw primary	Natomas	2.3	5[a]	2
	Raw primary	County Central	2.8	5[a]	5
	Lagooned anaerobically digested primary and waste-activated	County Central	4.2	30	30
	Waste-activated	Arden	4.4	5[a]	2
	Raw primary and waste-activated	Rio Linda	5.5	5[a]	5
	Raw primary and biofilter	Meadowview	0.6	5[a]	1
	Raw primary and biofilter	City Main	19	5[a]	4

All plants in Sacramento County, California.

[a]Weekly composites of daily samples.

4.7 Miscellaneous Wastewater Solids

In addition to the primary, biological, and chemical sludges discussed in previous sections, there are several other wastewater solids that must be properly handled to achieve good effluent, general environmental protection, and reasonable treatment plant operations. These solids include screenings, grit, scum, septage, and filter backwash.

When mixed with primary or secondary sludges, screenings, scum, grit, and septage can interfere with the processing and reuse of the sludge. Before mixing these wastewater solids with primary and secondary sludges, design engineers should consider the following:

- Screenings and scum detract from the final appearance, and marketability, and utilization of sludges. They can also clog piping, pumps, and mixers, and occupy valuable space in digesters and other tankage.

- Scum presents a special problem when mixed with other solids and subjected to gravity thickening, decanting, or centrifugation. Under these conditions, scum tends to concentrate in the sidestream and to be recycled to the wastewater processes. Eventually some of this recycled scum is discharged to the effluent.

- Grit can block pipelines, occupy valuable space in digesters and other tankage, and cause excessive wear to solids piping and processing equipment.

4.7.1 Screenings

Screenings are materials that can be removed from wastewater by screens or racks with openings of 0.01 inch (0.25 mm) or larger. Coarse screens or racks have openings larger than 0.25 inch (6 mm), whereas fine screens have openings from 0.01 to 0.25 inch (0.25 to 6 mm). If openings are larger than 1.5 inches (38 mm), the screens are often called trash racks.

Racks and screens are usually installed to treat the wastewater as it enters the treatment plant. Racks and coarse screens prevent debris from interfering with other plant equipment. Fine screens remove a significant fraction of the influent suspended solids and BOD_5, thus reducing the load on subsequent treatment processes. In this regard, fine screens may act like primary sedimentation tanks, although they do not ordinarily remove as much of the solids as do sedimentation tanks. Fine screens are usually protected by upstream coarse screens or racks.

4.7.1.1 Quantity of Coarse Screenings

Coarse screenings are basically debris. Items typically collected on coarse screens include rags, pieces of string, pieces of lumber, rocks, tree roots, leaves, branches, diapers, and plastics.

The quantity of coarse screenings is highly variable, but most plants report 0.5 to 5 cubic feet per million gallons (4 ml/m^3 to 40 ml/m^3) on average flows. Table 4-19 shows the quantities of screenings reported for a number of communities. The quantity of screenings depends on:

- <u>Screen opening size</u>. Generally, greater quantities are collected with smaller screen openings. This was seen most clearly at Grand Island, Nebraska, where a change from 0.5-inch to 1.25-inch (13 to 32 mm) openings caused screenings production to drop from about 7 to about 3 cubic feet per day (0.2 to 0.08 m^3/day)(114). Tests at Chicago, Illinois, and Adelaide, Australia, showed this tendency also (13).

- <u>Shape of openings</u>. For example, bar racks may have openings 0.75 inch (19 mm) wide and over 2 feet (over 600 mm) long. Such a rack will pass twigs, ballpoint pens, and other debris, that would be captured on a mesh-type screen with square openings of 0.75 inch (19 mm).

- <u>Type of sewer system</u>. Combined storm and sanitary sewers produce more screenings than separate sanitary sewers. This effect is especially pronounced where much or all of the combined wastewater is treated during and after storms, rather than being bypassed.

TABLE 4-19

SCREENING EXPERIENCE (109, 110)

Rack or screen opening, in.	City	Flow, mgd	Screenings, cu ft/mil gal
3-3/8	Norwalk, Connecticut	11.75	0.17
3	New Haven, Connecticut	8	1.0
3	East Hartford, Connecticut	4.0	1.33
3	San Jose, California	-	0.25
1-3/8	New York, New York, Jamaica	65	0.6
1-1/2	Philadelphia, Pennsylvania, North	48.2	2.20
1-1/2	Oklahoma City, Oklahoma, Southside	25.0	2.1
1-1/2	Cranston, Rhode Island	8.32	0.65
1-1/2	Taunton, Massachusetts	3.5	1.0
1-1/2	Meadville, Pennsylvania	2.5	0.6
1-1/2	Grove City, Pennsylvania	0.8	0.1
1-1/4	Uniontown, Pennsylvania	3.0	0.9
1-1/4	Fargo, North Dakota	2.7	4.55
1	New York, Wards Island	180	1.0
1	New York, Owls Head	160	0.6
1	Minneapolis-St. Paul, Minnesota	134	0.9
1	New York, Hunts Point	120	0.7
1	East Bay, Oakland, California	98	1.6
1	New York, Coney Island	70	1.4
1	New York, 26th Ward	60	1.1
1	New York, Tallmans Island	40	0.7
1	Bridgeport, Connecticut, West Side	17	0.93
1	New York, Rockaway	15	1.0
1	Waterbury, Connecticut	15	2.35
1	Bridgeport, Connecticut, East Side	14	2.04
1	Duluth, Minnesota	12	0.56
1	Austin, Minnesota	9	1.1
1	Fond du Lac, Wisconsin	7.2	5
1	Findlay, Ohio	7	0.39
1	Massillon, Ohio	5.2	1.5
1	York, Nebraska	5	1.5
1	Marion, Ohio	5.0	2.5
1	Gainesville, Florida	5	3.5
1	Marshalltown, Iowa	4.0	0.25
1	East Lansing, Michigan	3.8	0.4
1	Birmingham, Michigan	1.5	1.2
7/8	Boston, Massachusetts, Nut Island	125	1.2
7/8	Richmond, Indiana	6.2	1.2
3/4	Detroit, Michigan	450	0.47
3/4	New York, Bowery Bay	40	1.1
3/4	Hartford, Connecticut	39.0	1.6
3/4	Portsmouth, Virginia	9.7	0.82
3/4	Sheboygan, Wisconsin	8.0	0.25
3/4	Aurora, Illinois	8.0	1.42
3/4	Topeka, Kansas	7.5	1.30
3/4	Oshkosh, Wisconsin	6.0	1.7
1/2	Green Bay, Wisconsin	10.0	1.2
1/2	Manteca, California	1.5	5.2

1 in. = 2.54 cm.
1 mgd = 3,785 m^3/day.
1 cu ft/mil gal = 7.48 $m^3/1 \times 10^6$ m^3.

- Operating practices. Where manual cleaning is used, operators sometimes pass some screenings through or around the screens. Where automatic equipment is used, the operating pattern can greatly affect removals (112).

- Length of sewer system. The volume of screenings removed may double with a short, as opposed to lengthy, interceptor system. This condition may be explained by the fact that solids are more subject to disintegration with a lengthy collection system (5). Wastewater pumping will also tend to disintegrate large solids.

Screenings loads may increase dramatically during peak flows. It is estimated that, at the East Bay Municipal Utility District plant in Oakland, California, the screenings load was about 10 times the average during peak flows. For the most part, this plant services separate sanitary sewers, but the screenings load is concentrated (110).

4.7.1.2 Quantity of Fine Screenings

Fine screens are usually used as an alternative to conventional primary sedimentation to remove suspended solids. Screens with 0.09 to 0.25 inch (2 to 6 mm) openings remove about 5 to 10 percent of suspended solids from typical municipal raw wastewater. If 0.03 to 0.06 inch (0.8 to 1.5 mm) openings are used instead, about 25 to 35 percent of suspended solids may be removed (5). Higher removals increase the dry weight and the moisture content of the screenings. For example, consider fine screens that remove 25 percent of suspended solids from an influent concentration of 300 mg/l. In this case, screenings are 630 dry pounds per million gallons (75 mg/l) of wastewater. If the screenings are ten percent solids and weigh 60 wet pounds per cubic foot (961 kg/m^3), then the volume is 105 cubic feet per million gallons (14.04 $m^3/1x10^6$ m^3). This is over 25 times more than a typical value for coarse screenings of 4 cubic feet per million gallons (0.53 $m^3/1x10^6$ m^3).

4.7.1.3 Properties of Screenings

If screenings have not been incinerated, they may contain pathogenic microorganisms. They are also odorous and tend to attract rodents and insects. Screenings have been analyzed for solids content, volatile content, fuel value, and bulk wet weight. Some of the reported values are summarized in Table 4-20.

4.7.1.4 Handling Screenings

Screenings may be ground and handled with other sludges; direct landfilled; and incinerated, with the ash disposed in landfill. Table 4-21 summarizes the advantages and disadvantages of various methods.

TABLE 4-20

ANALYSES OF SCREENINGS

Solids content, percent dry solids	Volatile content, percent	Fuel value, Btu/lb dry solids	Bulk wet weight, lb/cu ft	Comments	References
20	-	5,400[a]	60	Coarse screenings. Fine screenings may have lower solids content.	5
10 - 20	80 - 90	-	40 - 60	Common values	21
8 - 23	68 - 94	-	53 - 67	Various plants, fine screens, 0.03 to 0.12 inch openings	13
6.1	96	-	-	Thickened ground screenings from 0.75-inch racks; after grinding, screenings were thickened on a static screen with 0.06-inch openings.	113
17	96	-	-	Dewatered ground screenings from 0.75-inch racks; after grinding, screenings were dewatered on a rotating drum screen with 0.03-inch openings.	113
-	86	7,820	-	Fine screenings	114

[a]Computed.

1 Btu/lb dry solids = 2.32 kJ/ dry solids.
1 lb/cu ft = 16.03 kg/m^3.
1 in. = 2.54 cm.

Some fecal solids accompany the larger materials such as rags and twigs. For this reason, as well as to save labor time and cost, it is desirable to mechanize screenings handling. Also, where coarse screenings are landfilled or incinerated, it is desirable to use the largest rack opening that will adequately protect downstream processes. This will minimize the quantity of screenings that must be handled separately.

Screenings may be transported pneumatically (116), in sluiceways, on conveyors, and in cans, dumpsters, or covered trucks. Screenings-water mixtures that are ground may be pumped. For thickening and dewatering, fine static screens, drum screens, centrifuges (113), and drum or screw presses may be used. Chemical conditioning is not required.

4.7.1.5 Screenings from Miscellaneous Locations

Screens are occasionally used on streams other than influent wastewater. For instance, when it is fed to a trickling filter, primary effluent may be screened to prevent clogging of orifices in the distributor on the trickling filter (109). At one heavily loaded plant where regular influent screening equipment was partially bypassed, screens installed in aeration basin effluent channels, chlorine contact tank outlets, and other locations prevented coarse, floating objects from being discharged with the effluent (117). Another example occurred at a plant where digested sludge was discharged to the ocean. Fine screens were used to prevent floatable materials from being discharged (118). Other examples of the use of screens on streams other than influent wastewater are the screening of overflow water from grit separators and the screening of feed sludge to disc-nozzle centrifuges to prevent clogging (113,119).

TABLE 4-21

METHODS OF HANDLING SCREENINGS

Method	Advantages	Disadvantages
1. Comminution within main wastewater stream; handle comminuted screenings with other wastewater solids, e.g., primary sludge	Highly mechanized, low operating labor requirement. Minimizes number of unit operations Usually free of nuisance from flies and odors Widely used, familiar to plant operators	Sludge contains screenings, which may interfer with public acceptance for reuse of sludge as a soil amendment. Sludge probably needs further maceration or screening if it is to be pumped or thickened in a disc centrifuge. If sludge is to be digested, digesters must be cleaned more often. Plastics and synthetic fabrics do not decompose in digesters. Aggravates digester scum problems. Ground screenings tend to agglomerate in digesters. Not appropriate if suspended solids removal is required (fine screens). Not appropriate for very large screenings loads, especially if high grit loads are also present (large plants, combined sewers)
2. Removal[a] from main stream, grinding or maceration, and return to main stream	Similar to Method 1, except more complex mechanically	Similar to Method 1, except Method 2 can be designed for very large flows and screenings loads. Method 2 is more expensive than Method 1 for small screenings loads.
3. Removal[a] from main stream, draining or dewatering, landfill	Keeps screenings out of other sludges; avoids disadvantages of Methods 1 and 2. Can be fairly well mechanized.	Transport of screenings may be difficult. Unless carefully designed and operated, causes fly and odor nuisances and health hazards. Regulations for landfill disposal may strongly affect operations.
4. Removal[a] from main stream, dewatering, incineration, landfill of ash.	Keeps screenings out of other sludges; avoids disadvantages of Methods 1 and 2. Ash is very small in volume and easy to transport and dispose of. If incineration is used for other sludges and/or grit, then screenings can be added at modest cost. Pathogen kill	High cost if an incinerator is required for screenings alone. Unless incinerator is properly designed and operated, air pollution (odor and particulates) will be serious. Not well adapted to wide fluctuations in screenings quantities, unless screenings are only a small part of the total incinerator load.
5. Anaerobic digestion of fine screenings alone (not mixed with other solids)	--	Digestion was tested at large scale at Milwaukee, Wisconsin, but found to be impractical. (115)
6. Anaerobic digestion of screenings together with scum but separate from other sludges	--	Tested at Malabar plant, Sydney, Australia, but found to be inoperable. Material handling was the chief difficulty.

[a]Mechanical removal is usually practiced at large plants. Manual removal is frequently used at small plants. The advantages of manual removal are simplicity and low capital cost; the disadvantages are high operating labor requirements and fly and odor problems. A common arrangement at small plants is to install a single comminutor with a manually cleaned bar rack as a standby unit.

4.7.2 Grit

Grit is composed of heavy, coarse solids associated with raw wastewater. It may be removed from wastewater before primary sedimentation or other major processes. Alternatively, it may be removed from primary sludge after the primary sludge is removed from the wastewater. Typical ingredients of grit are gravel, sand, cinders, nails, grains of corn, coffee grounds, seeds, and bottle caps.

4.7.2.1 Quantity of Grit

The amount of grit that is removed varies tremendously from one plant to another. Table 4-22 shows grit quantities measured at several plants. Additional values have been published elsewhere (5,109). The quantity of grit depends on:

- Type of collection system. If a system is combined, then street sanding, catch basin maintenance, and amount of combined sewer overflow become important.
- Degree of sewer system corrosion. Grit may include products of hydrogen sulfide corrosion derived from the pipes (122).
- Scouring velocities in the sewers. If scouring velocities are not regularly maintained, grit will build up in the sewers. During peak flows, the grit may be resuspended, and the treatment plant may receive heavy loads during peak flows.
- Presence of open joints and cracks in the sewer system. These permit soil around the pipes to enter the sewers. This effect also depends upon soil characteristics and groundwater levels.
- Structural failure of sewers. Such failures can deliver enormous amounts of grit to the wastewater system.
- Quantities of industrial wastes.
- Degree to which household garbage grinders are used.
- Efficiency of grit removal at the treatment plant (5).
- Amount of septage.
- Occurrence of construction in the service area or at the treatment plant.

It is not possible to develop a formula which allows for all these factors. Cautious use of available information is, therefore, recommended. It is important to recognize that extreme variations occur in grit volume and quantity. A generous safety factor should be used in calculations involving the storage, handling, or disposal of grit (5). In a new system where there are separate sanitary sewers and favorable conditions such as adequate scouring velocities, an allowance of 15 cubic feet per million gallons (2 $m^3/1x10^6$ m^3) should suffice for maximum flows. On the average, the quantity of grit in wastewater will usually be less than 4 cubic feet per million gallons (0.53 $m^3/1x10^6$ m^3) for separate sewer systems, (5) but higher values have been observed (see Table 4-22).

TABLE 4-22

GRIT QUANTITIES

Plant	Quantity, cu ft/mil gal	Comments	References
Santa Rosa, California (College Avenue)	0.88	Average. Separate sewers.	110
	0.3	Minimum month	-
	1.4	Maximum month	-
San Jose, California	2.5	Separate sewers. Older removal systems removed less grit (0.3 and 1.4 cu ft/mil gal)	110
Manteca, California	5.2	Average. Separate sewers.	110
	3.2	Minimum month	-
	9.5	Maximum month	-
Santa Rosa, California (Laguna)	5.0	Average. Separate sewers.	110
	2.1	Minimum month	-
	10.7	Maximum month	-
Seattle, Washington (West Point)	2.6	Average. Combined storm and sanitary sewers.	110
	11.2	Maximum day	-
Dublin-San Ramon, California	7	Average. Separate sewers.	120
Los Angeles, California (Hyperion)	2	1973 average. Separate sewers.	99
Livermore, California	1.0	Average over 24 months. Separate sewers.	68
	0.3	Lowest month	
	2.4	Highest month	
Gary, Indiana	8.6	Annual average. Combined sewers.	110
	89	Highest value on test runs.	121
Renton, Washington	1.7	Average over 19 months before improvements to grit removal equipment. Separate sewers.	119
	4.1	Average over 12 months after improvements.	-
	7.0	Maximum month, following improvements.	-

1 cu ft/mil gal = 7.48 $m^3/1 \times 10^6$ m^3

4.7.2.2 Properties of Grit

Grit has been analyzed for moisture, volatiles content, specific gravity, putrescibility, (123) particle size, and heating value. All of these depend on the kind of sewer system and the method of grit removal and washing.

The moisture content of grit is reported as ranging from 13 to 65 percent, and the volatiles content from 1 to 56 percent (109). Specific gravity of grit particles varies; values from 1.3 to 2.7 have been reported (109). The range for volatile solids was 8 to 46 percent (123). Particle size for grit removed from five plants is shown in Table 4-23, along with an analysis of digester bottom deposits.

TABLE 4-23

SIEVE ANALYSIS OF GRIT

		Percentage retained						
Sieve size[a]	Sieve opening, mm	Green Bay, Wisconsin	Kenosha, Wisconsin	Tampa, Florida	St. Paul, Minnesota	Renton, Washington[c]	Renton, Washington[d]	Digester deposits, Los Angeles, California
4	4.76	-	-	-	1 - 7	2.5 - 13.5	0 - 0.5	-
8	2.38	-	-	-	5 - 20	-	-	2.8
10	2.08	3.7	12	-	-	19.5 - 34.5	2 - 11	-
12[b]	1.41	-	-	-	-	-	-	7.3
20	0.84	9.1	-	-	12 - 53	50 - 74.5	10 - 41	-
28[b]	0.60	-	-	-	-	-	-	28.3
40	0.42	19.8	70	-	-	71 - 88.5	27 - 62	-
50	0.30	29.6	-	2.3	20 - 67	-	-	-
60	0.25	-	-	-	-	90.5 - 94	60 - 76.5	-
65[b]	0.21	51.7	-	-	-	-	-	59
80	0.18	-	95	-	-	-	-	-
100	0.149	78.2	-	59.3	97 - 99.9	97.5	85 - 92	-
150[b]	0.105	-	-	-	-	-	-	77.6
200	0.074	96.1	-	99.5	-	99.5	95 - 98	84.9
Source	-	(109)	(109)	(109)	(109)	(119)	(119)	(118)

[a] U.S. series, except as noted.

[b] Tyler series sieve.

[c] Dried at 103°C. Four tests. Volatile contents 34 to 55 percent.

[d] Same samples as previous column, ashed at 550°C and resieved.

Grit quality can be varied to some extent. If a "clean" grit with very low putrescibility is desired, it may be obtained by grit washing and operational adjustments to the grit removal system. However, such operations may make it impossible to remove fine sand (of less than 0.08 inch [0.2 mm]). For example, if a separate grit washer is used, fine sand may be recycled in the wash water. If it is essential, fine sand can be removed with high efficiency. However, the sand will be accompanied by large amounts of putrescible solids. A compromise between cleanliness of grit and high removals of fine particles is necessary (124). If good washing equipment is used, operators can often remove significant quantities of fine materials without sacrificing cleanliness. Grit should be regarded as containing pathogens unless it has been incinerated.

4.7.2.3 Handling Grit

The first step in grit handling is the separation of the grit from the main stream of wastewater. Grit may be removed from

4.7.3 Scum

Scum is the material that floats on wastewater, except where flotation is involved. In a flotation unit, scum is incorporated into the float. Scum may be removed from many treatment units including preaeration tanks, skimming tanks, primary and secondary sedimentation tanks, chlorine contact tanks, gravity thickeners, and digesters. The term "skimmings" refers specifically to scum that has been removed.

4.7.3.1 Quantities of Scum

Quantities of scum are generally small compared to those of such wastewater solids as primary sludge and waste-activated sludge. Table 4-24 lists some properties and quantities of scum. The data in this table are based on scum from primary sedimentation tanks. Scum is often removed from secondary clarifiers and chlorine contact tanks, but there is almost no available data on the quantities removed.

Although there is some data on the quantity of grease removed during wastewater treatment, grease loads are not indicators of scum quantities. As shown in Tables 4-2 and 4-3, the grease content of primary sludge can exceed 25 percent of the total solids. In biological sludges, it can be over ten percent. Since the quantities of these sludges are usually large compared to the amount of scum, it can be assumed that most of the grease is in the sludge, not in the scum. Typically, the grease content of raw domestic wastewater is 100 mg/l (2), but the largest amount of scum indicated in Table 4-24 is 17 mg/l, and in many instances, the amounts are lower. At one plant, it was estimated that only five percent of grease was removed in the scum. The remainder was in the primary sludge (131).

Scum production is influenced by:

- Wastewater temperature, dissolved solids, and pH.
- Design and operation of grease traps at commercial kitchens, gas stations, and industries.
- Amount and character of septage that is mixed with the wastewater.
- Habits of residential population and small businesses. (Spent motor oil and cooking fat are likely to be removed as scum if they reach the sewers.)
- Preaeration and prechlorination.

- Efficiency of upstream processes in removing colloidal grease. This is true for chlorine contact tank scum, since chlorine breaks emulsions, allowing grease particles to coalesce and float. Chlorine dose and mixing may also affect contact tank scum.

- Scum that is returned from sludge handling. Anaerobic digesters usually have a scum layer. Recycled digester supernatant may carry portions of this scum back to the influent wastewater. Similarly, scum may be returned in sidestreams from gravity thickening and centrifugation.

- Scum removal equipment effectiveness. Some arrangements produce better removal efficiencies than others. Also, some arrangements produce a scum with a high solids content and, therefore, a small volume.

- Tendency of sludge solids to float in sedimentation tanks due to formation of gas bubbles.

- Process unit from which scum is removed. If primary sedimentation is used, most of the scum is usually removed there. Amounts of scum from secondary clarifiers and chlorine contact tanks are normally small in comparison.

- Actinomycete growths in activated sludge (50). These growths may cause large amounts of solids to float in the clarifers.

At existing treatment plants, it is often possible to estimate scum quantities from such data as scum pump operating hours or the frequency with which scum pits must be emptied. Design calculations should always allow for large variations in quantity of scum.

4.7.3.2 Properties of Scum

Table 4-24 contains information on the solids content, volatile content, fuel value, and grease content of scum. Scum usually has a specific gravity of about 0.95 (110).

Varying quantities of vegetable and mineral oils, grease, hair, rubber goods, animal fats, waxes, free fatty acids, calcium and magnesium soaps, seeds, skins, bits of cellulosic material such as wood, paper or cotton, cigarette tips, plastic and pieces of garbage may comprise scum (110). When gases are entrained in particles of primary and secondary sludge, these particles become components of scum (126). At one plant, a variation in scum consistency was noted. At 36°F (10°C), the scum was a congealed, clotty mass. At 54°F (20°C), it flowed freely, in a manner similar to that of four percent combined thickened sludges (126). Scum should not be stored for more than a few days because the grease will begin to decompose, with a resulting odor production.

TABLE 4-24

SCUM PRODUCTION AND PROPERTIES

Treatment plant	Quantity (volume), gal/mil gal of wastewater	Quantity (dry weight) lb/mil gal of wastewater	mg/l of wastewater	Solids, percent	Volatile solids, percent of total solids	Fuel value, Btu/lb dry solids	Comments	Reference
Dublin-San Ramon, California	250	-	-	-	-	-	From primary sedimentation, domestic waste	120
Lower Allen Township, near Harrisburg, Pa.	14	31	4	25[a] 27[a]	46[a] 42[a]	6,900[a] 3,100[a]	From low lime primary sedimentation (pH 9.4 to 9.8), after heated thickener	125
Northwest Bergen County, Oakland, New Jersey	25	19	2.3	9	-	-	From gravity thickener	126
Wichita, Kansas	9	-	-	-	-	-	From primary sedimentation. Grease is 30 percent of skimmings after decanting.	127
	0.7	-	-	-	-	-	Grease balls from preaeration tanks.	127
Minneapolis-St. Paul, Minnesota	-	-	-	-	98	13,000	From primary sedimentation	128
East Bay, Oakland, California	19	82	9.8	54	96	-	Average, July 1969 - June 1970[b]	129
	-	110	13	64	99	-	Maximum month	129
	-	60	7.2	43	81	-	Minimum month	129
	29	-	-	51	-	14,000	1965 - 1966 data	130
West Point, Seattle, Washington	50	24	2.9	6	-	-	As pumped from primary sedimentation tanks	131
	8	19	2.3	30	-	-	As above, after decanting; 6.4 percent grease	131
	130	-	-	-	-	-	From sedimentation tanks under poor conditions[c]	131
Not stated	-	-	-	-	88.5	16,750	--	114
San Mateo, California	-	95	11	-	-	-	--	110
Salisbury, Maryland	200	-	-	-	-	-	From primary clarifiers. Heavy grease load from industry	132
Three New York City plants	0.3 - 5	1.2 - 15	0.1 - 2	40 - 52	-	-	From primary clarifiers; about 80 percent of solids are grease	133
Jamaica, New York City	3	10	1.2	48	-	-	From secondary clarifiers; (no primary)	133
County Sanitation Districts, Los Angeles County, CA	-	87	10	-	-	-	Primary sedimentation	134
Albany, Georgia	3,000	140	17	0.57	-	-	Primary sedimentation. Heavy industrial load.	135

[a] Two samples. About 58 percent of nonvolatile solids was calcium carbonate.

[b] 91 percent of total solids were oil and grease. Scum from primary sedimentation, measured after decanting in a heated unit.

[c] Sludge was tending to float in the sedimentation tanks. Amount shown is estimate of pumpage. Skimming system was unable to keep up with scum production under these poor conditions.

1 gal/mil gal = $m^3/l \times 10^6\ m^3$
1 lb/mil gal = 0.12 $kg/l \times 10^3\ m^3$
1 Btu/ lb dry solids = 2.32 kJ/kg

Ordinarily, scum should be seen as containing pathogens. However, some scum handling processes may disinfect. If scum has been heated to 176°F (80°F) for decanting, incinerated, or treated with a dose of caustic soda sufficient to produce a pH of 12, few pathogens are likely to remain.

4.7.3.3 Handling Scum

Table 4-25 lists the advantages and disadvantages of various approaches to scum disposal. Progressive cavity-type pumps have been found suitable for pumping scum, although they are unable to handle large grease balls (125) unless some sort of rack or disintegrator is provided. Pneumatic ejectors are suitable if grease does not interfere with the controls. Piping should be glass-lined and kept reasonably warm to minimize blockages.

TABLE 4-25

METHODS OF HANDLING SCUM

Method	Advantages	Disadvantages
1. Mix with other sludges, digest aerobically.	Partial decomposition occurs (134), so some of the scum does not require further handling. Avoids complexity of separate handling. Widely used	May cause grease balls to form, which must be manually removed and disposed of, and which may increase odors. May cause petroleum contamination of sludge, which will interfere with reuse. Degrades appearance of sludge if to be re-used. May cause scum buildup due to return of scum-containing liquors from sludge handling to influent wastewater.
2. Mix with other sludges, digest anaerobically.	Similar to Method 1, above.	If digester is not strongly mixed, greatly increases cleaning requirements. (119) Digester cleaning is expensive and odorous; also material still requires disposal. Even if digester is well mixed, a scum blanket will form to some extent; therefore, digester must be physically larger (136) Degrades appearance of sludge if to be re-used; may cause petroleum contamination. May cause scum buildup, like Method 1. Requires good decanting to avoid pumping excess water to the digester.
3. Landfill separately	Low capital cost	May have very high operating cost. Possible odors during storage. Requires good decanting to minimize volume and fluidity of scum.
4. Burn in open lagoon	Very low cost.	Severe air pollution (128); illegal under present laws.
5. Incinerate in separate "Watergrate" furnace (Nichols)[a]	Very small amount of ash in slurry.	High capital cost, especially for small plants Despite low emissions, may not be acceptable to air pollution regulators. Problems with feed systems.
6. Incinerate in separate single purpose multiple-hearth furnace[a]	Very small amount of ash	High capital cost (130) High maintenance cost Despite low emissions, may not be acceptable to air pollution regulators Requires good decanting
7. Incinerate in multiple-hearth furnace with other wastewater solids[a]	Low incremental cost Fuel value of scum can be used to offset fuel requirements of other solids	Requires good decanting Requires very careful feed to the furnace; otherwise causes high maintenance and severe smoke problems. These problems can be avoided. (137)
8. Incinerate in fluidized bed furnace with other wastewater solids[a]	Similar to Method 7.	Unless well decanted, can tax furnace capacity. (126) If scum is mixed with sludge before injection into furnace, unstable operation is likely. (126)
9. Reuse for cattle feed	Provides reuse, not disposal (however, do not expect revenue Low capital cost	Toxic organic materials (e.g., DDT) tend to concentrate in grease Erratic market demand for waste grease (133), it may be impossible to find anyone that wants it. Treatment for reuse must begin within a few days; otherwise grease begins to decompose. Requires good decanting because of long distance transportation. Subject to interference from actinomycete growths in activated sludge, which increase the amount of solids that are not grease but are in the scum.
10. Reuse for low grade soap manufacture	Same as Method 9.	Similar to Method 9, but less serious. Caustic soda could be added at the treatment plant, preventing decomposition and probably making the material more usable to grease reclaimers, but raising operating costs.
11. Return to influent wastewater	Almost zero direct cost Highly suitable for scum from chlorine contact tanks, secondary clarifiers, etc. when scum is removed from primary sedimentation tanks	Slight increase in hydraulic load on the treatment plant Inapplicable to the main source of scum (primary sedimentation tanks if used, secondary clarifiers if primary tanks are not used).

[a]For further information on scum incineration, see Chapter 11, High Temperature Processes.

Piping should be heated to a minimum of 60°F (15°C). Higher temperatures are preferred, especially if pipe sizes of less than four-inch diameter (100 mm) are used or if pipe lengths are substantial. Flushing connections and cleanouts should be liberally provided. When scum is to be incinerated, a small amount of fuel oil should be added as a convenient means of ensuring that the scum can be pumped (137). An in-line grinder should be provided if decanting or incinerating is to take place (125,137).

Decanting (simple thickening by flotation) is occasionally used to increase the solids content of the scum. Decanting requires some care in design, in order to reduce the effects of unpleasant odor and high grease and solids content in the decanted water. At least two manufacturers market a heated decanting unit. Heating scum to about 180°F (80°C) greatly improves the separation of solids from water. Thus, the decanted water will have a lower solids and grease content, whereas the thickened scum will contain less moisture.

4.7.4 Septage

Domestic septic tank wastes (septage) may be defined as a partially digested mixture of liquid and solid material that originates as waterborne domestic wastes. Septage accumulates in a septic tank or cesspool over a period of several months or years. Normally, household wastes derive from the toilet, bath or shower, sink, garbage disposal, dishwasher, and washing machine. Septage may also include the pumpings from the septic tanks of schools, motels, restaurants, and similar establishments. Septage is frequently discharged into municipal wastewater systems. With careful design and operation, municipal systems can handle septage adequately (138-140).

4.7.4.1 Quantities of Septage

For Connecticut, Kolega and others (138) estimated residential septage at 66 gallons per capita per year (250 l/capita/yr). Some tanks were pumped only after many years of service; others were pumped more than three times a year. Frequent pumping was associated with seasonally high groundwater levels. Based on the detailed observations of three tanks, Brandes recommended designing for a septage volume of 53 gallons per capita per year (200 l/capita/yr) (141). Others have recommended 50 to 360 gallons per capita per year (189 to 146 l/capita/year).

4.7.4.2 Properties of Septage

Table 4-26 contains a wide range of data on various constituents of septage. Septage may foam and generally has a highly offensive odor (140). Settling properties are highly variable. Some samples settle readily to about 20 to 50 percent of their original volume, whereas others show little settling.

Significant amounts of grit may be present (140). Large concentrations of total coliforms, fecal coliforms, and fecal streptococci have been found in septage (140,141).

TABLE 4-26

CHARACTERISTICS OF DOMESTIC SEPTAGE (140)

Parameter	Mean[a]	Standard deviation[a]	Range[a]	Number of samples
Total solids (TS)	38,800	23,700	3,600 - 106,000	25
Total volatile solids (TVS), percent of total solids	65.1	11.3	32 - 81	22
Suspended solids (SS)	13,014	6,020	1,770 - 22,600	15
Volatile suspended solids (VSS), percent of suspended solids	67.0	9.3	51 - 85	15
5-day biochemical oxygen demand (BOD_5)	5,000	4,570	1,460 - 18,600	13
Total chemical oxygen demand (COD_T)	42,850	36,950	2,200 - 190,000	37
Soluble chemical oxygen demand (COD_S)	2,570[b]	-	-	21
Total organic carbon (TOC)	9,930	6,990	1,316 - 18,400	9
Total Kjeldahl nitrogen (TKN)	677	427	66 - 1,560	37
Ammonia nitrogen (NH_3-N)	157	120	6 - 385	25
Total phosphorus (Total P)	253	178	24 - 760	37
pH (units)	6.9[c]	-	6.0 - 8.8	25
Grease	9,090	6,530	604 - 23,468	17
Linear alkyl sulfonate (LAS)	157	45	110 - 200	3
Iron (Fe)	205	184	3 - 750	37
Zinc (Zn)	49.0	40.2	4.5 - 153	38
Aluminum (Al)	48	61	2 - 200	9
Lead (Pb)	8.4	12.7	1.5 - 31	5
Copper (Cu)	6.4	8.3	0.3 - 38	19
Manganese (Mn)	5.02	6.25	0.5 - 32	38
Chromium (Cr)	1.07	0.64	0.3 - 2.2	12
Nickel (Ni)	0.90	0.59	0.2 - 3.7	34
Cadmium (Cd)	0.71	2.17	<.05 - 10.8	24
Mercury (Hg)	0.28	0.79	<.0002 - 4.0	35
Arsenic (As)	0.16	0.18	0.03 - 0.5	12
Selenium (Se)	0.076	0.074	<0.02 - 0.3	13

[a]Values are concentrations in mg/l, unless otherwise noted.

[b]Soluble COD is 6 percent of total COD.

[c]Median.

4.7.4.3 Treating Septage in Wastewater Treatment Plants

When treated at wastewater treatment plants, septage is often mixed with the influent wastewater. In some situations, however, it is treated or pre-treated separately. Septage may also be added directly to the wastewater sludge. Septage is delivered from tank trucks, loaded into the system immediately, or temporarily stored and added gradually to the wastewater or sludge. Holding tanks for septage are therefore recommended in many cases.

If septage is added to wastewater, the quantities of all wastewater solids in the treatment plant increase for the following reasons:

- Septage contributes to grit, scum, and screenings.

- The suspended solids in the septage may be largely removed in primary sedimentation, increasing the amount of primary sludge. One pilot study found 55 to 65 percent removals of septage suspended solids (140), but very different values might occur under other conditions.

- In biological processes, septage increases the BOD_5 load and, therefore, the sludge production. Furthermore, septage may produce as much as twice the amount of sludge per unit BOD_5 removed as ordinary wastewater, since the septage has a high ratio of suspended solids to BOD_5 (140).

- Addition of septage increases the phosphorus load at a treatment plant. For plants which must meet effluent limits on phosphorus, the addition of septage will increase the necessary chemical dose. Thus, costs and the amount of chemical sludge will increase.

At some plants, sludge thickening and dewatering properties have been degraded by septage, but there are few data available on the extent of the problem, and different results are obtained at different locations. At Shrewsbury, Massachusetts, dewatering difficulties were encountered when the septage/sewage hydraulic ratio exceeded about 0.0033 (140). Furthermore, problems associated with bulking activated sludge may be related to septage (140). Bulking sludge has very poor thickening and dewatering properties. The metals content of septage may also be high.

4.7.5 Backwash

Wastewater is sometimes filtered to remove suspended solids. As used in this section, the term "filters" includes sand filters, dual and mixed-media filters, and microstrainers. Solids accumulate in filters as they are removed from the wastewater. They are subsequently removed from the filters by backwashing. The volume of backwash water is great, often several percent of the total wastewater flow. However, the quantity of suspended solids in backwash is normally about 300 to 1,500 mg/l (0.03 to 0.15 percent). The dry weight load is usually small compared to those from primary, biological, and chemical sludges.

Backwash is normally returned to the influent wastewaters and its suspended solids are removed in wastewater processes such as primary sedimentation and activated sludge.

When designing a plant with filters, the following measures should be taken to allow for backwash and associated solids:

- If the backwash is produced intermittently, as is usually the case, then a spent backwash holding tank should be provided. Thus, the backwash need not drastically increase the flows to be treated. Solids may settle to some extent in the holding tank. Therefore, washout facilities or possibly air agitation should be provided.
- An allowance for increased flow due to recycle of backwash should be included when sizing wastewater treatment processes.
- Filter solids should be allowed for when primary, biological, and chemical sludge quantities are computed.

4.7.6 Solids from Treatment of Combined Sewer Overflows

Solids generated in the treatment of combined sewer overflows (CSOs) may be treated separately, or discharged under non-storm conditions to the dry-weather sludge treatment and disposal facilities. The volumes and characteristics of solids produced from CSO treatment vary widely. The volume of solids residuals evaluated in a recent study ranged from less than one percent to six percent of the raw volume treated and contained 0.12 percent to 11 percent suspended solids (142). The volatile content of these sludges varied between 25 percent and 63 percent, with biological treatment residuals showing the highest volatile content (about 60 percent).

Pesticides and PCB concentrations in the CSO sludges have been found to be high at some locations (142). PCB concentrations as high as 6,570 ug/kg dry solids have been measured.

Heavy metal concentrations in the CSO sludges have been found to vary widely. The range of heavy metal concentrations for the sites studied in reference 142 are given in Table 4-27.

TABLE 4-27

METALS CONCENTRATIONS IN SOLIDS FROM TREATMENT OF COMBINED SEWER OVERFLOWS (142)

Metal	Concentration, mg/kg dry solids
Zinc	697 - 7,154
Lead	164 - 2,448
Copper	200 - 2,454
Nickel	83 - 995
Chromium	52 - 2,471
Mercury	0.01 - 100.5

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 5. Thickening

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 5

THICKENING

5.1 Introduction

The purpose of this chapter is to provide the reader with rational design and operating information on which to base decisions about cost-effective thickening processes. Thickening is only one part of the wastewater solids treatment and disposal system and must be integrated into the overall treatment process, so that performance for both liquid and solids treatment is optimized and total cost is minimized (1-3).

5.1.1 Definition

Thickening is defined in this chapter as removal of water from sludge to achieve a volume reduction. The resulting material is still fluid.

5.1.2 Purpose

Sludges are thickened primarily to decrease the capital and operating costs of subsequent sludge processing steps by substantially reducing the volume. Thickening from one to two percent solids concentration, for example, halves the sludge volume. Further concentration to five percent solids reduces the volume to one-fifth its original volume.

Depending on the process selected, thickening may also provide the following benefits: sludge blending, sludge flow equalization, sludge storage, grit removal, gas stripping, and clarification.

5.1.3 Process Evaluation

Although it is good design practice to pilot thickening equipment before designing a facility, pilot testing does not guarantee a successful full-scale system. Designers must be cognizant of the difficulties involved in scale-up and the changing character of wastewater sludge and allow for them in design.

The main design variables of any thickening process are:

- Solids concentration and volumetric flow rate of the feed stream;

- Chemical demand and cost if chemicals are employed;

- Suspended and dissolved solids concentrations and volumetric flow rate of the clarified stream;

- Solids concentration and volumetric flow rate of the thickened sludge.

Specific design criteria for selection of a thickening process can also be dependent on the chosen downstream process train.

Another important consideration is the operation and maintenance (O/M) cost and the variables affecting it. In the past, O/M costs have not been given enough attention. This should change as USEPA begins to implement its new Operations Check List (4) in all phases of the Construction Grants Program.

Finally, thickening reliability is important for successful plant operation. A reliable thickening system is needed to maintain the desired concentration and relatively uninterrupted removal of sludge from a continuously operated treatment plant. Sludges are being generated constantly, and if they are allowed to accumulate for a long time, the performance of the entire plant will be degraded.

5.1.4 Types and Occurrence of Thickening Processes

Thickening is accomplished in sedimenation basins; gravity, flotation and centrifugal thickeners; and in miscellaneous facilities such as secondary anaerobic digesters, elutriation basins, and sludge lagoons.

5.2 Sedimentation Basins

5.2.1 Primary Sedimentation

A primary clarifier can be used as a thickener under certain conditions. Primary sludge thickens well, provided the sludge is reasonably fresh, solids of biological origin (for example, waste-activated sludge) are kept to a minimum, and the wastewater is reasonably cool. If sludge of five to six percent solids content is to be recovered from a primary sedimentation system, it is essential that the sludge transport facilities be designed to move those solids. This will require short suction piping, adequate net positive suction heads on the primary sludge pump, suction-sight glass inspection piping, and a positive means of ascertaining the quantity pumped and the concentration of the slurry (5).

5.2.2 Secondary Sedimentation

Thickening in secondary or intermediate clarifiers has not been successful in the past because biological sludges are difficult to thicken by gravity. Thickening has been improved by using side water depths of from 14 to 16 feet (4 to 5 m), suction sludge withdrawal mechanisms rather than plow mechanisms, and gentle floor slopes, for example, 1:12. Although thickening within a sedimentation basin can be beneficial under certain conditions, separate thickening is usually recommended.

5.3 Gravity Thickeners

5.3.1 Introduction

Separate, continuously operating gravity thickening for municipal wastewater sludges was conceptualized in the early 1950's (6). Until that time, thickening had been carried out within the primary clarifier. Operating problems such as floating sludge, odors, dilute sludge, and poor primary effluent led to the development of the separate thickening tank. Gravity thickeners became the most commonly used sludge concentrating device; now, however, their use is being challenged by other thickening processes.

Table 5-1 lists advantages and disadvantages of gravity thickeners compared to other thickeners.

TABLE 5-1

ADVANTAGES AND DISADVANTAGES OF GRAVITY THICKENERS

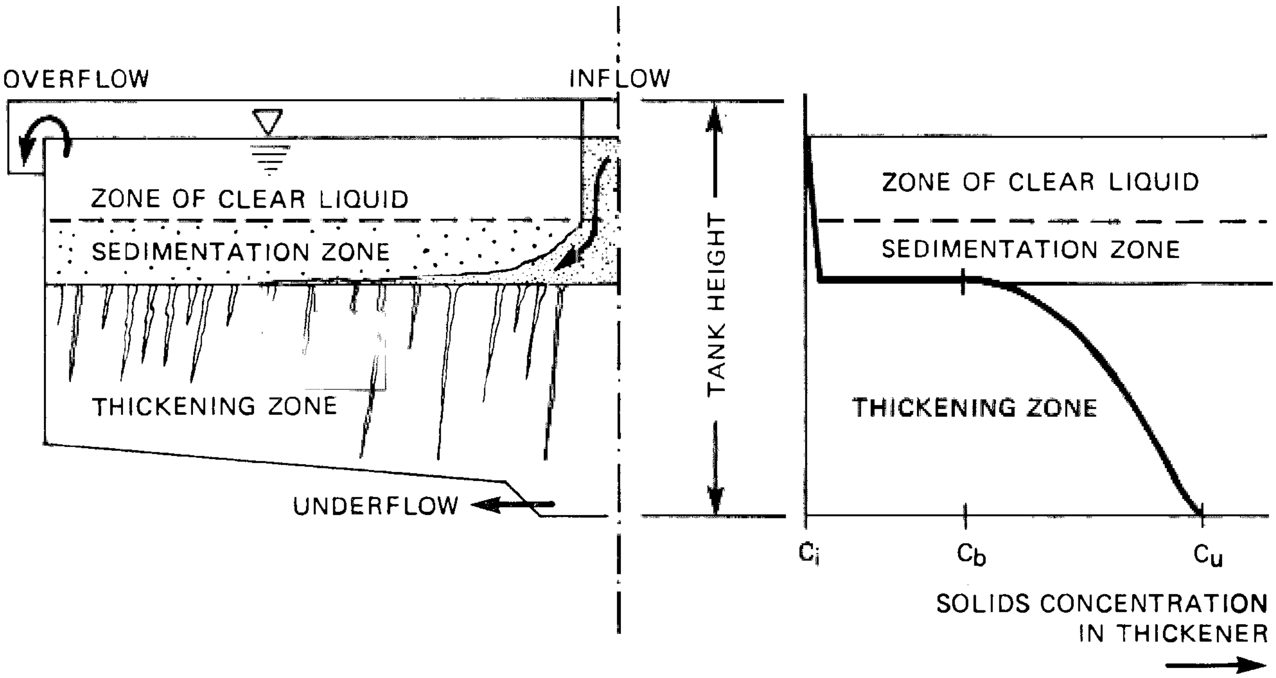
Advantages	Disadvantages
Provides greatest sludge storage capabilities	Requires largest land area
Requires the least operational skill	Contributes to the production of odors
Provides lowest operation (especially power) and maintenance cost	For some sludges, - solid/liquid separation can be erratic - can produce the thinnest least concentrated sludge

5.3.2 Theory

Since the early work of Coe and Clevenger (7), understanding of gravity thickening has slowly improved (8-11). The key to understanding the continuous gravity thickening process is recognition of the behavior of materials during thickening.

Coarse minerals thicken as particulate (nonflocculent) suspensions. Municipal wastewater sludges, however, are usually flocculent suspensions that behave differently (12).

Detailed, comprehensive analysis of current gravity thickening theory for municipal wastewater sludges is beyond the scope of this manual; those desiring such detail should consult Design and Operational Criteria for Thickening of Biological Sludges (13). A short descriptive summary of current theory follows (12).



C_i - INFLOW SOLIDS CONCENTRATION
C_b - LOWEST CONCENTRATION AT WHICH FLOCCULANT SUSPENSION IS IN THE FORM OF POROUS MEDIUM
C_u - UNDERFLOW CONCENTRATION FROM GRAVITY THICKENER

FIGURE 5-1

TYPICAL CONCENTRATION PROFILE OF MUNICIPAL WASTEWATER SLUDGE IN A CONTINUOUSLY OPERATING GRAVITY THICKENER

Figure 5-1 shows a typical solids concentration profile for municipal wastewater sludges within a continuously operating gravity thickener. Sludge moving into the thickener partially disperses in water in the sedimentation zone and partially flows as a density current to the bottom of the sedimentation zone. The solid phase of the sludge, both dispersed and in the density current, creates flocs that settle on top of the thickening zone. Flocs in the thickening zone lose their individual character. They have mutual contacts and thus become a part of the matrix of solids compressed by the pressure of the overlying solids. The displaced water flows upward through channels in the solids matrix.

Generally, in decision making about thickener size, the settling process in the sedimentation zone as well as the consolidation process in the thickening zone should be evaluated; whichever process (sedimentation or thickening) requires greater surface area dictates the size of the thickener. For municipal wastewater sludges, the thickening zone area required is almost always greater than that for the sedimentation zone.

5.3.3 System Design Considerations

Circular concrete tanks are the most common configuration for continuously operating gravity thickeners, though circular steel tanks and rectangular concrete tanks have also been used. Figure 5-2 shows a typical gravity thickener installation; Figure 5-3 is a cross-sectional view of a typical circular gravity thickener (14).

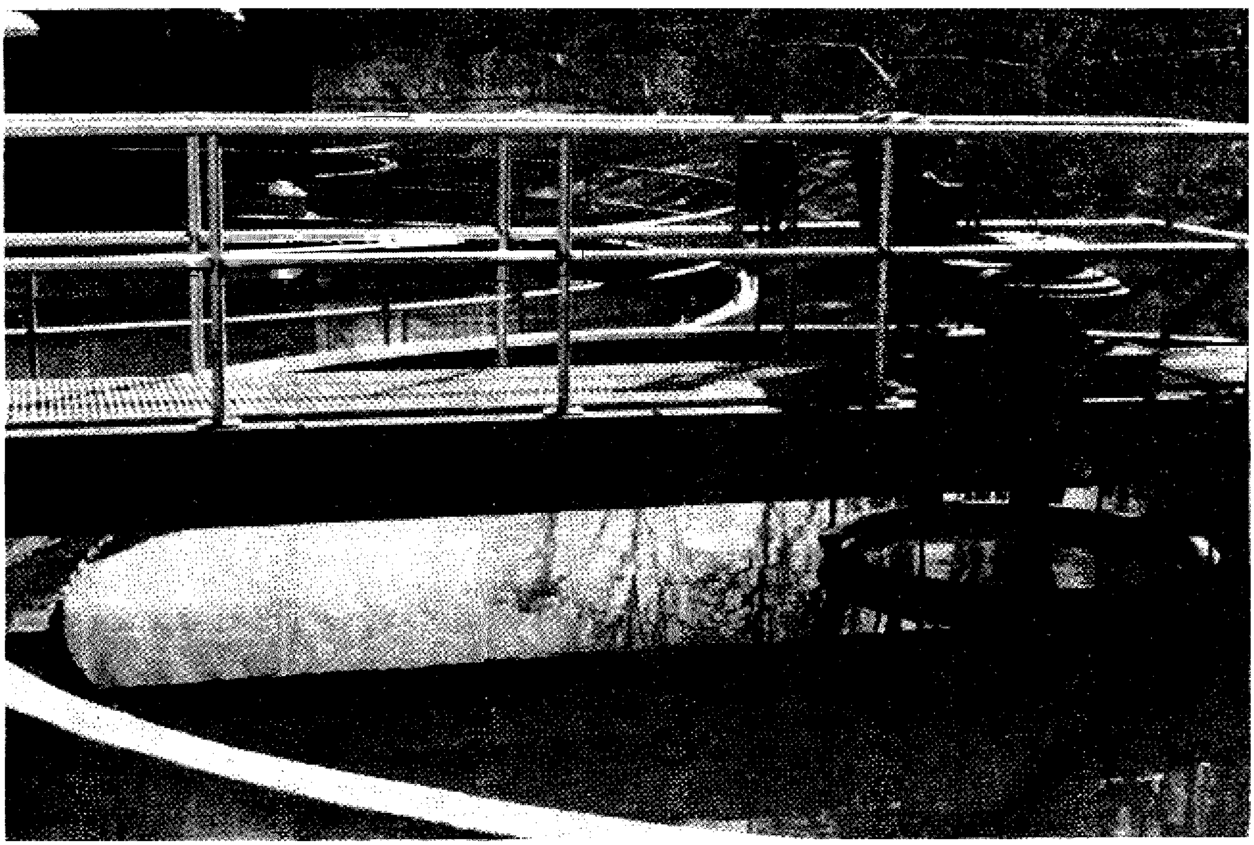


FIGURE 5-2

TYPICAL GRAVITY THICKENER INSTALLATION

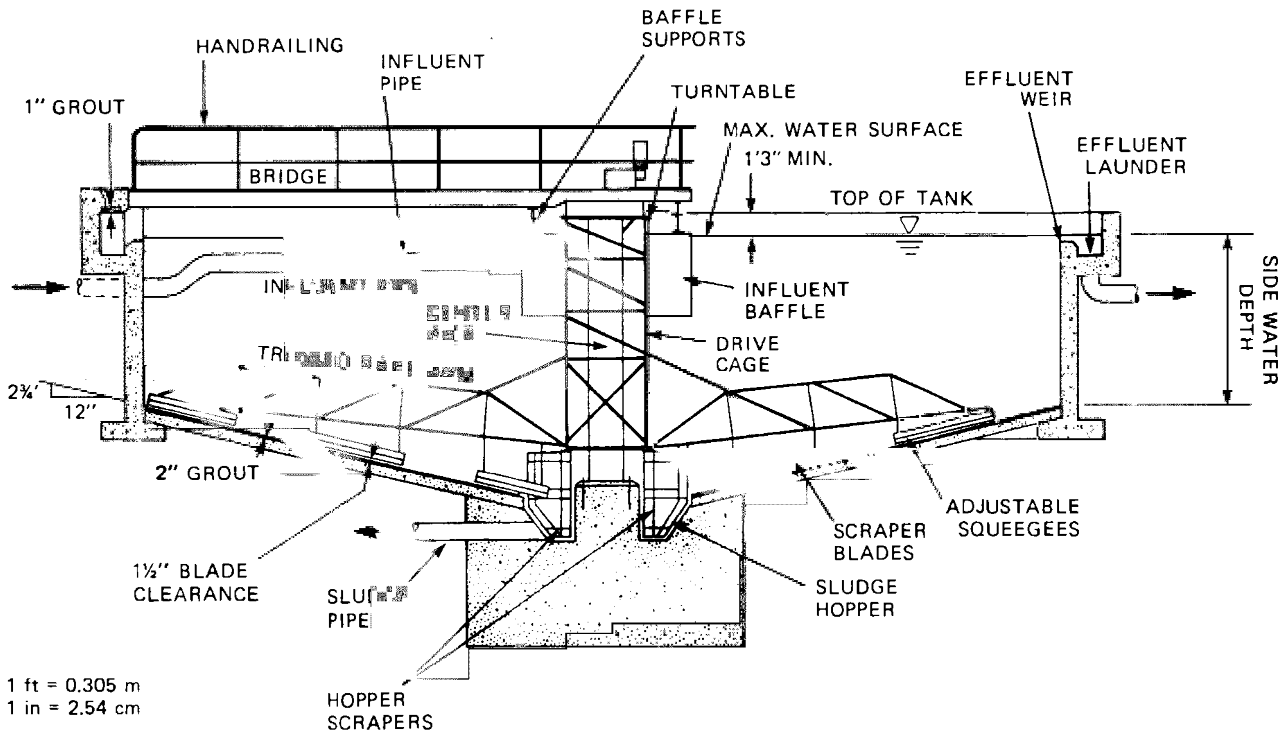


FIGURE 5-3

CROSS SECTIONAL VIEW OF A TYPICAL CIRCULAR GRAVITY THICKENER

At minimum, the following should be evaluated for every gravity thickener: minimum surface area requirements, hydraulic loading, drive torque requirements, and total tank depth. Floor slope and several other considerations will also influence the final design of the gravity thickener.

5.3.3.1 Minimum Surface Area Requirements

If sludge from the particular facility is available for testing, the required surface area can be found by using a settling column, developing a settling flux curve, and calculating the critical flux (mass loading, lbs/sq ft/hr) for that particular sludge (4, 13, 15). In most cases, however, the sludge to be thickened is not available, and the designer must resort to other methods.

Table 5-2 provides criteria for calculating required surface area when test data are not available and pilot plant work is not reasonable. The designer must specify the sludge type (for mixtures, the approximate proportions should be known), the range of solids concentrations that are expected in the thickener inflow, and the underflow concentration required for downstream processing. Part A of the design example (Section 5.3.4) illustrates the use of Table 5-2 in sizing gravity thickeners.

TABLE 5-2

TYPICAL GRAVITY THICKENER SURFACE AREA DESIGN CRITERIA[a]

Type of sludge	Influent solids concentration, percent solids	Expected underflow concentration, percent solids	Mass loading, lb/sq ft/hr[b]	Reference
Separate sludges:				
Primary (PRI)	2 - 7	5 - 10	0.8 - 1.2	16
Trickling filter (TF)	1 - 4	3 - 6	0.3 - 0.4	16
Rotating biological contactor (RBC)	1 - 3.5	2 - 5	0.3 - 0.4	16
Waste activated sludge (WAS)				
WAS - air	0.5 - 1.5	2 - 3	0.1 - 0.3	16
WAS - oxygen	0.5 - 1.5	2 - 3	0.1 - 0.3	17
WAS - (extended aeration)	0.2 - 1.0	2 - 3	0.2 - 0.3	16
Anaerobically digested sludge from primary digester	8	12	1.0	18
Thermally conditioned sludge:				
PRI only	3 - 6	12 - 15	1.6 - 2.1	19
PRI + WAS	3 - 6	8 - 15	1.2 - 1.8	19
WAS only	0.5 - 1.5	6 - 10	0.9 - 1.2	19
Tertiary sludge:				
High lime	3 - 4.5	12 - 15	1.0 - 2.5	18, 20
Low lime	3 - 4.5	10 - 12	0.4 - 1.25	18, 20
Alum	-	-	-	-
Iron	0.5 - 1.5	3 - 4	0.1 - 0.4	20
Other sludges:				
PRI + WAS	0.5 - 1.5	4 - 6	0.2 - 0.6	20
	2.5 - 4.0	4 - 7	0.3 - 0.7	16
PRI + TF	2 - 6	5 - 9	0.5 - 0.8	16
PRI + RBC	2 - 6	5 - 8	0.4 - 0.7	16
PRI + iron	2	4	0.25	18
PRI + low lime	5	7	0.8	18
PRI + high lime	7.5	12	1.0	18
PRI + (WAS + iron)	1.5	3	0.25	18
PRI + (WAS + alum)	0.2 - 0.4	4.5 - 6.5	0.5 - 0.7	20
(PRI + iron) + TF	0.4 - 0.6	6.5 - 8.5	0.6 - 0.8	20
(PRI + iron) + WAS	1.8	3.6	0.25	18
WAS + TF	0.5 - 2.5	2 - 4	0.1 - 0.3	16
Anaerobically digested PRI + WAS	4	8	0.6	18
Anaerobically digested PRI + (WAS + iron)	4	6	0.6	18

[a]Data on supernatant characteristics is covered later in this section.

[b]Typically, this term is given in lb/sq ft/day. Since wasting to the thickener is not always continuous over 24 hours, it is a more realistic approach to use lb/sq ft/hr.

1 lb/sq ft/hr = 4.9 kg/m^2/hr

5.3.3.2 Hydraulic Loading

Hydraulic loading is important for two reasons. First, it is related to mass loading. The quantity of solids entering the thickener is equal to the product of the flow rate and solids concentration. Since there are definite upper limits for mass loading, there will therefore be some upper limit for hydraulic loading. Secondly, high hydraulic loading causes excessive carryover of solids in the thickener effluent.

Typical maximum hydraulic loading rates of 25 to 33 gallons per square foot per hour (1,200 to 1,600 $l/m^2/hr$) have been used in the past but mainly for primary sludges. For sludges such as waste-activated or similar types, much lower hydraulic loading rates, 4 to 8 gallons per square foot per hour (200 to 400 $l/m^2/hr$) are more applicable (16). Table 5-3 gives some typical operating results. Note that the hydraulic loading rate in gallons per square foot per hour can be converted to an average upward tank velocity in feet per hour by dividing by 7.48.

TABLE 5-3

REPORTED OPERATING RESULTS AT VARIOUS OVERFLOW RATES FOR GRAVITY THICKENERS (20,21)

Location	Sludge type[b]	Influent solids concentration, percent solids	Hydraulic loading, gal/sq ft/hr	Mass loading, lb/sq ft/hr	Thickened solids concentration, percent solids	Overflow suspended solids, mg/l
Port Huron, MI	P+WAS	0.6	8	0.34	4.7	2,500
Sheboygan, WI	P+TF	0.3	18.6	0.46	8.6	400
	P+(TF+Al)	0.5	19.0	0.73	7.8	2,000
Grand Rapids, MI	WAS	1.2	4.1	0.42	5.6	140
Lakewood, OH	P+(WAS+Al)	0.3	25.8	0.6	5.6	1,400

[a] Values shown are average values only. For example, at Port Huron, MI the hydraulic loading varies between 7 to 9 gal/sq ft/hr (300-400 $l/m^2/hr$), the thickened solids in the underflow between 4.0 and 6.0 percent solids; and the suspended solids in the overflow, from 100 to 10,000 mg/l.

[b] P = Primary sludge
TF = Trickling filter sludge
WAS = Waste-activated sludge
Al = Alum sludge

1 gal/sq ft/hr = 40.8 $l/m^2/hr$
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$

Using the typical maximum hydraulic loading rates mentioned above, maximum velocities for primary sludges are 3.3 to 4.4 feet per hour (1.0 to 1.3m/hr) and for waste-activated sludge are 0.5 to 1.1 feet/hour (0.2 to 0.3 m/hr).

Several researchers have related overflow rates to odor control, but odor is due to excessive retention of solids and can be better controlled by removing the thickened sludge from the thickener at an increased frequency.

5.3.3.3 Drive Torque Requirements

Sludge on the floor of a circular thickener resists the movement of the solids rake and thus produces torque. Calculation of torque for a circular drive unit is based on the simple cantilevered beam equation represented by Equation 5-1:

$$T = WR^2 \qquad (5\text{-}1)$$

where:

T = torque, ft/lb

W = uniform load--this is sludge specific, lb/ft (see Table 5-4)

R = tank radius, ft

TABLE 5-4

TYPICAL UNIFORM LOAD (W) VALUES

Sludge type	Truss arm W, lb/ft[a]
Primary only (little grit)	30
Primary only (with grit)	40
Primary + lime	40 to 60
Waste-activated sludge (WAS)	
Air	20
Oxygen	20
Trickling filter	20
Thermal conditioned	80
Primary + WAS	20 to 30
Primary + trickling filter	20 to 30

[a]Rake arms typically have a tip speed between 10 to 20 ft/min (3 to 6 m/min).

1 lb/ft = 1.49 kg/m

Note that there are several levels of torque which must be specified for a circular gravity thickener (22). Table 5-5 lists and defines the various torque conditions.

5.3.3.4 Total Tank Depth

The total vertical depth of a gravity thickener is based on three considerations: tank free board, settling zone (zone of clear liquid and sedimentation zone), and compression and storage zone (thickening zone).

TABLE 5-5

DEFINITION OF TORQUES APPLICABLE TO CIRCULAR GRAVITY THICKENERS (22)

Running torque - this is the torque value calculated from equation 5-1
Alarm torque - torque setting, normally 120 percent of running, which tells the operator that there is something wrong
Shut-off torque - torque setting, normally 140 percent of running, which would shut off the mechanism
Peak torque - torque value, determined by the supplier of the drive unit. This torque is provided only for an instant and is normally 200 percent of the running torque

Free Board

Tank free board is the vertical distance between tank liquid surface and top of vertical tank wall. It is a function of tank diameter, type of bridge structure--half or full bridge--type of influent piping arrangement, and whether or not skimming is provided. It will usually be at least 2 to 3 feet (.6 to .9 m) although free-board distances up to 7 to 10 feet (2 to 3 m) have been used by some designers.

Settling Zone

This zone encompasses the theoretical zone of clear liquid and sedimentation zone as shown on Figure 5-1. Typically 4 to 6 feet (1.2 to 1.8 m) is necessary, with the greater depth being for typically difficult sludges, such as waste-activated or nitrified sludge.

Compression and Storage Zone

Sufficient tank volume must be provided so that the solids will be retained for the period of time required to thicken the slurry to the required concentration. In addition, sufficient storage is necessary to compensate for fluctuations in solids loading rate.

Another consideration is that gas may be produced because of anaerobic conditions or denitrification. Development of these conditions depends on the type of sludge, liquid temperature, and the length of time sludge is kept in the thickener. Plant operating experience has indicated that the total volume in this zone should not exceed 24 hours of maximum sludge wasting.

5.3.3.5 Floor Slope

The floor slopes of thickeners are normally greater than 2 inches of vertical distance per foot of tank radius (17/cm/m). This is steeper than the floor slopes for standard clarifiers. The steeper slope maximizes the depth of solids over the sludge hopper, allowing the thickest sludge to be removed. The steeper slope also reduces sludge raking problems by allowing gravity to do a greater part of the work in moving the settled solids to the center of the thickener.

5.3.3.6 Other Considerations

Lifting Devices

Optimum functioning of a thickener mechanism can be inhibited by heavy accumulation of solids due to power outages or inconsistent accumulations of heavy or viscous sludges. Thickeners can be provided with either a manual or an automatic lifting device that will raise the mechanism above these accumulations. This device has not been considered necessary in the majority of municipal wastewater treatment plants except in applications involving very dense sludges (for example, thermally-conditioned sludge or primary plus lime sludge).

Skimmers

Several years ago, it was rare for skimmers to be installed on gravity thickeners. Today it is common practice to specify skimming and baffling for new plants. The reason for the change is the increased processing of biological sludges and the inherent floating scum layer associated with those sludges.

Polymer Addition

Addition of polymer to gravity thickener feed has been practiced at several plants (23,24). Results indicate that the addition of polymers improves solids capture but has little or no effect on increasing solids underflow concentration. (See Chapter 8 for further discussion).

Thickener Supernatant

Thickener supernatant or overflow is normally returned to either the primary or secondary treatment process. As indicated in Table 5-3, the strength of the overflow, as measured by total solids, can vary significantly. The liquid treatment system must be sized to handle the strongest recycled load. (See Chapter 16 for further discussion).

Pickets

Stirring with pickets in gravity thickeners is thought to help consolidate sludge in the thickening zone (25). However, the support rake mechanism usually can provide sufficient sludge mixing to make special pickets unnecessary.

Feed Pump and Piping

The following guidelines are applicable for feed pump and piping:

- Use positive displacement feed pumps with variable speed drives for variable head conditions and positive feed control.

- Provide as nearly continuous pumpage as possible.

- Design piping for operational flexibility.

Thickener Underflow Pump and Piping

For variable head conditions and typical abrasiveness of many sludges, a positive displacement pump with variable speed drive should be used and its operations should be controlled by some type of solids sensor, for example, either by a sludge blanket level indicator or solids concentration indicator. Pumps should be located directly adjacent to the thickener for shortest possible suction line. A positive or pressure head should be provided on the suction side of the pump. A minimum of 10 feet (3 m) should be provided for primary sludges and a minimum of 6 feet (2 m) for all other sludges. It is critical to provide adequate clean-outs and flushing connections on both the pressure and suction sides of the pump. Clean-outs should be brought to an elevation greater than that of the water surface so that the line may be rodded without emptying the thickener.

5.3.4 Design Example

A designer has calculated that it is necessary to thicken a maximum of 2,700 pounds (1,225 kg) per day of waste sludge, (dry weight). The sludge consists of 1,080 pounds (490 kg) of primary at 4.0 percent solids and 1,620 pounds (735 kg) of activated at 0.8 percent solids. Wasting from the primary clarifier will be initiated by a time clock and terminated by a sludge density meter when the sludge concentration drops below a given value. Waste-activated sludge will be pumped from the final clarifier 24 hours per day at 17 gallons per minute (64 l/min).

Thickener Surface Area

Since this is a new facility and pilot testing is not possible, the designer must utilize Table 5-2.

There are two possible thickening alternatives. The first alternative is thickening of straight waste-activated sludge with a maximum influent solids concentration of 0.8 percent solids. At maximum conditions, the designer has selected a mass loading of 0.2 pounds per square foot per hour (1.47 kg/m^2/hr) and will design for a 2.0 percent solids in the underflow.

$$\frac{1{,}620 \text{ lb/day}}{(0.2 \text{ lb/sq ft/day})\ (24 \text{ hrs/day})} = 337.5 \text{ sq ft } (31.4 \text{ m}^2)$$

The second alternative is thickening a combination of waste-activated sludge and primary sludge. The density meter on the primary clarifier will be set to allow the sludge pump to continue as long as the solids concentration is greater than or equal to 4.0 percent solids. The primary sludge pump will be equipped with a variable speed controller and has a maximum rated pumping capacity of 10 gallons per minute (38 l/min).

On a mass loading basis, the designer's past experience indicates that surface area required for the combination of primary and waste-activated sludge is less than that required for waste-activated alone. However, to assure system reliability, sufficient surface area should be provided to thicken only waste-activated. With the addition of primary sludge, the expected underflow solids concentration is 4.0 percent.

Hydraulic Loading

The maximum possible hydraulic flow to the gravity thickener would be 17 gallons per minute (1.0 l/sec) of waste-activated and 10 gallons per minute (0.63 l/sec) of primary sludge. The designer is cognizant of the solids recycle problem from the thickener overflow and has selected a value of 6 gallons per square feet per hour (250 l/m^2/hr) as the maximum overflow rate.

$$\frac{((17 + 10) \text{ gal/min}) \times (60 \text{ min/hr}))}{6 \text{ gal/sq ft/hr}} = 270 \text{ sq ft } (25.1 \text{ m}^2)$$

The area required for hydraulic loading is less than that required for mass loading.

Since continuous operation of the sludge handling system is essential, two gravity thickeners, each capable of handling the sludge flow, will be provided. The minimum required area is 337.5 square feet (31.4 m^2), which is equivalent to a 20.7-foot (6.2 m) diameter unit. In this size range, equipment manufacturers have standardized on 1-foot (0.3 m) increments; therefore, a 21-foot (6.3 m) diameter, 346-square-foot (32.2 m^2) unit will be specified.

Torque Requirements

The 30 pounds per foot (45 kg/m) value will be used for the truss arm loading (Table 5-4). From Equation 5-1, the running torque required is:

$$\frac{30 \text{ pounds}}{\text{foot}} \times (10.5 \text{ feet})^2 = 3{,}307 \text{ ft-lb } (465 \text{ m-kg})$$

The designer will specify a minimum running torque capacity of 3,307 foot pounds (465 m-kg). The other torques (alarm, shut-off, and peak) would be specified as in Table 5-5.

Tank Depth

Because both the full and the half bridge systems work equally well and the full bridge is less expensive to install, the designer will use a full bridge thickener mechanism that will rest atop the gravity thickener and will have a skimming mechanism attached.

In order to accommodate the skimming arm beneath the bridge and allow room to perform maintenance work, the designer has selected 24 inches (0.61 m) for the freeboard in the thickener.

From past experience, the designer has selected a typical depth of 5 feet (1.54 m) for the settling zone.

To calculate the depth of the thickening zone, it is assumed that the average solids concentration in the zone would be 1.4 percent solids and that one-day storage would be utilized.

The following assumptions were made in order to arrive at this percentage:

- Only waste-activated sludge would be thickened.
- The top of the thickening zone would hold 0.8 percent solids.
- The bottom of the thickening zone would hold 2.0 percent solids.
- The average concentration would be equal to 0.8 plus 2.0 quantity divided by 2.

$$\frac{1{,}620 \text{ lb of waste-activated sludge}}{(0.014)(8.34)(7.48 \text{ gal/cu ft})(346 \text{ sq ft})} = 5.36 \text{ ft } (1.61 \text{ m})$$

The total vertical side-wall depth of the gravity thickener is the sum of the free board, settling zone, and required thickening zone. In this case, it would be 12.36 feet (3.77 m). At this time, no allowance has been made for the depth of the cone height of the thickener which would reduce slightly (21 inches [.27 m] the vertical side wall depth of the thickening zone when subtracted from the thickening zone depth.

5.3.5 Cost

5.3.5.1 Capital Cost

Several recent publications have developed capital cost curves for gravity thickeners (26-28). Probably the most factual is the reference based on actual USEPA bid documents for the years 1973-1977 (27).

According to a USEPA Municipal Wastewater Treatment Plant Construction Cost Index - 2nd quarter 1977 (27), although the data were scattered, a regression analysis indicated that the capital cost could be approximated by Equation 5-2.

$$C = 3.28 \times 10^4 Q^{1.10} \qquad (5\text{-}2)$$

where:

C = capital cost of process in dollars

Q = plant design flow in million gallons of wastewater flow per day

The associated costs include those for excavation, process piping, equipment, concrete, and steel. In addition, such costs as those for administrating and engineering are equal to 0.2264 times Equation 5-2 (27).

5.3.5.2 Operating and Maintenance Cost

Staffing

Figure 5-4 indicates annual man-hour requirements for operation and maintenance. As an example, for a gravity thickener surface area of 1,000 square feet (93 m^2), a designer would include 350 man-hours of operation and maintenance in the cost analysis.

Power

Figure 5-5 shows annual power consumption for a continuously operating gravity thickener as a function of gravity thickener surface area. As an example, for a gravity thickener surface area of 1,000 square feet (93 m^2), a designer would include a yearly power usage of 4,500 kWhr (16.2 GJ) in the cost analysis. Figure 5-5 does not include accessories such as pumps or polymer feed systems.

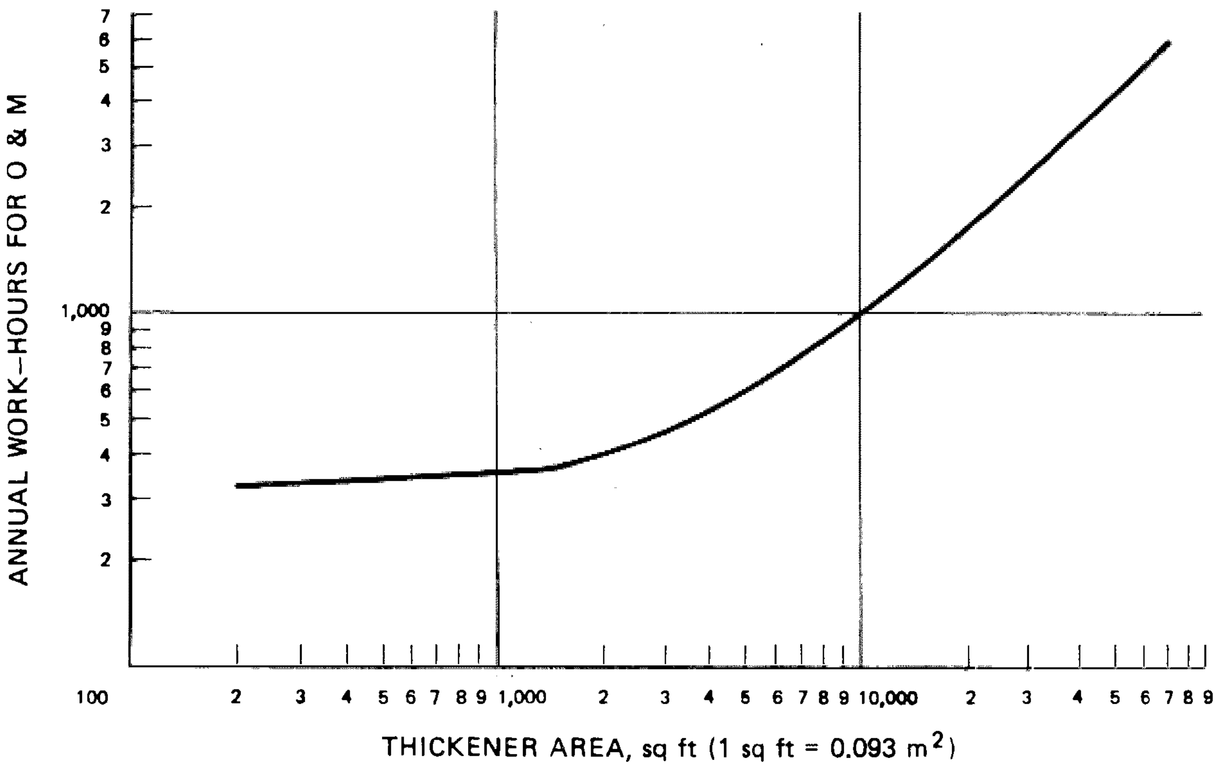


FIGURE 5-4

ANNUAL O&M MAN-HOUR REQUIREMENTS - GRAVITY THICKENERS

<u>Maintenance Material Costs</u>

Figure 5-6 shows a curve developed for estimating circular gravity thickener maintenance material costs as a function of gravity thickener surface area. As an example, for a gravity thickener surface area of 1,000 square feet (93 m^2), a designer would estimate a yearly materials cost of $375. Since this number is based on a June 1975 cost, it must be adjusted to the current design period.

5.4 Flotation Thickening

Flotation is a process for separating solid particles from a liquid phase. Flotation of solids is usually created by the introduction of air into the system. Fine bubbles either adhere to, or are absorbed by, the solids, which are then lifted to the surface. Particles with a greater density than that of the liquids can be separated by flotation (24,29).

In one flotation method, dissolved air flotation, small gas bubbles (50-100 μm) are generated as a result of the precipitation of a gas from a solution supersaturated with that gas. Supersaturation occurs when air is dispersed through the sludge in a closed, high pressure tank. When the sludge is removed from the tank and exposed to atmospheric pressure, the previously dissolved air leaves solution in the form of fine bubbles.

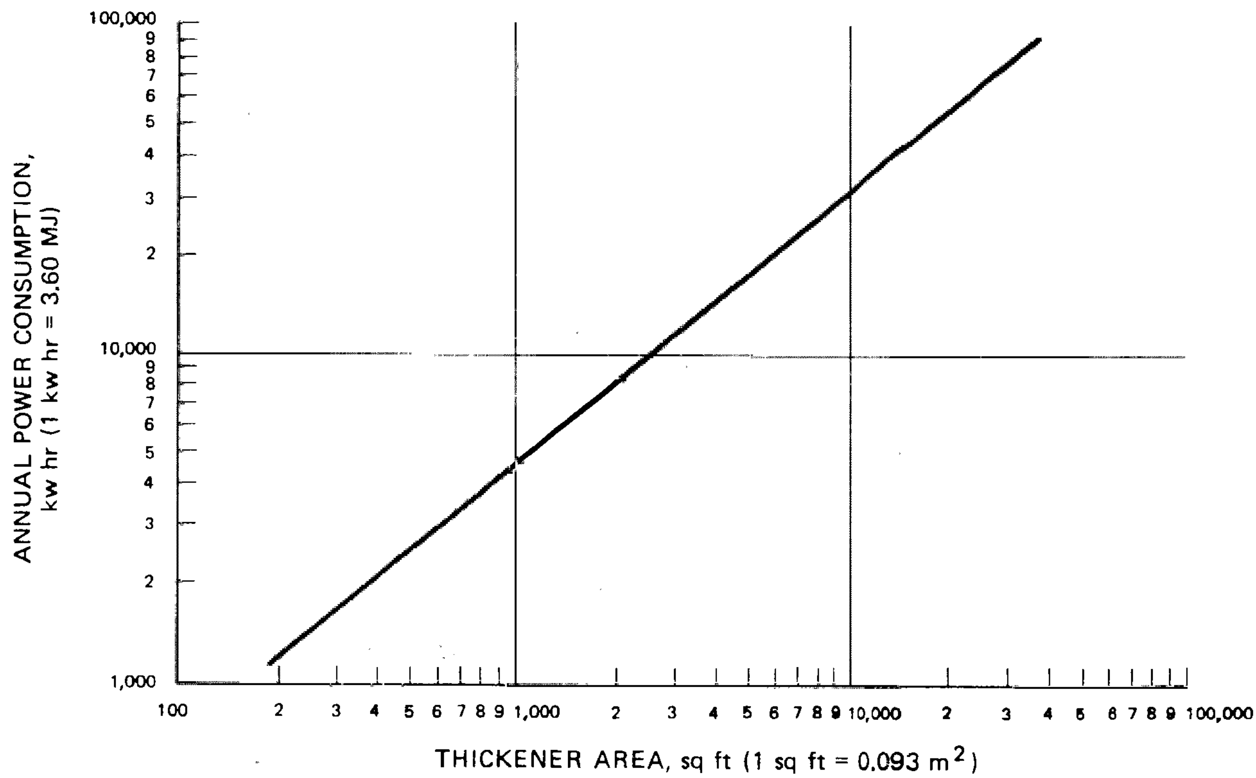


FIGURE 5-5

ANNUAL POWER CONSUMPTION - CONTINUOUS OPERATING GRAVITY THICKENERS

In a second method, dispersed air flotation, relatively large gas bubbles (500-1000 μm) are generated when gas is introduced through a revolving impeller or through porous media (30,31).

In biological flotation, the gases formed by natural biological activity are used to float solids (32-34).

In vacuum flotation, supersaturation occurs when the sludge is subjected initially at atmospheric pressure, to a vacuum of approximately 9 inches (230 mm) of mercury in a closed tank (35,36).

Although all four methods have been used in wastewater sludge treatment systems, the dissolved air flotation process has been the dominant method used in the United States.

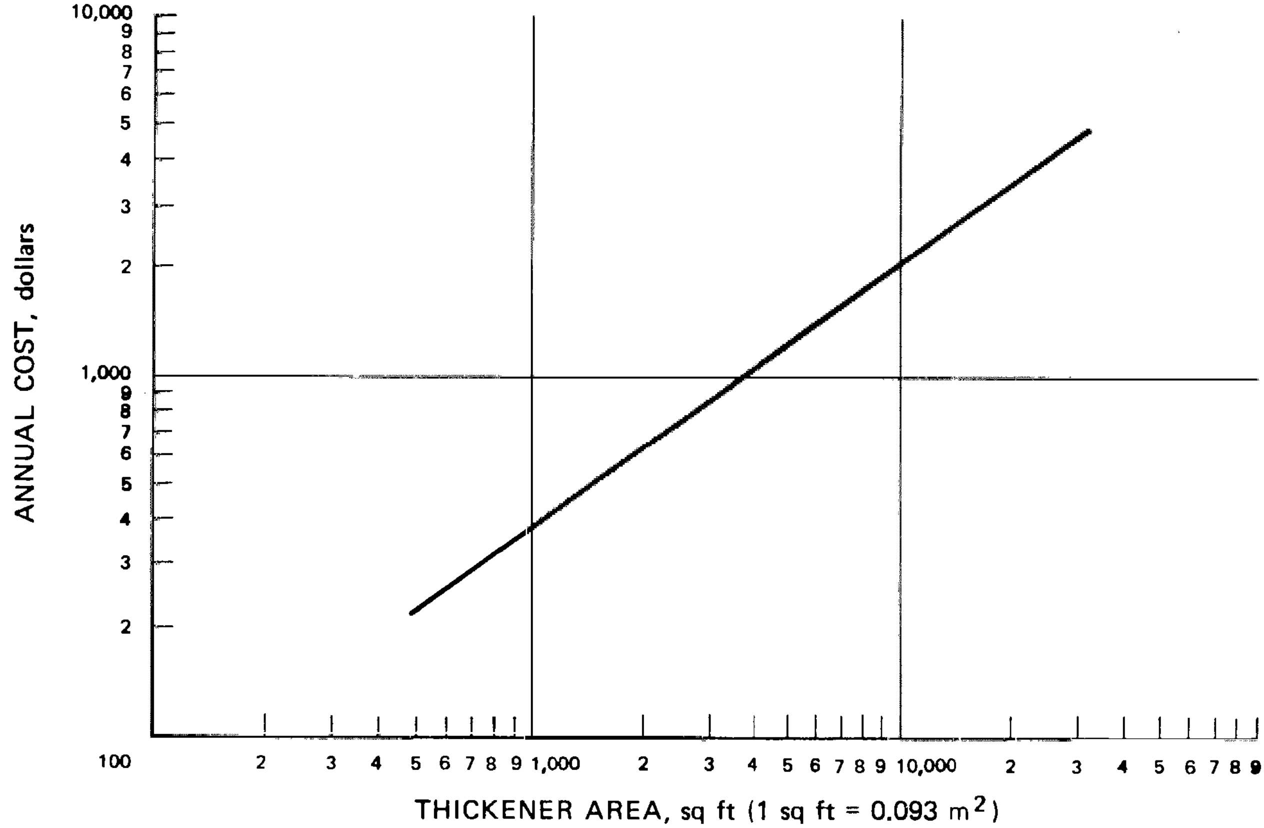


FIGURE 5-6

ESTIMATED JUNE 1975 MAINTENANCE MATERIAL COST FOR CIRCULAR GRAVITY THICKENERS

TABLE 5-6

TYPES OF MUNICIPAL WASTEWATER SLUDGES BEING THICKENED BY DAF THICKENERS

Primary only	Primary plus trickling filter
Waste activated sludge (WAS) - air only	Aerobically digested WAS
WAS (oxygen) only	Aerobically digested primary plus WAS (air)
Trickling filter only	Alum and ferrous sludge from phosphorus removal
Primary plus WAS (air)	

5.4.1 Dissolved Air Flotation (DAF)

Since the 1957 installation of the first municipal DAF thickener in the Bay Park Sewage treatment plant, Nassau County, New York, about 300 U.S. municipal installations (over 700 units) have been installed. Although the principal use of the DAF thickener has been to thicken waste-activated sludge, about 20 percent of the installations handle other sludge types (37). Table 5-6 lists the types of municipal wastewater sludges currently being thickened by DAF thickeners.

Table 5-7 lists advantages and disadvantages of DAF thickeners compared to other major thickening equipment.

TABLE 5-7

ADVANTAGES AND DISADVANTAGES OF DAF THICKENING

Advantages	Disadvantages
Provides better solids-liquid separation than a gravity thickener	Operating cost of a DAF thickener is higher than for a gravity thickener
For many sludges, yields higher solids concentration than gravity thickener	Thickened sludge concentration is less than in a centrifuge
Requires less land than a gravity thickener	Requires more land than a centrifuge
Offers excellent sludge equalization control	Has very little sludge storage capacity
Has less chance of odor problems than a gravity thickener	
Can remove grit from sludge processing system	
Removes grease	

5.4.1.1 Theory

In the DAF thickening process, air is added at pressures in excess of atmospheric pressure either to the incoming sludge stream or to a separate liquid stream. When pressure is reduced and turbulence is created, air in excess of that required for saturation at atmospheric pressure leaves the solution as very small bubbles of 50 to 100 µm in diameter. The bubbles adhere to the suspended particles or become enmeshed in the solids matrix. Since the average density of the solids-air aggregate is less than that of water, the agglomerate floats to the surface. The floated solids build to a depth of several inches at the water surface. Water drains from the float and affects solids concentration. Float is continuously removed by skimmers (35). Good solids flotation occurs with a solids-air aggregate specific gravity of 0.6 to 0.7.

5.4.1.2 System Design Considerations

DAF thickeners can be utilized either to thicken wastewater solids prior to dewatering or stabilization or to thicken aerobically digested or other solids prior to disposal or dewatering.

DAF thickeners can be rectangular or circular, constructed of concrete or steel, and can operate in the full, partial, or recycle pressurization modes.

Full, Partial and Recycle Pressurization

There are three ways in which a DAF system can be operated. The first method is called "full or total pressurization." With this design, the entire sludge flow is pumped through the pressure retention tank, where the sludge is saturated with air and then passed through a pressure reduction valve before entering the flotation chamber. A distribution device is used to dissipate inlet energy and thus to prevent turbulence and limit short circuiting. The primary advantage of pressurizing the total flow is that it minimizes the size of the flotation chamber, a significant part of the capital cost. However, the advantage of a smaller chamber may be partially offset by the cost of a higher head feed pump, larger pressure vessel, and more expensive operation. Operational problems may result from floc shearing and clogging when sludge is passed through the pressure regulating valve.

The second method of operation is called "partial pressurization." With this design only part of the sludge flow is pumped through the pressure retention tank. After pressurization the unpressurized and pressurized streams are combined and mixed before they enter the flotation chamber. In this arrangement the pressurizing pump and pressure vessel are smaller and the process is not as susceptible to flow variations as is total pressurization; this is the case when the necessary pump controls are included in the design. The size of the flotation chamber would be the same as that for a total pressurization system.

The third method is called "recycle pressurization." Here, a portion of the clarified liquor (subnatant) or an alternate source containing relatively little suspended matter is pressurized. Once saturated with air, it is combined and mixed with the unthickened sludge before it is released into the flotation chamber.

The major advantage of this system over the total and partial pressurization system is that it minimizes high shear conditions, an important parameter when dealing with flocculent-type sludges. Another advantage arises when wastewater sludge streams containing stringy materials are thickened. The recycle pressurization system eliminates clogging problems with the pressurization pump, retention tank, and pressure release valve. For the above reasons, recycle pressurization systems are the most commonly used units in the United States. Figure 5-7 shows a typical rectangular steel tank installation.

In this system, the pressure retention tank may be either unpacked or packed (meaning that the tank is filled with a packing material to create turbulence). The use of either is dependent principally on the source of the pressurized recycle flow.

The pressurized recyle flow can be obtained either from the subnatant stream or, typically, from the secondary effluent. The advantages of using secondary effluent are that it results in a much cleaner stream (low suspended solids and low grease content) and allows the use of a packed pressure retention tank. A packed tank is smaller than a packless tank, has lower associated capital cost, and provides for a more efficient saturation of the liquid stream. In this case, less air is required to achieve the same level of liquid saturation as a packless tank and power requirements are lower. Packed tanks may, however, eventually require cleaning, and the use of secondary plant effluent will significantly increase the flow through the secondary treatment system, thereby increasing pumping costs and possibly affecting the performance of the secondary clarifier.

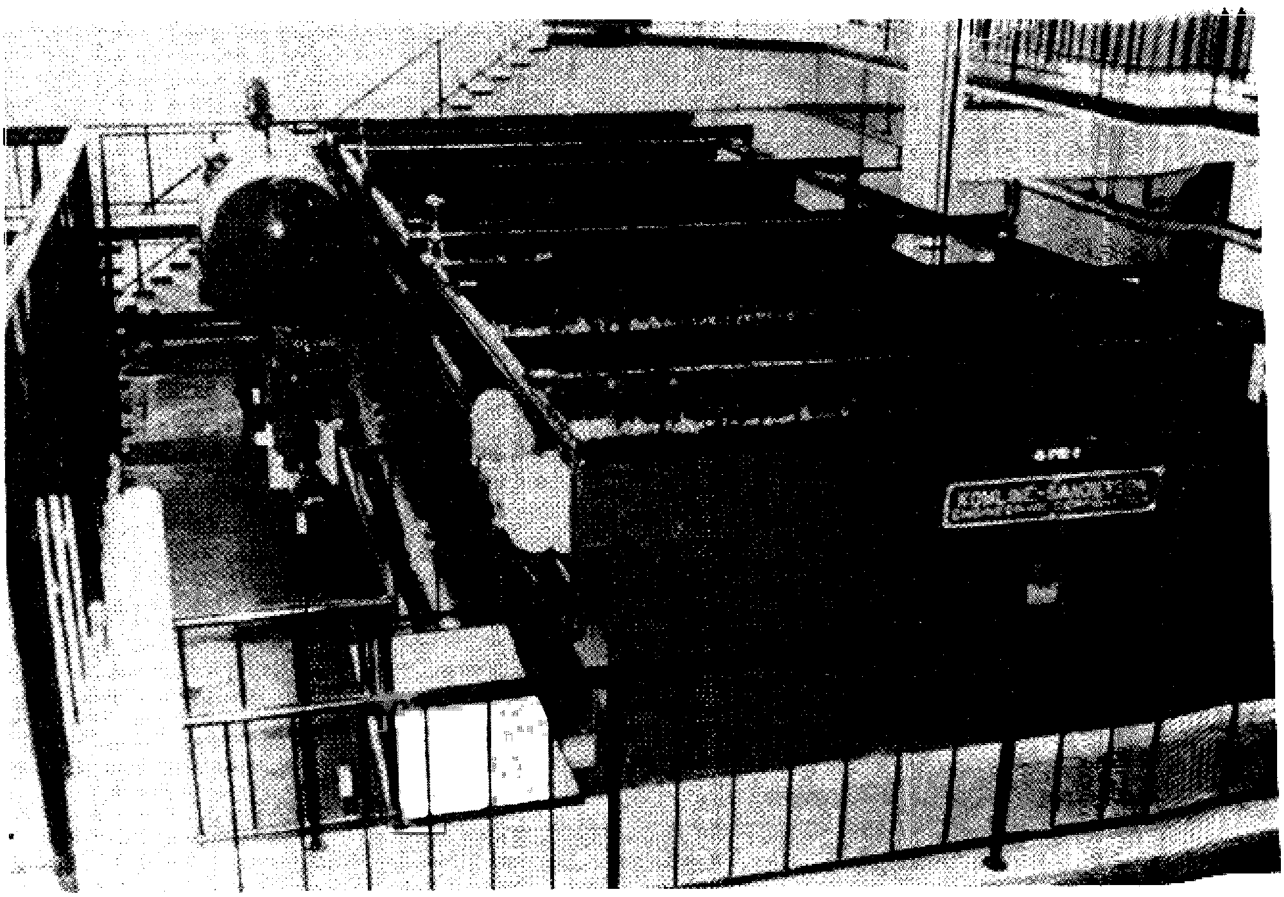


FIGURE 5-7

TYPICAL RECTANGULAR, STEEL TANK, RECYCLE PRESSURIZATION DISSOLVED AIR FLOTATION THICKENER

Rectangular or Circular

The use of rectangular DAF thickeners has a number of advantages over circular units in float removal. First, skimmers can easily be closely spaced; secondly, they can be designed to skim the entire surface. Because of the side-walls, float does not easily move around the end of the skimmers. Bottom sludge flights are usually driven by a separate unit and, hence, can be operated independently of the skimmer flights. Water level in the tank can be changed readily by adjusting the end weir. This permits changing the depth of water and flight submergence to accommodate changes in float weight and displacement, which affect the ability to remove this material from the unit.

The main advantage of circular units is their lower cost in terms of both structural concrete and mechanical equipment. For example, two 60-foot (18 m) diameter circular units are the equivalent of three 20-foot by 90-foot (6 m by 27 m) rectangular units. The rectangular units require approximately 11 percent more structural concrete, as well as more drives and controls which increase maintenance requirements.

Concrete or Steel

Steel tanks come completely assembled and only require a concrete foundation pad and piping and wiring hookups. Although equipment purchase price is much higher for steel tanks, considerable field labor and expensive equipment installation are eliminated. Structural and shipping problems limit steel DAF units to the smaller sizes (450 square feet [40.5 m^2] or less for rectangular units and 100 square feet [9 m^2] for circular units).

For a large installation requiring multiple tanks or large tanks, concrete tanks are more economical.

Pilot- or Bench-Scale Testing

If sludge is available, the designer should, as a minimum, perform bench-scale testing (38,39). If money is available, consideration should be given to renting a pilot DAF thickener and conducting a four- to six-week test program to evaluate the effects of such parameters as recycle ratio, air-to-solids ratio, solids and hydraulic loading, and polymer type and dosage. If sludge is not available, then a detailed review must be made of experience at installations where a similiar type of sludge is being thickened by DAF thickeners.

Feed Characteristics

The first step in designing a DAF thickener is to evaluate the characteristics of the feed stream. The designer must evaluate the type of sludge(s) to be thickened and the approximate quantities of each under various plant loadings and modes of operation. If waste-activated sludge is to be thickened, the expected range of sludge ages must be determined, since sludge age can significantly affect DAF thickening performance (40). Information is needed about the source of waste sludge and the range of solids concentrations that can be expected. Also, there should be an evaluation of any characteristic of the feed stream that may affect air solubility--for example, concentration of dissolved salts, and range of liquid temperatures.

Surface Area

To calculate the effective surface area of a DAF thickener, a designer must know the net solids load, solids surface loading rate, and hydraulic surface loading rate.

Net Solids Load

Since a DAF thickener is not entirely efficient, more sludge must be pumped into the thickener than the actual amount removed. The actual amount removed is the net solids load. From a design standpoint, the net load is the amount of solids that must be removed from the liquid processing train each day. This value divided by the appropriate solids loading rate gives the required effective surface area.

The gross solids load is calculated by dividing the net load by the expected solids capture efficiency of the system. The gross solids load is important in sizing system hydraulic piping.

Solids Loading Rate

The allowable solids loading rate is related to the minimum solids flux that will occur within the range of sludge concentrations found in the thickener (41). This flux is a function of the type of sludge processed, the float concentration desired, and polymer used. Pounds of dry solids per square foot per day or pounds of dry solids per square foot per hour are the units used to express this rate.

The effect of sludge type on the solids loading rate is shown in Table 5-8. The loading rates indicated will normally result in a minimum of four percent solids concentration in the float. Actual operating data are listed in Table 5-9.

TABLE 5-8

TYPICAL DAF THICKENER SOLIDS LOADING RATES NECESSARY TO PRODUCE A MINIMUM 4 PERCENT SOLIDS CONCENTRATION

Type of sludge	Solids loading rate, lb/sq ft/hr: No chemical addition	Solids loading rate, lb/sq ft/hr: Optimum chemical addition
Primary only	0.83 - 1.25	up to 2.5
Waste activated sludge (WAS)		
Air	0.42	up to 2.0
Oxygen	0.6 - 0.8	up to 2.2
Trickling filter	0.6 - 0.8	up to 2.0
Primary + WAS (air)	0.6 - 1.25	up to 2.0
Primary + trickling filter	0.83 - 1.25	up to 2.5

1 lb/sq ft/hr = 4.9 $kg/m^2/hr$

TABLE 5-9

FIELD OPERATION RESULTS FROM RECTANGULAR DAF THICKENERS

Installation	Sludge type[a]	Solids loading rate, lb/sq ft/hr	Feed solids concentration, mg/l	Polymer dosage, lb per dry ton solids	Float concentration, percent solids	Subnatant suspended solids, mg/l	Ref
Eugene, OR	P+TF	1.25	5,000	0	4.5-5.0	500	43
Springdale, AR	P+TF	2.5	20,000	7	6.5	200	43
Athol, MA	A	3.2	8,000	2	4.0	50	43
Westgate Fairfax, VA	A[b]	7.0	14,000	1-4	7.3	20	43
Warren, MI	A[c]		11,000	40	5.0	200	16
Frankenmuth, MI	A[c]	0.58	5,000	0	3.0	750	14
	A[c]		8,000	26	3.5-5.5	90	
Cinnaminso, NJ	A	2.0	5,000	5	4.0	250	16
San Jose, CA	P+A[d]	1.9	23,000	0	7.1		14
	P+A[e]	1.6	17,000	0	5.3		14
Boise, ID	A	1.0	4,600	0	4.0		14
	A	1.17	5,000	3	3.8	500	14
	A	1.13	5,000	6	4.0	500	14
Levittown, PA	A	0.54	8,000	0	6.5		14
	P+A	1.00	6,400	0	8.6		14
Xenia, OH	A		4,000	30	2.5-3.0	100	16
Indianapolis, IN	P+A		10,000	30	3.5-4.2	100-1,000	16
Columbus, OH (Jackson Pike)	A		6,000	0	3.2	800	16
Wayne County, MI	A	0.83	4,500	0	4.6		14
Dalton, GA	P+A	0.75	12,900	0	6.1		14
Middletown, NJ	A	2.0	10,000	5-6	4.0	500	14

[a] P = Primary sludge
A = Waste-activated sludge
TF = Trickling filter sludge

[b] Oxygen plant

[c] Considerable brewery waste

[d] Non-canning season

[e] Canning season

1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 lb/ton = 0.5 kg/t

In general, increasing the solids loading rate decreases the float concentration. Figure 5-8 illustrates this phenomenon without polymer addition, and Figure 5-9 with polymer addition.

The addition of polyelectrolyte will usually increase the solids loading rate.

Hydraulic Loading

The hydraulic loading rate for a DAF thickener is normally expressed as gallons per minute per square foot. When like units are cancelled, the hydraulic loading rate becomes a velocity equivalent to the average downward velocity of water as it flows through the thickening tank. The maximum hydraulic rate must always be less than the minimum rise rate of the sludge/air particles to ensure that all the particles will reach the sludge float before the particle reaches the effluent end of the tank.

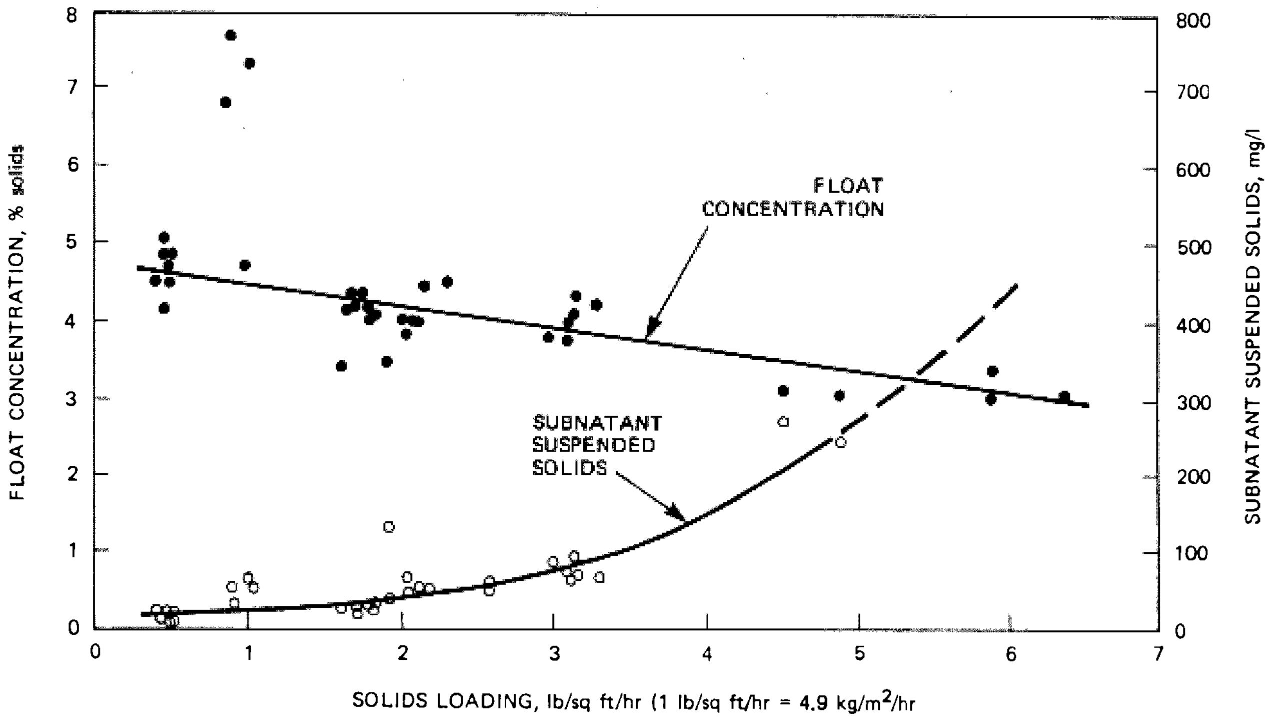


FIGURE 5-8

FLOAT CONCENTRATION AND SUBNATANT SUSPENDED SOLIDS VERSUS SOLIDS LOADING OF A WASTE ACTIVATED SLUDGE - WITHOUT POLYMERS (16)

Reported values for hydraulic loading rates range from 0.79 to 4.0 gallons per minute per square foot (0.54-2 to.7 l/min/m^2) (32,42-46). This wide range probably indicates a lack of understanding of the term. In some cases, the hydraulic loading refers simply to the influent sludge flow, while in others, the recycle flow is included. In most sources, no definition of the term was given. Table 5-10 indicates the hydraulic loading rates found in the literature.

Since the total flow through the thickener affects the particles, the hydraulic loading rate should be based on the total flow (influent plus recycle). Extensive research on waste-activated sludge (48) has resulted in the conclusion that a peak rate of 2.5 gallons per minute per square foot (1.7 l/sec/ m^2) should be employed. This value is based on use of polymers. When polymers are not used, this value is expected to be lower, but no design criterion has been suggested at this time. Figure 5-10 shows the effects of polymer and hydraulic loading rate on DAF thickener subnatant chemical oxygen demand (COD) (48).

Air-to-Solids-Ratio

Another design parameter to be considered in DAF thickening is that of the air-to-solids (A/S) ratio. Theoretically, the quantity of air required to achieve satisfactory flotation is directly proportional to the quantity of solids entering the thickener (defined as gross solids load in the previous section). For domestic wastewater sludges, reported ratios range from 0.01 to 0.4, with most systems operating at a value under 0.1.

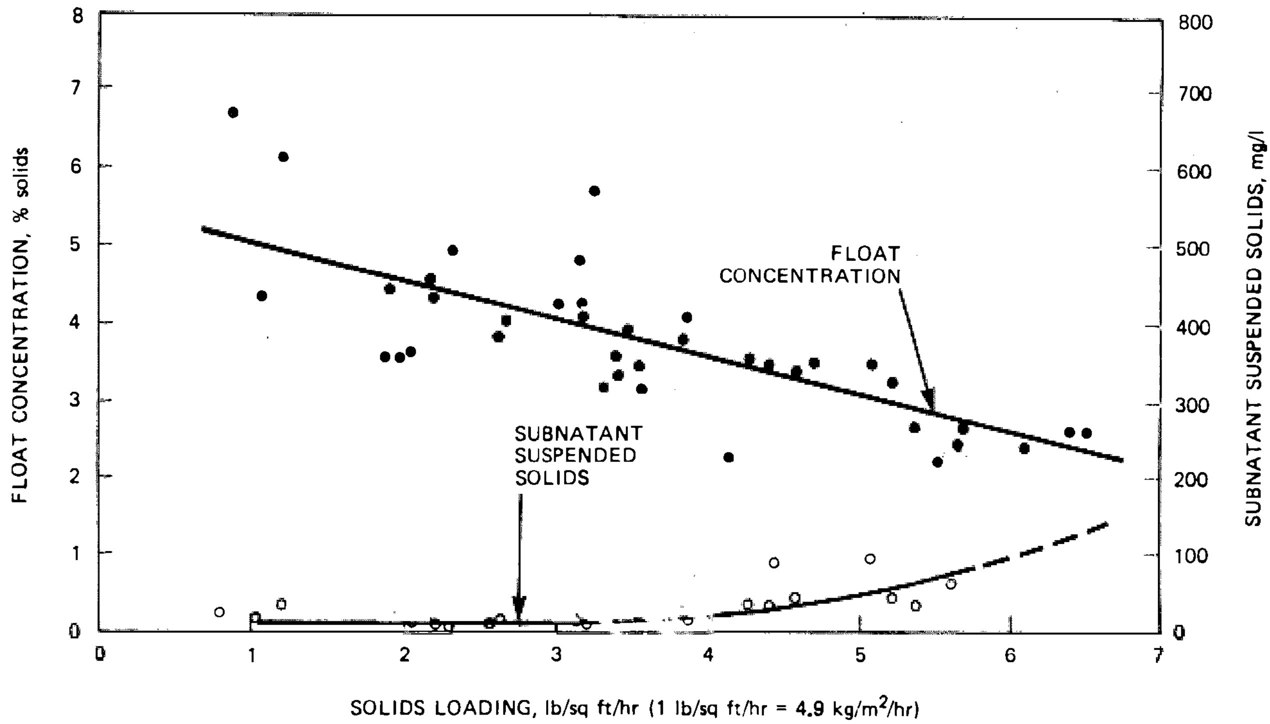


FIGURE 5-9

FLOAT CONCENTRATION AND SUBNATANT SUSPENDED SOLIDS VERSUS SOLIDS LOADING OF A WASTE ACTIVATED SLUDGE - WITH POLYMERS (16)

The appropriate A/S ratio for a particular application is a function of the characteristics of the sludge, principally, the sludge volume index (40), the pressurization systems air dissolving efficiency, and the distribution of the gas-liquid mixture into the thickening tank. Figures 5-11 and 5-12 show the effects of A/S of float concentration and subnatant suspended solids, with and without polymer addition.

Polymer Usage

Polymers have a marked effect on DAF thickener performance, and a designer must therefore be careful to differentiate between performance with and without polymer use.

Polyelectrolytes may improve flotation by substantially increasing the size of the particles present in the waste. The particles in a given waste may not be amenable to the flotation process because their small size will not allow proper air bubble attachment. Doubling the diameter or size of the particle can result in a fourfold increase in the rise rate provided the previous A/S ratio is maintained. The surface properties of the solids may have to be altered before effective flotation can occur. Sludge particles can be surrounded by electrically charged layers that disperse these particles in the liquid phase. Polyelectrolytes can neutralize the charge, causing the particles to coagulate so that air bubbles can attach to them for effective flotation. Thus, with use of polymers, the following operating advantages may occur: the size of the DAF thickener may be reduced; solids capture may be improved, thus reducing the amount of solids recycled back to the liquid handling system; an existing, overloaded facility in which polymers are not being utilized may be upgraded. They also act a surfactant, thus allowing better attachment of air bubbles.

TABLE 5-10

REPORTED DAF THICKENER HYDRAULIC LOADING RATES[a]

Hydraulic loading rate (gpm/sq ft)		
Influent only	Influent plus recycle	Reference
	1.5-2.5	44
	2.5	45
	1.0-4.0	46
	0.79	47
	1.25-1.5	48
0.9	3.0	49

[a]All values reported are associated with polymer usage. Values for systems not using polymer could not be found in the literature.

1 gpm/sq ft = 40.8 l/min/m^2

The major disadvantage of polymers is cost (polymer cost, operation and maintenance of polymer feed equipment) when calculated over the useful lifetime of the plant. In addition, the actual amount required is very difficult to determine until flotation studies can be run on the actual installation. If polymers are to be used, it is best to design conservatively, so that the possibility of the exceptionally high polymer demand needed to keep marginal operation at capacity is avoided. Table 5-9 lists current operating results of plants with and without polymer addition.

Pressurization System

The air dissolution equipment, which consists of the pressurization pump, air dissolution tank, and other mechanical equipment, is the heart of a DAF thickener system. In sizing a pressurization system, the designer must decide on an operating pressure and a quantity of pressurized flow and must be aware of factors affecting the performance of the system.

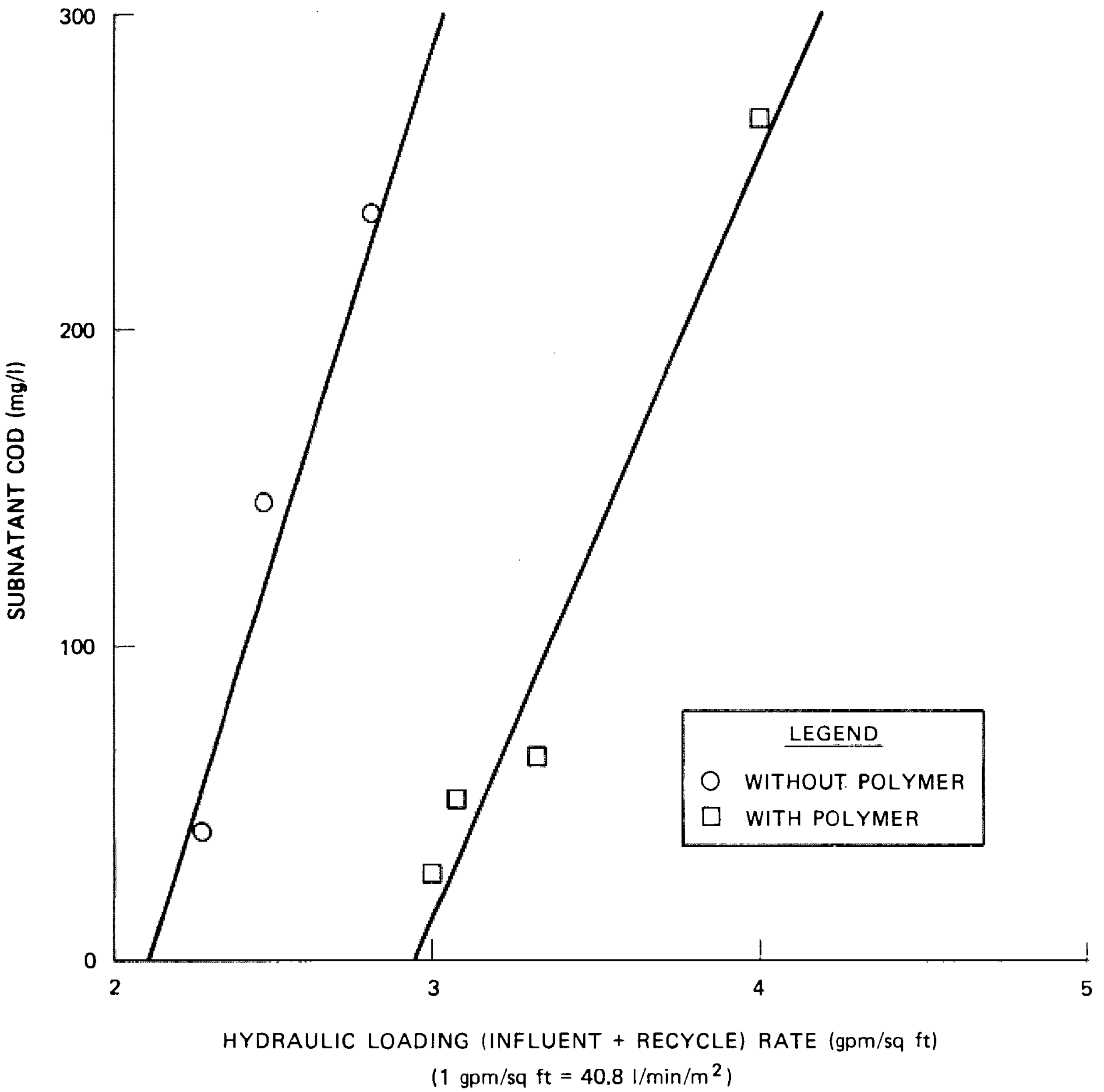


FIGURE 5-10

EFFECT OF HYDRAULIC LOADING ON PERFORMANCE IN THICKENING WASTE ACTIVATED SLUDGE (48)

Operating Pressure

Most commercial available pressurization systems operate at 40 to 80 psig (276 to 522 kN/m^2). For a given A/S ratio, the air required to float the sludge can be obtained by increasing the operating pressure of the system to dissolve more air, or holding a lower operating pressure and increasing the volume of pressurized flow.

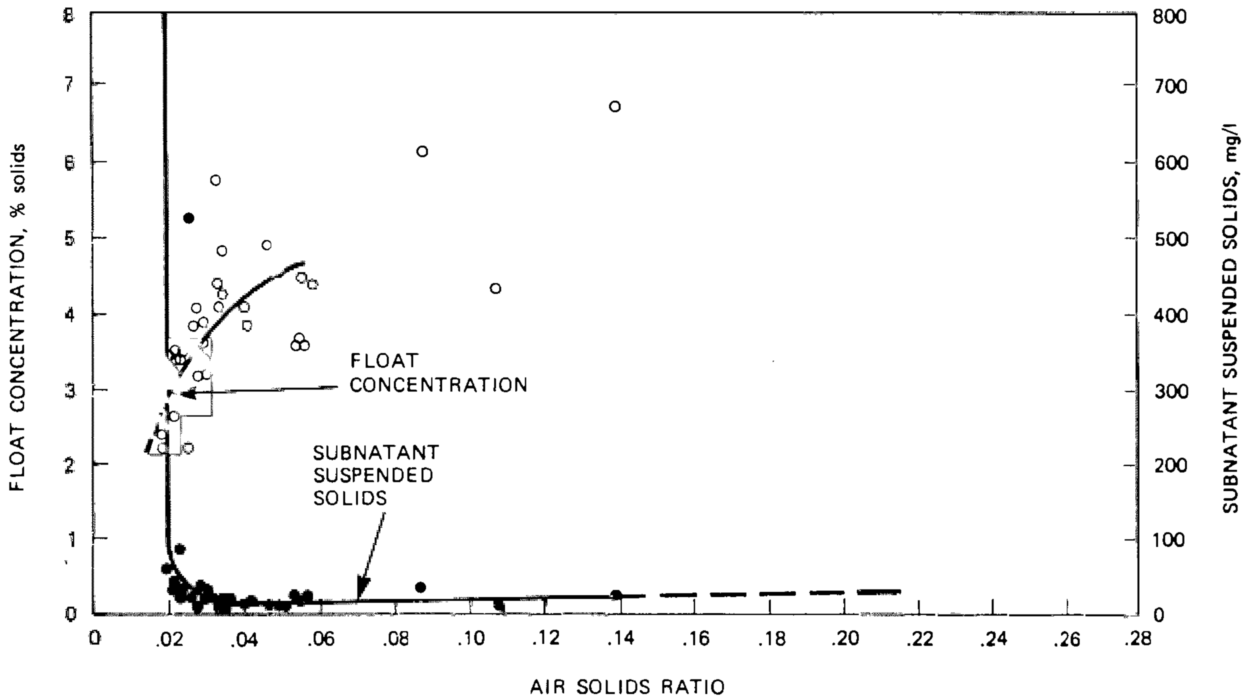


FIGURE 5-11

FLOAT CONCENTRATION AND SUBNATANT SUSPENDED SOLIDS VERSUS AIR-SOLIDS RATIO WITH POLYMER FOR A WASTE ACTIVATED SLUDGE (16)

In one study (40), it was shown that the higher the operating pressure of a flotation thickener system, the lower the rise rate of the sludge. The reason for a higher rise rate at 40 psig (276 kN/m^2) than at 60 or 80 psig (414 or 552 kN/m^2) is that the optimum bubble size is predominant at this lower operating pressure. This study concludes that attempting to raise the A/S ratio by increasing the operating pressure is detrimental to the thickening process. These results are important in that it will be in the user's best interest to operate at the lowest pressure possible. The requirement for higher head pumps, larger air compressors, and higher pressure rated retention tanks raises the initial cost of the process as well as operating costs.

Quantity of Pressurized Flow

For a DAF thickener to work effectively, the proper amount of air must be present for each pound of solids to be handled (A/S ratio). The design pressurized flow should be based on the maximum gross solids load that the DAF thickener is designed to receive. For multiple units, each basin should have its own independent pressurization system. This is especially important to remember if the thickening system is designed to operate over a wide range of influent solids concentrations and flows.

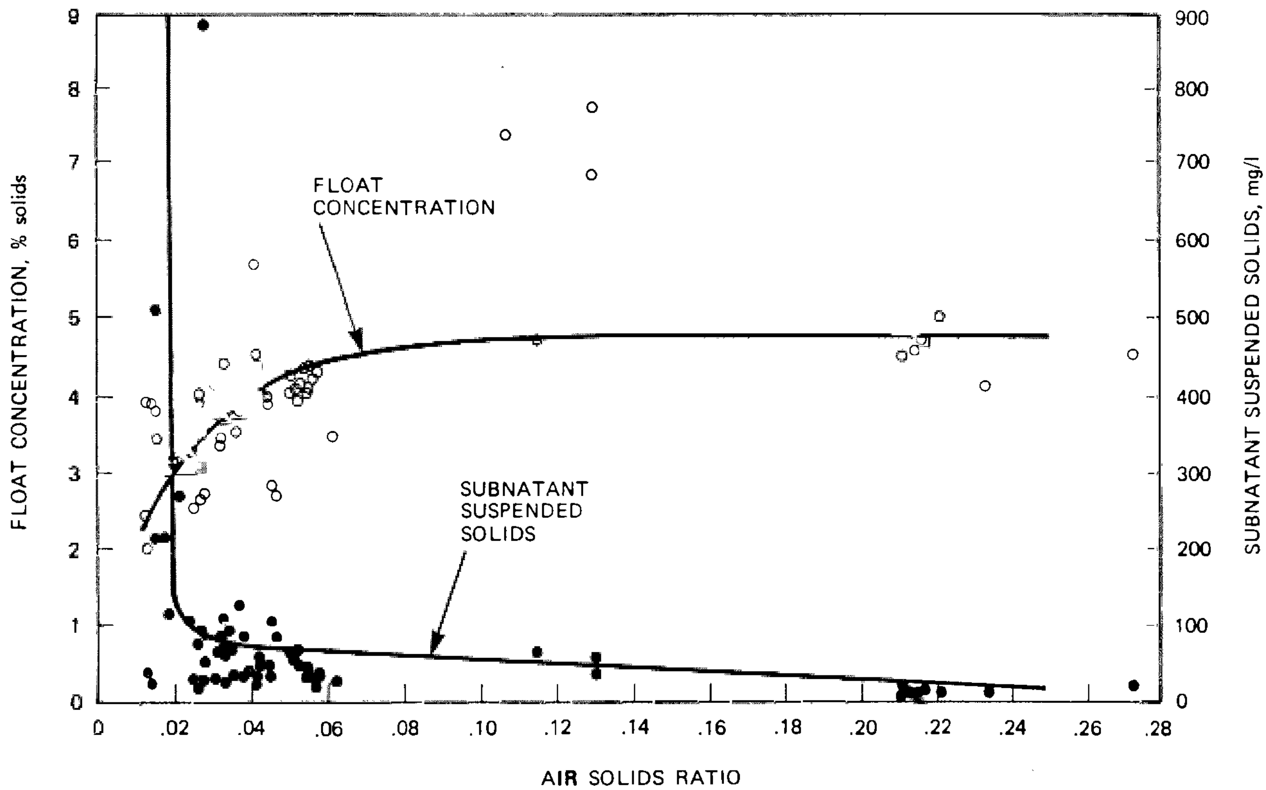


FIGURE 5-12

FLOAT CONCENTRATION AND SUBNATANT SUSPENDED SOLIDS VERSUS AIR-SOLIDS RATIO WITHOUT POLYMER FOR A WASTE ACTIVATED SLUDGE

Factors Affecting Performance

The designer should be aware of two physical factors, air saturation and turbulence, which can affect the performance of the pressurizing system.

Air Saturation. The basic mechanism that makes flotation possible is the increase in the amount of gas dissolved when pressure is increased. The relationship between pressure and quantity dissolved is shown in Henry's Law, which states that if no reaction prevails between the gas and liquid phases, the solubility of the gas is directly proportional to the absolute pressure of the gas at equilibrium with the liquid at constant temperature.

In practice, the actual amount of air dissolved for a given air input depends on the efficiency of the pressurization device, liquid temperature and concentration of solutes in the liquid stream being pressurized.

Normally a pressure retention tank is used to optimize the air-water interface for efficient air transfer in the shortest detention time. Depending on tank design (packed tank, packless tank, tanks with mechanical mixers, etc.), efficiencies can range from as low as 50 percent to over 90 percent. It is current design practice in the United States to specify a minimum of 85 to 90 percent efficiency.

The equilibrium concentration of a gas in a liquid is inversely related to the temperature of the liquid phase. The temperature effect is substantial. For example, the saturation of air in water at 140°F (60°C) is about one half less than the saturation of air in water at 66°F (18.8°C) at one atmosphere.

The presence of salts such as chloride will normally decrease the air solubility at a given temperature and pressure. The effect of salt concentration on air dissolving efficiency is best evaluated by conducting bench-scale treatability tests or a pilot unit test program.

Turbulence. The proper amount of turbulence must be present at the point of pressure reduction to cause bubble formation. Without the necessary turbulence, the rate at which air bubbles form is slow and may occur too late in the process. Excessive turbulence can result in increased bubble agglomeration and floc shear. Under this condition, the majority of bubbles formed will be considerably larger than the 50 to 100 µm needed for effective flotation.

Number of Units to be Used

The number of DAF thickeners to be provided at a facility depends on the following factors:

- The availability and configuration of available land.
- The operating cycle that will be used, for example, seven days per week, 24 hours per day; five days per week; eight hours per day; etc.
- Seasonal variability; for example, the operation of a food processor six months of the year, the waste flow from which will go to the municipal facility.
- The variance in average-to-peak hourly solids load that can be expected on a day-to-day basis.

Adequate capacity to thicken peak hourly waste sludge production is necessary. In addition, provision must be made to handle the sludge flow if a unit must be taken out of service. (See discussion in Chapter 2).

Other Considerations

In addition to the system design considerations previously discussed, the designer must also give consideration to feed sludge line sizing, thickened sludge removal, bottom draw-off piping, subnatant piping, pressurized flow piping, and controls. Each of these items is briefly discussed below.

Feed Sludge Line

Feed sludge flow rate must be controlled to stay within allowable limits. This requires a flow meter that accurately measures a high solids stream and piping large enough to handle maximum flow.

Thickened Sludge Removal

The surface skimmer brings the thickened sludge over the dewatering beach and deposits it in a sludge hopper. The thickened sludge must then be pumped to the next phase of the solids handling system. In pump selection, it is important to remember that air has been entrained in this sludge by the flotation thickening process. Pumps that can air lock should not be used; positive displacement pumps are common in this application.

For pipe sizing and final pump selection, consider that the thickened sludge can reach concentrations in the range of ten percent. (See Chapter 14 for further discussion).

Bottom Sludge Draw Off

In a rectangular DAF tank, the bottom collector moves the settled solids to the influent end of the basin. Here it is deposited into either multiple hoppers or a cross-screw conveyor that delivers it to a hopper. The bottom collector in a circular DAF tank delivers the settled solids directly to a hopper in the center of the tank. Once the solids are in the hopper, they must be removed from the tank. Depending on where this flow goes, it can be handled by either gravity or pumps.

One major consideration that applies to either removal system, but particularly to gravity removal, is the static head available. Since the draw-off point is at the bottom of the flotation basin, the entire depth of the liquid in the basin must be considered as available static head. Although fine control is not required, this head must be dissipated in order to restrict the flow. A positive displacement pump with variable speed drive will assure control of bottom sludge withdrawal.

This draw-off is at the lowest point in the basin and therefore could also be used as a basin drain. If a tee and drain valve is installed on this line at the outside of the tank wall, draining can take place. The line from the drain valve can go to the plant's drain system.

Subnatant Line

Pipe sizing should be such that it can handle the maximum total flow (influent plus recycle) without any appreciable head loss.

Pressurized Flow Piping

Because of the high pressure requirements of this flow, the pressurization liquor is usually delivered to the pressure tank by a high-speed, closed impeller centrifugal pump. Piping must be sized to handle the maximum liquid throughput rate of the pressure tank selected.

Controls

The controls for a DAF thickener are dependent upon the system, the degree of automation required, and the equipment manufacturer's design. They usually include, at a minimum, a pressure controller for the pressure vessel and flow meters for the feed and thickened sludge flows.

5.4.2 Design Example

A designer has calculated that it will be necessary to thicken a maximum of 2,700 pounds (1,225 kg) per day of waste sludge at 0.5 to 0.8 percent solids from a contact stabilization plant employing no primary clarification. The facility will have a sludge handling system consisting of a DAF thickener for the waste activated sludge, mechanical dewatering by belt press and composting. The treatment plant will be manned eight hours per day, seven days per week but dewatering operations will only take place six hours per day, five days per week. Thickening operation would take place 7.5 hours per day, five days per week. Waste sludge flow from the final clarifier would be continuous during the thickening operation--that is, 7.5 hours per day, five days per week.

The designer has decided to provide polymer feed equipment for the DAF thickener to be used in emergency situations only. Polymers are not used in normal operation.

The designer has also decided to use a packed pressurization tank, which requires a relatively clean source of pressurized flow. Secondary effluent will be utilized.

Effective Surface Area

The maximum daily waste sludge production expected was given as 2,700 pounds (1,225 kg) of waste-activated sludge with a solids concentration of 5,000 to 8,000 mg/l.

The maximum net hourly load (actual amount of solids that must be captured and removed per hour by the thickener) is:

$$\frac{(2{,}700 \text{ lb/day})(7 \text{ days/wk})}{(7.5 \text{ hrs/day})(5 \text{ day/wk operation})} = 504 \text{ lb/hr } (228.6 \text{ kg/hr})$$

The sludge being thickened is considered to be equivalent to a straight waste-activated sludge even though primary solids are mixed with it. From Table 5-8, a value of 0.42 pounds per square foot per hour (2.1 kg/m^2/hr) is selected.

$$\frac{504 \text{ lb/hr max. net load}}{0.42 \text{ lb/sq ft/hr loading rate}} = 1{,}200 \text{ sq ft } (108 \text{ m}^2)$$

Based on the solids loading rate (hydraulic loading rate needs to be checked), the maximum effective surface area required is 1,200 square feet (108 m^2).

Flow Determination

Feed, pressurized recycle, thickened sludge, and subnatant must be calculated to determine pump size and piping requirements.

Feed Flow Rate - Both the gross solids load and minimum solids concentration must be known to calculate the feed flow rate.

The gross solids load is the amount of solids that must be fed to the thickener in order for the system to capture and thicken the required net solids load. The maximum net hourly load has already been calculated to be 504 pounds per hour (228.6 kg/hr). Since polymers are not to be used during normal operation, a capture efficiency of 85 percent is used (standard for the industry). The maximum gross solids load is then calculated as follows:

$$\frac{504 \text{ lb/hr max. net load}}{0.85 \text{ efficiency factor}} = 593 \text{ lb/hr } (269 \text{ kg/hr})$$

The minimum solids concentration expected is 5,000 mg/l. The maximum feed flow rate can now be calculated as follows:

$$\frac{593 \text{ lb/hr}}{(0.005)(8.34)(60 \text{ min/hr})} = 237 \text{ gpm } (897 \text{ l/min})$$

Pressurized recycle flow rate - The design pressurized flow should be based on the maximum gross solids load expected from the DAF thickener. For this example, the maximum hourly gross solids load used was 593 pounds per hour (269 kg/hr).

After discussing the operating conditions with several DAF thickener equipment suppliers, the engineer designed for a maximum of 237 gallons per minute (14.95 l/sec).

Thickened sludge flow rate - The maximum hourly net solids load was 504 pounds per hour (228.6 kg/hr). At the minimum four percent solids concentration, the expected flow rate can be calculated as follows:

$$\frac{504 \text{ lb/hr}}{(0.04)(8.34)(60 \text{ min/hr})} = 25.2 \text{ gpm } (1.59 \text{ l/sec})$$

Subnatant flow rate - This rate is equal to the maximum total flow into the tank--237 gallons per minute (14.95 l/sec) feed plus 237 gallons per minute (14.95 l/sec) recycle.

Hydraulic Surface Loading Rate

Based on solids loading, the minimum thickener surface area was calculated to be 1,200 square feet (108 m^2). The total maximum flow rate (influent plus recycle) was calculated to be 474 gallons per minute (1,794 l/min). The maximum hydraulic surface loading rate would be:

$$\frac{1{,}200 \text{ sq ft}}{474 \text{ gpm}} = 2.53 \text{ gpm/sq ft } (1.72 \text{ l/sec/m}^2)$$

The 2.53 gallon per minute per square foot (105 l/min/m^2) is on the high side for a system that does not employ polymer addition. Under maximum conditions, polymer usage would be required.

Number of Units

Only one unit will be used, with an adequate spare parts inventory to minimize down time.

Manufacturer's Recommendations

Several reputable manufacturers of DAF thickeners were contacted for their comments on the designer's calculations and proposed application.

5.4.3 Cost

5.4.3.1 Capital Cost

Several recent publications have developed capital cost curves for DAF thickeners (26-28). As discussed in Section 5.3.5.1, the most factual is the reference based on actual USEPA bid documents for the years 1973-1977 (27). Although the data were scattered, a regression analysis indicated the capital cost could be approximated by Equation 5-3:

$$C = 2.99 \times 10^4 Q^{1.14} \qquad (5\text{-}3)$$

where:

C = capital cost of process in dollars;

Q = plant design flow in mil gal wastewater flow per day.

The associated costs include, those for, excavation, process piping, equipment, concrete and steel. In addition, such cost as those for administrating and engineering are equal to 0.2264 times Equation 5-3 (27).

5.4.3.2 Operating and Maintenance Costs

Staffing

Figure 5-13 indicates annual man-hour requirements for operations and maintenance. As an example, for a DAF thickener surface area of 1,000 square feet (93 m^2) a designer would include 2,700 man-hours of operation and maintenance in the cost analysis.

Power

Figure 5-14 shows annual power consumption for a continuously operating DAF thickener as a function of DAF thickener surface area. As an example, for a DAF thickener surface area of 1,000 square feet (93 m^2), a designer would include a yearly power usage of 720,000 kWhr (2,592 GJ) in the cost analysis. Figure 5-14 does not include accessories such as pumps or polymer feed systems.

Maintenance Material Cost

Figure 5-15 shows a curve developed for estimating DAF thickener maintenance material cost as a function of DAF thickener surface area. As an example, for DAF thickener surface area of 1,000 square feet (93 m^2), a designer would estimate a yearly materials cost of $275. Since this number is based on a June 1975 cost, it must be adjusted to the current design period.

5.5 Centrifugal Thickening

5.5.1 Introduction

The concept of using centrifuges for thickening municipal wastewater sludges (waste-activated sludge) was first considered in the United States in the late 1930's (49). At that time, disc nozzle centrifuges were used. Early installations used machines developed for industrial processing. Equipment manufacturers did not appreciate that the composition of municipal wastewater sludges is extremely variable from plant to plant and within a plant, and that most wastewater treatment facilities provided little, if any, of the preventive maintenance common in industrial applications.

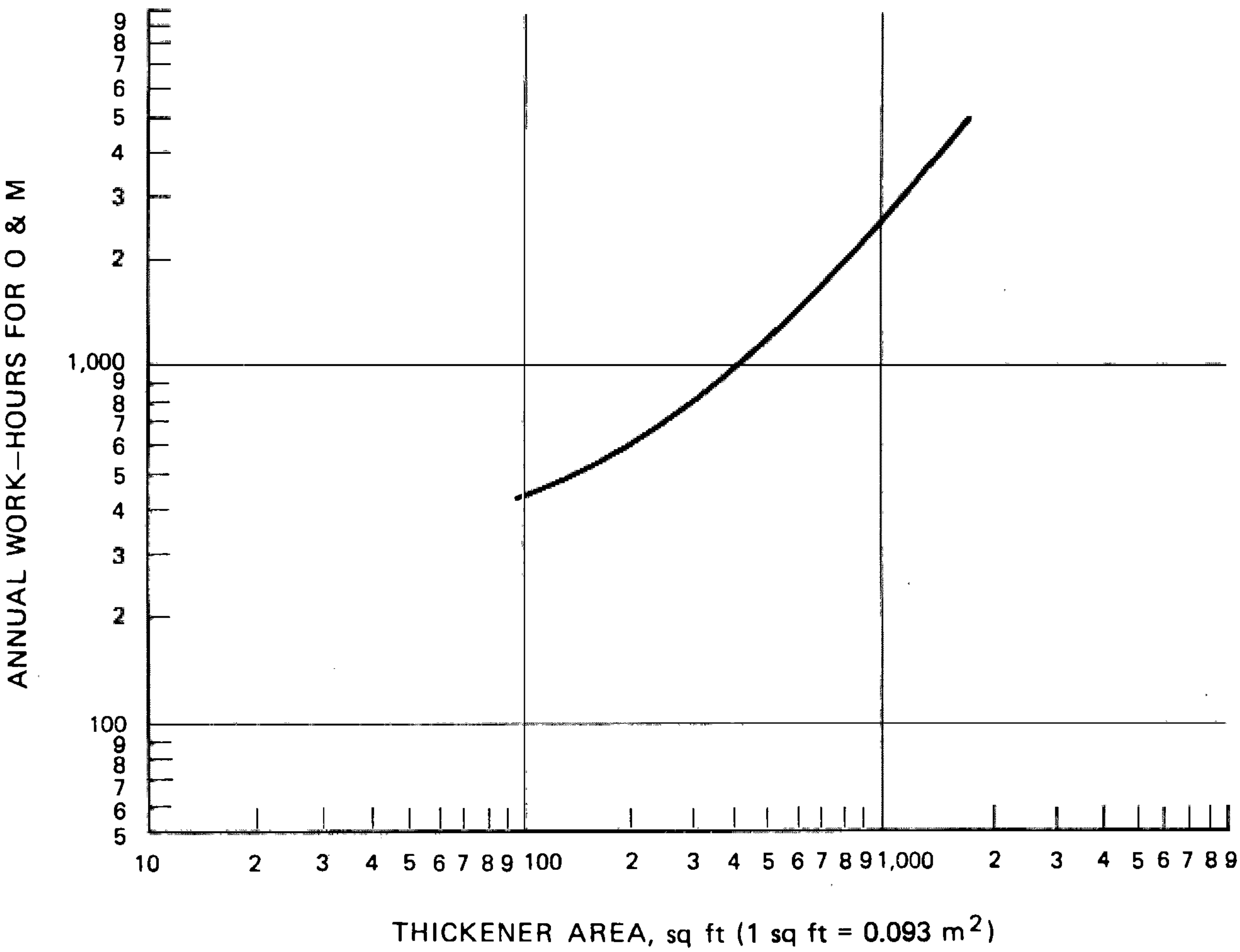


FIGURE 5-13

ANNUAL O&M MAN-HOUR REQUIREMENTS - DAF THICKENERS (28)

Consequently, early installations developed numerous operational and maintenance problems; thus, for a period of time designers and users did not favor the centrifuge.

By the late 1960's, equipment manufacturers had designed new machines specifically for wastewater sludge applications, and centrifuges began to be used once again. Considerable experience resulted in improved application of centrifuges and centrifuge support systems (chemical conditioning and chemical feed systems, pumps, and electrical controls). Today, more sophisticatd machines are being built that require less power and attention and produce less noise.

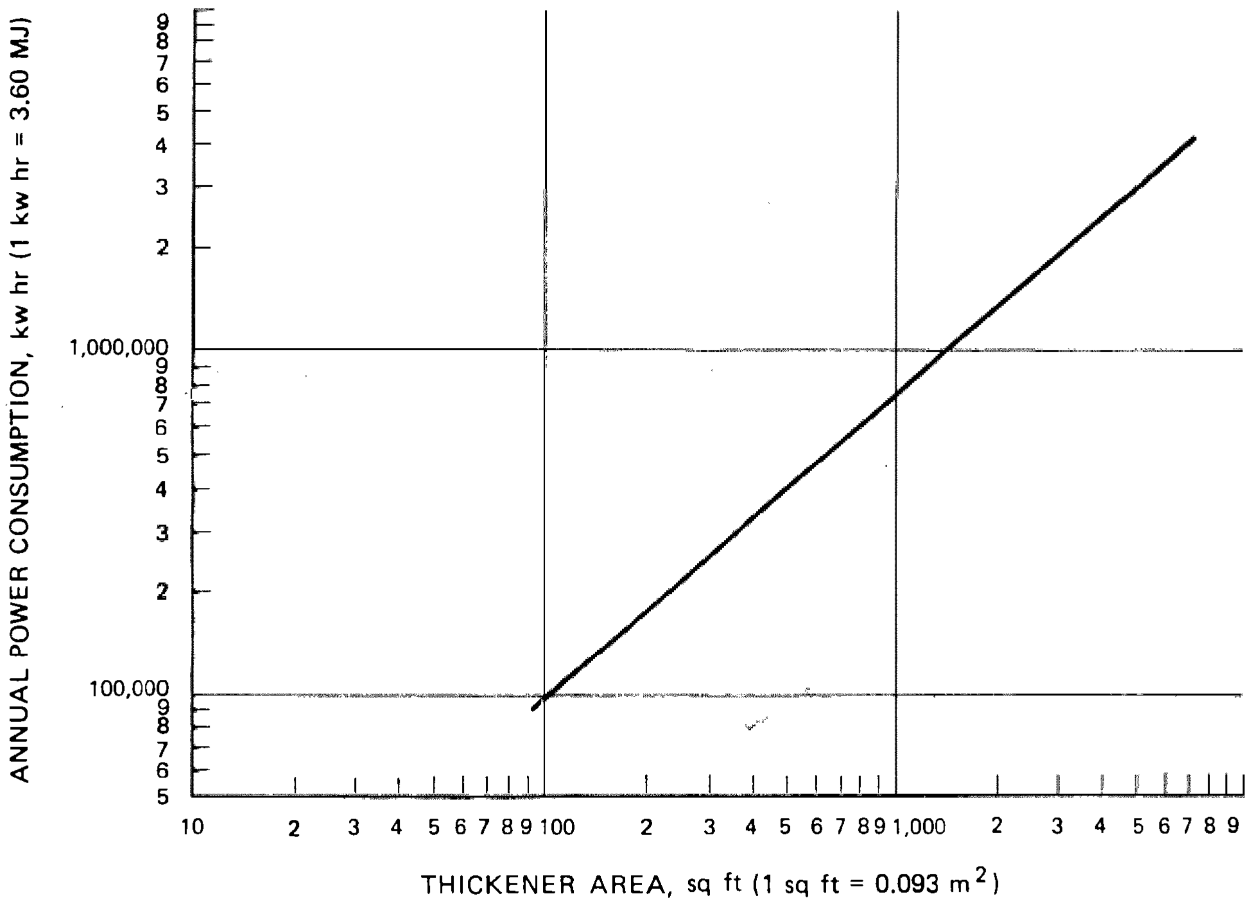


FIGURE 5-14

ANNUAL POWER CONSUMPTION - CONTINUOUS OPERATING DAF THICKENERS (28)

At present, disc nozzle, imperforate basket and scroll-type decanter centrifuges are used in municipal wastewater sludge thickening.

5.5.2 Theory

Centrifugation is an acceleration of sedimentation through the use of centrifugal force. In a settling tank, solids sink to the bottom and the liquid remains at the top. In a centrifuge, the rotating bowl acts as a highly effective settling tank. Space limitations within this manual make it impossible to discuss the theory and mathematics involved in centrifugation. Complete discussions can be found in other references (50-52).

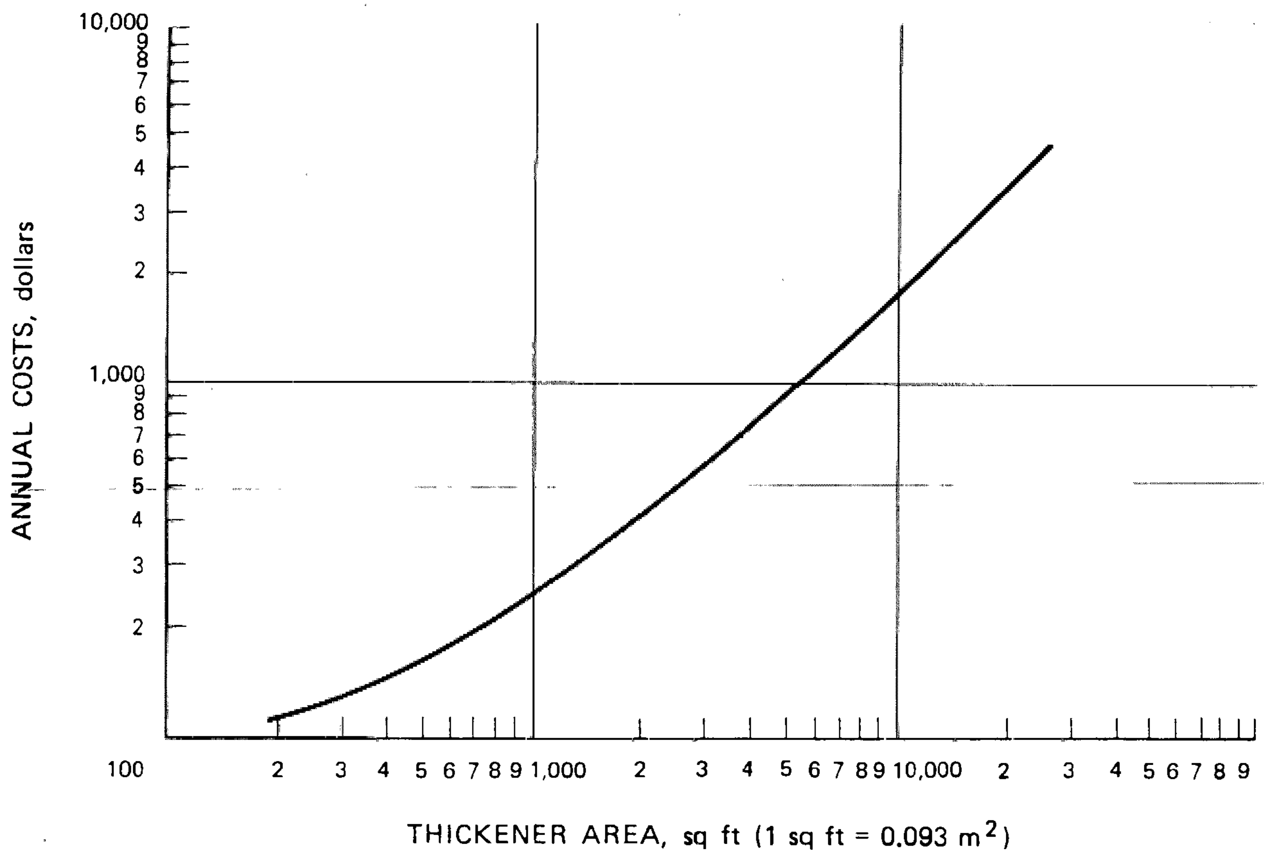


FIGURE 5-15

ESTIMATED JUNE 1975 MAINTENANCE MATERIAL COST FOR DAF THICKENERS (28)

One aspect that should be mentioned about centrifuge theory, because of its misapplication by the wastewater design profession, is the use of a Sigma factor to evaluate bids from different centrifuge manufacturers. First developed in 1952 (53), the Sigma concept is an established method developed to predict the sedimentation performance of centrifuges that are geometrically and hydrodynamically similar. It cannot, however, be used in engineering bid specifications to compare different units when the two basic assumptions, geometric and hydrodynamic similarity, are not valid. This is normally the case in scroll-type decanters.

5.5.3 System Design Considerations

5.5.3.1 Disc Nozzles

Disc nozzles were first used in the United States in 1937 (49). To date, approximately 90 machines have been installed at over

50 municipalities (37). Table 5-11 lists the advantages and disadvantages of a disc nozzle as compared to other thickening systems. Figure 5-16 shows a typical disc nozzle centrifuge.

TABLE 5-11

ADVANTAGES AND DISADVANTAGES OF DISC NOZZLE CENTRIFUGES

Advantages	Disadvantages
Yields highly clarified centrate without the use of chemicals	Can only be used on sludges with particle sizes of 400 μm or less
Has large liquid and solids handling capacity in a very small space	Requires extensive prescreening and grit removal
Produces little or no odor	Requires relatively high maintenance if pretreatment system is improperly designed
	Requires skilled maintenance personnel

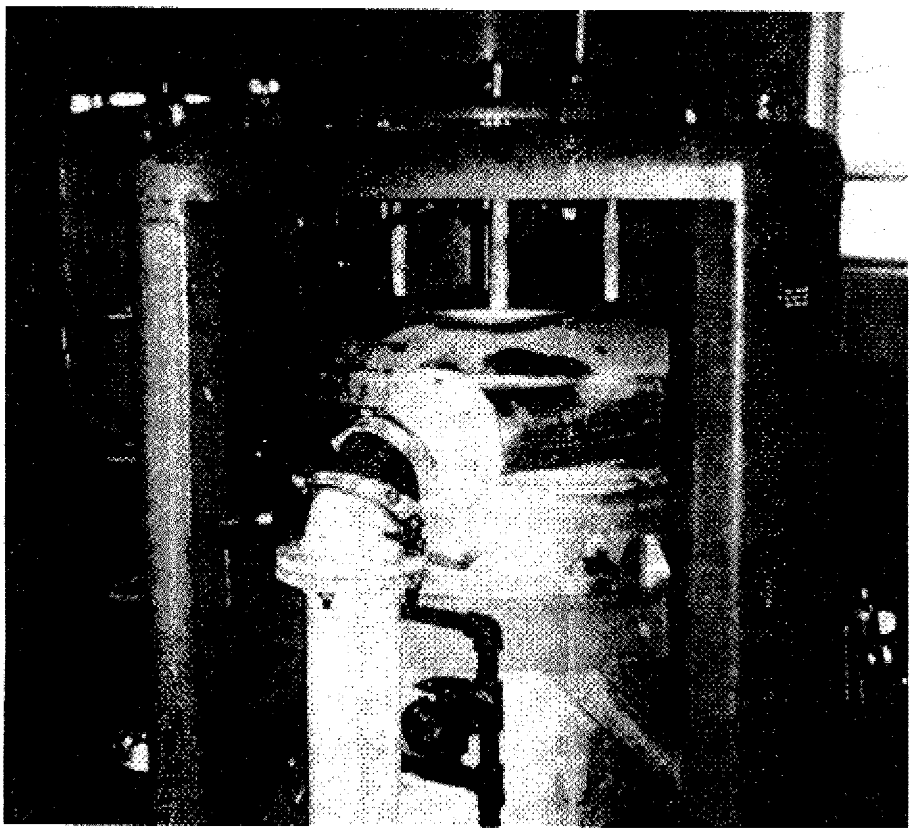


FIGURE 5-16

TYPICAL DISC NOZZLE CENTRIFUGE IN THE FIELD

Principles of Operation

Figure 5-17 features a cut away view of a disc nozzle centrifuge. The feed normally enters through the top (bottom feed is also possible) and passes down through a feedwell in the center of the rotor. An impeller within the rotor accelerates and distributes the feed slurry, filling the rotor interior. The heavier solids settle outward toward the circumference of the rotor under increasingly greater centrifugal force. The liquid and the lighter solids flow inward through the cone-shaped disc stack. These lighter particles are settled out on the underside of the discs, where they agglomerate, slide down the discs, and migrate out to the nozzle region. The gap of 0.050 inches (1.27 mm) between the discs means that the particles have a short distance to travel before settling on the disc surface. The clarified liquid passes on through the disc stack into the overflow chamber and is then discharged th[illegible] the effluent line.

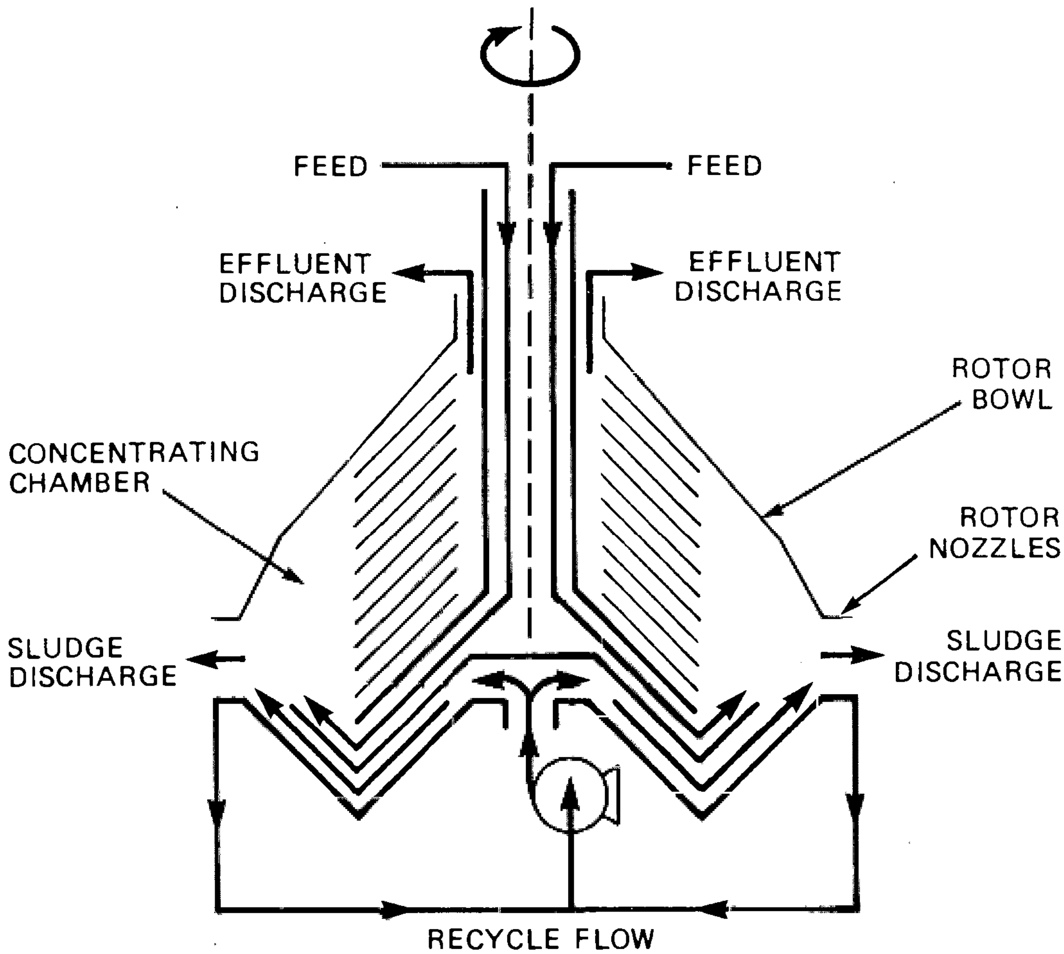


FIGURE 5-17

SCHEMATIC OF A DISC NOZZLE CENTRIFUGE

The centrifugal action causes the solids to concentrate as they settle outward. At the outer rim of the rotor bowl, the high energy imparted to the fluid forces the concentrated material through the rotor nozzles. One part of this concentrated sludge is drawn off as the thickened product and another is recycled back to the base of the rotor and pumped back into the concentrating chamber; there, it is subjected to additional centrifugal force and is further concentrated before it is once again discharged through the nozzles. This recirculation is advantageous because it increases the overall underflow concentration; minimizes particle accumulation inside the rotor by flushing action; allows the use of larger nozzles, thus decreasing the potential for nozzle plugging; and helps to achieve a stable separation equilibrium that lends itself to precise adjustment and control.

Application

Disc nozzle centrifuges can be applied only to sludges consisting of smaller particles (less than 400 m [54]) and void of fibrous material. In early installations, severe operating and maintenance problems occurred from pluggage (24,49,55,56). For wastewater treatment, then, only those systems that provide primary treatment and separate the primary sludge from the waste-activated sludge can be equipped with a disc nozzle centrifuge and only activated sludge can be thickened in this way. Even for those systems that keep the necessary separation, designers have frequently forgotten the amount of fibrous material that can be recycled back into the aeration system from a dirty anaerobic digester supernatant stream. This also eventually causes severe pluggage.

Pretreatment

To further reduce operation and maintenance requirements, current design recommendations provide for pretreatment of the disc nozzle feed stream. Figure 5-18 shows a disc nozzle pretreatment system.

Raw WAS is pumped to a strainer in order to remove large solids and fibrous material. Strainers should be made of stainless steel, should be self-cleaning, and should be easily accessible. Approximately one percent of the inlet flow will be rejected. The reject stream should go to the primary sludge handling system.

After screening, the flow goes to a degritter; however, even after aerated grit removal and primary treatment, some grit gets into the aeration basin. Under the velocities generated in a disc nozzle, this grit becomes abrasive and causes nozzle deterioration. The degritter does not eliminate the problem completely but it does increase the running time between nozzle replacements. Approximately 10 percent of the degritter inlet flow is rejected, and this rejected stream is usually combined with the screen flow.

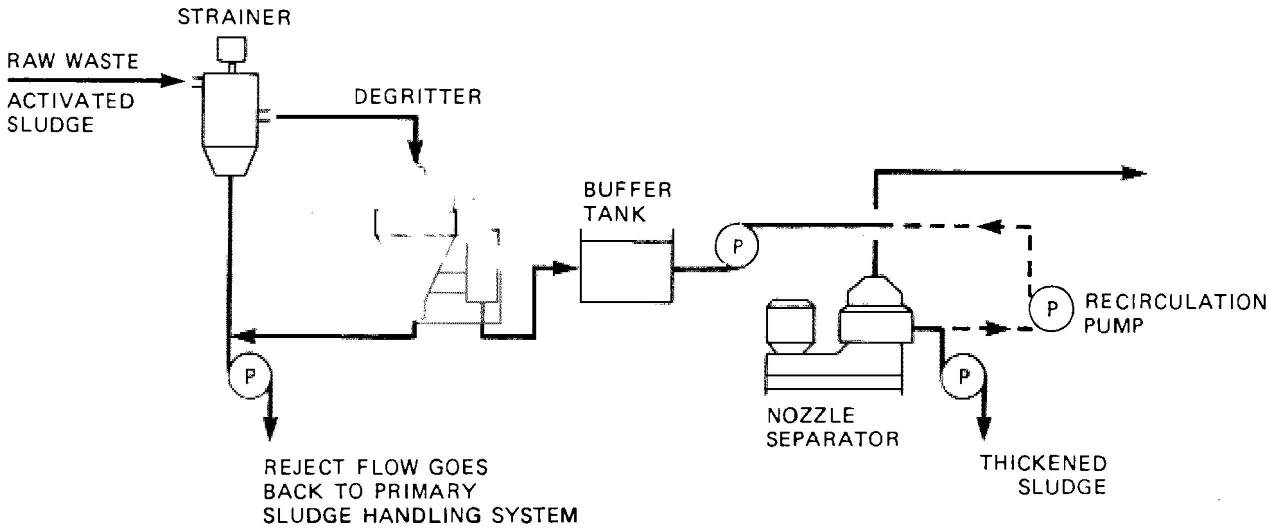


FIGURE 5-18

TYPICAL DISC NOZZLE PRETREATMENT SYSTEM

Performance

Table 5-12 lists typical performance that can be expected of disc nozzle centrifuges. In addition to the standard process variables, the disc nozzle machine variables considered are bowl diameter, bowl speed, operation of recycle, disc spacing, and nozzle configuration. Possibly the most important consideration, however, is the nature of the sludge. As with other centrifuge applications, an increasing sludge volume index (SVI) influences machine performance. Figure 5-19 shows the effect of SVI's on capture and thickening (57).

TABLE 5-12

TYPICAL PERFORMANCE OF DISC NOZZLE CENTRIFUGE

Ref	Capacity, gallons per minute	Feed solids, percent solids	Underflow solids, percent solids	Solids recovery, percent	Polymer, pounds per dry ton of solids
5	150	0.75-1.0	5-5.5	90+	None
5	400	?	4.0	80	None
5	50-80	0.7	5-7	93-87	None
5	60-270	0.7	6.1	97-80	None
24	66	1.5	6.5-7.5	87-97	None
60	200	0.75	5.0	90	None

1 gpm = 3.78 l/min
1 lb/ton = 0.5/kg/t

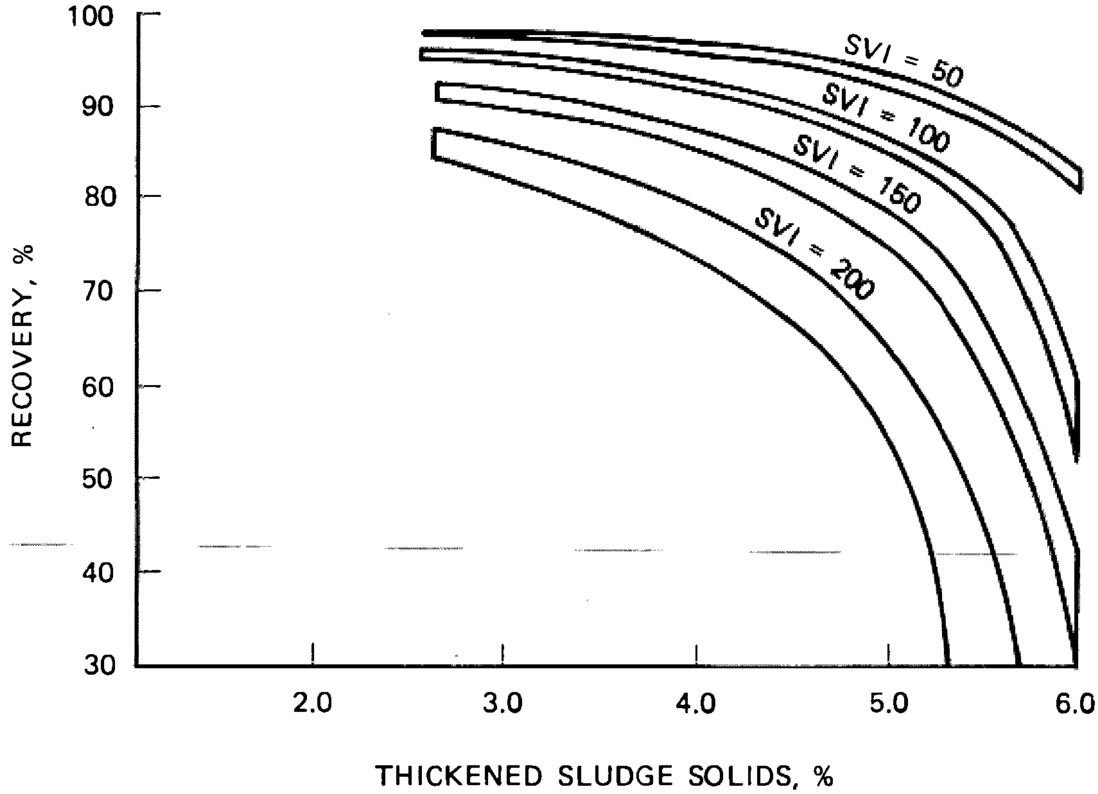


FIGURE 5-19

EFFECT OF ACTIVATED SLUDGE SETTLEABILITY ON CAPTURE AND THICKENING (57)

In general, it can be said of disc nozzle performance that the concentration of the thickened sludge tends to increase with increasing solids concentration in the inlet. Depending on inlet solids concentration, thickened sludge will be five to ten times more concentrated than the feed. The capability to concentrate will decrease as the inlet solids become more concentrated. Solids capture of 90 percent or better for the material fed into the disc nozzle (after screening and grit removal) should be obtainable without the use of polymers.

Other Considerations

As noted in the discussion of pretreatment requirements, approximately 11 percent of the flow to the disc nozzle system is rejected. The reject stream contains two to three percent solids and is usually pumped to the primary sludge handling system.

The centrate stream is normally returned to the aeration tank. This line should be designed to handle the entire flow being pumped to the pretreatment system.

Typically, equipment suppliers furnish disc nozzle systems complete, including all necessary pumps. The system must be assembled in the field.

5.5.3.2 Imperforate Basket

Imperforate basket centrifuges were first used in the U.S. in 1920, and to date, approximately 100 municipal installations (over 300 machines) have been installed (37). About one half are used for thickening. In fact, the largest centrifuge facility in the world, the Joint Water Pollution Plant of the County Sanitation Districts of Los Angeles County, California, utilizes 48 imperforate basket centrifuges. Table 5-13 lists the advantages and disadvantages of an imperforate basket centrifuge compared to other thickening systems.

TABLE 5-13

ADVANTAGES AND DISADVANTAGES OF IMPERFORATE BASKET CENTRIFUGE

Advantages	Disadvantages
Facility can be designed so that same machine can be used both for thickening and dewatering	Unit is not continuous feed and discharged
Is very flexible in meeting process requirements	Requires special structural support
Is not affected by grit	Has the highest ratio of capital cost to capacity
Of all the centrifuges, has the lowest operation and maintenance requirements	
Compared to gravity and DAF thickener installations, is clean looking and has little to no odor problems	
Is an excellent thickener for hard-to-handle sludges	

Principles of Operation

Figure 5-20 is a schematic of a top feed imperforate basket centrifuge illustrating general location of sludge inlet, polymer feed, and centrate piping and location of cake discharge.

The following describes one complete batch operating cycle of a basket centrifuge. When the "cycle start" button is pushed, the centrifuge begins to accelerate. After approximately 30 seconds, the feed pump is started through a timer relay. Depending on the feed pump rate, it will take one to three minutes for the bowl to reach operating speed. Sludge enters the unit through a stationary feed pipe mounted through the curb cap. This pipe extends to the bottom portion of the basket and ends at an angle just above the floor in order to impart a tangential velocity to the input stream. The duration of the feed time is controlled by either a pre-set timer or a centrate monitor that shuts the feed pump off when a certain level of suspended solids appears in the centrate. The centrate is normally returned to the inlet of the secondary treatment system.

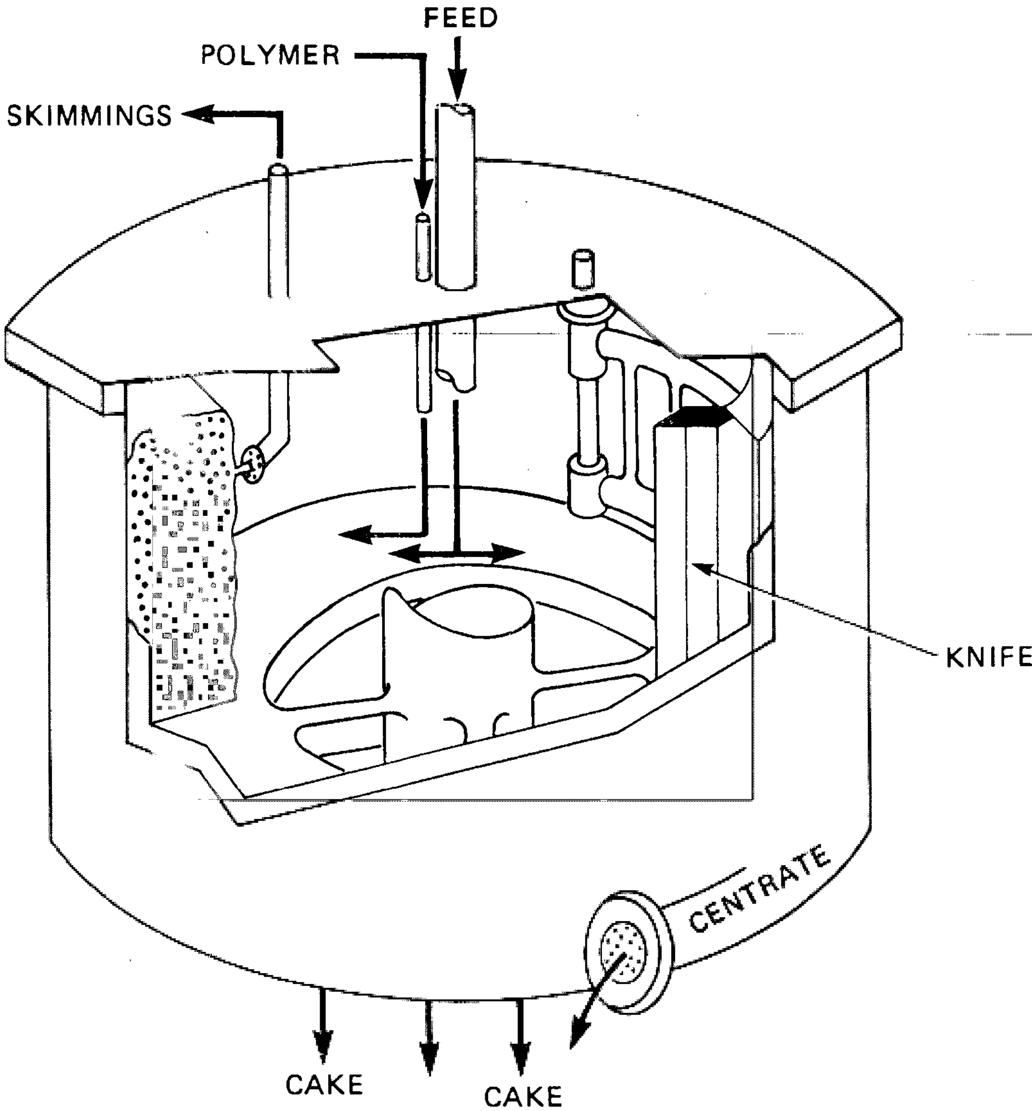


FIGURE 5-20

GENERAL SCHEMATIC OF IMPERFORATE BASKET CENTRIFUGE

Deterioration in the centrate indicates that the centrifuge bowl is filled with solids, and separation can no longer take place. At this point, the sludge feed pump is turned off.

Turning off or diverting the feed pump decelerates the centrifuge. When the centrifuge has decelerated to 70 rpm's, a plow (located by the center spindle shaft) is activated and starts to travel horizontally into the bowl where the solids have accumulated.

When the plow blade reaches the bowl wall, a dwell timer is activated to keep the plow in the same position for approximately 5 to 15 seconds until all the solids have been discharged. When the plow retracts, a cycle has been completed and the machine will automatically begin to accelerate, starting a new cycle.

Application

Basket centrifuge is a good application for small plants (under 1 to 2 MGD [44 to 88 l/sec]) pumping capacity. The appropriate plant would provide neither primary clarification nor grit removal (that is, extended aeration, aerated lagoons, contact stabilization), but would require:

- Thickening before aerobic or anaerobic digestion,
- Solids content of less than ten percent to minimize cost of hauling liquid sludge for land disposal, and
- A machine that can thicken sludge part of the time and dewater sludge part of the time.

Performance

Table 5-14 lists typical basket centrifuge performance on several types of sludges. Figure 5-21 shows the relative influence of one process variable as a function of feed solids content, holding all other process variables constant.

TABLE 5-14

TYPICAL THICKENING RESULTS USING IMPERFORATE BASKET CENTRIFUGE

Sludge type	Feed solids concentration, percent solids	Average cake solids concentration, percent solids	Polymer required, pounds dry per ton dry feed solids	Recovery based on centrate, percent
Raw waste-activated sludge	0.5-1.5	8-10	0	85-90
			1.0-3.0	90-95
Aerobically digested sludge	1-3	8-10	0	80-90
			1.0-3.0	90-95
Raw trickling filter sludge (rock & plastic media)	2-3	8-9	0	90-95
		9-11	1.5-3.0	95-97
Anaerobically digested sludge, primary and rock trickling filter sludge (70:30)	2-3	8-10	0	95-97
		7-9	1.5-3.0	94-97

1 lb/ton = 0.5 kg/t

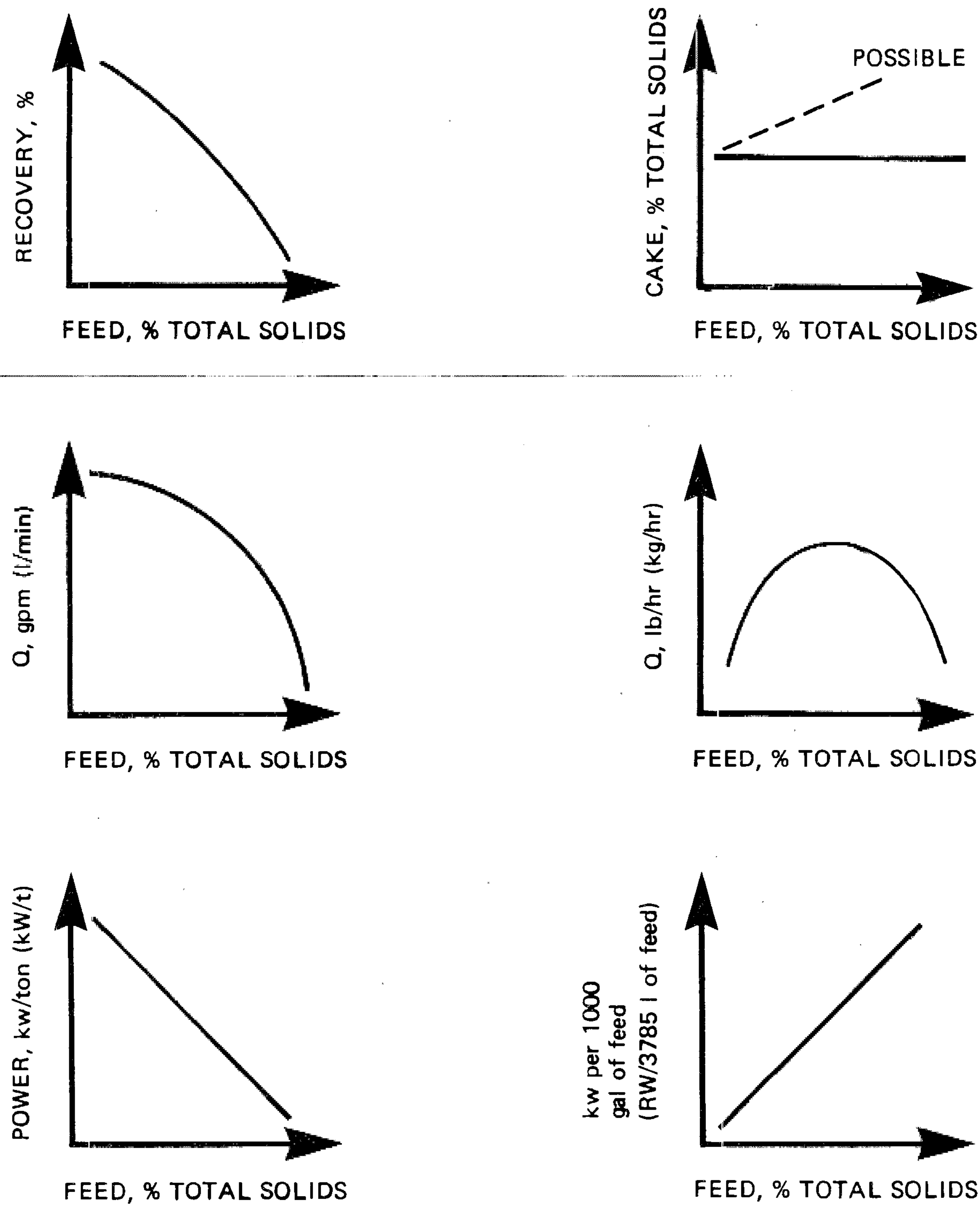


FIGURE 5-21

RELATIVE INFLUENCE OF ONE PROCESS VARIABLE AS A FUNCTION OF FEED SOLIDS CONTENT FOR IMPERFORATE BASKET CENTRIFUGE HOLDING ALL OTHER PROCESS VARIABLES CONSTANT

Other Considerations

In discussions of hydraulic flow rate, a distinction must be made between instantaneous feed rate and average feed rate. Instantaneous feed rate is the actual hydraulic pump rate to the basket. The average feed rate includes the period of time during a cycle when sludge is not being pumped to the basket (acceleration, deceleration, discharge). Therefore, dividing total gallons pumped per cycle by total cycle time gives the average feed rate.

Basket centrifuge performance is affected by the solids feed rate to the machine. As the solids concentration changes, the flow rate must be adjusted. Every effort should be made to minimize floc shear. For this reason, positive displacement cavity feed pumps with 4 to 1 speed variation are recommended.

Cake solids concentration can only be discussed as average solids concentration. The solids concentration in a basket centrifuge is maximum at the bowl wall and decreases toward the center. The solids concentration discharged will be the average for the mixture.

The centrate stream should be returned to the secondary system.

5.5.3.3 Solid Bowl Decanter

The first solid bowl decanter centrifuge in the U.S. to operate successfully on municipal wastewater sludge was installed in the mid-1930's (58). Since then there have been approximately 150 installations (over 400 machines) (37). Few of these units were used for thickening because the rotating scroll created disturbances in the thickening sludge, and the gravity force that had to be overcome in climbing the beach made it more difficult for the liquid thickened sludge to be discharged.

Technological advances have made solid bowl decanters for thickening waste-activated sludge available. Table 5-15 lists the current advantages and disadvantages of solid bowl decanter centrifuges in waste-activated sludge thickening.

Principles of Operation

Figure 5-22 is a schematic of a solid bowl decanter centrifuge. The sludge stream enters the bowl through a feed pipe mounted at one end of the centrifuge.

As soon as the sludge particles are exposed to the gravitational field, they start to settle out on the inner surface of the rotating bowl. The lighter liquid, or centrate, pools above the sludge layer and flows towards the centrate outlet ports located at the large end of the machine.

TABLE 5-15

ADVANTAGES AND DISADVANTAGES OF SOLID BOWL DECANTER CENTRIFUGES

Advantages	Disadvantages
Yields high throughput in a small area	Is potentially a high maintenance item
Is easy to install	May require polymers in order to operate successfully
Is quiet	Requires grit removal in feed stream
Causes no odor problems	Requires skilled maintenance personnel
Has low capital cost for installation	
Is a clean looking installation	
Has ability to constantly achieve four to six percent solids in the thickened sludge	

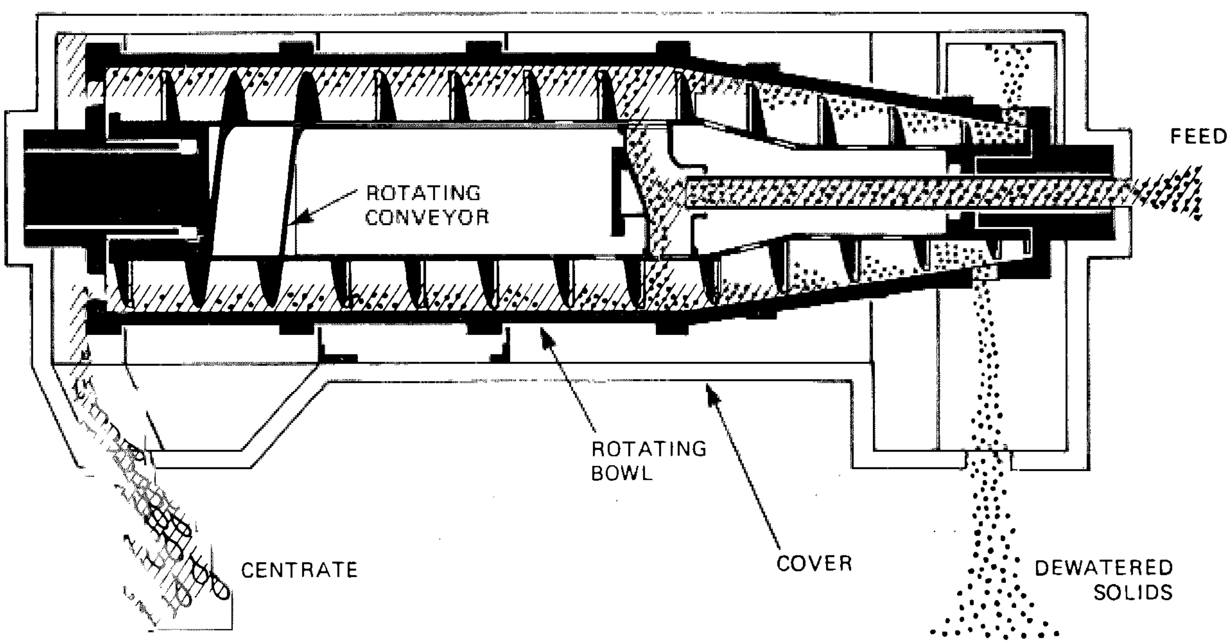


FIGURE 5-22

SCHEMATIC OF TYPICAL SOLID BOWL DECANTER CENTRIFUGE

The settled sludge on the inner surface of the rotating bowl is transported by the rotating conveyor towards the conical section (small end) of the bowl. In a decanter designed for dewatering, the sludge, having reached the conical section, is normally conveyed up an incline to the sludge outlet. Waste-activated sludge is too "slimy" to be conveyed upward without large doses of polyelectrolyte. In the newly designed machines, maximum pool depths are maintained; in addition, a specially designed baffle is located at the beginning of the conical section. This baffle, working in conjunction with the deep liquid pool, allows hydrostatic pressure to force the thickened sludge out of the machine independent of the rotating conveyor. This design eliminates the need for polymer addition to aid in conveying thickened sludge up the incline towards the sludge discharge and allows only the thickest cake at the bowl wall to be removed. Figure 5-23 shows a typical installation of a centrifuge designed for thickening.

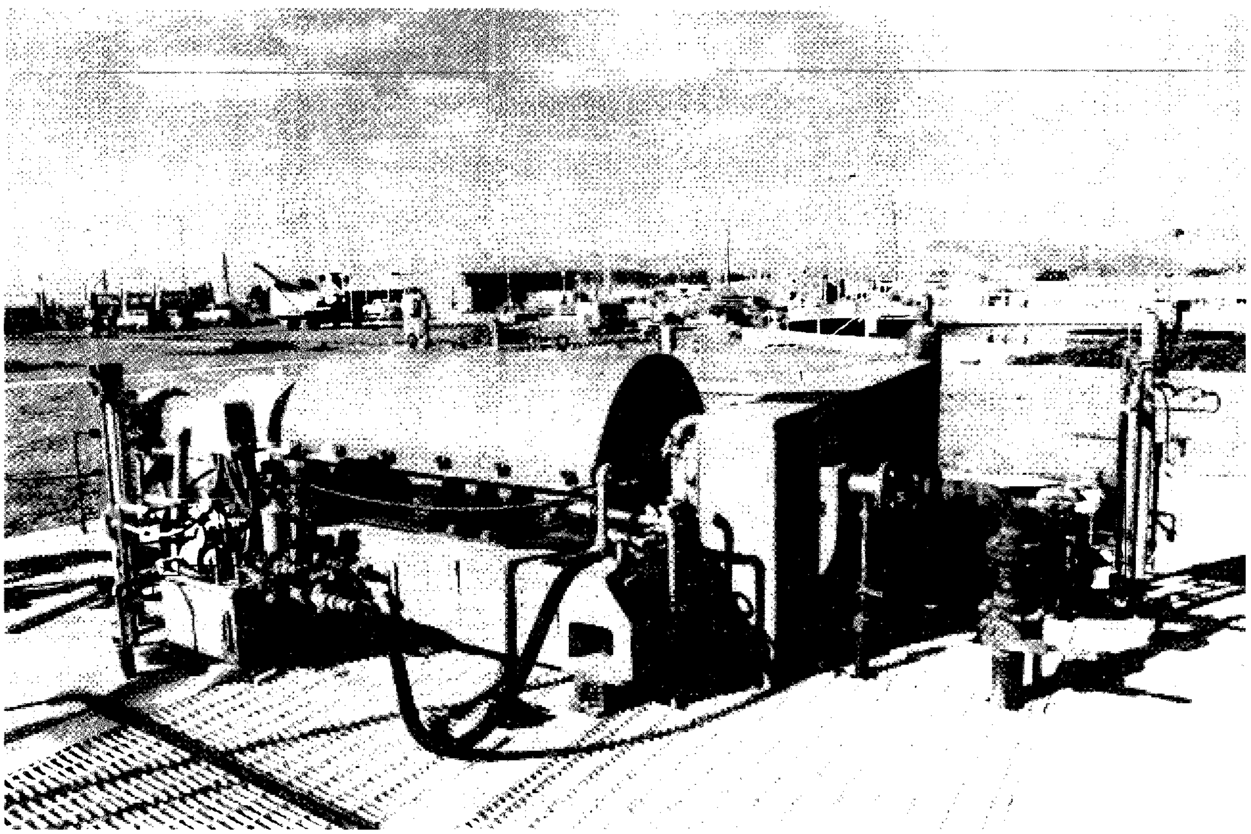


FIGURE 5-23

SOLID BOWL DECANTER CENTRIFUGE INSTALLATION

Application

Because of the specially designed baffle, the new type of thickening decanter centrifuge can be used to thicken only straight waste-activated or aerobically digested waste-activated sludge. A thickening-type decanter centrifuge cannot be used for primary or equivalent sludges, whereas the old style decanters without baffle can be used to thicken any sludge.

Performance

Operating data on the newly designed machines are very limited. Table 5-16 shows typical operating results supplied by one equipment manufacturer.

TABLE 5-16

TYPICAL CHARACTERISTICS OF THE NEW TYPE THICKENING DECANTER CENTRIFUGE ON WAS (63)

Parameter	Solid bowl conveyor
Operating method	Continuous
Bowl diameters, inches	14-40
Normal G range	1,400-2,100
WAS feed solids, percent	0.5-1.5
Thickened WAS solids, percent	5-8
Recovery, percent	85-95
Polymer range, lb/ton	0-6

1 inch = 2.54 cm
1 lb/ton = 0.5 kg/t

Other Considerations

Pumps should provide positive displacement and variable speed. There should be no rigid piping connections to the centrifuge.

Several points of polymer addition should be provided. This is necessary because of differences in polymer charge densities, effect of polymer reaction times with the sludge, and variances in sludge characteristics. Polymer can be added at the sludge feed line, just before either the junction of the feed pipe and the centrifuge or the inlet side of the sludge feed pump, or immediately downstream from the outlet side of the sludge feed pump.

There should be a moveable overhead hoist for removing and replacing the internal conveyor.

A washwater connection must be provided in the feed line to wash the decanter internally if the unit is to be shut down for more than several hours. It is important that the material not dry out within the machine, as it can cause a load imbalance.

5.5.4 Case History

The following is a summary of a three-year project in which a disc nozzle, imperforate basket and solid bowl decanter centrifuge were evaluated for their ability to thicken waste-activated sludge. The study was concluded at the Village Creek Plant, Fort Worth, Texas (59), where wastewater temperatures reach 86°F (30°C). The plant had been unable to gravity thicken waste-activated sludge over a maximum of 2.5 percent. In addition, sludge blanket turnovers and other process upsets proved troublesome. Use of polymers, dilution water, and mixing with primary sludge did not resolve the problems associated with gravity thickening waste-activated sludge.

After some pilot testing, two disc-nozzle centrifuges were installed to concentrate waste-activated sludge prior to anaerobic digestion, and an equipment testing program was undertaken on other centrifuges. An expansion from 45 to 96 MGD (2 to 4 m^3/s) was anticipated without an increase in the plant's existing digester capacity. This meant that sludge would have to be concentrated to at least five percent total solids.

Over a three-year period, the existing disc nozzle centrifuge system was redesigned and optimized and other centrifuges (imperforate basket and solid bowl decanter) were tested.

The test program at Village Creek graphically illustrated that the thickening characteristics of waste-activated sludges vary markedly depending on the design and operating criteria of the activated sludge process and on the storage conditions of the sludges. These variations can be reduced considerably by the use of polyelectrolyte conditioners. The effect of polyelectrolytes on unit process costs varies; the advisability of using them must be determined for each individual case.

Disc Nozzle

Testing was conducted on a 24-inch (61 cm) diameter unit, operating at 4,290 rpm and having a 0.07-inch (1.7 mm) nozzle opening. The optimum design for obtaining a five percent sludge and 90 percent recovery was at 200 gpm (12.62 l/sec) and 750 pounds per hour (340 kg/hr) of solids.

In operation, the nozzles on a disc-nozzle machine will plug up in minutes if prescreening is not provided. For activated sludge the screen must be chosen with care. Vibrating screens can become coated with grease and fiber. They may coat over even when provided with spray nozzles, or they may tear from abrasion. A rotating drum wedge wire screen with either 0.010-inch (0.25 mm) or 0.020-inch (0.51 mm) openings offered the best results. The rejects from this screen were about 5 to 15 percent of the feed solids. These rejects consisted of approximately 60 percent hexane extractables and 30 percent fiber.

Even with prescreening, the centrifuge nozzles eventually plug up, and performance deteriorates. An examination of the centrifuge after performance deterioration revealed that grease had built up and had begun to back up into the disc stack and interfere with clarification. The centrifuge then had to be disassembled and cleaned, about an eight-hour (16 man-hour) operation. With only drum screening, runs of about three days' duration were experienced, but when an in-line wedge-wire backup screen was installed, the runs were of seven to ten days duration.

Other installations have had success removing this grease in-line by periodically flushing the centrifuges with hot water introduced into the feed pipe; the run is thereby lengthened to more than thirty days.

In addition, the nozzles, their holders, and recycle tubes also underwent extreme wear. Erosion due to fine grit in the sludge (despite primary treatment) was ruining one nozzle or its holder about every three days until cyclone degritters were installed. These reduced the pressure to 100 gallons per minute (6.31 l/sec) at 45 psi (310 kN/m^2) and removed grit down to 75 mm. They also reduced wear, so that the nozzle had to be replaced only once every six months.

Imperforate Basket

Testing was conducted on a 40-inch (102-cm) diameter unit operating at 1,500 rpm. Polymer usage was not evaluated. The optimum design was for a six percent cake and 80 percent recovery at an average feed rate of 40 gpm (252 l/sec) and 150 pounds per hour (68 kg/ hr) of solids.

Solid Bowl Decanter

Testing was conducted and scaled up for a 2.5-inch (63.5-cm) diameter bowl unit. Polymer usage was not evaluated. The optimum design was for a 7.5 percent cake and 90 percent recovery at 150 gpm (9.46 l/sec) and 562 pounds per hour (255 kg/hr) of solids.

Analysis of Results

Since all three types of centrifuges were capable of producing, without polymer, cake solids content and solids capture considered adequate at Fort Worth, the issues of reliability and cost came into question. Cost is based on 73,300 pounds per day (33,275 kg/ day), the maximum expected solids to be generated over an entire month. This would require 20 basket, six horizontal scroll, and four disc nozzle centrifuges. The horizontal scroll and disc nozzle centrifuges would require cycloning grit removal equipment and the disc nozzle prescreening. Comparative capital and operation and maintenance costs are listed in Table 5-17. Estimated operating costs consist of power and additional head for cyclones. Maintenance costs were known from plant data for disc nozzle machines and other manufacturer's horizontal bowls and considered minimal for the basket. Cleaning costs were included for the disc nozzle.

TABLE 5-17

ESTIMATED CAPITAL AND O/M COST FOR VARIOUS CENTRIFUGES FOR THICKENING OF WASTE-ACTIVATED SLUDGE AT VILLAGE CREEK - FORT WORTH, TEXAS

	Dollars		
Item	Six solid bowl decanters	Five disc nozzle	Twenty imperforate basket
Capital cost[a]			
Centrifuges	900,000	600,000	1,400,000
Associated equipment	300,000	300,000	1,500,000
Annual cost			
20-yr life, 7 percent interest	113,280	84,960	179,360
Operating cost			
Maintenance parts	17,800	20,000	10,000
Manpower ($10/hr)	12,480	41,600	20,800
Electricity (1.75 cents/kWhr)	55,188	51,739	144,975
Total cost of thickening	180,948	198,299	325,135
Cost/ton of sludge processed	12.33	13.40	21.97

[a]Building, piping, and pumping to and from facility not included.

1 kWhr = 3.6 MJ

5.5.5 Cost

5.5.5.1 Capital Cost

Disc Nozzle Centrifuge

Capital cost data for disc nozzle systems are not readily available. In one study (59) the 1978 cost for five 200-gpm (12.62 l/sec) units with pretreatment equipment would be $900,000. This cost figure was restricted to equipment.

Basket Centrifuge

Capital cost curves for basket centrifuge installations are not available at this time. In June 1979, a typical top feed, 48-inch by 30-inch (122 cm by 76 cm) imperforate basket (the size most commonly used) with drive, electrical control panel, flexible connectors, necessary spare parts, air compressor, sludge feed pump, polymer feed system and start-up services was $160,000 to $170,000.

Solid Bowl Decanter Centrifuge

Figure 5-24 shows estimated June 1975 capital cost for a solid bowl decanter installation. The cost includes centrifuge equipment, pumps, hoist, electrical facilities, and building.

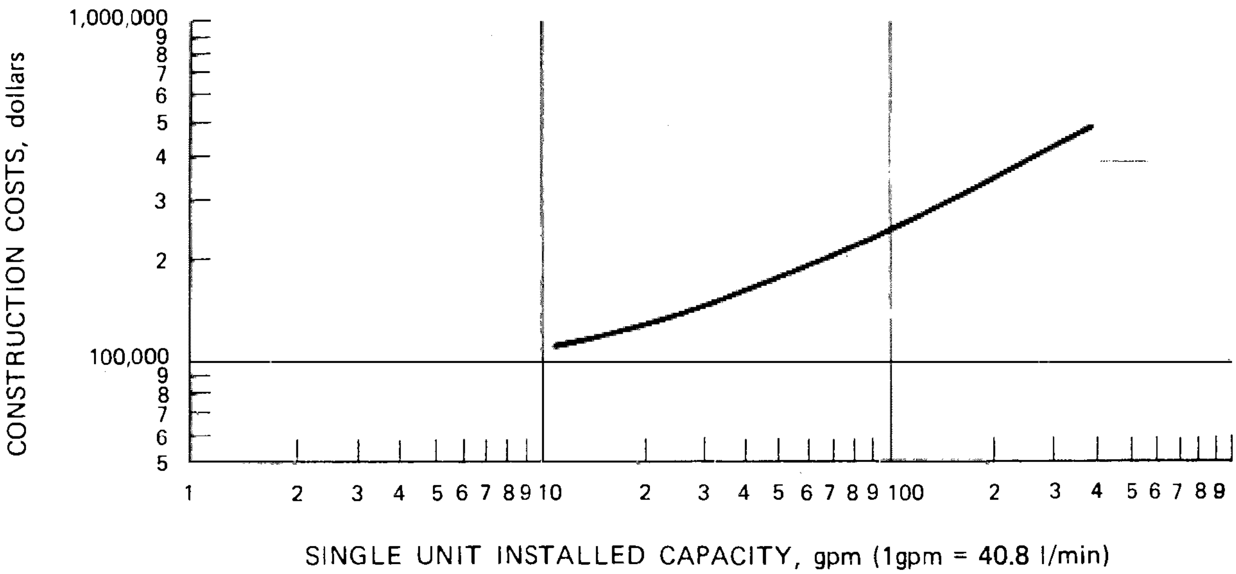


FIGURE 5-24

ESTIMATED JUNE 1975 SOLID BOWL DECANTER INSTALLATION CAPITAL COST (28)

5.5.5.2 Operating and Maintenance Cost

Disc Nozzle Centrifuge

Operating and maintenance cost data for disc nozzle systems are not readily available. In one study (59) the following 1978 costs were given for operating four 200-gpm (12.62 l/sec) units 24 hours per day:

- Maintenance parts - $20,000/year
- Manpower cost at $10/hr - $41,600
- Electricity at 1.75 cents/kWhr - $51,739

The following provides a rough guide for operating and maintenance requirements for a disc nozzle centrifuge:

- It is best to run a disc nozzle 24 hours per day to prevent shutdowns from materials that will dry out between stacked plates when machine is not operating.

- At least once every eight hours, each machine should be inspected for general machine operation, product, and amperage draw--1/2 man-hour per unit.

- At least once a week, each machine should be shut down to be given a thorough flushing, and nozzles should be removed and cleaned--two man-hours per unit.

- If grease is present in the system, the machine should be flushed with hot water at least once every other day--three man-hours per unit.

- Depending on sludge characteristics, the length of time before a machine has to be completely disassembled and cleaned is quite variable. A complete cleaning will take approximately 16 man-hours.

- Even with good pretreatment, nozzles, holders and recycle tubes will have to be replaced.

- Other parts that will need replacing are drive belts and pumps.

Imperforate Basket Centrifuge

For a well designed system, operation and maintenance for one 48-inch by 30-inch (122 cm x 76 cm) basket using a hydraulic drive can be approximated as follows:

- Normal start-up and shutdown - 0.5 man-hour.

- Observation time per eight-hour shift--1.0 man-hour.

- Basket oil change (1 quart SAE 10-40 motor oil [0.95 l] 10-40 motor oil) is required every 200 operating hours--0.5 man-hour.

- General machine lubrication is needed every 200 operating hours--0.5 man-hour.

- Air compressor should be serviced every 1,000 operating hours--1.0 man-hour.

- Hydraulic oil change (65 gallons [246 l]) is required every 3,500 operating hours or once per year--3.0 man-hours.

- High pressure oil filter should be changed every 1,000 operating hours--0.5 man-hour.
- If the machine is to be shut down for more than 24 hours, the basket should be cleaned with water (tap water pressure). This can be provided as an automatic or a manual operation--0.5 man-hour for manual operation.
- Basket bearings should be replaced every 100,000 operating hours--40 man-hours.
- Standard materials repair cost per 1,000 machine operating hours is $300 to $350 (June 1979).
- Specific power draw for this size basket centrifuge ranges from 1.1 to 1.3 horsepower per gallon per minute (13 to 15 kW/l/sec) flow rate.

Solid Bowl Decanter Centrifuge

Figure 5-25 indicates annual man-hour requirements for operation and maintenance. Included in the curve are labor requirements directly related to the centrifuge, sludge conditioning, and other associated equipment.

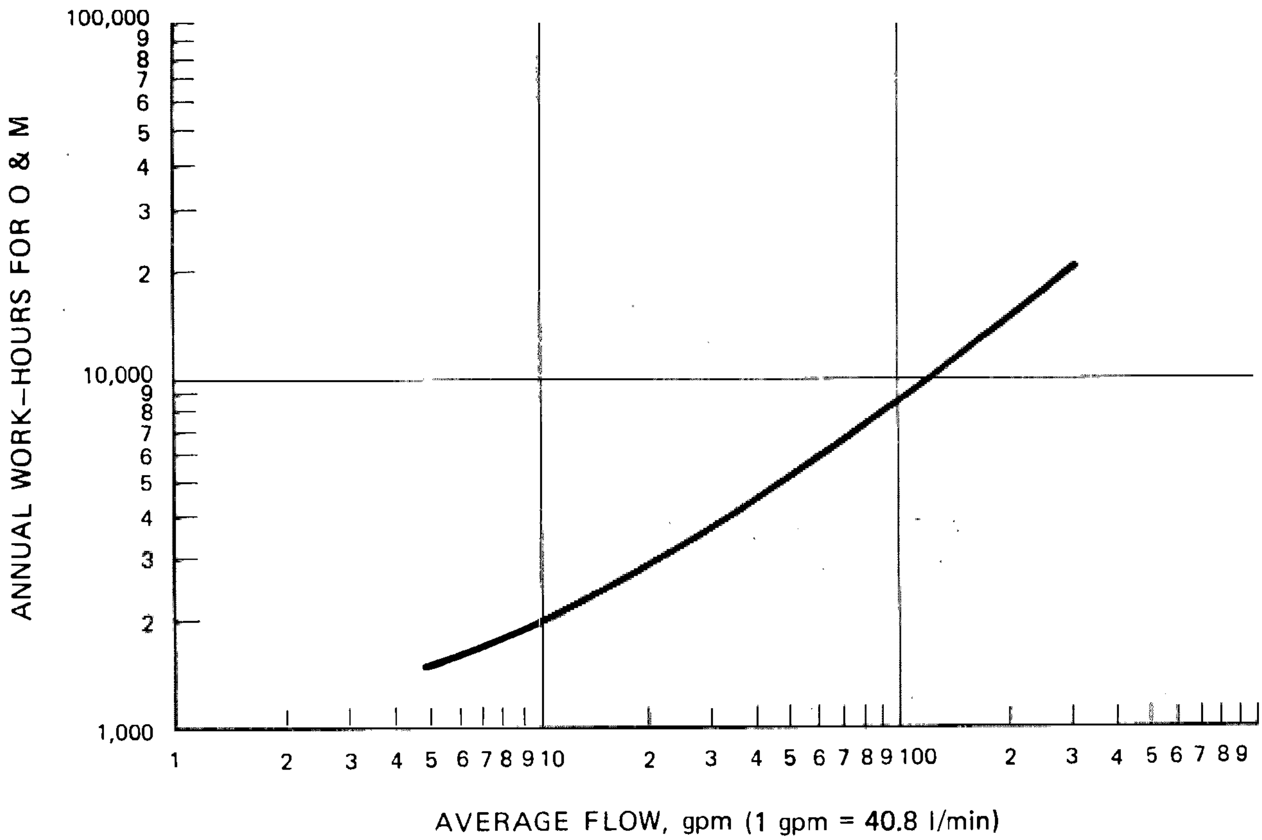


FIGURE 5-25
ANNUAL O&M REQUIREMENTS - SOLID BOWL DECANTER CENTRIFUGE (28)

Power

Power is dependent on machine design, but it should range from 0.28 to 0.37 horsepower per gallon per minute flow rate (3.3 to 4.4 kW/l/sec).

Maintenance Material Costs

Figure 5-26 shows a curve developed for estimating solid bowl decanter centrifuge maintenance material cost.

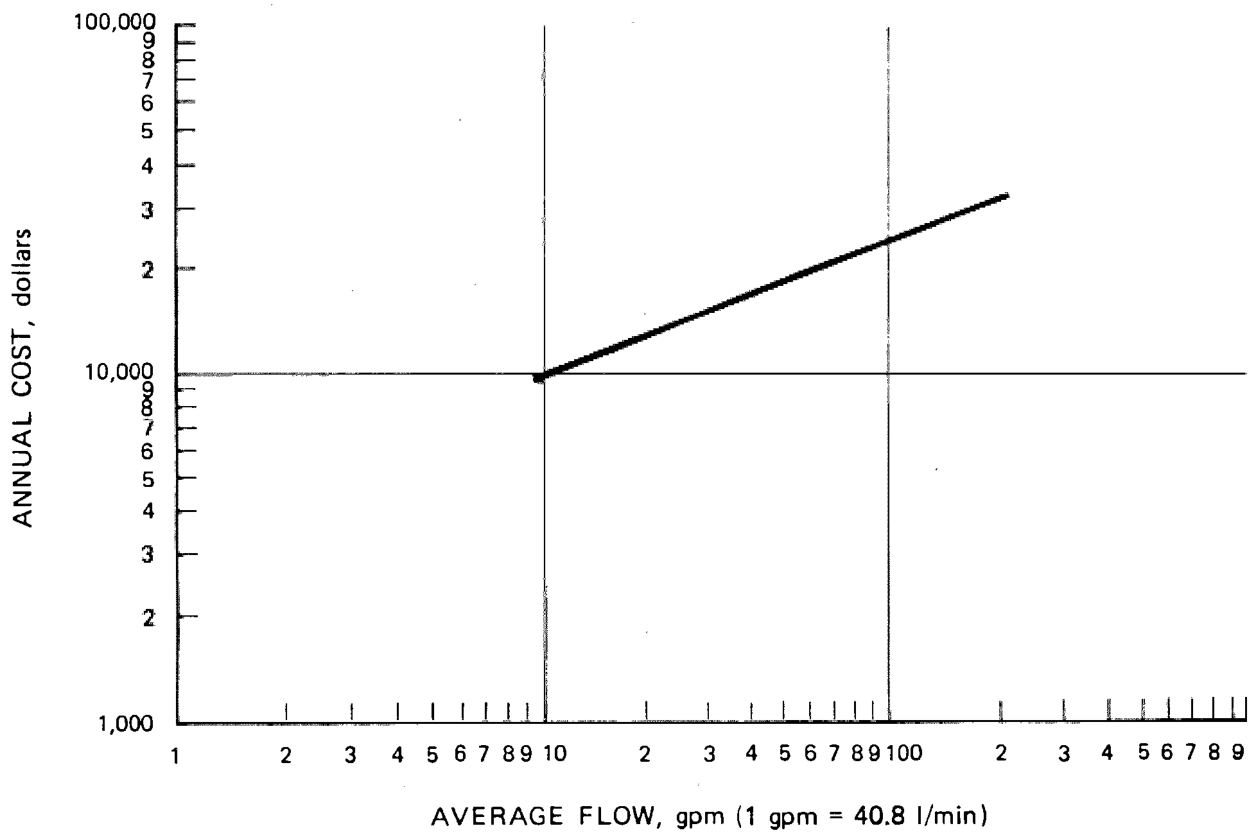


FIGURE 5-26

ESTIMATED JUNE 1975 MAINTENANCE MATERIAL COST FOR SOLID BOWL DECANTER CENTRIFUGE

5.6 Miscellaneous Thickening Methods

5.6.1 Elutriation Basin

Elutriation is a satisfactory process for washing and thickening digested primary sludges. Elutriation is also effective for mixtures of primary and biological sludges as long as a small dosage of flocculent is used to coflocculate the mixed sludges. This prevents excessive loss of fines in the overflow elutriate. (See Chapter 8 for further discussion.)

5.6.2 Secondary Anaerobic Digesters

Gravity thickening of biologically produced sludges in secondary anaerobic digesters does not work well as presently designed. Digesters should not be relied upon to function as gravity thickeners. They may, however, be used to generate more methane (five to ten percent) and to function as sludge holding tanks (only if equipped with floating-type covers). (See Chapter 6 for further discussion.)

5.6.3 Facultative Sludge Lagoons

Although sludge lagoons are out of favor with many designers, properly designed facultative sludge lagoons can provide an effective means for further concentrating anaerobically digested sludge (60). (See Chapter 15 for further discussion.)

5.6.4 Ultrafiltration

Thickening waste-activated sludge from one to six percent solids by ultrafiltration has been studied (61). Minimum estimated membrane area required to concentrate one ton (0.9 t) of waste-activated sludge per day from one to six percent solids was 260 square feet (23.4 m^2). High pressure drops of 25 to 75 psi (17 to 52 N/cm^2) had to be used. Power requirements were approximately 540 kWhr per ton (595 kWh/t) of dry feed solids.

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 6. Stabilization

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

September 1979

CHAPTER 6

STABILIZATION

6.1 Introduction

The principal purposes of stabilization are to make the treated sludge less odorous and putrescible and to reduce the pathogenic organism content. Some procedures used to accomplish these objectives can also result in other basic changes in the sludge. The selection of a certain method hinges primarily on the final disposal procedure planned. If the sludge is to be dewatered and incinerated, frequently no stabilization procedure is employed. Most stabilization methods, particularly anaerobic and aerobic digestion, result in a substantial decrease in the amount of suspended sludge solids. Hence, the corollary function of conversion is included in the description of these processes.

This chapter provides detailed discussion of four processes that have the primary function of sludge stabilization. These processes are anaerobic digestion, aerobic digestion, lime stabilization, and chlorine oxidation. Both anaerobic and aerobic digestion are currently increasing in popularity. The former is receiving revived attention from some cities and new attention from others for several reasons. The production of methane in anaerobic digestion is attractive in view of energy shortages, as is the suitability of anaerobically digested sludges to disposal on land. Also, it is being recognized that problems experienced previously with anaerobic digestion were actually due to other wastewater process considerations. Interest in aerobic digestion of excess activated sludge is growing because it has the potential for providing a good quality liquid process stream and can produce exothermic reaction conditions. A major impetus for processes such as anaerobic and aerobic digestion and lime treatment is the growing emphasis on utilization of sludge rather than mere disposal. Chlorine oxidation is of limited use for special situations or where septic tank wastes are involved.

Several other sludge treatment processes provide varying degrees of stabilization, although this is not their principal function. Composting is practiced in several United States cities and is being actively investigated for others. This process is considered important enough, with the emphasis on recycling of sludge to the land, that it alone is discussed in Chapter 12. Heat treatment, discussed in Chapter 8, has been installed in several new United States plants to improve sludge conditioning and dewatering economics. Some processes used to disinfect sludge, such as heat drying and pasteurization, also provide limited stabilization. These processes are discussed in Chapters 7 and 10.

Selection of the optimum stabilization method for any treatment and disposal system requires an in-depth understanding of the method and its limitations. The designer must recognize these limitations and accommodate them in the design of the subsequent processing and disposal steps.

6.2 Anaerobic Digestion

6.2.1 Process Description

Anaerobic digestion is the biological degradation of complex organic substances in the absence of free oxygen. During these reactions, energy is released and much of the organic matter is converted to methane, carbon dioxide, and water. Since little carbon and energy remain available to sustain further biological activity, the remaining solids are rendered stable.

6.2.1.1 History and Current Status

Anaerobic digestion is among the oldest forms of biological wastewater treatment. It was first used a century ago to reduce both the quantity and odor of sewage sludges. Originally, anaerobic digestion was carried out in the same tank as sedimentation, but the two-story tanks developed in England by Travis and in Germany by Imhoff began a trend toward separating the two processes. Separate sludge digestion tanks came into use in the first decades of this century. At first, these were little more than simple holding tanks, but they provided the opportunity to control environmental conditions during anaerobic digestion and, thereby, improve process performance. With the development of digester heating and, subsequently, mixing, anaerobic digestion became the most common method of stabilizing sludge.

As both industrial waste loads and the general degree of wastewater treatment increased, the sludges generated by treatment plants became more varied and complex. Digester systems failed because their design and operation were empirically developed under simpler conditions. As a result, anaerobic sludge digestion fell into disfavor. However, interest in anaerobic digestion of dilute wastes stimulated a new wave of research into the process. The resulting development of steady state models in the 1960s (1,2,3), dynamic models in the 1970s (4,5,6), and increasing research into the basic biochemical processes (7,8,9,10) led to significant improvements in both reliability and performance of anaerobic digesters.

Currently, sludge stabilization by anaerobic digestion is used extensively. A 1977 survey (11) of 98 municipal wastewater treatment plants in the United States found that 73 used anaerobic digestion to stabilize and reduce the volume of sludge. Because of emphasis on energy conservation and recovery and environmental pressure to use wasteewater sludges on land, it is expected that anaerobic digestion will continue to play a major role in municipal sludge processing.

6.2.1.2 Applicability

A wide variety of sludges from municipal wastewater treatment plants can be stabilized through anaerobic digestion. Table 6-1 lists some types of sludge that have been anaerobically digested in full-scale, high rate digesters.

TABLE 6-1

TYPE AND REFERENCE OF FULL-SCALE STUDIES ON HIGH RATE ANAEROBIC DIGESTION OF MUNICIPAL WASTEWATER SLUDGE (13,14,15,16-34)

	Reference	
Sludge type	Mesophilic digestion	Thermophilic digestion
Primary and lime	16, 17	-
Primary and ferric chloride	18	-
Primary and alum	19	-
Primary and trickling filter	20, 21	-
Primary, trickling filter, and alum	22	-
Primary and waste activated	23, 24, 25, 26	25, 27, 28, 29
Primary, waste activated, and lime	30, 31	-
Primary, waste activated, and alum	30, 32, 33	-
Primary, waste activated, and ferric chloride	30	-
Primary, waste activated, and sodium aluminate	32, 33	-
Waste activated only (pilot plant only)	13, 14, 15, 34	13, 14, 15

Solids-liquid separation of digested primary sludge is downgraded by even small additions of biological sludge, particularly activated sludge. Although mixtures of primary and biological sludge will break down readily under anaerobic conditions, the net rate of the reaction is slowed slightly (12). Experience with full-scale anaerobic digestion of straight activated sludge is limited, although laboratory (13,14) and pilot-scale studies (15) demonstrate that separate digestion of activated sludge is feasible.

Chemical sludges have been successfully digested anaerobically, although in several cases, volatile solids reduction and gas production were low, compared with conventional sewage sludges (35,36). Decreased performance appears to result from reduced biodegradability, rather than from toxic inhibition of the anaerobic microorganisms (35).

Anaerobic digestion is a feasible stabilizing method for wastewater sludges that have low concentrations of toxins and a volatile solids content above 50 percent. The obligate anaerobic microorganisms are sensitive and do not thrive under fluctuating operating conditions. Consequently, the process must be carefully considered for use at treatment plants where wide variations in sludge quantity and quality are common.

6.2.1.3 Advantages and Disadvantages

Anaerobic digestion offers several advantages over other methods of sludge stabilization; specifically, the process:

- Produces methane, a usable source of energy. In most cases, the process is a net energy producer, since the energy content of digester gas exceeds the energy demand for mixing and heating. Surplus methane is frequently used for heating buildings, running engines, or generating electricity (37,38,39). (Refer to Chapter 18.)

- Reduces total sludge mass through the conversion of organic matter to primarily methane, carbon dioxide, and water. Commonly, 25 to 45 percent of the raw sludge solids are destroyed during anaerobic digestion. This can substantially reduce the cost of sludge disposal.

- Yields a solids residue suitable for use as a soil conditioner. Anaerobically digested sludge contains nutrients and organic matter that can improve the fertility and texture of soils. Odor levels are greatly reduced by anaerobic digestion.

- Inactivates pathogens. Disease-producing organisms in sludge die off during the relatively long detention times used in anaerobic digestion. The high temperatures used in thermophilic digestion (122 to 140°F, 50 to 60°C) have an additional bactericidal effect. Pathogen reduction during anaerobic digestion is discussed in Chapter 7.

Principal disadvantages of anaerobic sludge digestion are that it:

- Has a high capital cost. Very large, closed digestion tanks are required, which must be fitted with systems for feeding, heating, and mixing the sludge.

- Is susceptible to upsets. Microorganisms involved in anaerobic decomposition are sensitive to small changes in their environment. Monitoring of performance and close process control are required to prevent upsets.

- Produces a poor quality sidestream. Supernatants from anaerobic digesters often have a high oxygen demand and high concentrations of nitrogen and suspended solids. Recycling of digester supernatant to the plant influent may upset the liquid process stream or produce a build-up of fine particles in the treatment plant. In plants that are required to remove nitrogen from the wastewater, the soluble nitrogen in the supernatant can cause problems and/or increased costs of treatment.

- Keeps methane-producing bacteria growth at a slow rate. Large reactors are required to hold the sludge for 15 to 30 days to stabilize the organic solids effectively. This slow growth rate also limits the speed with which the process can adjust to changes in waste loads, temperature, and other environmental conditions (40).

6.2.1.4 Microbiology

Anaerobic digestion involves several successive fermentations carried out by a mixed culture of microorganisms (7,10). This web of interactions compromises two general degradation phases: acid formation and methane production. Figure 6-1 shows, in simplified form, the reactions involved in anaerobic digestion.

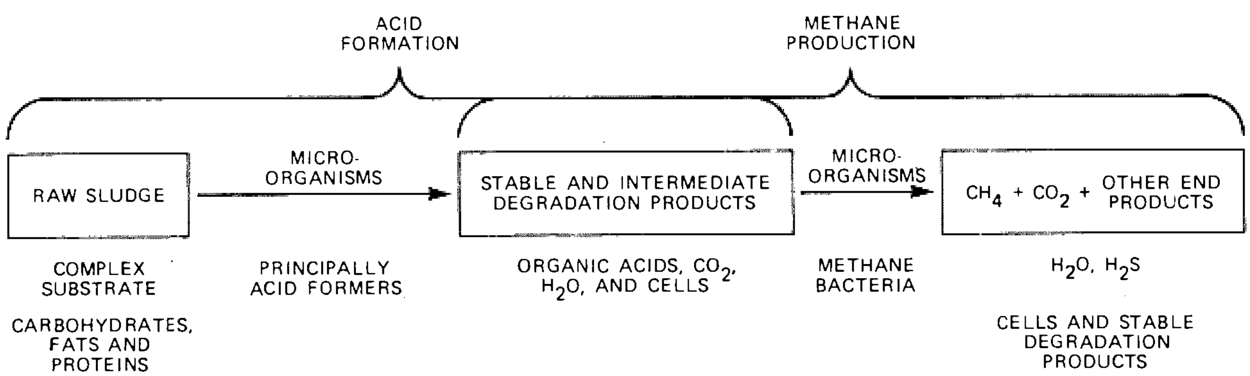


FIGURE 6-1

SUMMARY OF THE ANAEROBIC DIGESTION PROCESS

In the first phase of digestion, facultative bacteria convert complex organic substrates to short-chain organic acids--primarily acetic, propionic, and lactic acids. These volatile organic acids tend to reduce the pH, although alkaline buffering materials are also produced. Organic matter is converted into a form suitable for breakdown by the second group of bacteria.

In the second phase, strictly anaerobic bacteria (called methanogens), convert the volatile acids to methane (CH_4), carbon dioxide (CO_2), and other trace gases. There are several groups of methanogenic bacteria, each with specific substrate requirements, that work in concert to reduce complex wastes such as sewage sludge. Tracer studies indicate that there are two major pathways of methane formation:

- The cleavage of acetic acid to form methane and carbon dioxide.

  $$CH_3COOH \longrightarrow CH_4 + CO_2$$

- The reduction of carbon dioxide, by use of hydrogen gas or formate produced by other bacteria, to form methane.

  $$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$$

When an anaerobic digester is working properly, the two phases of degradation are in dynamic equilibrium; that is, the volatile organic acids are converted to methane at the same rate that they are formed from the more complex organic molecules. As a result, volatile acid levels are low in a working digester. However, methane formers are inherently slow-growing, with doubling times measured in days. In addition, methanogenic bacteria can be adversely affected by even small fluctuations in pH, substrate concentrations, and temperature. In contrast, the acid formers can function over a wide range of environmental conditions and have doubling times normally measured in hours. As a result, when an anaerobic digester is stressed by shock loads, temperature fluctuations, or an inhibitory material, methane bacteria activity begins to lag behind that of the acid formers. When this happens, organic acids cannot be converted to methane as rapidly as they form. Once the balance is upset, intermediate organic acids accumulate and the pH drops. As a result, the methanogens are further inhibited, and the process eventually fails unless corrective action is taken.

The anaerobic process is essentially controlled by the methane bacteria because of their slow growth rate and sensitivity to environmental change. Therefore, all successful designs must be based around the special limiting characteristics of these microorganisms.

6.2.2 Process Variations

Experimentation over the years has yielded four basic variations in anaerobic sludge digestion: low-rate digestion, high-rate digestion, anaerobic contact, and phase separation.

High-rate digestion is obviously an improvement over low-rate digestion, and its features have been incorporated into standard practice. The anaerobic contact process and phase separation, while offering some specific benefits, have not been used for sludge digestion in full-scale facilities.

6.2.2.1 Low-Rate Digestion

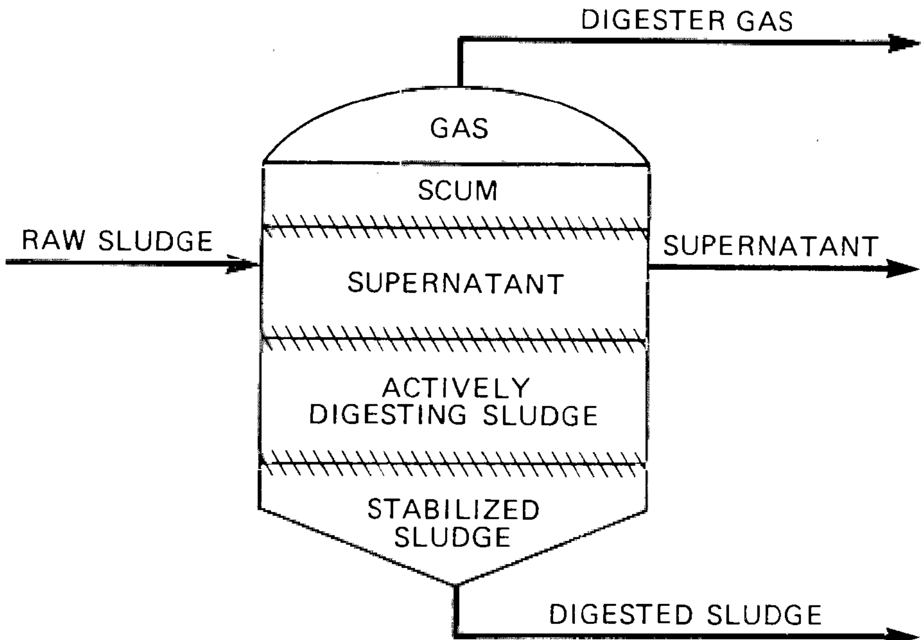
The simplest and oldest type of anaerobic sludge stabilization process is low-rate digestion. The basic features of this process layout are shown on Figure 6-2. Essentially, a low-rate digester is a large storage tank. With the possible exception of heating, no attempt is made to accelerate the process by controlling the environment. Raw sludge is fed into the tank intermittently. Bubbles of sludge gas are generated soon after sludge is fed to the digester, and their rise to the surface provides the only mixing. As a result, the contents of the tank stratify, forming three distinct zones: a floating layer of scum, a middle level of supernatant, and a lower zone of sludge. Essentially, all decomposition is restricted to the lower zone. Stabilized sludge, which accumulates and thickens at the bottom of the tank, is periodically drawn off from the center of the floor. Supernatant is removed from the side of the tank and recycled back to the treatment plant. Sludge gas collects above the liquid surface and is drawn off through the cover.

6.2.2.2 High-Rate Digestion

In the 1950s, research was directed toward improving anaerobic digestion. Various studies (24,41,42,43,44) documented the value of heating, auxiliary mixing, thickening the raw sludge, and uniform feeding. These four features, the essential elements of high-rate digestion, act together to create a steady and uniform environment, the best conditions for the biological process. The net result is that volume requirements are reduced and process stability is enhanced. Figure 6-3 shows the basic layout of this process.

<u>Heating</u>

The contents of a high-rate digester are heated and consistently maintained to within 1°F (0.6°C) of design temperature. Heating is beneficial because the rate of microbial growth and, therefore, the rate of digestion, increases with temperature. Anaerobic organisms, particularly methanogens, are easily inhibited by even small changes in temperature. Therefore, close control of the temperature in a digester helps maintain the microbial balance and improves the balance of the digestion process.



UNHEATED
UNMIXED
INTERMITTENT FEEDING AND WITHDRAWAL
DETENTION TIME: 30-60 DAYS
LOADING RATE: 0.03-0.10 lb VSS/cu ft/day
(0.4-1.6 kg VSS/m^3/day)

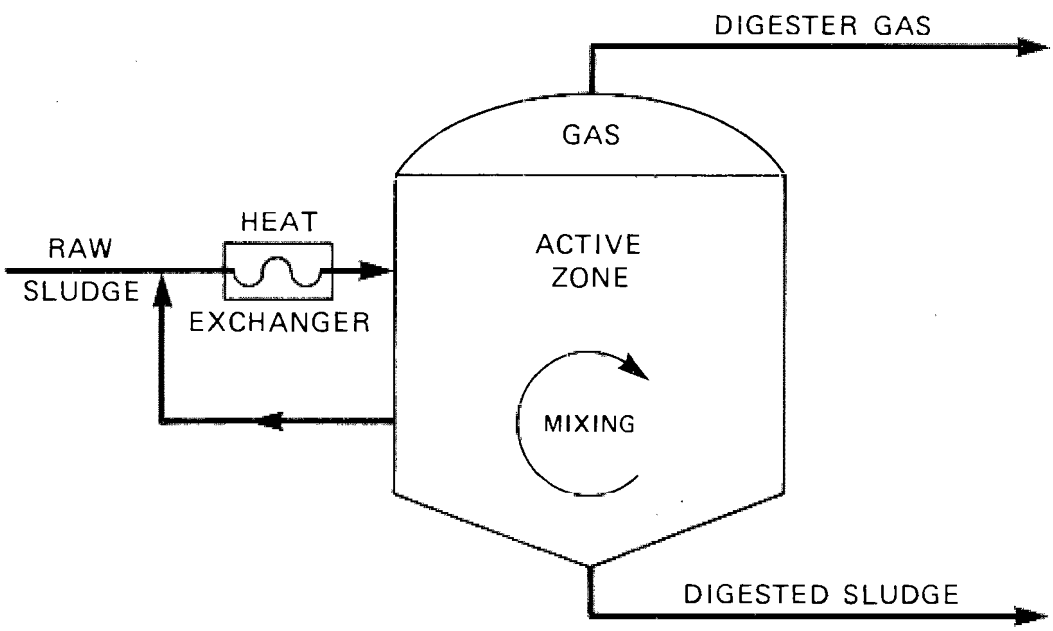
FIGURE 6-2

LOW-RATE ANAEROBIC DIGESTION SYSTEM

Methane production has been reported at temperatures ranging from 32°F to as high as 140°F (0 to 60°C). Most commonly, high-rate digesters are operated between 86 and 100°F (30 and 38°C). The organisms that grow in this temperature range are called mesophilic. Another group of microorganisms, the thermophilic bacteria, grow at temperatures between 122 and 140°F (50 and 60°C). Thermophilic anaerobic digestion has been studied since the 1930s, both at laboratory scale (13,45,46) and plant scale (27,28,29). This research was recently reviewed by Buhr and Andrews (47). In general, the advantages claimed for thermophilic over mesophilic digestion are: faster reaction rates that permit lower detention times, improved dewatering of the digested sludge, and increased destruction of pathogens.

Disadvantages of thermophilic digestion include their higher energy requirements for heating; lower quality supernatant, containing larger quantities of dissolved materials (29);

and poorer process stability. Thermophilic organisms are particularly sensitive to temperature fluctuation. More detailed information on the effects of temperature on digestion is included in Section 6.2.4. Design of digester heating systems is discussed in Section 6.2.6.2.



HEATED TO CONSTANT TEMPERATURE
MIXED
CONTINUOUS FEEDING AND WITHDRAWAL
DETENTION TIME: 10-15 DAY MINIMUM
LOADING RATE: 0.10-0.50 lb VSS/cu ft/day
(1.6-8.0 kg VSS/m^3/day)

FIGURE 6-3

SINGLE-STAGE, HIGH-RATE ANAEROBIC DIGESTION SYSTEM

Auxiliary Mixing

Sludge in high-rate digesters is mixed continuously to create a homogeneous environment throughout the reactor. When stratification is prevented, the entire digester is available for active decomposition, thereby increasing the effective detention time. Furthermore, mixing quickly brings the raw sludge into contact with the microorganisms and evenly distributes metabolic waste products and toxic substances. Methods of mixing and mixing system designs are described in Section 6.2.6.3.

Pre-thickening

The benefits of thickening raw sludge before digestion were first demonstrated by Torpey in the early 1950s (24). By gravity thickening a combination of primary and excess secondary sludge before digestion, he was able to achieve stabilization equivalent to digestion without thickening in one quarter of the digester volume. In addition, liquid that had previously been removed as digester supernatant was instead removed in the preceding thickener. Since thickener supernatant is of far better quality than digester supernatant, it had significantly less adverse impact when returned to the wastewater treatment stream. Also, heating requirements were considerably reduced by pre-thickening, since smaller volumes of raw sludge entered the digesters.

Later full-scale studies by Torpey and Melbinger (48) showed that thickening of digester feed sludge could be improved by recycling a portion of the digested sludge back to the gravity thickener. This variation of high-rate digestion, often called the Torpey process, is shown schematically on Figure 6-4. The results of Torpey and Melbinger's studies are summarized in Table 6-2. While the initial effect of recirculation was to improve thickening, further benefits were obtained. Improved thickening of the feed sludge increased the detention time (solids retention time) in the digesters and, thereby, enhanced solids reduction during digestion. The result was that the volume of sludge for final disposal was reduced by 43 percent. These results were obtained with the same overall plant treatment efficiencies and wastewater aeration requirements as had been achieved prior to the recycling of digested sludge.

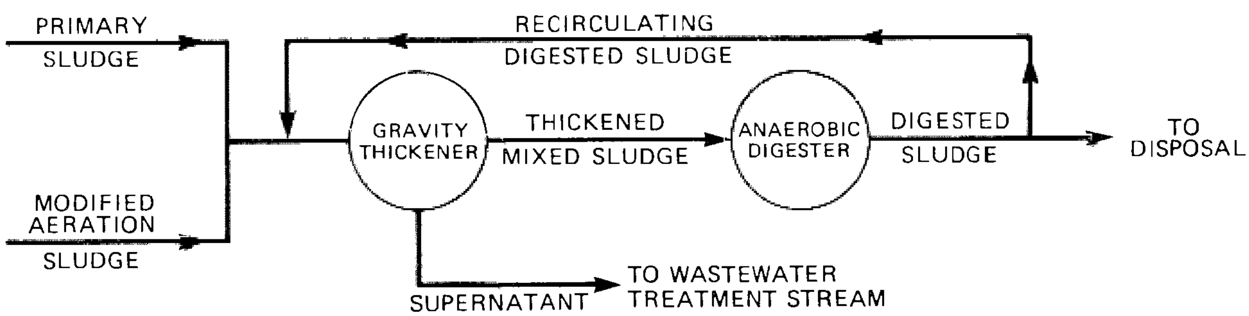


FIGURE 6-4

FLOW DIAGRAM FOR THE TORPEY PROCESS

There is, however, a point beyond which further thickening of feed sludge has a detrimental effect on digestion. Two problems can result from over-concentration of feed sludge.

1. Good mixing becomes difficult to maintain. The solids concentration in the digester affects the viscosity, which, in turn, affects mixing. Sawyer and Grumbling (49) experienced difficulty in mixing when the solids content in the digester exceeded six percent. Because of the reduction of volatile solids occurring during digestion, the solids concentration within the digester is less than the feed solids concentration. Therefore, feed solids concentrations may reach eight to nine percent before mixing is impaired.

2. Chemical concentrations can reach levels that can inhibit microbial activity. A highly thickened feed sludge means that the contents of the digester will be very concentrated. Compounds entering the digester, such as salts and heavy metals, and end products of digestion, such as volatile acids and ammonium salts, may reach concentrations toxic to the bacteria in the digester (50). For example, in one case, digester failure followed a three-month period during which feed solids concentrations ranged from 8.2 to 9.0 percent (51). It is believed that this caused ammonium alkaline products to reach toxic concentrations.

TABLE 6-2
RESULTS OF RECIRCULATING DIGESTED SLUDGE TO THE THICKENER AT BOWERY BAY PLANT, NEW YORK (48)

	Without recirculation[a]	With recirculation[b]
Raw sludge		
Dry weight, lb/day	108,000	101,500
Digester feed (includes recirculation)		
Dry weight, lb/day	108,000	144,300
Solids concentration, percent	8.2	9.9
Digested sludge to disposal		
Dry weight, lb/day	60,000	47,500
Solids concentration, percent	4.6	6.1
Volume, cu ft/day	20,700	12,300

[a]Averages for operation in 1961. Average treatment plant flow = 105 MGD.

[b]Averages for 15 months of operation with 33, 50, or 67 percent recirculation of digested sludge. Average treatment flow = 101 MGD.

1 lb/day = 0.454 kg/day
1 cu ft/day = 0.0283 m^3/day

Uniform Feeding

Feed is introduced into a high-rate digester at frequent intervals to help maintain constant conditions in the reactor.

In the past, many digesters were fed only once a day or even less frequently. These slug loadings placed an unnecessary stress on the biological system and destabilized the process. Although continuous feeding is ideal, it is acceptable to charge a digester intermittently, as long as this is done frequently (for example, every two hours). Methods of automating digester feeding are described in Section 6.2.6.5.

Two-Stage Digestion

Frequently, a high-rate digester is coupled in series with a second digestion tank (Figure 6-5). Traditionally, this secondary digester is similar in design to the primary digester, except that it is neither heated nor mixed. Its main function is to allow gravity concentration of digested sludge solids and decanting of supernatant liquor. This reduces the volume of the sludge requiring further processing and disposal. Very little solids reduction and gas production takes place in the second stage (23).

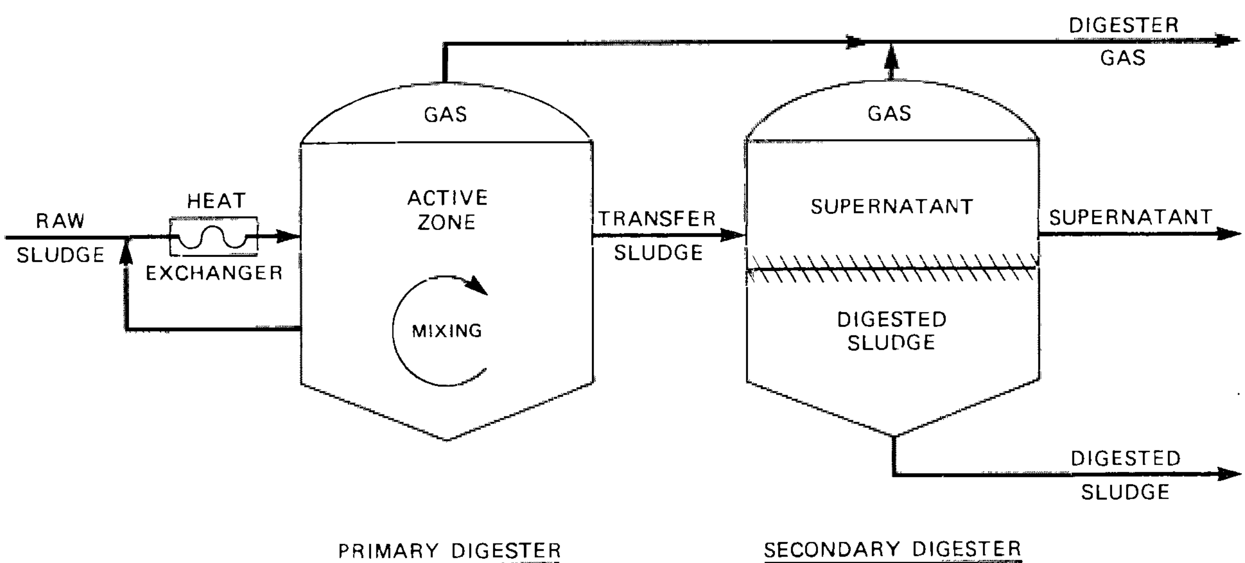


FIGURE 6-5

TWO-STAGE, HIGH-RATE ANAEROBIC DIGESTER SYSTEM

Unfortunately, many secondary digesters have performed poorly as thickeners, producing dilute sludge and a high strength supernatant. The basic cause of the problem is that, in most cases, anaerobically digested sludges do not settle readily. Basically, two factors contribute to this phenomenon (52).

1. Flotation of solids. The contents of the primary digestion tank may become supersaturated with digester gas. When this sludge is transferred into the secondary digestion tank, the gas will come out of solution, forming small bubbles. These bubbles attach to sludge particles and provide a buoyant force that hinders settling.

2. High proportion of fine-sized particles. Fine-sized solids are produced during digestion by both mixing (53) and the natural breakdown of particle size through biological decomposition (54). These fines settle poorly and enter the supernatant. The problem is compounded when secondary and tertiary sludges are fed into the digesters. The solids in these sludges have quite often been flocculated and, thus, are more easily broken up during digestion than primary sludge solids.

The return to the head of a plant of poor quality supernatant from two-stage digestion often has an adverse impact on the performance of other treatment processes. Supernatant commonly contains larger quantities of dissolved and suspended materials. (See Section 6.2.4.3 for a more detailed description of supernatant quality). For example, Figure 6-6 shows that at one secondary treatment plant, most of the carbon and nitrogen leaving the secondary digester was found in the supernatant and, consequently, was returned to the liquid process stream. The impact of high recycle loads on treatment at one midwestern plant is shown on Figure 6-7. When digester supernatant was recycled, solids built up in the plant, and the total amount of suspended solids in the final effluent increased by 22 percent.

Suggestions for improving liquid-solids separation in secondary digesters have included vacuum degassing (56), elutriation (57), and enlarging the secondary digester. However, in many cases, particularly when biological sludges are digested, it is better to eliminate the secondary digester altogether (52). Digested sludge is then taken directly to either a facultative sludge lagoon (see Chapter 15) or mechanical dewatering equipment (see Chapter 9). Since solids capture is better in the units, their sidestreams are of relatively high quality compared with supernatant from secondary digesters.

A secondary digester may successfully serve the following functions:

- Thickening digested primary sludge.

- Providing standby digester capacity. If the secondary digester is equipped with adequate heating, mixing, and intake piping.

- Storing digested sludge. A secondary digester fitted with a floating cover can provide storage for sludge.

- Assuring against short-circuiting of raw sludges through digestion. This may be important for odor control if digested sludge is transferred to open basins or lagoons (see Chapter 15). It also provides a margin of safety for pathogen reduction.

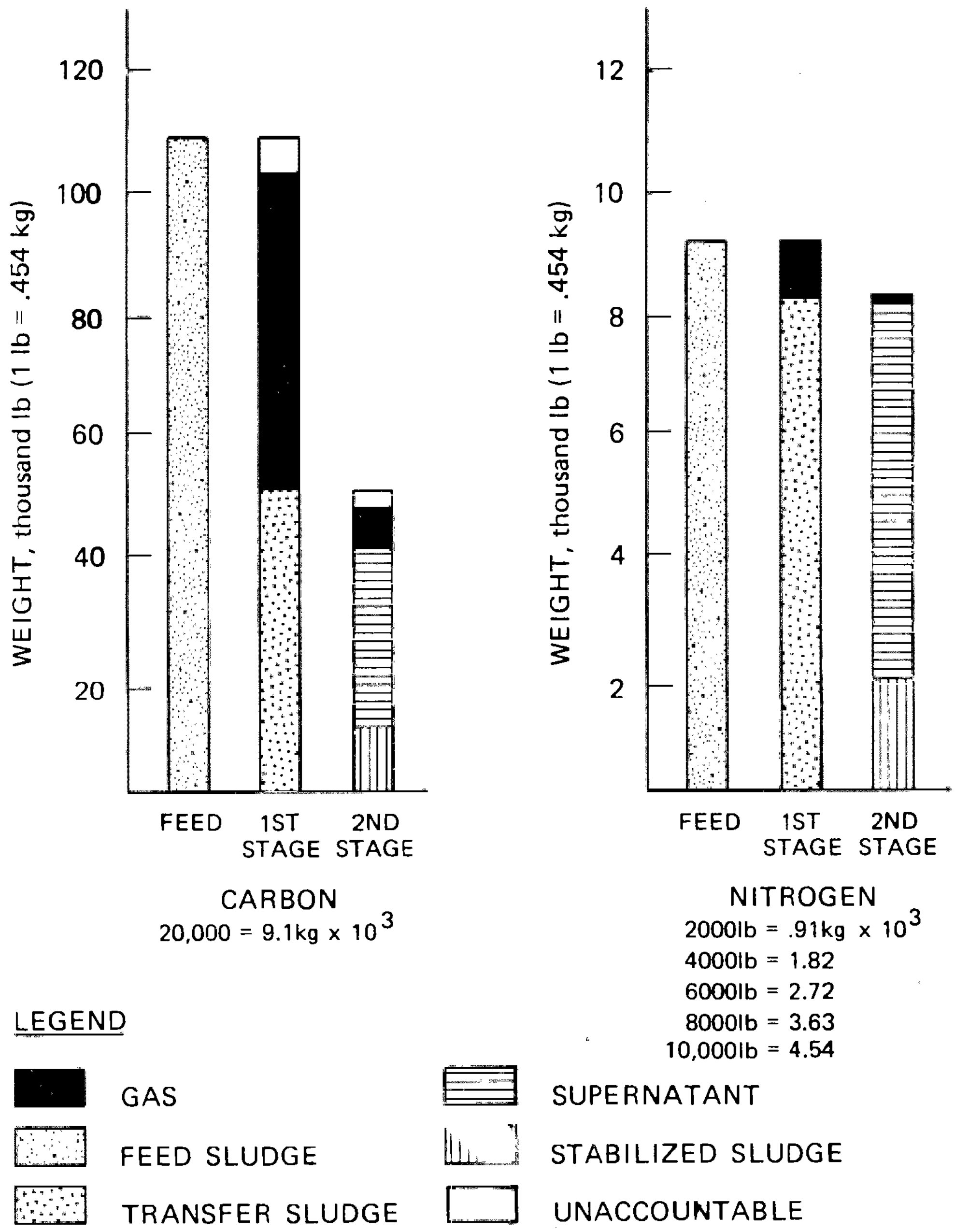
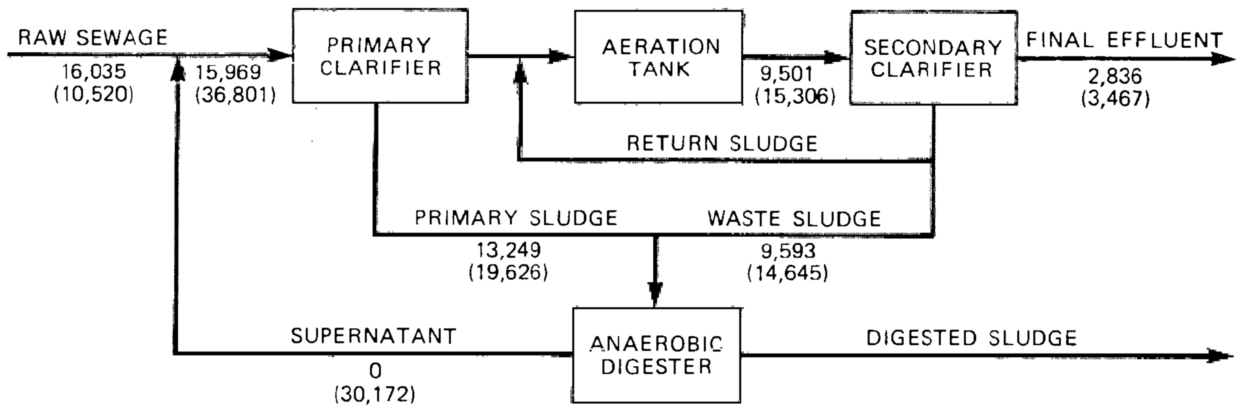


FIGURE 6-6

CARBON AND NITROGEN BALANCE FOR A TWO-STAGE, HIGH-RATE DIGESTION SYSTEM (23)



DATA IN PARENTHESES WERE OBTAINED WHEN UNTREATED SUPERNATANT WAS RETURNED TO THE HEAD OF THE PLANT. (AVERAGE OF THREE GRAB SAMPLES). DATA NOT IN PARENTHESES WERE OBTAINED WHEN NO SUPERNATANT WAS RECYCLED. (AVERAGE OF THIRTEEN GRAB SAMPLES). SOLIDS FLOWS DO NOT BALANCE BECAUSE OF GRAB SAMPLING. ALL VALUES EXPRESSED AS lb SS/day (1 lb day = 0.454 kg/day).

FIGURE 6-7

EFFECT OF RECYCLING DIGESTER SUPERNATANT ON THE SUSPENDED SOLIDS FLOW THROUGH AN ACTIVATED SLUDGE PLANT (55)

6.2.2.3 Anaerobic Contact Process

The anaerobic contact process is the anaerobic equivalent of the activated sludge process. As shown on Figure 6-8, the unique feature of this variation is that a portion of the active biomass leaving the digester is concentrated and then mixed with the raw sludge feed. This recycling allows for adequate cell retention to meet kinetic requirements while operating at a significantly reduced hydraulic detention time.

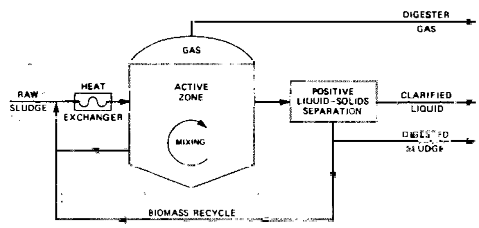


FIGURE 6-8

ANAEROBIC CONTACT PROCESS

Positive solids-liquid separation is essential to the operation of the anaerobic contact process. To gain any of the benefits from recycling, the return stream must be more concentrated than the contents of the digester. The difficulties in thickening anaerobically digested sludge have been discussed above. Vacuum degasifiers have been used in anaerobic contact systems to reduce the buoyancy effect of entrapped gas, thereby improving cell settling (56).

The anaerobic contact process has found application in the treatment of high strength industrial wastes (56,58,59), and it has been operated successfully at a laboratory scale to stabilize primary sludge (60). Nevertheless, this system configuration is rarely considered in municipal anaerobic sludge digestion because of the difficulty in achieving the necessary concentration within the return stream.

6.2.2.4 Phase Separation

As discussed in Section 6.2.1.4, anaerobic digestion involves two general phases: acid formation and methane production. In the three preceding anaerobic digestion processes, both phases take place in a single reactor. The potential benefits of dividing these two phases into separate tanks were discussed as early as 1958 (61).

Subsequent research (62,63) has shown that two-phase digestion is feasible for the treatment of sewage sludges. Figure 6-9 shows a schematic of this multi-stage system as conceived by Ghosh, and others (63).

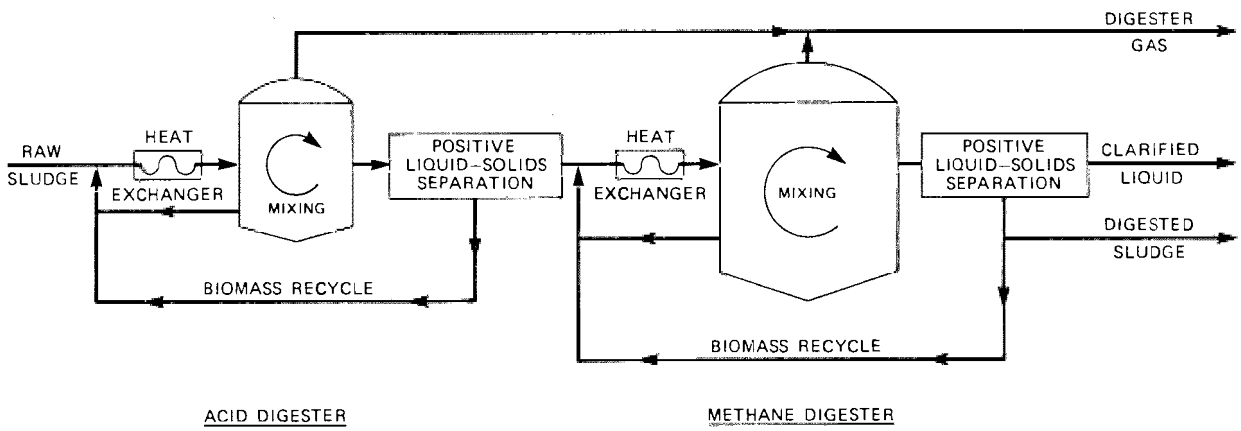


FIGURE 6-9

TWO-PHASE ANAEROBIC DIGESTION PROCESS

An effective means of separating the two phases is essential to the operation of anaerobic digestion in this mode. Possible separation techniques include dialysis (62), addition of chemical inhibitors, adjustment of the redox potential (64), and kinetic control by regulating the detention time and recycle ratio for each reactor (63). The latter approach is the most practical and has been developed into a patented process (U.S. Patent 4,022,665).

Operating data for a bench-scale system, summarized in Table 6-3, show the differences between the reactors in a two-phase system. The acid digester has a very short detention time (0.47 to 1.20 days), low pH (5.66 to 5.86), and produces negligible amounts of methane. Conditions in the methane digester are similar to those found in a conventional high-rate digester, which is operated to maintain the optimum environment for the methanogenic bacteria. The detention time listed in Table 6-3 for the methane digester (6.46 days) is significantly lower than the detention time in a conventional high-rate digester. However, this is probably because the two-phase system was operated in a bench-scale system rather than in a full-scale system where conditions are not ideal. The main advantage of a two-phase system is that it allows the creation of an optimum environment for the acid fermenters. As of 1979, a two-phase system has never been operated at a plant scale.

TABLE 6-3

OPERATING AND PERFORMANCE CHARACTERISTICS FOR THE BENCH-SCALE, TWO-PHASE ANAEROBIC DIGESTION OF WASTE ACTIVATED SLUDGE (63)

Parameter	Acid digester	Methane digester	Combined two-phase system
Temperature, °C	37	37	37
Detention time, day	0.47-1.20	6.46	6.86-7.66
Loading,			
lb VS/day/cu ft	1.54-2.67	0.18	0.20
pH	5.66-5.86	7.12	7.12
Ammonia nitrogen, mg/l	490-600	766	766
Average alkalinity, mg/l $CaCO_3$	790	4,127	4,127
Gas composition, mole percent			
CH_4	19-44	69.7	65.9
CO_2	73-33	29.0	32.3
N_2	8-23	1.3	1.8
Gas yield, standard cu ft/lb VS reduced	0.2-0.9	17.7	15.7
Methane yield, standard cu ft/lb VS reduced	0.1-0.3	11.9	10.7
VS reduction, percent	8.5-31.1	29.3	40.2
Effluent volatile acid, mg/l HAc	3,717	134	134

1 lb/day/cu ft = 16.0 kg/day/m^3
1 cu ft/lb = .0623 m^3/kg

6.2.3 Sizing of Anaerobic Digesters

Determination of digestion tank volume is a critical step in the design of an anaerobic digestion system. First, and most important, digester volume must be sufficient to prevent the process from failing under all expected conditions. Process failure is defined as the accumulation of volatile acids (volatile acids/alkalinity ratio greater than 0.5) and the cessation of methane production. Once a digester turns sour, it usually takes at least a month to return it to service. Meanwhile, raw sludge must be diverted to the remaining digesters, which may become overloaded in turn. Furthermore, sludge from a sour digester has a strong, noxious odor, and therefore, its storage and disposal are a great nuisance.

Digester capacity must also be large enough to ensure that raw sludge is adequately stabilized. "Sufficient stabilization" must be defined on a case-by-case basis, depending on the processing and disposal after digestion. In the past, digested sludge quality has been acceptable as long as the digester remained in a balanced condition and produced methane. However, higher levels of stabilization may be required after the 1970s because wastewater sludges increasingly are being applied to land and coming into closer contact with the public.

6.2.3.1 Loading Criteria

Traditionally, volume requirements for anaerobic digestion have been determined from empirical loading criteria. The oldest and simplest of these criteria is per capita volume allowance. Table 6-4 lists typical design values. This crude loading factor should be used only for initial sizing estimates, since it implicitly assumes a value for such important parameters as per capita waste load, solids removal efficiency in treatment, and digestibility of the sludge. These parameters vary widely from one area to the next and cannot accurately be lumped into one parameter.

A more direct loading criterion is the volatile solids loading rate, which specifies a certain reactor volume requirement for each unit of volatile dry solids in the sludge feed per unit of time. This criterion has been commonly used to size anaerobic digesters. However, as early as 1948, Rankin recognized that process performance is not always correlated with the volatile solids loading rate. The problem stems from the fact that this parameter is not directly tied to the fundamental component in anaerobic digestion, the microorganisms actually performing the stabilization.

6.2.3.2 Solids Retention Time

The most important consideration in sizing an anaerobic digester is that the bacteria must be given sufficient time to reproduce so that they can (1) replace cells lost with the withdrawn sludge, and (2) adjust their population size to follow fluctuations in organic loading.

In a completely mixed anaerobic digester, cells are evenly distributed throughout the tank. As a result, a portion of the bacterial population is removed with each withdrawal of digested sludge. To maintain the system in steady state, the rate of cell growth must at least match the rate at which cells are removed. Otherwise, the population of bacteria in the digester declines and the process eventually fails.

TABLE 6-4

TYPICAL DESIGN CRITERIA FOR SIZING MESOPHILIC ANAEROBIC SLUDGE DIGESTERS (65,66)

Parameter	Low-rate digestion	High-rate digestion
Volume criteria, cu ft/capita		
Primary sludge	2-3	1.3
Primary sludge + Trickling filter humus	4-5	2.7 - 3.3
Primary sludge + Activated sludge	4-6	2.7 - 4
Solids loading rate, lb VSS/day/cu ft	0.04-0.1	0.15 - 0.40
Solids retention time, days	30-60	10 - 20

1 cu ft/capita = .028 m^3/capita
1 lb/day/cu ft = 16.0 kg/day/m^3

To ensure that the process will not fail, then, it is critical to know the growth rate of the bacteria in the digester. It is not practical to measure directly the rate at which the anaerobic bacteria multiply. However, as these bacteria grow and reproduce, they metabolize the waste and produce end products. As a result, the bacterial growth rate can be determined by monitoring the rate at which substrate is reduced and end products are produced. Studies of these rates of change began in the late 1950s and have led to an understanding of digester process kinetics (9,10,67).

The key design parameter for anaerobic biological treatment is the biological solids retention time (SRT), which is the average time a unit of microbial mass is retained in the system (68). SRT can be operationally defined as the total solids mass in the treatment system divided by the quantity of solids withdrawn daily. In anaerobic digesters without recycle, the SRT is equivalent to the hydraulic detention time. Recycling of a concentrated stream back to the head of the system, which is the unique feature of the anaerobic contact process, increases the SRT relative to the hydraulic detention time.

Figure 6-10 illustrates the relationship between SRT and the performance of a lab-scale anaerobic digester fed with raw primary sludge. Specifically, the figure shows how the production of methane, as well as the reduction of degradable proteins, carbohydrates, lipids, chemical oxygen demand, and volatile solids, are related to the SRT. As the SRT is reduced, the concentration of each component in the effluent gradually increases until the SRT reaches a value beyond which the concentration rapidly increases. This breakpoint indicates the SRT at which washout of microorganisms begins--that is, the point where the rate at which the organisms leave the system exceeds their rate of reproduction. Figure 6-10 shows that the lipid-metabolizing bacteria have the slowest growth rate and, therefore, are the first to washout. As the SRT is shortened beyond the first breakpoint (occurring at an SRT between eight to ten days at 95°F [35°C]), more types of bacteria are washed out and performance is increasingly inhibited. The SRT can be lowered to a critical point (SRT_C) beyond which the process will fail completely. Calculations based on process kinetics predict an SRT_C of 4.2 days for the digestion of wastewater sludge at 95°F (35°C) (69), which corresponds with Torpey's pilot-scale study (70), in which anaerobic sludge digesters operating at 99°F (37°C) failed at an SRT of 2.6 days. Performance began deteriorating sharply as the SRT was reduced below five days.

Temperature has an important effect on bacterial growth rates and, accordingly, changes the relationship between SRT and digester performance. The effect of temperature on methane production and volatile solids reduction is shown on Figure 6-11. The significance of this relationship is that stabilization is slowed at lower temperatures, with 68°F (20°C) appearing to be the minimum temperature at which sludge stabilization can be accomplished within a practical solids retention time (69). The critical minimum solids retention time (SRT_C) is also affected by temperature. O'Rourke (69) found that the SRT_C for the digestion of a primary sewage sludge in a bench-scale digester was 4.2 days at 95°F (35°C), 7.0 days at 77°F (25°C), and 10.1 days at 50°F (10°C).

6.2.3.3 Recommended Sizing Procedure

The size of an anaerobic digester should be adequate to ensure that the solids retention time in the system never falls below a certain critical value. This design solids retention time

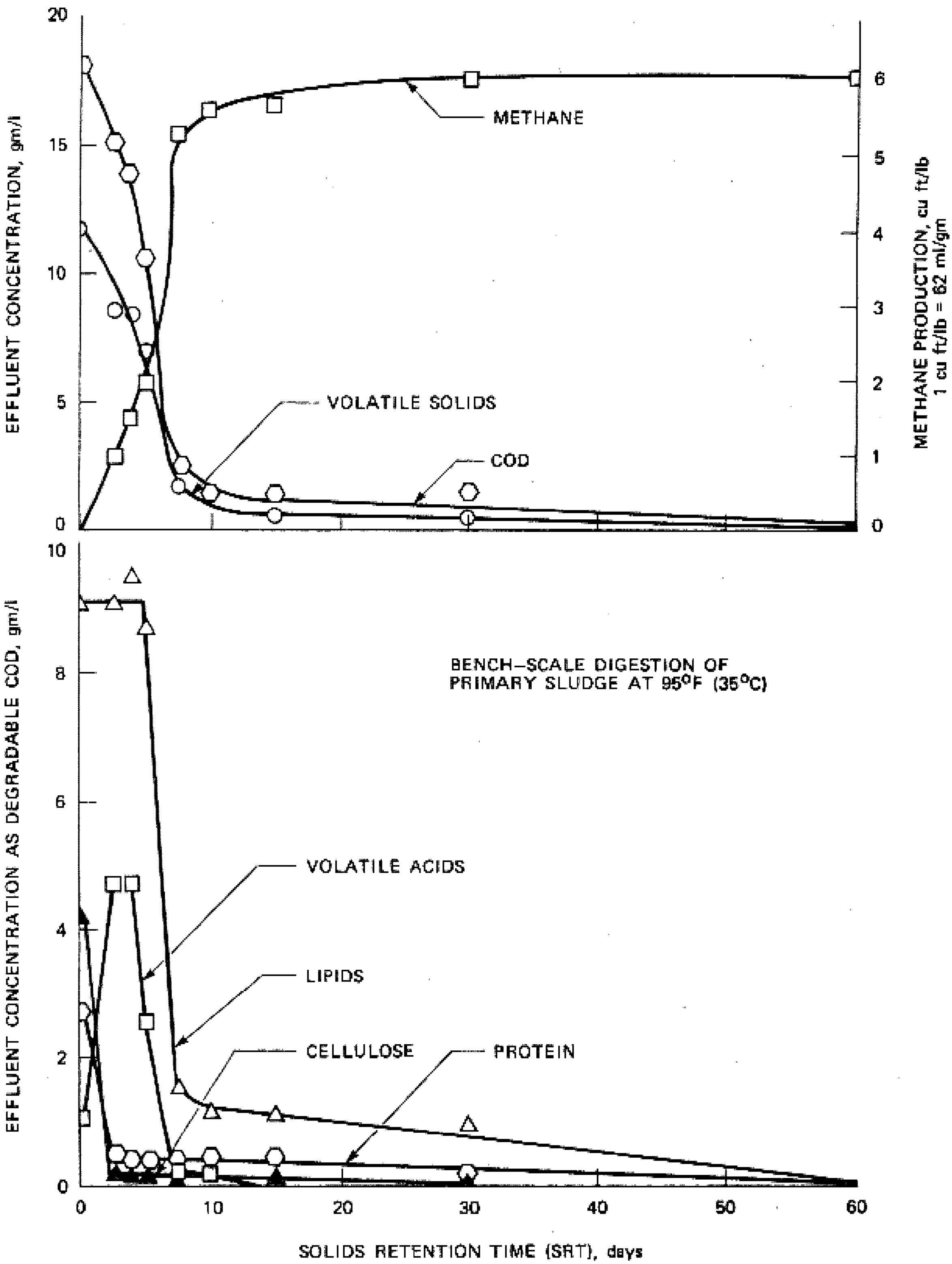


FIGURE 6-10

EFFECT OF SRT ON THE RELATIVE BREAKDOWN OF DEGRADABLE WASTE COMPONENTS AND METHANE PRODUCTION (69)

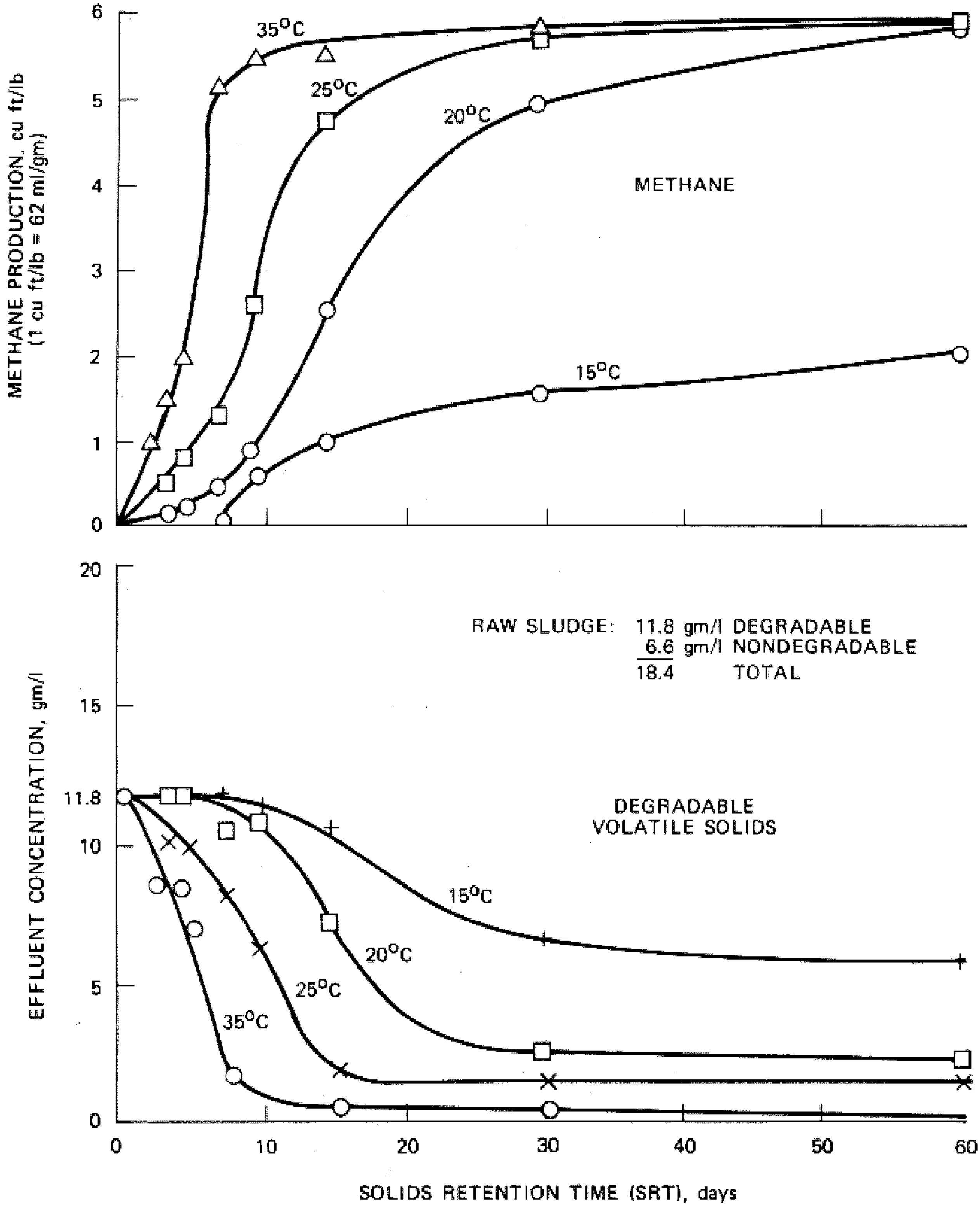


FIGURE 6-11

EFFECT OF TEMPERATURE AND SRT ON THE PATTERN OF METHANE PRODUCTION AND VOLATILE SOLIDS BREAKDOWN (69)

(SRT_d) and the conditions under which it must be met should be selected with care. A margin of safety must be provided, since SRT_c was determined on the basis of bench-scale digesters maintained at such ideal conditions as complete mixing, uniform feeding and withdrawal rates, and closely controlled digestion temperature. However, in a full-scale facility, the ideal condition of complete mixing is not achieved. Both the quantity and the chemical characteristics of the feed sludge vary over time, and sludge temperature may fluctuate. All these actual-system characteristics tend to slow the rate of the microbial digestion process. As a result, SRT_d must be considerably greater than SRT_c. McCarty (71) recommends a minimum safety factor of 2.5.

Several researchers (43,49,57,72,73,74,75) have recommended ten days as a minimum acceptable solids retention time for high-rate digesters operating near 95°F (35°C). (Values for systems operated at other temperatures are shown in Table 6-5.) This sizing criterion is reasonable, since it corresponds with the replication time of the slowest growing bacteria. However, this criterion must be met under all expected conditions, including:

- Peak hydraulic loading. This value should be estimated by combining poor thickener performance with the maximum plant loading expected during seven continuous days during the design period.

- Maximum grit and scum accumulations. Considerable amounts of grit and scum may accumulate before a digester is cleaned. This reduces the active volume of the tank.

- Liquid level below highest level. Several feet of liquid level variability (two to three, usually) must be retained to allow for differences in the rate of feeding and withdrawal and to provide reasonable operational flexibility.

These conditions may very well occur simultaneously and, therefore, the designer should compound them when applying the ten-day SRT_d sizing criterion. In the past, "liberal" detention time criteria have been applied at the average conditions. However, problems arise during critical periods, not when conditions are average. For this reason, the most rational approach to sizing a full-scale facility is to apply experimentally based design criteria (increased by a reasonable margin of safety) to the actual set of expected peak conditions. (An example is included in Section 6.2.9.3).

6.2.4 Process Performance

The primary result of anaerobic sludge digestion is the reduction of both volatile solids and pathogenic organisms. Volatile solids are degraded into smaller molecules, and eventually a large portion are converted into gas, primarily methane (CH_4) and carbon dioxide (CO_2). Pathogens are reduced through natural die-off because the anaerobic environment is unsuitable for their survival. (Refer to Chapter 7). Many other chemical and physical changes occur during anaerobic sludge digestion, some of which are described later in this section.

TABLE 6-5

SOLIDS RETENTION TIME DESIGN CRITERIA FOR HIGH RATE DIGESTION (71)

Operating temperature, °F	Solids retention time, days	
	Minimum (SRT_c)	Suggested for design (SRT_d)
65	11	28
75	8	20
85	6	14
95	4	10
105	4	10

It is not possible to predict precisely the nature and extent of all changes occurring during anaerobic digestion. Wastewater sludges have a complex, variable character and there are many reactions that occur during digestion within the mixed culture of anaerobic microorganisms. This section describes general trends of digester performance and identifies the major influences on anaerobic digestion.

To provide an overview of anaerobic digester performance, operating data for a full-scale digestion facility are shown in Tables 6-6 and 6-7. These data are for a two-stage, high-rate digester system in which only the primary digester was heated and mixed (23). The second tank provided a quiescent zone for the gravity separation of digested solids from supernatant liquor. Operating temperature in the first stage was maintained at 94°F (34°C), and detention time in each tank was 39 days. Feed sludge consisted of approximately equal amounts of primary sludge and waste-activated sludge.

Essentially, all stabilization occurred in the primary digester. In this first stage, 57 percent of the volatile solids were converted to liquid or gas. Only 2.8 percent of the volatile solids in the raw sludge were reduced in the secondary digester. A similar pattern of performance is shown in Table 6-7 for carbohydrate, lipid, and protein reduction. While data indicate that fixed solids also decreased during digestion, this is a little understood phenomenon, and research on the subject is continuing (76).

TABLE 6-6

AVERAGE PHYSICAL AND CHEMICAL CHARACTERISTICS OF SLUDGES FROM TWO-STAGE DIGESTER SYSTEM (23)

Component	Concentration, mg/l[a] Feed sludge	Transfer sludge	Supernatant	Stabilized sludge
pH	5.7	7.7	7.8	7.8
Alkalinity	758	2,318	2,630	2,760
Volatile acids	1,285	172	211	185
Total solids	35,600	18,200	12,100	32,800
Fixed solids	9,000	6,600	3,310	12,300
Carbohydrates	9,680	1,550	1,020	3,100
Lipids	8,310	2,075	1,321	3,490
Carbon	15,450	6,950	4,440	10,910
Proteins, as gelatin	18,280	11,200	6,580	17,200
Ammonia nitrogen, as NH_3	213	546	618	691
Organic nitrogen, as NH_3	1,346	879	564	1,455
Total nitrogen, as NH_3	1,559	1,425	1,182	2,146

[a]Except pH.

TABLE 6-7

MATERIALS ENTERING AND LEAVING TWO-STAGE DIGESTER SYSTEM[a] (23)

	Quantity, tons				Gas	
	Feed sludge	Transfer sludge	Supernatant	Stabilized sludge	1st stage	2nd stage
Volatile solids	79.9	34.1	23.4	8.5	-	-
Fixed solids	26.9	19.4	8.8	5.1	-	-
Carbohydrates (as glucose)	28.9	4.55	2.71	1.28	-	-
Lipids	24.8	6.09	2.40	1.44	-	-
Carbon	46.2	20.4	11.8	4.5	22.1	2.7
Ammonia nitrogen	0.64	1.61	1.64	0.28	-	-
Organic nitrogen	4.02	2.58	1.50	0.60	-	-
Proteins (as gelatin)	54.6	32.9	17.1	7.1	-	-
Total nitrogen (as NH_3)	4.66	4.20	3.25	0.89	0.47	0.04

[a]Period of analysis = 33 days.
1 ton = .907 t

Reduction of solids during digestion has the effect of producing a more dilute sludge. For example, in this case, the raw sludge fed to the system had a total solids concentration of 3.56 percent, yet the solids concentration was reduced to 1.86 percent in the first stage of digestion. Although gravity concentration did occur in the second-stage tank, the largest portion of the digested solids was contained in the supernatant. At this plant, the supernatant was recycled to the primary clarifiers and then the solids it contained either returned to the primary digester or left the plant in the final effluent.

The preceding example illustrates the general performance of anaerobic digesters. In the remainder of this section, three topics are discussed in more detail: solids reduction, gas production and supernatant quality.

6.2.4.1 Solids Reduction

Solids reduction is one of the main objectives of anaerobic digestion. It not only makes the sludge less putrescible but also reduces the amount of solids for ultimate disposal. It is usually assumed that this reduction takes place only in the volatile portion of the sludge solids. Therefore, a common measure of digester performance is the percent of the volatile solids destroyed. Volatile solids reduction in anaerobic digesters usually ranges between 35 to 60 percent. The degree of volatile solids reduction achieved in any particular application depends on both the character of the sludge and the operating parameters of the digestion system.

The character of the sludge determines the upper limit for volatile solids reduction. Not all of the volatile solids can be converted by the anaerobic bacteria. Limited research (77 to 80) suggests that only 60 to 80 percent of the volatile solids in municipal wastewater sludge is readily biodegradable. The remaining fraction consists chiefly of inert organics such as lignins and tannins. These complex organic molecules may eventually be degraded when held for several months in a facultative sludge lagoon, but can be considered indigestible within the contact times normally associated with anaerobic digestion.

The most important operating parameters affecting volatile solids reduction are solids retention time and digestion temperature. As shown on Figure 6-12, volatile solids reduction climbs rapidly to 50 to 60 percent as the SRT is increased. Beyond this point, further reduction is minimal even with substantial increases in the SRT. Similar curves have been produced by other researchers (43,60,81). The shape of the response curve and the point at which it levels out are influenced strongly by the temperature of the digester. Figure 6-12 shows that at any given SRT, raising the operating temperature to 95°F (35°C) will increase the proportion of volatile solids destroyed during digestion. This response to temperature change is not instantaneous but would

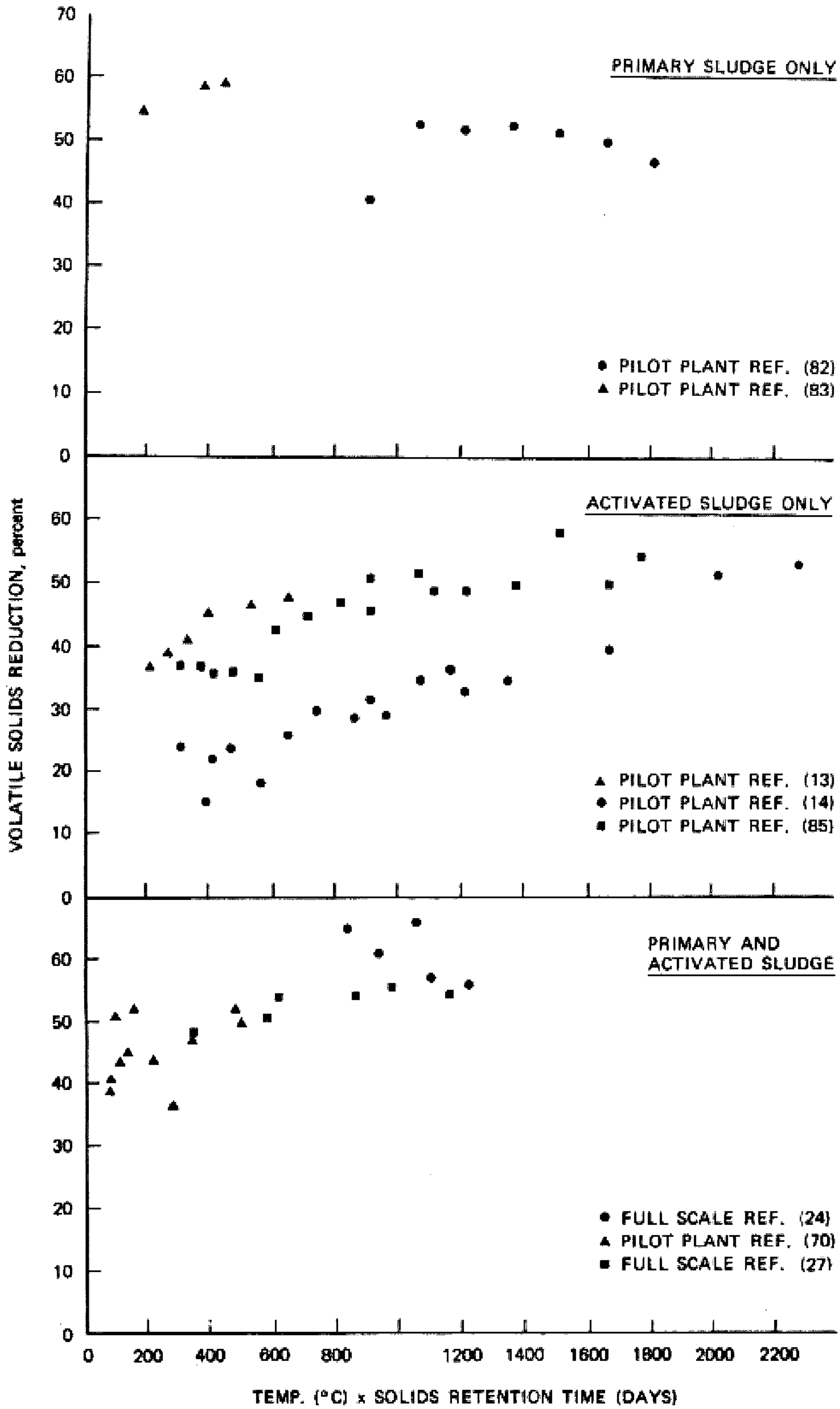


FIGURE 6-13

VOLATILE SOLIDS REDUCTION VS TEMPERATURE X SRT FOR THREE TYPES OF FEED SLUDGES (82-85)

6.2.4.2 Gas Production

A particular advantage of anaerobic digestion over other methods of sludge stabilization is that it produces a medium-energy gas as a by-product. Digester gas can be burned to provide heat and generate electricity for the treatment plant. Several off-site uses of digester gas are also feasible, including: blending with the domestic gas supply, generation of steam or electricity for sale to adjacent industries, bottling for use as a portable fuel, and production of chemicals such as ammonia and methanol. Utilization of digester gas is described further in Sections 6.2.6.2, 6.2.7, and Chapter 18. Before any utilization program can be established, the quantity and quality of available digester gas must be determined.

The generation of digester gas is a direct result of the destruction of solids. The microbiology and biochemistry of this conversion are described in Section 6.2.1.4. Because of this close relation between gas production and solids retention, gas production is best expressed in terms of the volume of gas produced per unit of solids destroyed. This parameter, termed specific gas production, is commonly expressed as cubic feet of gas per pound of volatile solids (VS) destroyed. Specific gas production values for the anaerobic digestion of some of the principal components of sludge are presented in Table 6-8. Fatty substances have a higher energy content per unit weight than other forms of organic matter. Thus, the breakdown of a sludge with a high proportion of fats, oils, and greases can be expected to yield a greater quantity of gas per unit of solids destroyed.

TABLE 6-8

GAS PRODUCTION FOR SEVERAL COMPOUNDS IN SEWAGE SLUDGE (86)

Material	Specific gas production, cu ft/lb destroyed	CH_4 content, percent
Fats	18 - 23	62 - 72
Scum	14 - 16	70 - 75
Grease	17	68
Crude Fibers	13	45 - 50
Protein	12	73

1 cu ft/lb = .0623 m^3/kg

Specific gas production for anaerobically digested municipal sludges generally ranges between 12 to 17 cu ft per lb of occur after a period of acclimatization. The graph also points out that at higher SRTs, the effect of temperature is less pronounced.

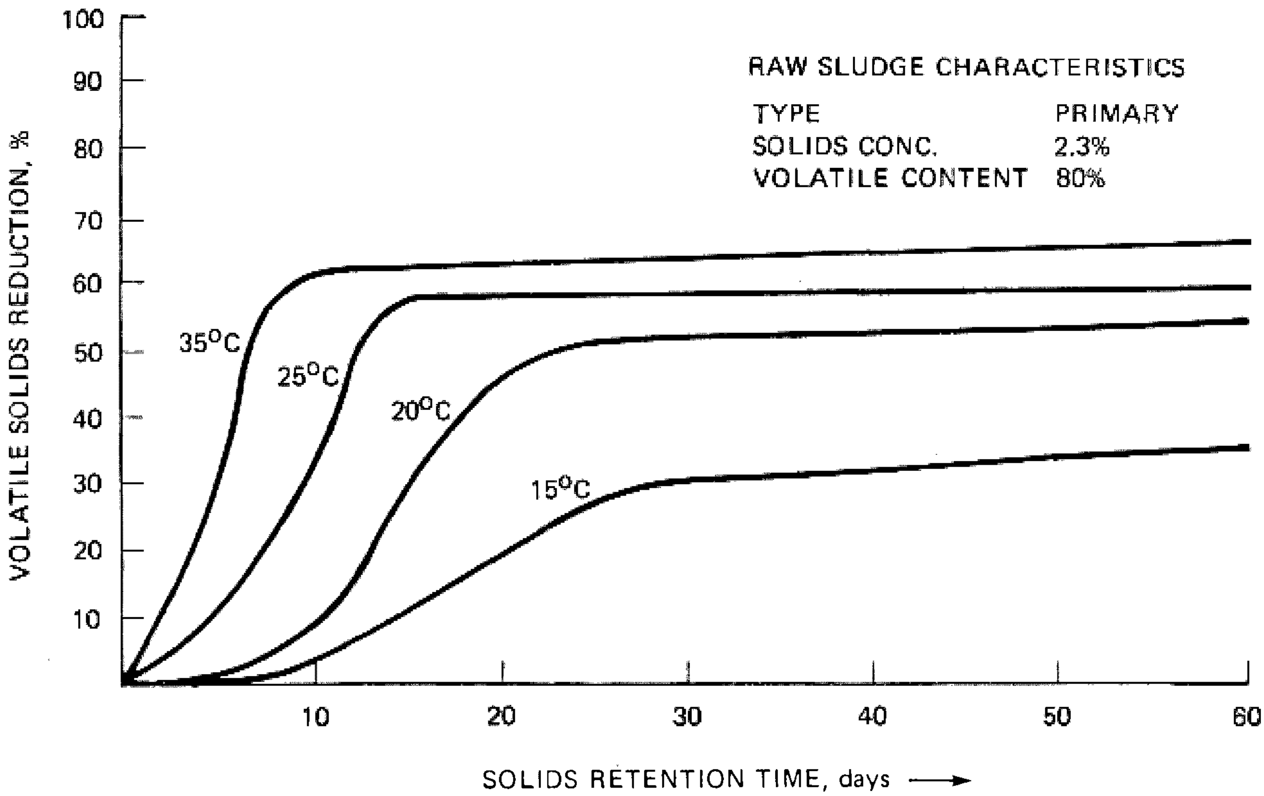


FIGURE 6-12

EFFECT OF SOLIDS RETENTION TIME AND TEMPERATURE ON VOLATILE SOLIDS REDUCTION IN A LABORATORY-SCALE ANAEROBIC DIGESTER (69)

The combined effect of SRT and temperature on volatile solids reduction for three common sludges is plotted on Figure 6-13. Although the data points are somewhat scattered, they suggest that primary sludge degrades faster than a mixture of primary and waste-activated sludge, which in turn degrades faster than straight activated sludge (12). The empirical correlation term, temperature times SRT, has been found useful when the spread of temperatures in a set of data is not great.

A 1978 laboratory study (34) found that thermal treatment of activated sludge (347°F [175°C]) for a half hour prior to anaerobic digestion increased volatile solids reduction and resultant gas production. Dewaterability of the digested sludge was also improved by thermal pretreatment.

volatile solids destroyed (0.75 to 1.1 m^3/kg). Figure 6-14 shows how specific gas production is affected by temperature. Conversion of volatile solids is most efficient at about 95°F (35°C) and 130°F (54°C). Detention time, or SRT, has essentially no effect on specific gas production so long as the SRT is exceeded. Lengthening the SRT, however, increases the total quantity of gas produced because volatile solids reduction is increased. As discussed earlier, the mix of organic compounds in the feed sludge strongly influences specific gas production values.

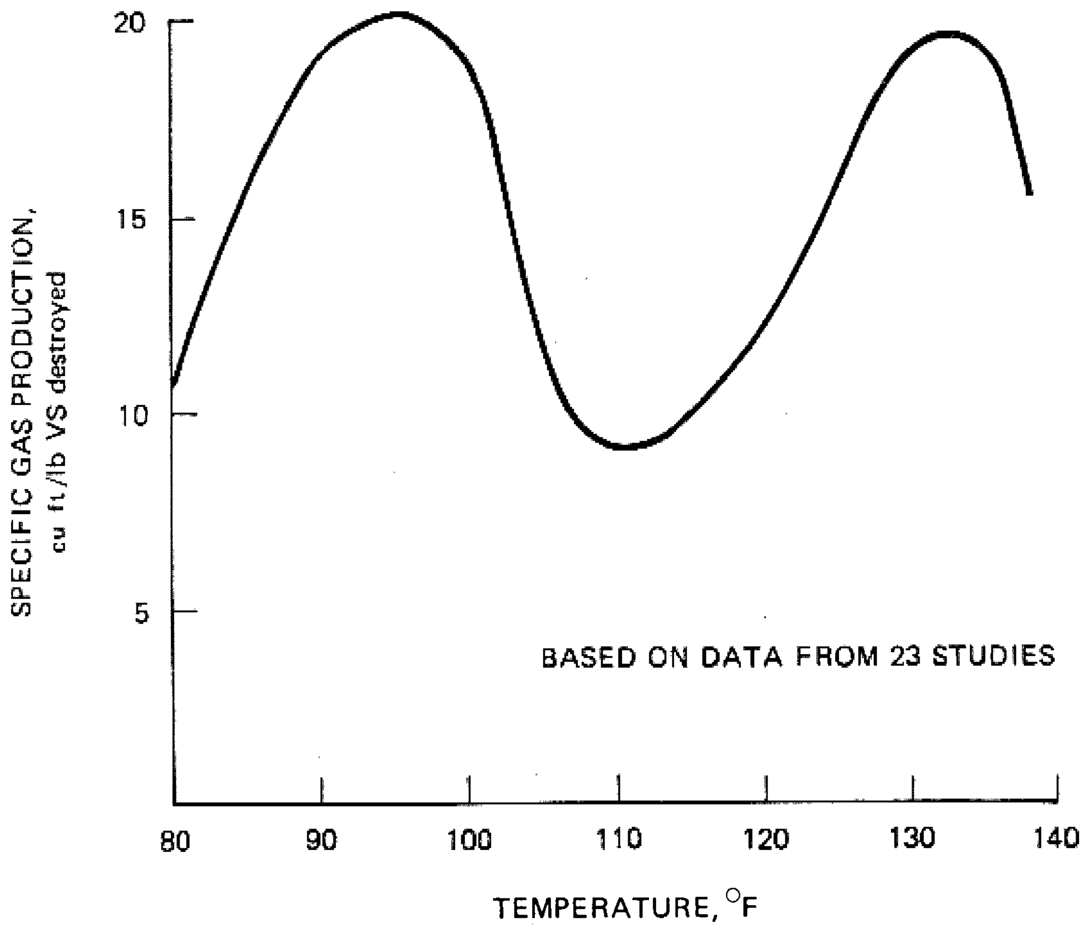


FIGURE 6-14

EFFECT OF TEMPERATURE ON GAS PRODUCTION (87)

Instantaneous rates of gas production can vary widely because of fluctuations in the feed rate, sludge composition, and bacterial activity. These momentary peaks must be considered in sizing gas piping and storage facilities. Generally, gas production increases soon after sludge is fed to the digester. Therefore, continuous feeding aids in providing uniform gas production.

The characteristics of sludge gas from several digester installations are shown in Table 6-9. A healthy digestion process produces a digester gas with about 65 to 70 percent methane, 30 to 35 percent carbon dioxide, and very low levels of nitrogen, hydrogen, and hydrogen sulfide. The carbon dioxide concentration of digester gas has been found to increase with the loading rate (60,88).

TABLE 6-9

CHARACTERISTICS OF SLUDGE GAS[a] (85)

Constituent	Values for various plants, percent by volume[b]							
Methane (CH_4)	42.5	61.0	62.0	67.0	70.0	73.7	75.0	73 - 75
Carbon dioxide (CO_2)	47.7	32.8	38.0	30.0	30.0	17.7	22.0	21 - 24
Hydrogen (H_2)	1.7	3.3	-[c]	-	-	2.1	0.2	1 - 2
Nitrogen (N_2)	8.1	2.9	-[c]	3.0	-	6.5	2.7	1 - 2
Hydrogen sulfide (H_2S)	-	-	0.15	-	0.01 - 0.02	0.06	0.1	1 - 1.5
Heat value, Btu/cu ft	459	667	660	624	728	791	716	739 - 750
Specific gravity (air = 1)	1.04	0.87	0.92	0.86	0.85	0.74	0.78	0.70 - 0.80

[a]Data from 1966 studies by Herpers and Herpers.

[b]Except as noted.

[c]Trace.

The hydrogen sulfide content of the gas is affected by the chemical composition of the sludge (84). Sulfur-bearing industrial wastes and saltwater infiltration tend to increase H_2S levels in sludge gas. However, metal wastes and metal ions added during chemical treatment or conditioning can reduce the amount of H_2S in the sludge by forming insoluble salts. H_2S, a major source of odors in digested sludge, can also be corrosive in the presence of moisture, by forming sulfuric acid.

Although the hydrogen content has some effect on the heat value, methane is the chief combustible constituent in digester gas. The high heat value for digester gas ranges between 500 to 700 Btu per cu ft (4.5 to 6.2 kg-kcal/m^3), with an average of about 640 Btu per cu ft (5.7 kg-kcal/m^3) (84). The high heat value is the heat released during combustion as measured in a calorimeter. However, gas engine efficiencies are usually based on the low heat value, which is the heat value of gas when none of the water vapor formed by combustion has been condensed. By way of comparison, sludge gas containing 70 percent methane and no other combustibles has a low heat value of 640 Btu per cu ft (5.7 kg-kcal/m^3) and a high heat value of 703 Btu per cu ft (6.26 kg-kcal/m^3) (84).

6.2.4.3 Supernatant Quality

Supernatant from an anaerobic digestion system can contain high concentrations of organic material, dissolved and suspended solids, nitrogen, phosphorus, and other materials that, when returned to the plant, may impose extra loads on other treatment processes and effluent receiving waters. Mignone (89) has reviewed the literature on anaerobic digester supernatant quality. Methods of treating digester supernatant are described in Chapter 16 and in other references (90,91,92). However, in most cases it is preferable to minimize or eliminate, rather than treat, highly polluted digester supernatant (52).

It is very difficult to generalize about supernatant quality because it can vary widely, even at a single treatment plant. Table 6-10 presents reported characteristics of anaerobic digester supernatant for three common types of feed sludge. Many factors contribute to the wide range of variation in supernatant quality (90,91,97,98).

The suspended solids, biochemical oxygen demand, soluble phosphorus, phenols, and ammonia in the supernatant can all cause problems in a treatment plant. If the anaerobic supernatant must be returned to the plant flow for treatment, it should be recycled continuously to spread the loading.

Suspended Solids

Supernatants may contain high concentrations of finely divided suspended solids because, as discussed in Section 6.2.2.2, anaerobically digested sludges settle poorly, particularly when biological sludge is fed into the digestion system. Unless these fine-sized particles are removed with the digested sludge, they will build up in the plant, causing process overloading and eventually, degradation of the plant effluent.

Biochemical Oxygen Demand

Because suspended and dissolved solids from an anaerobic digester are in a chemically reduced state, they impose a large oxygen demand when returned to the liquid process stream. The aeration requirement for aerobic biological treatment is often increased substantially by the recycling of high BOD digester supernatant.

Soluble Phosphorus

The recent emphasis on removal of phosphorus from wastewaters has created sludges that contain high proportions of this element. In biological phosphorus removal, phosphorus is taken up by the growing cell mass and is removed from the wastewater stream in the wasted biological sludge (99,100). Chemical methods of phosphorus removal entail the precipitation of phosphates with metal ions--predominantly ferrous, ferric, aluminum, and calcium. The fate of phosphorus during the anaerobic digestion of phosphorus-laden biological and chemical sludges has been the subject of several studies (55,101-104). The results of these studies are not entirely consistent. In some cases (99,101), bound phosphorus was resolubilized during anaerobic digestion and released to the digester supernatant. The return of this phosphorus-laden supernatant to the liquid treatment stream can substantially reduce the net phosphorus removal efficiency of the plant (101) and/or increase chemical demand. However, in most studies (55,102-104), release of soluble phosphorus into digester supernatant was minimal.

TABLE 6-10

SUPERNATANT, CHARACTERISTICS OF HIGH-RATE, TWO-STATE, MESOPHILIC, ANAEROBIC DIGESTION AT VARIOUS PLANTS (90,93,94,95,96)

Parameter	Concentration[a], mg/l									
	Primary sludge		Primary and trickling filter sludge			Primary and activated sludge				
Reference	(95)	(90)[b]	(94)	(95)	(90)[c]	(94)	(94)	(95)	(96)	(90)[b]
Total solids	9,400	-	4,545	-	-	1,475	2,160	-	-	-
Total volatile solids	4,900	-	2,930	-	-	814	983	-	-	-
Suspended solids										
Average	-	4,277	2,205	1,518	7,772	383	143	740	1,075	4,408
Maximum	-	17,300	-	-	32,400	-	-	-	-	14,650
Minimum	-	660	-	-	100	-	-	-	-	100
Volatile suspended solids										
Average	-	2,645	1,660	-	4,403	299	118	-	750	3,176
Maximum	-	10,850	-	-	17,750	-	-	-	-	10,650
Minimum	-	420	-	-	60	-	-	-	-	75
BOD										
Average	-	713	-	-	1,238	-	-	-	515	667
Maximum	-	1,880	-	-	6,000	-	-	-	-	2,700
Minimum	-	200	-	-	135	-	-	-	-	100
COD	-	-	4,565	2,230	-	1,384	1,310	1,230	-	-
TOC	-	-	1,242	-	-	443	320	-	-	-
Total (PO_4)-P	-	-	143	85	-	63	87	100	-	-
NH_3-N	-	-	853	-	-	253	559	-	480	-
Organic N	-	-	291	678	-	53	91	360	560	-
pH	8.0	-	7.3	7.2	-	7.0	7.8	7.0	7.3	
Volatile acids	-	-	264	-	-	322	250	-	-	-
Alkalinity (as $CaCO_3$)	2,555	-	3,780	-	-	1,349	1,434	-	-	-
Phenols										
Average	-	0.23	-	-	0.23	-	-	-	-	0.35
Maximum	-	0.80	-	-	0.50	-	-	-	-	1.00
Minimum	-	0.06	-	-	0.06	-	-	-	-	0.08

[a]Unless noted, all values are average for the sampling period studied.

[b]Values indicated are a composite from seven treatment plants.

[c]Values indicated are a composite from six treatment plants.

Phenols

Phenols have been found in digester supernatants in concentrations sufficient to inhibit biological activity (56). Typical phenol concentrations are included in Table 6-10. The source of phenols is not usually industrial waste discharges but putrefaction of proteins, which begins in the human body and continues in the sewage system. Phenols are very toxic and are used commercially as an antiseptic. In dilute concentrations, phenols do not necessarily kill bacteria but slow their growth and inhibit their normal metabolic activity. As a result, the phenols contained in digester supernatant, combined with phenolic compounds already in the sewage, may be an important cause of sludge bulking (90). In addition, the recycling of phenols in supernatant may contribute to odor problems.

Ammonia

As shown in Table 6-10, high levels of ammonia are often found in digester supernatant. In plants that are nitrifying, the supernatant return will provide a large portion of the ammonia feed to the wastewater process. The conversion of this ammonia to nitrate will therefore result in increased costs to provide the required oxygen for treatment. In plants that must achieve a nitrogen limitation in their effluent, the recycle ammonia loadings must be carefully evaluated as to their overall effect in meeting the standards.

6.2.5 Operational Considerations

6.2.5.1 pH

As was noted in Section 6.2.1, anaerobic digestion is a two-step process consisting of "acid-forming" and "methane-forming" steps. During the first step, the production of volatile acids tends to reduce the pH. The reduction is normally countered by destruction of volatile acids by methanogenic bacteria and the subsequent production of bicarbonate.

Close pH control is necessary because methane-producing bacteria are extremely sensitive to slight changes in pH. Early research (105-107) showed that the optimum pH for methane-producing bacteria is in the range of 6.4-7.5 and that these bacteria are very sensitive to pH change. A 1970 study (108) seems to indicate that the pH tolerance of methane-producing bacteria is greater than previously thought. The bacteria are not necessarily killed by high and low pH levels; their growth is merely stopped. Because of the importance of these findings to system control, more research is needed to verify these results.

Several different acid-base chemical equilibria are related to pH. In the anaerobic digestion process, the pH range of interest is 6.0 to 8.0, which makes the carbon dioxide-bicarbonate relationship the most important. As Figure 6-15 indicates, system pH is controlled by the CO_2 concentration of the gas phase and the bicarbonate alkalinity of the liquid phase. A digester with a given gas-phase CO_2 concentration and liquid-phase bicarbonate alkalinity can exist at only one pH. If bicarbonate alkalinity is added to the digester and the proportion of CO_2 in the gas phase remains the same, digester pH must increase. For any fixed gas-phase CO_2 composition, the amount of sodium bicarbonate required to achieve the desired pH change is given by the following equation:

$$D = 0.60\ (\text{BA at initial pH} - \text{BA at final pH}) \qquad (6\text{-}1)$$

where:

D = sodium bicarbonate dose, mg/l

BA = digester bicarbonate alkalinity as mg/l $CaCO_3$

The pH increase is less important, however, than the effect on system buffering capacity, (that is, the system's ability to resist pH changes). If bicarbonate alkalinity is added, buffering capacity is increased, system pH is stabilized, and the system becomes less susceptible to upset. The effect of buffering capacity on anaerobic digester operations is discussed elsewhere (110,111).

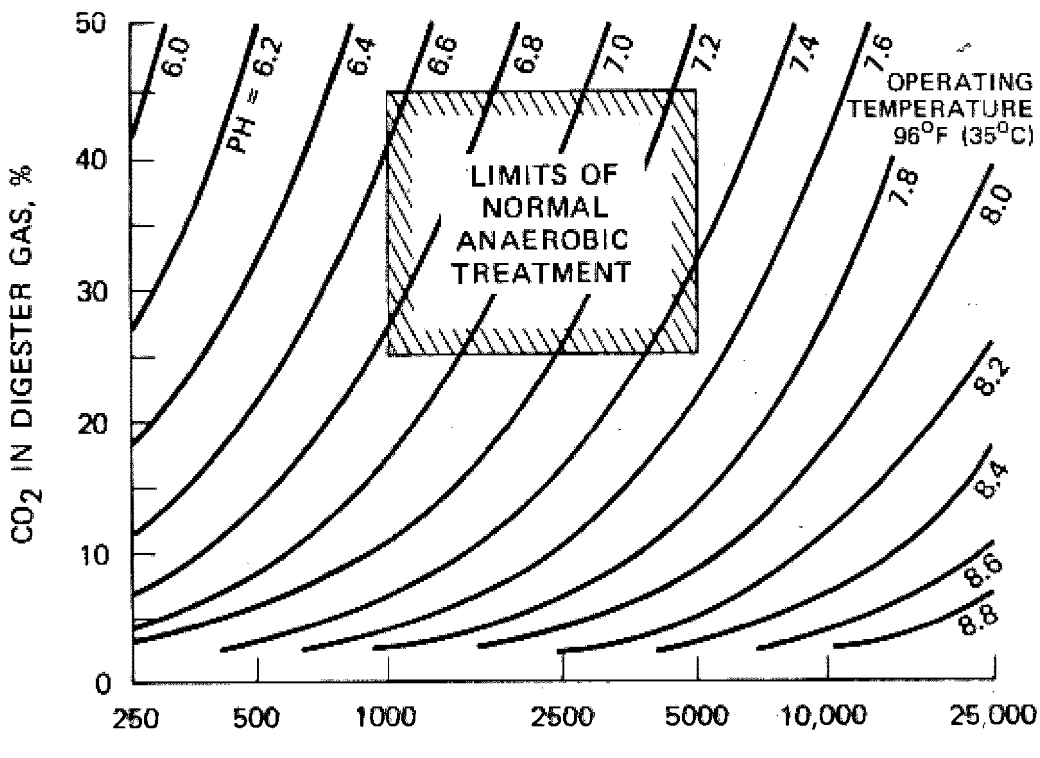


FIGURE 6-15

RELATIONSHIP BETWEEN pH AND BICARBONATE CONCENTRATION NEAR 95°F (35°C) (109)

Bicarbonate alkalinity can be calculated from total alkalinity by the following equation:

$$BA = TA - 0.71\ (VA) \qquad (6\text{-}2)$$

where:

BA = bicarbonate alkalinity as mg/l $CaCO_3$

TA = total alkalinity as mg/l $CaCO_3$ determined by titration to pH 4.0

VA = volatile acids measured as mg/l acetic acid

0.71 is obtained by the multiplication of two factors, (0.83 and 0.85). 0.83 converts volatile acids as acetic acid to volatile acid alkalinity as $CaCO_3$. 0.85 is used because in a titration to pH 4.0, about 85 percent of the acetate has been converted to the acid form.

It has been suggested (110) that the only sensible way to increase digester pH and buffering capacity is by the addition of sodium bicarbonate. Other materials, such as caustic soda, soda ash, and lime, cannot increase bicarbonate alkalinity without reacting with soluble carbon dioxide, which causes a partial vacuum within the system. Above pH 6.3, lime may react with bicarbonate to form insoluble calcium carbonate, promoting scale formation or encrustation. Ammonia gas (NH_3) could be used without causing vacuum problems, but control of pH with sodium bicarbonate is preferred because it provides good buffering capacity without raising the pH as much as NH_3 would. Both sodium and ammonia can inhibit anaerobic bacteria; care must be taken during pH control to avoid reaching toxic concentrations of these chemicals.

6.2.5.2 Toxicity

Much of the published data on toxicity in anaerobic digestion systems are erroneous and misleading because of inadequate experimental techniques and a general lack of understanding (112). Therefore, before any discussion of toxicity can take place, a review of several fundamentals is needed.

First, for any material to be biologically toxic, it must be in solution. If a substance is not in solution, it cannot pass through the cell wall and therefore cannot affect the organism.

Second, toxicity is a relative term. There are many organic and inorganic materials which, if soluble, can be either stimulatory or toxic. A good example is the effect, shown in Table 6-11, of ammonia nitrogen on anaerobic digestion.

TABLE 6-11

EFFECT OF AMMONIA NITROGEN ON ANAEROBIC DIGESTION (113,114)

Ammonia concentration, as N, mg/l	Effect
50 - 200	Beneficial
200 - 1,000	No adverse effects
1,500 - 3,000	Inhibitory at pH over 7.4 - 7.6
Above 3,000	Toxic

Acclimatization is the third consideration. When the levels of potentially toxic materials are slowly increased within the environment, many organisms can rearrange their metabolic resources and overcome the metabolic block produced by the toxic material. Under shock load conditions, there is not sufficient time for this rearrangement to take place and the digestion process fails.

Finally, there is the possibility of antagonism and synergism. Antagonism is defined as a reduction of the toxic effect of one substance by the presence of another. Synergism is defined as an increase in the toxic effect of one substance by the presence of another. These are important relationships in cation toxicity.

Though there are many potentially toxic materials, this section concerns itself only with the following:

- Volatile acids
- Heavy metals
- Light metal cations
- Oxygen
- Sulfides
- Ammonia

Volatile Acids

Until the 1960s, it was commonly believed that volatile acid concentrations over 2,000 mg/l were toxic to anaerobic digestion. There was also considerable controversy about whether or not alkaline substances should be added to maintain adequate buffer capacity.

In the early 1960s, McCarty and his coworkers published results from carefully controlled studies (113,115,116). Their results showed:

- That volatile acids, at least up to 6,000-8,000 mg/l, were not toxic to methanogenic bacteria as long as there was adequate buffer capacity to maintain the system pH in the range of 6.6-7.4.

- That pH control by the addition of an alkaline material was a valid procedure as long as the cation associated with the alkaline material did not cause toxicity. It was found that alkaline sodium, potassium, or ammonium compounds were detrimental but that alkaline magnesium or calcium compounds were not.

Heavy Metals

Heavy metal toxicity has frequently been cited as the cause of anaerobic digestion failures. Even though trace amounts of most heavy metals are necessary for maximum biological development (117), the concentrations in raw wastewater sludges could be problematic.

Heavy metals tend to attach themselves to sludge particles (118,119). Heavy metals which cannot be detected in the influent wastewater can be concentrated to measurable levels in the sludge. Table 6-12 gives the range of influent concentrations of some heavy metals. The range is quite wide, with the higher values normally attributed to a local industrial polluter.

TABLE 6-12

INFLUENT CONCENTRATIONS AND EXPECTED REMOVALS OF SOME HEAVY METALS IN WASTEWATER TREATMENT SYSTEMS (120,121)

Heavy metal	Influent concentration, mg/l	Removal efficiency, percent	
		Secondary treatment	Alum treatment
Cadium	<.008 - 1.142	20 - 45	60
Chromium			
+3	<.020 - 5.8	40 - 80	90
+6	<.020 - 5.8	0 - 10	-
Copper	<.020 - 9.6	0 - 70	90
Mercury	<.0001 - .068	20 - 75	65
Nickel	<.1 - 880	15 - 40	35
Lead	<.05 - 12.2	50 - 90	85
Zinc	<.02 - 18.00	35 - 80	85
Arsenic	.002 - .0034	28 - 73	-
Iron	<.1 - 13	72	-
Manganese	.02 - .95	25	-
Silver	<.05 - .6	-	-
Cobalt	Below detection	-	-
Barium	-	47	-
Selenium	-	79	-

Table 6-12 gives the typical range of removal that can be expected from standard secondary treatment. Published data seem to indicate that the percent removal, without chemical addition, is a function of influent concentration: the higher the influent concentration, the higher the percent removal.

The last column of Table 6-12 shows removals of heavy metals achieved with additions of alum. In treatment systems that add chemical coagulants for phosphate removal, a significant amount of influent heavy metals will also be removed (122).

Soluble and total heavy metal concentrations are often greatly different because anions such as carbonate and sulfide can remove heavy metals from solution by precipitation and sequestering. Consequently, it is not possible to define precise total toxic concentrations for any heavy metal (123). Total individual metal concentrations that have caused severe inhibition of anaerobic digestion are shown in Table 6-13. However, only the dissolved fraction of these metals caused the inhibition. Table 6-14 shows the total and soluble concentrations of heavy metals in anaerobic digesters. Inhibition of anaerobic digestion occurs at soluble concentrations of approximately 3 mg/l for Cr, 2 mg/l for Ni, 1 mg/l for Zn, and 0.5 mg/l for Cu (129).

TABLE 6-13

TOTAL CONCENTRATION OF INDIVIDUAL METALS REQUIRED TO SEVERELY INHIBIT ANAEROBIC DIGESTION (123,124)

	Concentration in digester contents		
Metal	Metal as percent of dry solids	Millimoles metal per kilogram dry solids	Soluable metal, mg/l
Copper	0.93	150	0.5
Cadmium	1.08	100	-
Zinc	0.97	150	1.0
Iron	9.56	1,710	-
Chromium			
+6	2.20	420	3.0
+3	2.60	500	-
Nickel	-	-	2.0

Except for chromium, heavy metal toxicity in anaerobic digesters can be prevented or eliminated by precipitation with sulfides (124-127). Hexavalent chromium is usually reduced to trivalent chromium, which, under normal anaerobic digester pH conditions, is relatively insoluble and not very toxic (128).

Sulfide precipitation is used because heavy metal sulfides are extremely insoluble (129). If sufficient sulfide is not available from natural sources, it must be added in the form of sulfate, which is then reduced to sulfide under anaerobic conditions.

TABLE 6-14

TOTAL AND SOLUBLE HEAVY METAL CONTENT OF DIGESTERS (124)

Metal	Total concentration, mg/l	Soluble concentration, mg/l
Chromium +6	88 - 386	0.03 - 3.0
Copper	27 - 196	0.1 - 1.0
Nickel	2 - 97	0 - 5
Zinc	11 - 390	0.1 - 0.7

One potential drawback of using the sulfide saturation method is the possible production of hydrogen sulfide gas or sulfuric acid from excess dissolved sulfide in the digester. Because of this, it is recommended that ferrous sulfate be used as a source of sulfide (112). Sulfides will be produced from the biological breakdown of sulfate, and the excess will be held out of solution by the iron in the sulfide form. However, if heavy metals enter the digester, they will draw the sulfide preferentially from the iron because iron sulfide is the most soluble heavy metal sulfide. Excess sulfide additions can be monitored by either analysing digester gas for sulfide or by the use of a silver-silver electrode located within the digester (126,130).

Light Metal Cations

The importance of the light metal cations (sodium, magnesium, potassium, calcium) in anaerobic digestion was shown in the mid 1960s (112,131,132). Domestic wastewater sludges have low concentrations of light metal cations. However, significant contributions, enough to cause toxicity, can come from industrial operations and the addition of alkaline material for pH control. Not only can each of these cations be either stimulatory or toxic, depending on concentration (Table 6-15), but certain combinations of them will form either an antagonistic or a synergistic relationship (Table 6-16). Inhibition caused by an excess of a certain cation can be counteracted by the addition of one or more of the antagonist cations listed in Table 6-16.

TABLE 6-15

STIMULATING AND INHIBITORY CONCENTRATIONS OF LIGHT METAL CATIONS (133)

Cation	Concentration, mg/l		
	Stimulatory	Moderately inhibitory	Strongly inhibitory
Calcium	100 - 200	2,500 - 4,500	8,000
Magnesium	75 - 150	1,000 - 1,500	3,000
Potassium	200 - 400	2,500 - 4,500	12,000
Sodium	100 - 200	3,500 - 5,500	8,000

TABLE 6-16

SYNERGISTIC AND ANTAGONISTIC CATION COMBINATIONS (112, 132)

Toxic cations	Synergistic cations	Antagonistic cations
Ammonium	Calcium, magnesium, potassium	Sodium
Calcium	Ammonium, magnesium	Potassium, sodium
Magnesium	Ammonium, calcium	Potassium, sodium
Potassium	---	Ammonium, calcium, magnesium, sodium
Sodium	Ammonium, calcium, magnesium	Potassium

Oxygen

Many engineers have expressed concern over the possibility of oxygen toxicity caused by using dissolved air flotation thickeners for sludge thickening. Fields and Agardy (134) injected oxygen into a bench-scale digester at the rate of 0.1 ml O_2 per liter per hour (equivalent to one volume of air per 2,100 volumes of digester contents per hour). Total gas production fell 36.5 percent after 19 hours and ceased completely after 69 hours. However, this rate of oxygen injection is significantly higher than would be produced by a dissolved air flotation thickening system. Consequently, no problems are expected under normal circumstances.

Sulfides

Soluble sulfide concentrations over 200 mg/l are toxic to anaerobic digestion systems (125,135). The soluble sulfide concentration within the digester is a function of the incoming source of sulfur, the pH, the rate of gas production, and the amount of heavy metals available to act as precipitants. High levels of soluble sulfide can be reduced by the addition of iron salts (136) to the liquid, or scrubbing of the recirculated gas.

Ammonia

Ammonia, produced during the anaerobic degradation of proteins and urea, may reach toxic levels in highly concentrated sludges (113,114,133). Two forms of ammonia are found in anaerobic digestion: ammonium ion (NH_4^+) and dissolved ammonia gas (NH_3). Both forms can inhibit anaerobic digestion, although ammonia gas has a toxic effect at a much lower concentration than ammonium ion.

The two forms of ammonia are in equilibrium and the relative concentration of each depends on pH, as indicated by the following equilibrium equation:

$NH_4^+ \rightleftharpoons NH_3 + H^+$

At low pH levels, the equilibrium shifts to the left and ammonium ion toxicity is more likely to be a problem. At higher pH levels, the equilibrium shifts to the right so that inhibition is related to the ammonia gas concentration.

Ammonia toxicity is evaluated by analyzing the total ammonia-nitrogen concentrations. If the total ammonia-nitrogen concentration is from 1,500 to 3,000 mg/l and the pH is above 7.4-7.6, inhibition may result from ammonia gas. This can be controlled by the addition of enough HCl to maintain the pH between 7.0 and 7.2. If total ammonia-nitrogen levels are over 3,000 mg/l, then the NH_4^+ ion will become toxic no matter what the pH level. The only solution is to dilute the incoming waste sludge.

6.2.6 System Component Design

6.2.6.1 Tank Design

Anaerobic digestion tanks are either cylindrical, rectangular, or egg-shaped. A simplified sketch of each tank design type is shown on Figures 6-16, 6-17, and 6-18.

The most common tank design is a low, vertical cylinder ranging in diameter from 20 to 125 feet (6 to 38 m), with a side water depth between 20 to 40 feet (6 to 12 m). Gas-lift mixing is most effective when the ratio of tank radius to water depth is between 0.7 and 2.0 (137). The tanks are usually made of concrete, with either internal reinforcing or post-tensioning rods or straps. The latter design is the least expensive of the two for tanks with diameters greater than 65 feet. Some steel tank digesters have been constructed to diameters of 70 feet.

The floor of a cylindrical digester is usually conical, with a minimum slope of 1:6. Sludge is withdrawn from the low point in the center of the tank. Digestion tanks with "waffle bottoms" have been put into operation at the East Bay Municipal Utility District Plant in Oakland, California (138,139). Digesters with similar bottoms have been designed for Tacoma, Washington, and Portland, Oregon.

The principal objective of the waffle floor design is to minimize grit accumulation and, to practically eliminate the need for cleaning. As shown on Figure 6-16, the tank floor is subdivided into pie-shaped hoppers, each sloping toward a separate drawoff port along the outside edge of tank. Subdivision of the bottom area and use of multiple drawoff ports allow steeper floor slopes and reduce the distance that settled solids must travel. As a result, less grit is likely to accumulate. Construction costs are higher for this type of bottom because it requires more complex excavation, form work, and piping than a conventional bottom. It has been estimated that the incremental construction cost for waffle bottoms on the 90-foot (27 m) diameter digesters in Oakland was estimated to be $120,000 per tank (1978 dollars) (139). However, it is expected that savings will be realized during operation because cleaning requirements will be greatly reduced.

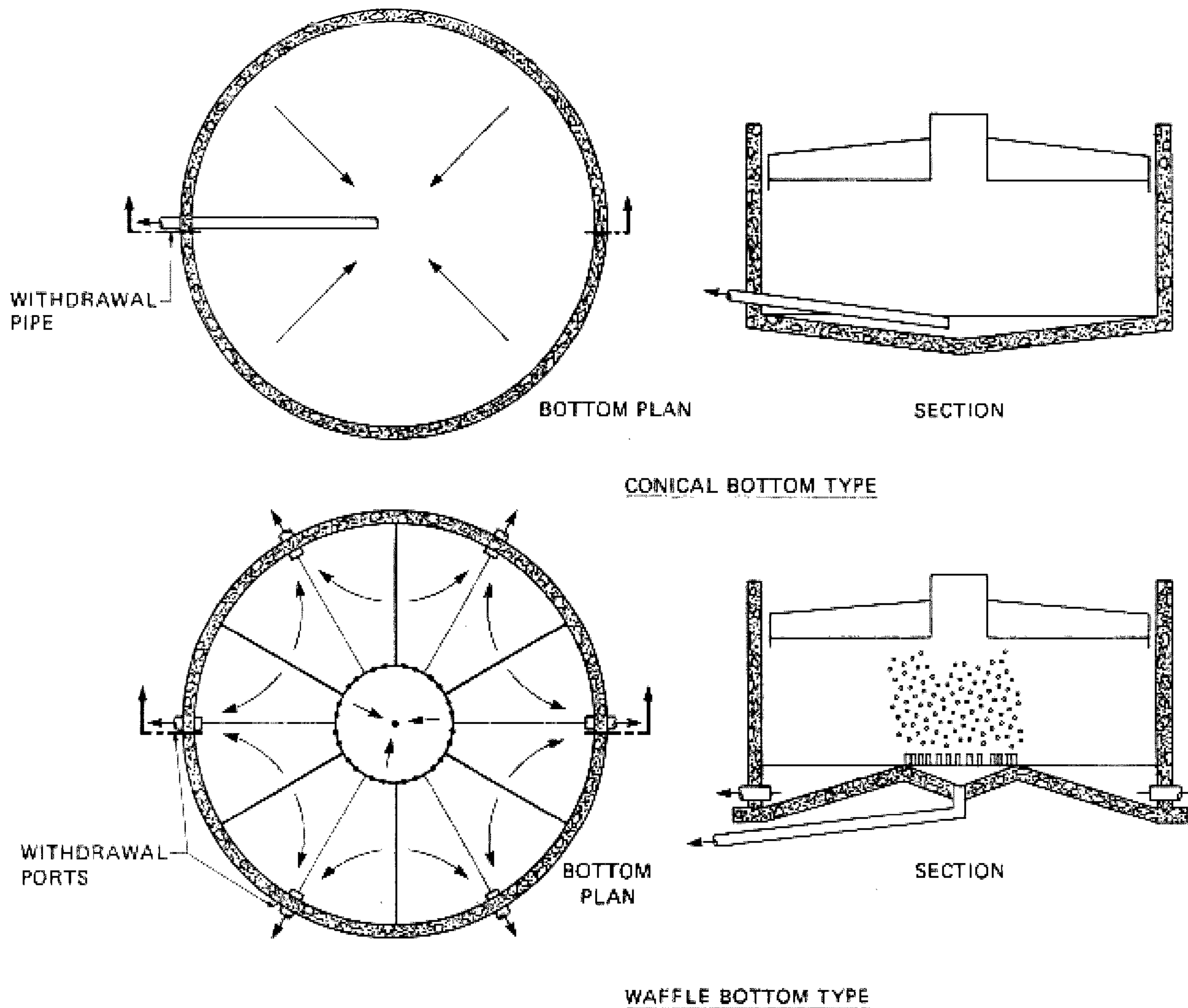


FIGURE 6-16

CYLINDRICAL ANAEROBIC DIGESTION TANKS

The primary advantages of rectangular digestion tanks are simplified construction and efficient use of a limited plant site. However, it is more difficult to keep the contents of a rectangular digester uniformly mixed because "dead spots" tend to form at the corners. Figure 6-17 shows a plan and section of a rectangular digestion tank.

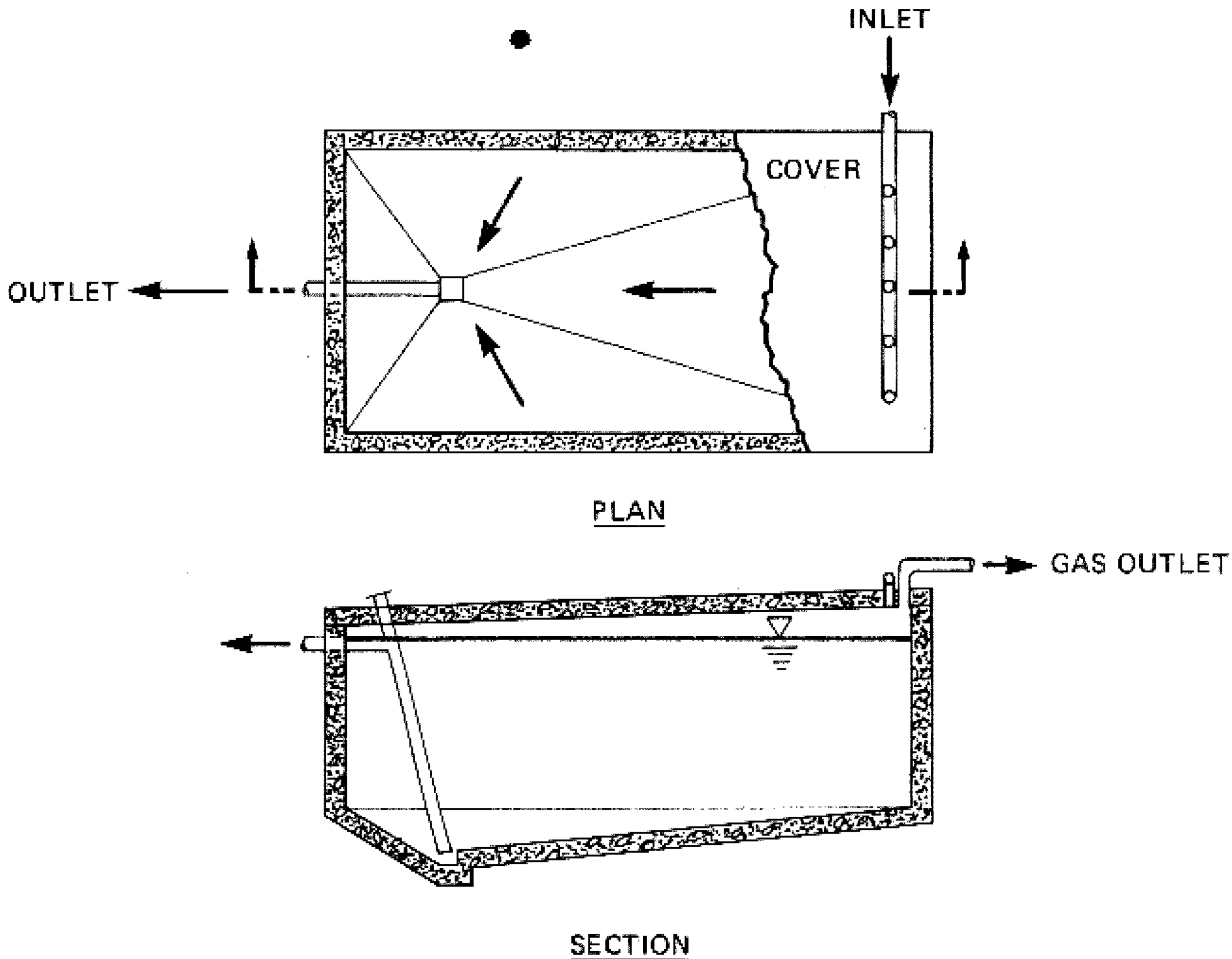


FIGURE 6-17

RECTANGULAR ANAEROBIC DIGESTION TANK

Although egg-shaped digesters have been used extensively in Europe, originating in Germany over 20 years ago, they are only now entering American practice. The first egg-shaped digesters in the United States were built in Kansas City, Kansas, in the mid-1970s, and four more are now under construction (1979) in Los Angeles, California, at the Terminal Island Wastewater Treatment Plant. Each of the Terminal Island digesters will have a capacity of 184,000 cubic feet (5,200 m^3) and measure 100 feet (30 m) from top to bottom, with a maximum horizontal diameter of 68 feet (21 m) (140).

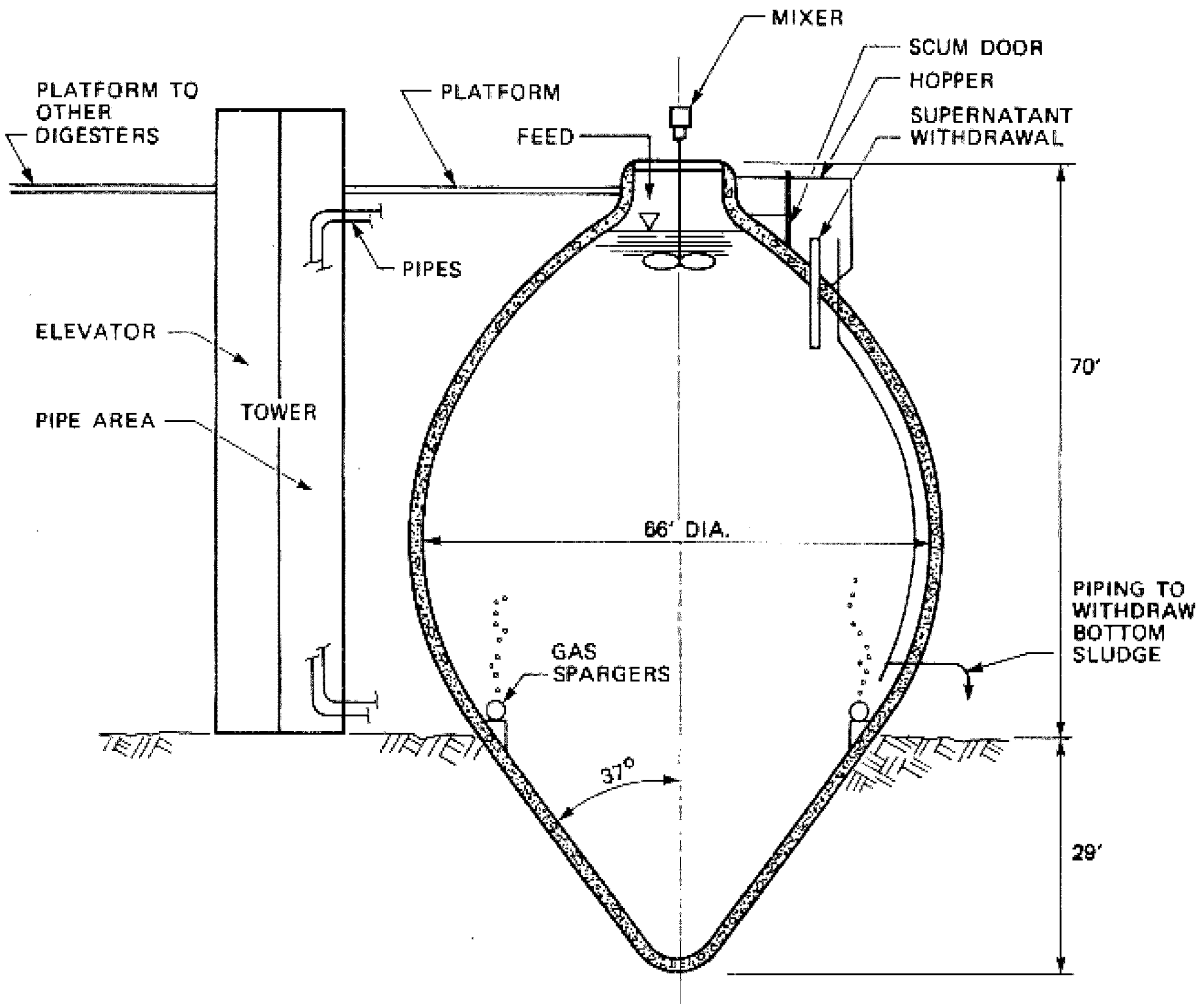


FIGURE 6-18

EGG-SHAPED ANAEROBIC DIGESTION TANK AT TERMINAL ISLAND TREATMENT PLANT, LOS ANGELES

The purpose of forming an egg-shaped tank is to eliminate the need for cleaning. The digester sides form a cone so steep at the bottom that grit cannot accumulate (Figure 6-18). The top of the digester is small, so that scum contained there can be kept fluid with a mixer and removed through special scum doors. Mixing in the Los Angeles digesters is promoted by gas evolution during digestion combined with pumped circulation of sludge from the bottom to the top of the tank. A 60 horsepower (45 kW) pump is used at the rate of 500 gpm (32 l/s). Gas spargers ring the inside wall of each tank and can be used to detach any material adhering to the walls or to increase mixing, if necessary. Construction of egg-shaped tanks requires complex form work and special building techniques. Accordingly, capital costs are higher than for other tank designs. The 1976 construction cost estimate for the four digesters in Los Angeles was about $5,000,000.

6.2.6.2 Heating

A heating system is an important feature of a modern anaerobic digester. Raising the temperature of the digesting sludge increases the metabolic rate of the anaerobic organisms and reduces digestion time. Maintenance of the temperature consistently within ±1°F (0.6°C) of design temperatures improves process stability by preventing thermal shock.

Methods of Heating

Heating equipment must be capable of delivering enough heat to raise the temperature of incoming sludge to operating levels and to offset losses of heat through the walls, floor, and cover of the digester. Methods used to transfer heat to sludge include:

- Heat exchanger coils placed inside the tank
- Steam injection directly into the sludge
- External heat exchanger through which sludge is circulated
- Direct flame heating in which hot combustion gases are passed through the sludge (141)

External heat exchangers are the most commonly used heating method. Internal heat exchanger coils were used in early digesters; however, they are difficult to inspect and clean. This is a serious disadvantage because the coils become encrusted, reducing the rate of heat transfer. To minimize caking of sludge on the coils, water circulating through the coils is kept between 120 to 130°F (49 to 55°C) (84). Typical values of heat-transfer coefficients for hot-water coils are listed in Table 6-17.

Steam injection heating requires very little equipment but dilutes the digesting sludge and requires 100 percent boiler makeup water. The cost of this water may be considerable, particularly if hardness must be removed before addition to the boiler.

Three types of external heat exchangers are commonly used for sludge heating: water bath, jacketed pipe, and spiral. In the water bath exchanger, boiler tubes and sludge piping are located in a common water-filled container. Gravity circulation of hot water across the sludge pipes is augmented with a pump, to increase heat transfer. The heat exchanger and boiler are combined in a single unit, a feature which can increase the explosion hazard in the digester area. In a jacketed pipe exchanger, hot water is pumped counter-current to the sludge flow, through a concentric pipe surrounding the sludge pipe. The spiral exchanger is also a counter-flow design; however, the sludge and water passageways are cast in a spiral. One side of the heat exchanger is liquid, providing ready access to the interior of the sludge passageway for cleaning. Heat transfer coefficients for design of external heat exchangers range between 150 to 275 Btu/hr/sq ft/degree F (740 to 1,350 kg-cal/hr/m^2/°C) depending on heat exchanger construction and fluid turbulence. To minimize clogging with rags and debris, sludge passageways in a heat exchanger should be as large as possible. The interior of these passageways should be easily accessible to allow the operator to quickly locate and clear a blockage.

TABLE 6-17

HEAT TRANSFER COEFFICIENTS FOR HOT WATER COILS IN ANAEROBIC DIGESTERS (84)

Material surrounding hot water coils	Transfer coefficient (u), Btu/hr/sq ft/^{o}F
Thin supernatant	60 - 80
Thin sludge	30
Thick sludge	8 - 15

1 Btu/hr/sq ft/^{o}F = 4.9 kg-cal/hr/m^2/^{o}C.

A piping arrangement used to control hot water supply to a jacketed pipe or spiral heat exchanger is shown on Figure 6-19. Hot water is pumped through the heat exchanger and circulated through the secondary heat loop. When the temperature of the sludge leaving the heat exchanger falls below the set point, some hot water from the primary heat loop is introduced through a modulating valve into the secondary heat loop, displacing an equal volume of cooler water back into the primary heat loop. Balancing valves are required to assure that the secondary loop will not be bypassed altogether and to allow adjustment of circulation pump capacity. Supply water temperature is kept below 155°F (68°C). Although higher temperatures will increase the rate of heat transfer, caking of sludge will occur when the flow of sludge is stopped. This system allows the heat source to be remote from the heat exchanger. This assures maximum safety and supports the recovery of waste heat (see Chapter 18). Figure 6-20 shows a spiral heat exchanger operating off a secondary heat loop.

Each digester should have a separate heat exchanger and in larger plants, addition of a single heat exchanger for warming raw sludge should be considered. Cold raw sludge should never be added directly to the digester. The thermal shock will be detrimental to the anaerobic bacteria, and isolated pockets of cold sludge may form. Raw sludge should be preheated or mixed with large quantities of warm circulating sludge before being fed to the digester.

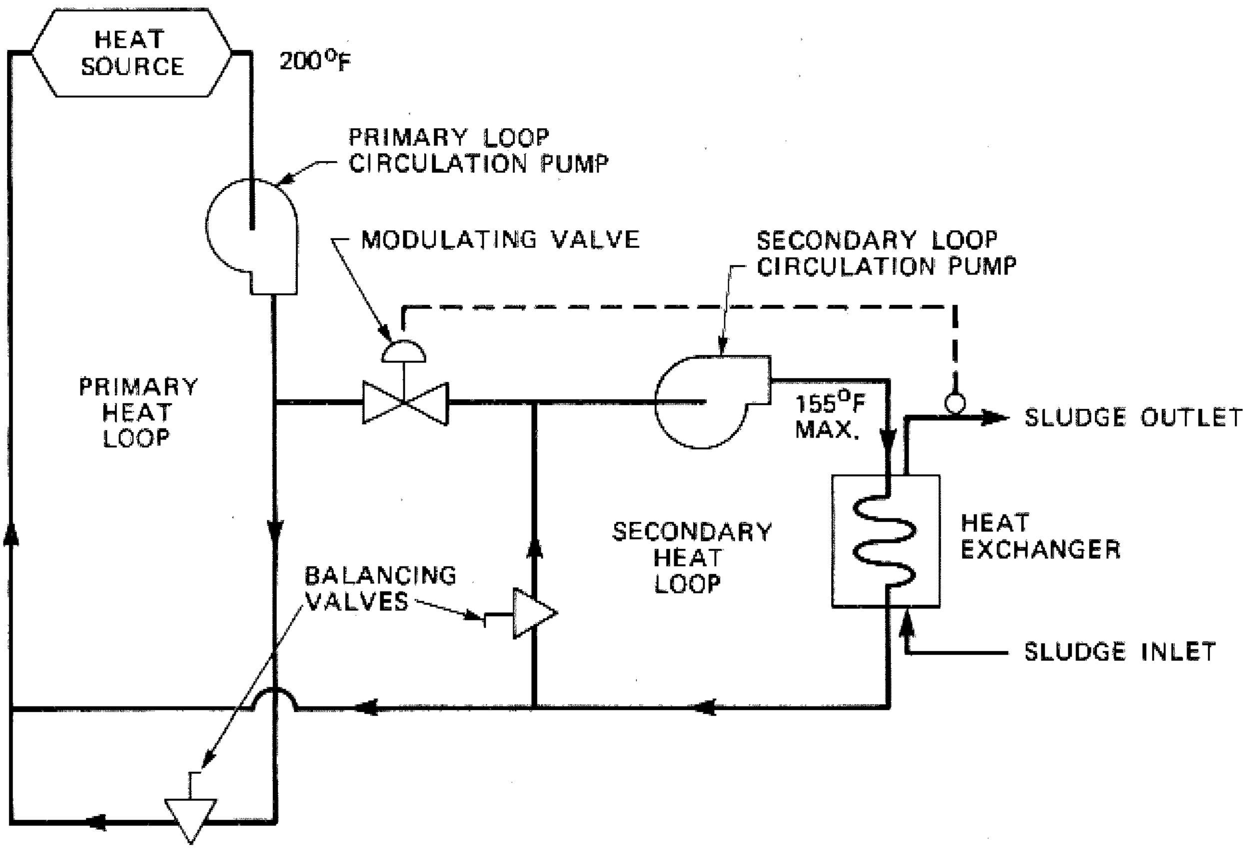


FIGURE 6-19

SCHEMATIC OF THE HEAT RESERVOIR SYSTEM FOR A JACKETED PIPE OR SPIRAL HEAT EXCHANGER

Heat Sources

The hot water or steam used to heat digesters is most commonly generated in a boiler fueled by sludge gas. Up to 80 percent of the heat value of sludge gas can be recovered in a boiler. Provisions for burning an alternate fuel source (natural gas, propane, or fuel oil) must be included to maintain heating during periods of low digester gas production or high heating demand.

Natural gas is the most compatible alternate fuel because it has a low heat content and, consequently, can be blended and burned in a boiler with minimal equipment adjustment.

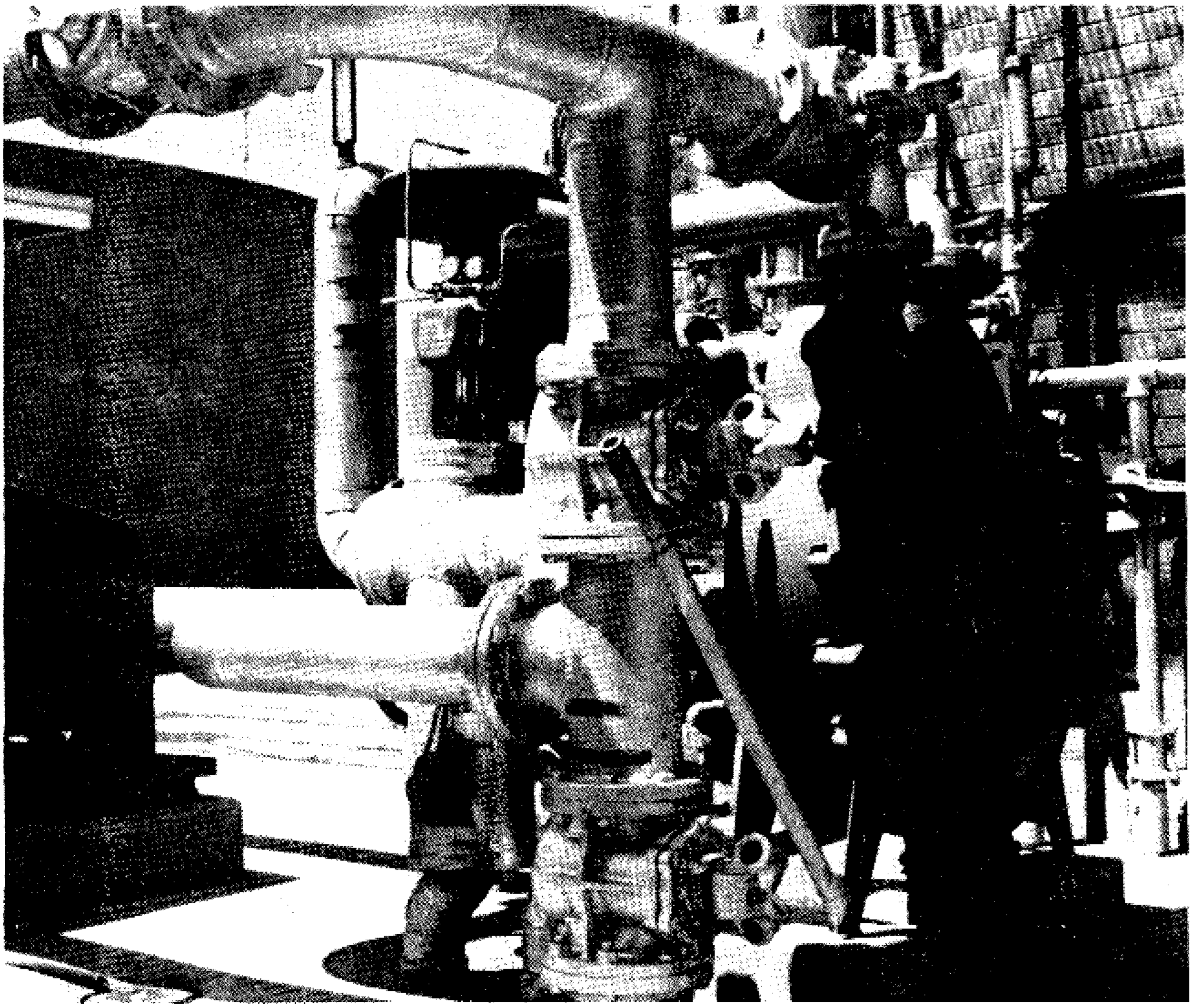


FIGURE 6-20

SPIRAL HEAT EXCHANGER OPERATING OFF SECONDARY HEAT LOOP AT SUNNYVALE, CALIFORNIA

Often, waste heat from sludge gas-powered engines used to generate electricity or directly drive equipment is sufficient to meet digester heating requirements. Typically, 18 to 20 percent of the low heating value of engine fuel can be recovered from the engine cooling system (38). Engines can be cooled by either a forced draft system in which water is pumped through the engine or a natural draft system (termed ebullient cooling) in which water is vaporized and circulates without pumping. The latter method yields a higher temperature (and thus more useful) source of heat and also increases engine life. A combination exhaust silencer and heat-recovery unit can be used to extract from the exhaust an additional ten to thirteen percent of the low heating value of the engine fuel (38). To prevent formation of corrosive acids, exhaust gases should not be cooled below 400°F (200°C).

Solar energy has been successfully used to heat anaerobic digesters (142), freeing sludge gas for higher grade uses. Heat is transferred to the raw sludge feed by passing the sludge piping through a tank of solar-heated water. The optimal size solar-heating system can supply 82 to 97 percent of the total annual heat load from solar energy, depending on geographical location (142). The economic attractiveness of using solar heating for digesters, however, is strongly dependent on the economic value of the sludge gas saved.

A unique method of generating heat is to precede anaerobic digestion with pure oxygen aerobic digestion (143). Biologically generated heat released in the aerobic reactor is sufficient to warm the sludge to as high as 125 to 140°F (52 to 60°C), as long as the solids concentration of the feed to the digestion system is kept above about 3.5 percent and the tank is well insulated. Heat balance calculations indicate that these temperatures are only attainable when pure oxygen is used because the low gas flow does not cool the reactor (144). The warm sludge is transferred to the anaerobic digester, where the bulk of stabilization occurs. In pilot tests (143), the contents of the anaerobic digester were maintained at 95°F (35°C) without the addition of supplemental energy, other than the power required to generate the pure oxygen. Temperature is controlled by changing the flow of oxygen to the aerobic digester. As yet there have been no full-scale installations of this method of heating digesters.

<u>Heat Required for Raw Sludge</u>. It is necessary to raise the temperature of the incoming sludge stream. The amount of heat required is:

$$Q_s = \left(\frac{\text{gal of sludge}}{\text{hr}}\right)\left(\frac{8.34\ \text{lb}}{\text{gal}}\right)(C_p)\ (T_2 - T_1) \qquad (6\text{-}3)$$

where:

Q_s = heat required to raise incoming sludge stream from temperature T_1 to T_2, Btu/hr

C_p = specific heat of sludge (approximately 1.0 Btu/lb/°F)

T_1 = temperature of raw sludge stream, °F

T_2 = temperature desired within the digestion tank, °F

As shown on Figure 6-21, the solids concentration of the raw sludge has a direct impact on the heating requirement. The significance of this graph is that a seemingly small change in feed sludge concentration can have a substantial effect on the raw sludge heating requirement.

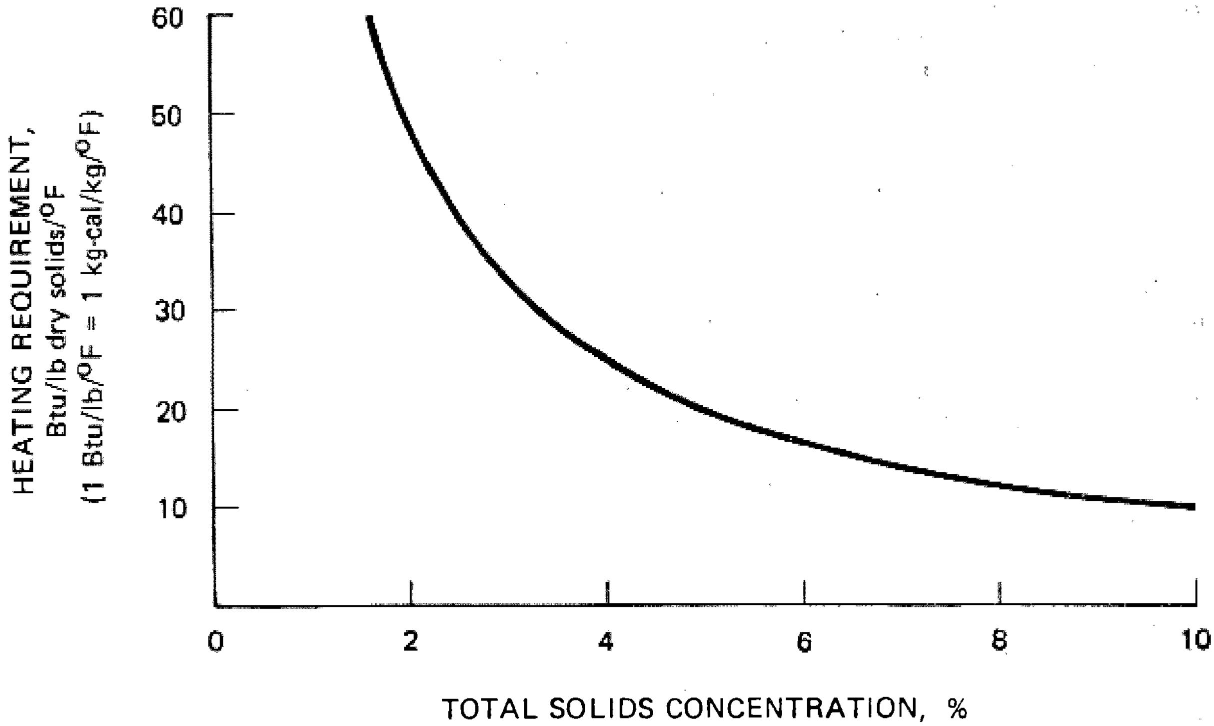


FIGURE 6-21

EFFECT OF SOLIDS CONCENTRATION ON THE RAW SLUDGE HEATING REQUIREMENT

Heat Required to Make up for Heat Losses. The amount of heat lost to the air and soil surrounding a digester depends on the tank shape, construction materials, and the difference between internal and external temperatures. The general expression for heat flow through compound structures is:

$$Q = (U)(A)(T_2 - T_3) \qquad (6-4)$$

where:

Q = heat-loss rate, Btu/hr

A = area of material normal to direction of heat flow, sq ft

T_2 = temperature within the digestion tank, °F

T_3 = temperature outside the digestion tank, °F

U = heat transfer coefficient, Btu/hr/sq ft/°F, which is directly affected by the film coefficient for interior surface of tank, and the film coefficient for exterior surface of tank, and inversely affected by the thickness of individual wall material, and the thermal conductivity of individual wall material.

Several other factors may affect the heat transfer coefficient U; however, they may be considered negligible for the purposes of digester design. Further discussion of heat transfer principles, along with lists of values for film coefficients and thermal conductivities, is available (84,145,146). Various values of U for different digester covers, wall construction, and floor conditions are given in Table 6-18.

TABLE 6-18

HEAT TRANSFER COEFFICIENTS FOR VARIOUS ANAEROBIC DIGESTION TANK MATERIALS (147)

Material	Heat transfer coefficient (u), Btu/hr/sq ft/°F
Fixed steel cover (1/4 in. plate)	0.91
Fixed concrete cover (9 in. thick)	0.58
Floating cover (Downes-type with wood composition roof)	0.33
Concrete wall (12 in. thick) exposed to air	0.86
Concrete wall (12 in. thick), 1 in. air space and 4 in. brick	0.27
Concrete wall or floor (12 in. thick) exposed to wet earth (10 ft thick)	0.11
Concrete wall or floor (12 in. thick exposed to dry earth (10 ft thick)	0.06

1 Btu/hr/sq ft/°F = 4.9 kg-cal/hr/m²/°C.
1 in. = 2.54 cm
1 ft = 0.304 m

Heat losses can be reduced by insulating the cover and the exposed walls of the digester. Common insulating materials are glass wool, insulation board, urethane foam, lightweight insulating concrete and dead air space. A facing is placed over the insulation for protection and to improve aesthetics. Common facing materials are brick, metal siding, stucco, precast concrete panels, and sprayed-on mastic.

6.2.6.3 Mixing

Digester mixing is considered to have the following beneficial effects:

- Maintaining intimate contact between the active biomass and the feed sludge.

- Creating physical, chemical, and biological uniformity throughout the digester.

- Rapidly dispersing metabolic end products produced during digestion and any toxic materials entering the system, thereby minimizing their inhibiting effect on microbial activity.

- Preventing formation of a surface scum layer and the deposition of suspended matter on the bottom of the tank. Scum and grit accumulations adversely affect digester performance by consuming active volume in the tank.

While the benefits of digester mixing are widely accepted, controversy and confusion arise in attempting to answer such questions as how much mixing is adequate, and what the most effective and efficient method is for mixing digesting sludge.

Although general theory of slurry mixing is well developed (148,149), little research has been focused on mixing of sludge. Studies of mixing in full-scale digesters have been made of both dye (150) and radioactive (105,151) tracers. These and other studies have shown that the contents of the digester are not completely mixed and that the degree of mixing attained is closely related to the total power actually delivered to the contents of the tank, irrespective of the actual mixing method used.

A certain amount of natural mixing occurs in an anaerobic digester, caused by both the rise of sludge gas bubbles and the thermal convection currents created by the addition of heated sludges. The effect of natural mixing is significant (150,152), particularly in digesters fed continuously and at high loading rates. However, natural mixing does not maximize the benefits of mixing and is insufficient to ensure stable performance of the digestion process. Therefore, mixers are an essential component in a high-rate digestion system. Methods used for mixing include external pumped circulation, internal mechanical mixing, and internal gas mixing. A review of digester mixing methods is available (57).

External Pumped Circulation

Pumped circulation, while relatively simple, is limited in a physical sense because large flow rates are necessary for high-rate digester mixing. However, this method can effect substantial mixing, provided that sufficient energy (0.2 to 0.3 hp per thousand cu ft of reactor (5 to 8 W/m^3) is dissipated in the tank (75). Greater pump power will be required if piping losses are significant. Pumped circulation is used most advantageously in combination with other mixing systems. Besides augmenting agitation, circulation allows external exchangers to be used for heating the digester and uniform blending of raw sludge with heated circulating sludge prior to the raw sludge's entering the digester.

A pumped circulation mixing system was recently installed in an 80-foot (24 m) diameter, fixed cover anaerobic digester at the Las Vegas Street Plant in Colorado Springs. Sludge is withdrawn from the top-center of the tank and pumped with a 16-inch (41 cm) horizontal, solids handling centrifugal pump to two discharge nozzles. These nozzles are located at the base of the sidewall, on opposite sides of the tank, and direct the sludge flow tangentially, inducing an upward spiral motion in the tank. Return flow from the pump can be directed to a single scum-breaker nozzle mounted near the liquid surface. The pump capacity is rated at 6,800 gallons per minute (429 l/s) at 21 feet total dynamic head (6.4 m) and is sufficient to pump the entire digester contents in 3.5 hours. The new mixing system has successfully eliminated temperature stratification and scum buildup. Another type of pumped circulation system using sequential pumping through multiple pipes strapped to the floor of the digester is described in Reference 153.

Internal Mechanical Mixing

Mixing by means of propellers, flat-bladed turbines, or similar devices is widely practiced in the process industries. Its usefulness, when applied to wastewater sludge digesters, is limited by the nature of non-homogeneous wastewater sludge. The large amounts of raggy and relatively inert, nonfluid material in wastewater sludge results in fouling of the propellers and subsequent failure of the mechanisms. The practice of grinding screenings within the wastewater flow will accelerate ragging.

Mechanical mixers can be installed through the cover or walls of the tank. In one design, a propeller drives sludge through a draft tube to promote vertical mixing. Wall installations restrict maintenance and repair to the time when the digester has been emptied (usually every three to five years in well maintained plants). Strong mechanical mixing can be effected with about 0.25 hp/thousand cubic feet of reactor (6.6 W/m^3) (75).

Internal Gas Mixing

Several variations of gas mixing have been used for digesters, including:

- The injection of a large sludge gas bubble at the bottom of a 12-inch (30 cm) diameter tube to create piston pumping action and periodic surface agitation.

- The injection of sludge gas sequentially through a series of lances suspended from the digester cover to as great a depth as possible, depending on cover travel.

- The free or unconfined release of gas from a ring of spargers mounted on the floor of the digester.

- The confined release of gas within a draft tube positioned inside the tank.

The first method generally has a low power requirement, and consequently, produces only a low level of mixing. As a result, the major benefit derived from its use is in scum control. Lance free gas lift, and draft tube gas mixing, however, can be scaled to induce strong mixing of the digester contents. The circulation patterns produced by these two mixing methods differ. As shown on Figure 6-22 in the free gas lift system, the gas bubble velocity at the bottom of the tank is zero, accelerating to a maximum as the bubble reaches the liquid surface. Since the pumping action of the gas is directly related to the velocity of the bubble, there is no pumping from the bottom of the tank with a free gas lift system. In contrast, a draft tube acts as a gas lift pump which, by the law of continuity, causes the flow of sludge entering the bottom of the draft tube to be the same as that exiting at the top. Thus, the pumping rate is largely independent of height, as shown on Figure 6-23. The significance of this difference is that draft tube mixers induce bottom currents to prevent or at least reduce accumulations of settleable material. Velocity profiles shown on Figure 6-24 (see page 6-58) indicate that lance type mixers induce comparable bottom velocities. Another difference among internal gas mixing systems is that the gas injection devices in a free gas lift system are fixed on the bottom of the digester and thus cannot be removed for cleaning without draining the tank. To reduce clogging problems, provisions should be made for flushing the gas lines and diffusers with high pressure water. With the lance and draft tube systems, the gas diffusers are inserted from the roof and, therefore, can be withdrawn for cleaning without removing the contents of the tank. A drawback of these systems, though, is that the draft tube and gas lines suspended inside the tank may foul with rags and debris contained in the digesting sludge.

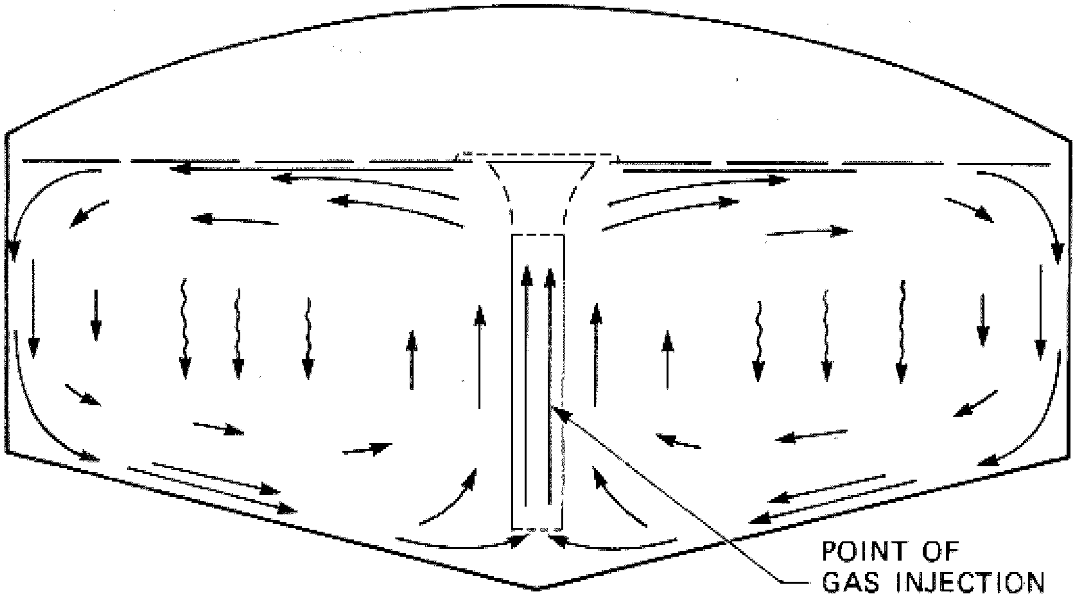
Basis for Sizing Gas Lift Mixers. Three basic criteria have been used to determine the size of gas lift mixing systems:

- Unit power (power per unit volume)

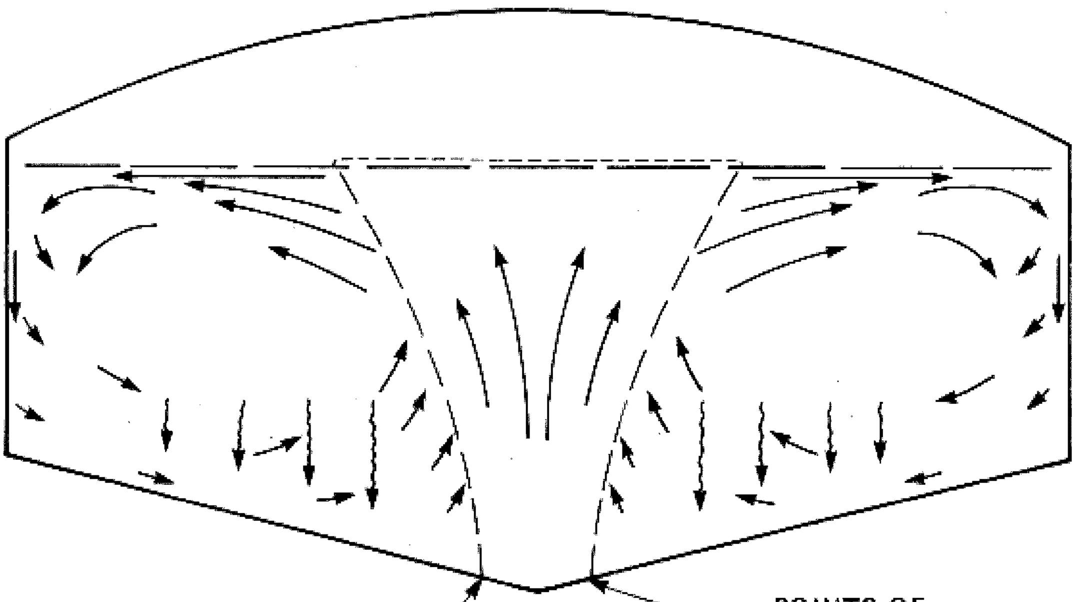
- Velocity gradient (G value)

- Unit gas flow (gas flow per unit volume)

Each of these criteria is interrelated so that one can be calculated from the other once a few assumptions are made about gas discharge pressure and sludge viscosity. The size of new



DRAFT TUBE MIXER



FREE GAS LIFT MIXER

FIGURE 6-22

CIRCULATION PATTERNS PRODUCED BY DRAFT TUBE AND FREE GAS LIFT MIXERS mixing systems has tended to increase in recent years as the importance of strong mixing in anaerobic digesters has become more widely recognized. However, oversizing of mixing systems not only results in excess equipment and operating costs but also may aggravate foaming problems.

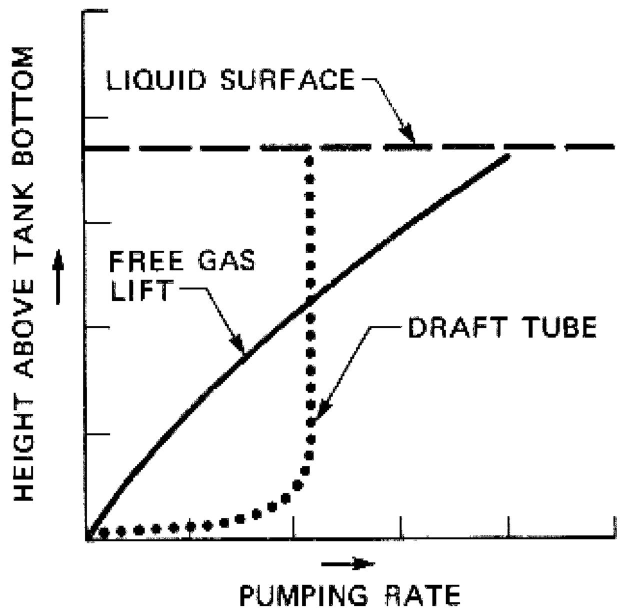


FIGURE 6-23

DRAFT TUBE AND FREE GAS LIFT PUMPING RATE

Unit Power. The use of the unit power criterion stems from the observation that the relative effectiveness of mixing is closely related to the total power expended (137,152). Generally, strong mixing can be achieved if 0.2 to 0.3 hp is used to mix each thousand cubic feet (5 to 8 W/m^3) of digester volume. The unit power criterion is expressed in terms of the motor horsepower used to drive the compressor. Less power is actually delivered to the liquid because of losses in the mixing system (for example, friction losses, compressor inefficiency).

Velocity Gradient. Camp and Stein (154) have suggested use of the root-mean-square velocity gradient (G) as a measure of mixing intensity expressed mathematically:

$$G = \sqrt{\frac{W}{\mu}} \qquad (6-5)$$

where:

G = root-mean-square velocity gradient, $\frac{ft/sec}{ft} = sec^{-1}$

W = power dissipated per unit volume

$$\frac{\text{ft-lb}_{\text{force}}/\text{sec}}{\text{cu ft}} = \text{lb}_f/\text{sq ft/sec}$$

$$W = \frac{E}{V} \qquad (6\text{-}6)$$

where:

E = rate of work on energy transfer (power), ft-lb$_f$/sec, and

V = volume of reactor, cu ft

μ = absolute viscosity of the liquid, lb$_f$-sec/sq ft

The velocity gradient is a more refined design criterion for mixing than the unit power criterion in that it takes into account the power actually transferred to the liquid (E), and the viscosity of the liquid ( ). Determination of these values for gas lift mixing in digesters is described below.

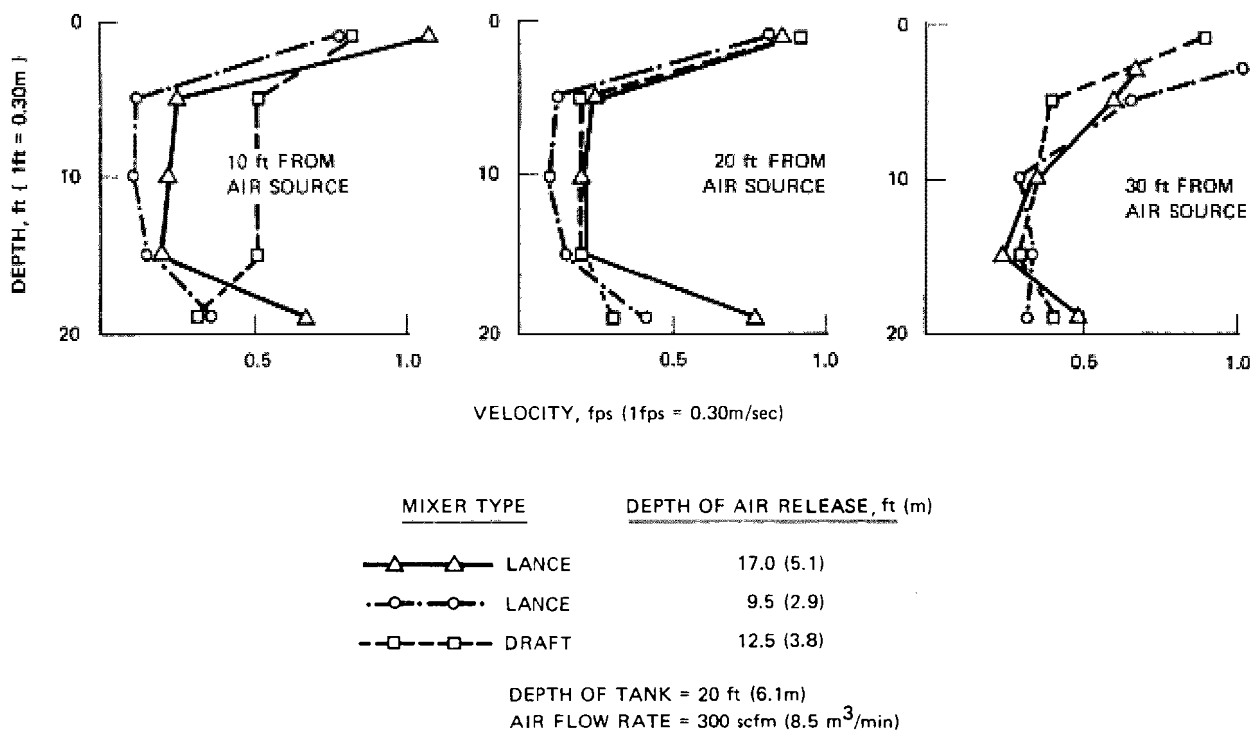


FIGURE 6-24

COMPARISON OF LANCE AND DRAFT TUBE MIXING IN CLEAN WATER (147)

When gas is discharged into a digester, liquid flow results from the transfer of energy from the gas to the liquid as the gas isothermally expands and rises to the surface. If the liquid vapor pressure and the kinetic energy of the gas are ignored, the power transferred from the gas to the liquid may be expressed as (155):

$$E = 2.40\ P_1(Q)\ln\left(\frac{P_2}{P_1}\right) \qquad (6\text{-}7)$$

where:

E = rate of work or energy transfer (power), ft-lb_f/sec

Q = gas flow, cfm

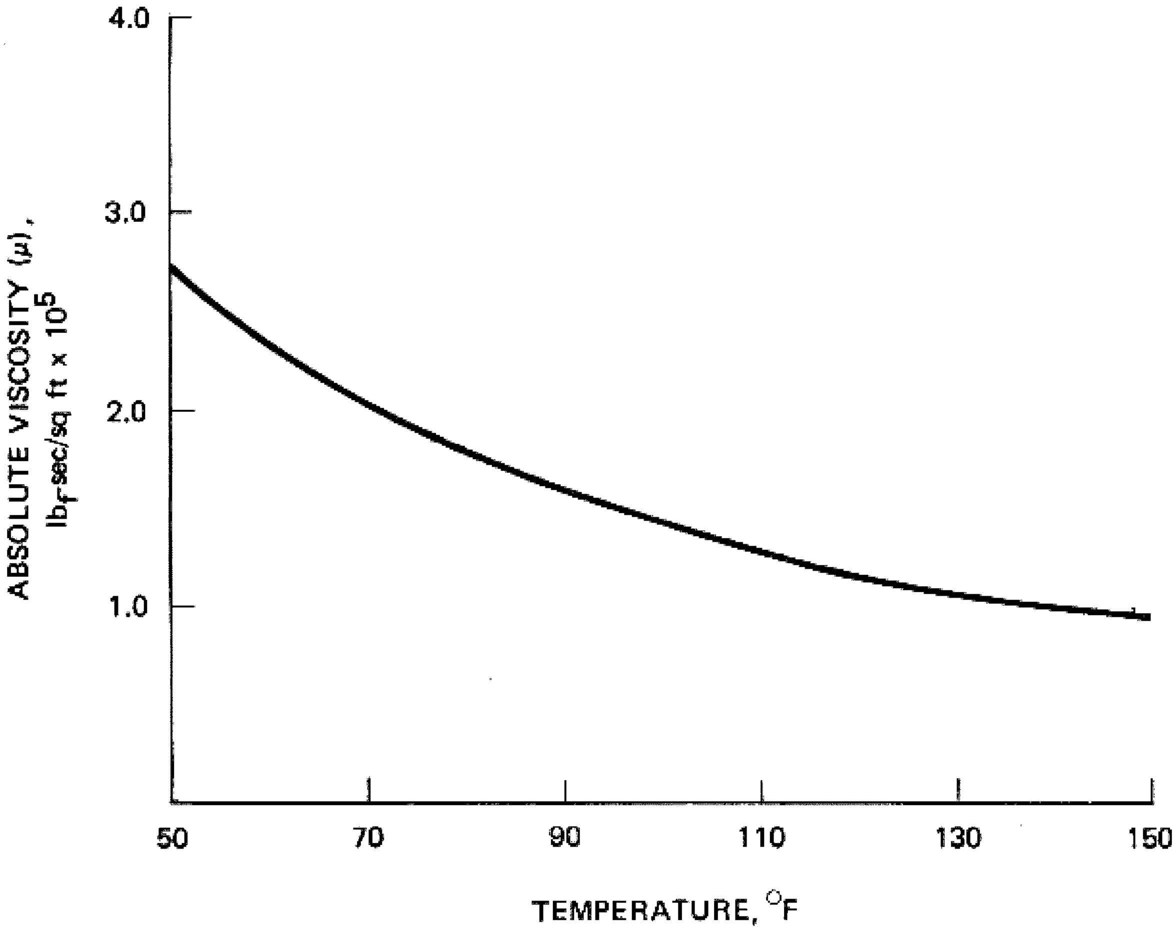
P_1 = absolute pressure at the liquid surface, psi

P_2 = absolute pressure at the depth of gas injection, psi

Therefore, given a gas flow through a mixer system and the depth of the diffuser, Equation 6-7 can be used to calculate the power transferred to the digester liquid (E). The power dissipated per unit volume (W) can then be calculated by dividing the rate of energy transfer (E) by the volume of the digester (V).

There is little information on the rheology (flow properties) of unstabilized wastewater sludges although some data does exist on the rheology of anaerobically digested sludge (156,157). This is partly because it is extremely difficult to do such studies correctly (158). In general, digesting sludge seems to be a pseudoplastic material exhibiting only slight thixotropic properties (156). Pseudoplastic liquids become less viscous at higher shearing rates. Thixotropic liquids become less viscous with time at a constant sharing rate. Chapter 14 has additional information on sludge rheology.

Three parameters--temperature, solids concentration, and volatile content appear to affect sludge viscosity. As the temperature of sludge is increased, its viscosity is reduced. The relationship between temperature and viscosity for water is presented on Figure 6-25. (A similar relationship between temperature and sludge viscosity exists, although this has not been documented.) The viscosity of sludge increases exponentially as the solids concentration increases (159), as shown on Figure 6-26. This graph also shows that viscosity increases with the volatile content of the sludge; however, the effect is only noticeable when the solids content of the digesting sludge is greater than three percent. The entrapment of gas bubbles in digesting sludge may also affect viscosity, although the magnitude of this effect has not been measured. In general, then, it is not possible to pinpoint the viscosity of digesting sludge although major influences can be identified.

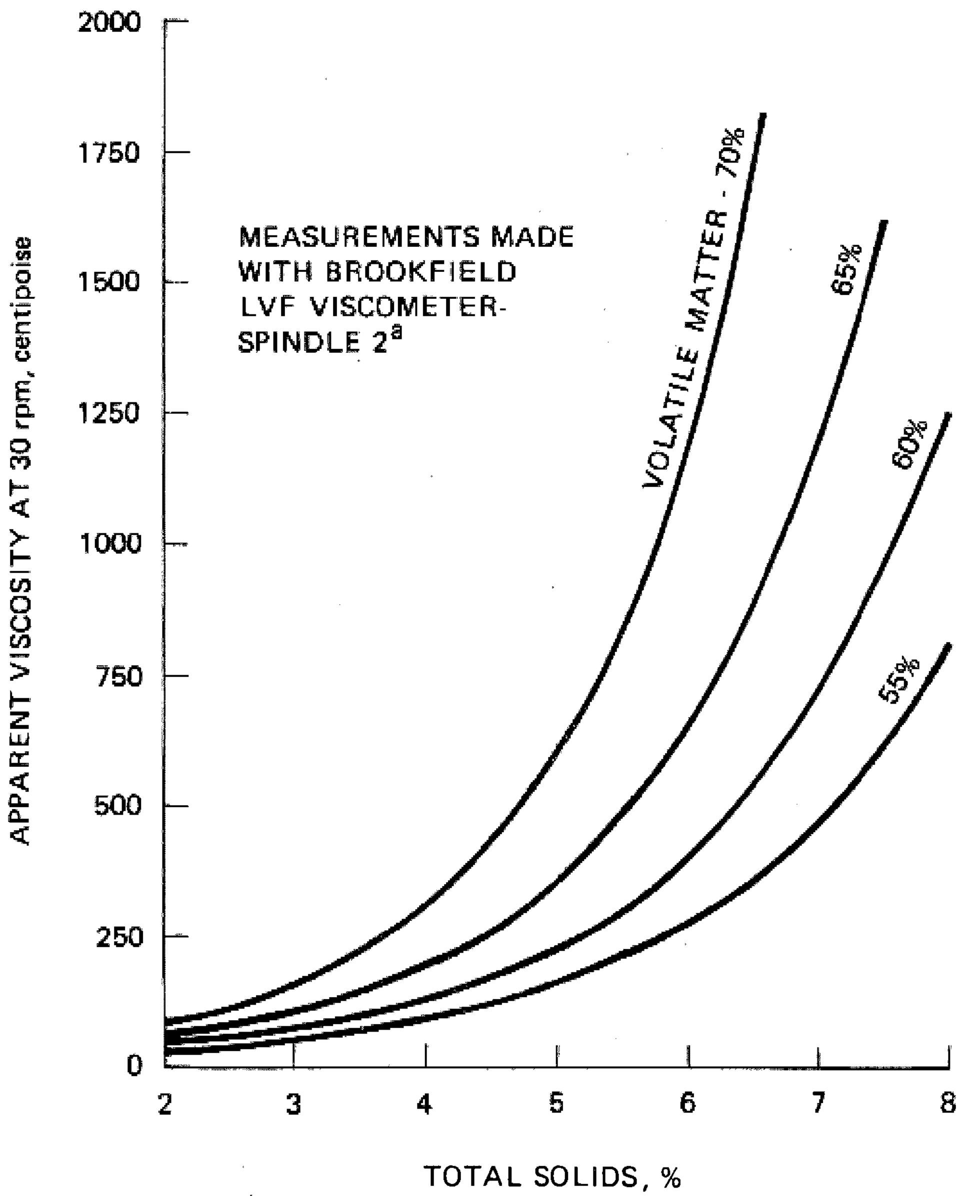


(1 centipoise = 2.08×10^{-5} lb-sec/ft ^{2})

FIGURE 6-25

EFFECT OF TEMPERATURE ON THE VISCOSITY OF WATER

The appropriate "G value" to use for design is difficult to determine. In general, the "G value" should be between 50 and 80 sec^{-1}. Walker (75) recommends a "G value" of 85 sec^{-1} for substantial auxiliary mixing. A design value at the high end of the range should be selected for a large digester with only a single mixer, or in a case where grit or scum problems appear likely. A lower "G value" is appropriate in cases where several mixers are distributed through the tank or where sufficient detention time has been provided to allow a slower rate of



[a] THE BROOKFIELD VISCOMETER OPERATES IN A VERY LOW SHEAR STRESS RANGE, SO APPARENT VISCOSITIES ARE VERY HIGH. THIS DATA SHOULD NOT BE USED TO CALCULATE SLUDGE FLOW IN PIPES IN THE LAMINAR FLOW REGIME.

FIGURE 6-26

EFFECT OF SOLIDS CONCENTRATION AND VOLATILE CONTENT ON THE VISCOSITY OF DIGESTING SLUDGE (156) digestion. The use of a two-speed compressor provides the capability to match mixing intensity with variations in operating conditions.

An example of gas mixer sizing is found in Section 6.2.9.3.

Unit Gas Flow. As described in the preceding paragraphs, gas flow through a mixing system can be related to the mixing energy delivered to the liquid. Therefore, a simple way to size a gas lift mixer is to specify a unit gas flow. For a draft-tube system, 5 to 7 scfm/thousand cubic foot of digester (5 to 7 $m^3/min/km^3$) at about 6 psig (41.4 kN/m^2) is sufficient to produce strong mixing. Less gas is required for a free-lift system, 4.5 to 5 cfm per thousand cubic feet (4.5 to 5 $m^3/min/km^3$) of reactor; however, the pressure must be higher since the gas is discharged at the bottom of the tank (75). 1.5 to 2.0 cfm per foot (0.14 to 0.19 $m^3/min/m$) of diameter (0.14 to 0.19 $m^3/min/m$) has also been recommended for free gas lift mixers (137).

The unit gas flow can be related to the velocity gradient by combining equations 6-5, 6-6 and 6-7 and solving for $\frac{Q}{V}$, the unit gas flow:

$$\frac{Q}{V} = \frac{G^2 \mu}{\left(P_1\right) \ln \left(\frac{P_2}{P_1}\right)} \qquad (6\text{-}8)$$

The values in Table 6-19 were calculated from this equation.

6.2.6.4 Covers

Anaerobic sludge digestion tanks are covered to contain odors, maintain operating temperature, keep out oxygen, and collect digester gas. Digester covers can be classified as either fixed or floating. Cross sections of both types are shown on Figure 6-27. Floating covers are more expensive but allow independent additions and withdrawals of sludge, reduce gas hazards, and can be designed to control formation of a scum-mat.

Fixed digester covers are fabricated from steel, reinforced concrete and, since the mid-1970s, corrosion-proof fiberglass reinforced polyester (FRP). In most cases, fixed covers are dome-shaped, although conical and flat concrete covers have been built. Concrete roofs are susceptible to cracking caused by rapid temperature changes. Consequently, gas leakage has been a frequent problem with reinforced concrete covers (75).

Generally, fixed-cover digesters are operated so as to maintain a constant water surface level in the tank. Rapid withdrawals of digested sludge (without compensating additions of raw sludge) can draw air into the tank, producing an explosive mixture of sludge gas and oxygen. The explosive range of sludge gas in air is 5 to 20 percent by volume (52). In addition, there have been cases in which the liquid level under the fixed cover has been allowed to increase sufficiently to damage the cover structurally. Usually, this involves a tightly clogged overflow system and a forgotten feed valve.

TABLE 6-19

RELATIONSHIP BETWEEN THE VELOCITY GRADIENT AND UNIT GAS FLOW

G Velocity gradient, sec^{-1}	Q/V Unit gas flow[a], cfm/1,000 cu ft
40	2.1
50	3.3
60	4.4
70	6.4

[a]Calculated assuming depth of gas release is 13 ft and that absolute viscosity of sludge is the same as for water at 95°F.

1 cfm/1,000 cu ft = 1 m^3/min/1,000 m^3

Traditionally, floating covers have followed one of two designs: the pontoon or Wiggins type and the Downes type (Figure 6-27). Both types of covers float directly on the liquid and commonly have a maximum vertical travel of 6 to 8 feet (2 to 3 m). These cover designs differ primarily in the method used to maintain buoyancy, which, in turn, determines the degree of submergence. In the Wiggins design, the bottom of the cover slopes steeply along the outer edge. This outer portion of the cover forms an annular pontoon or float that results in a large liquid displacement for a small degree of cover-plate submergence. Therefore, Wiggins covers have only a portion of the annular area submerged, with the largest portion of the cover exposed to the gas above the liquid surface. However, for the Downes design, as shown on Figure 6-27, the bottom of the cover slopes gradually throughout the entire radius, thereby providing only a small liquid displacement for a greater degree of ceiling plate submergence. Typically, the outer one-third of the radius of the Downes cover is in contact with the liquid. However, it is desirable to increase the degree of submergence by adding ballast to the cover, thus keeping the liquid level a few inches within the central gas dome. This keeps floating matter submerged and subject to mixing action, reduces the area exposed to corrosive sludge gas, and adds to cover stability. The fundamental principle used to calculate ballast requirements is that at equilibrium, a floating cover displaces a volume of liquid equal in weight to the total weight of the cover. Ballast can be added as concrete blocks or as a layer of concrete spread across the upper surface of the cover.

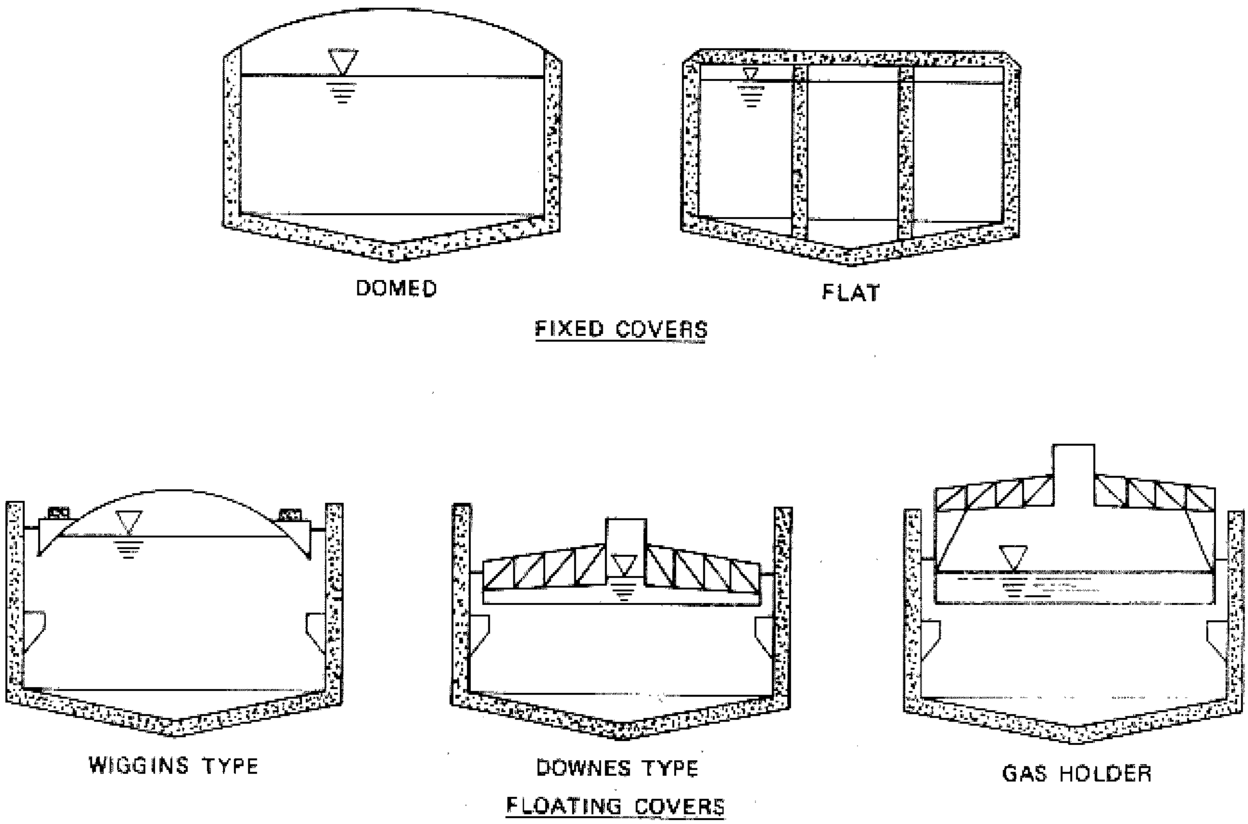


FIGURE 6-27

TYPES OF DIGESTER COVERS

A variation of the floating cover is the floating gas holder, shown on Figure 6-27. Basically, a gas holder is a floating cover with an extended skirt (up to 10 feet [3 m] high) to allow storage of gas during periods when gas production exceeds demand. However, storage pressure in a gas holder is low--a maximum of 15 inches water column (3.7 kN/m^2). Therefore, this type of cover will store up to three to six hours of gas production, based on about six feet (2 m) of net travel. Greater storage is achieved by compressing the gas for high pressure storage in spheres or horizontal cylinders, or by providing a separate low pressure displacement storage tank.

Gas-holding covers are less stable than conventional floating covers because they are supported entirely by a cushion of compressible gas rather than incompressible liquid and because they expose a large side area to lateral wind loads. To prevent tipping or binding, ballast at the bottom of the extended skirt and spiral guides must be provided.

Typical appurtenances for a digester cover include sampling ports; manholes for access, ventilation, and debris removal during cleaning; a liquid overflow system; and a vacuum-pressure relief system equipped with a flame trap. The permissible range of gas pressure under a digester cover is typically 0 to 15 inches of water (0 to 3.7 kN/m^2). Figure 6-28 provides an overview of four floating covered digesters with appurtenant equipment.

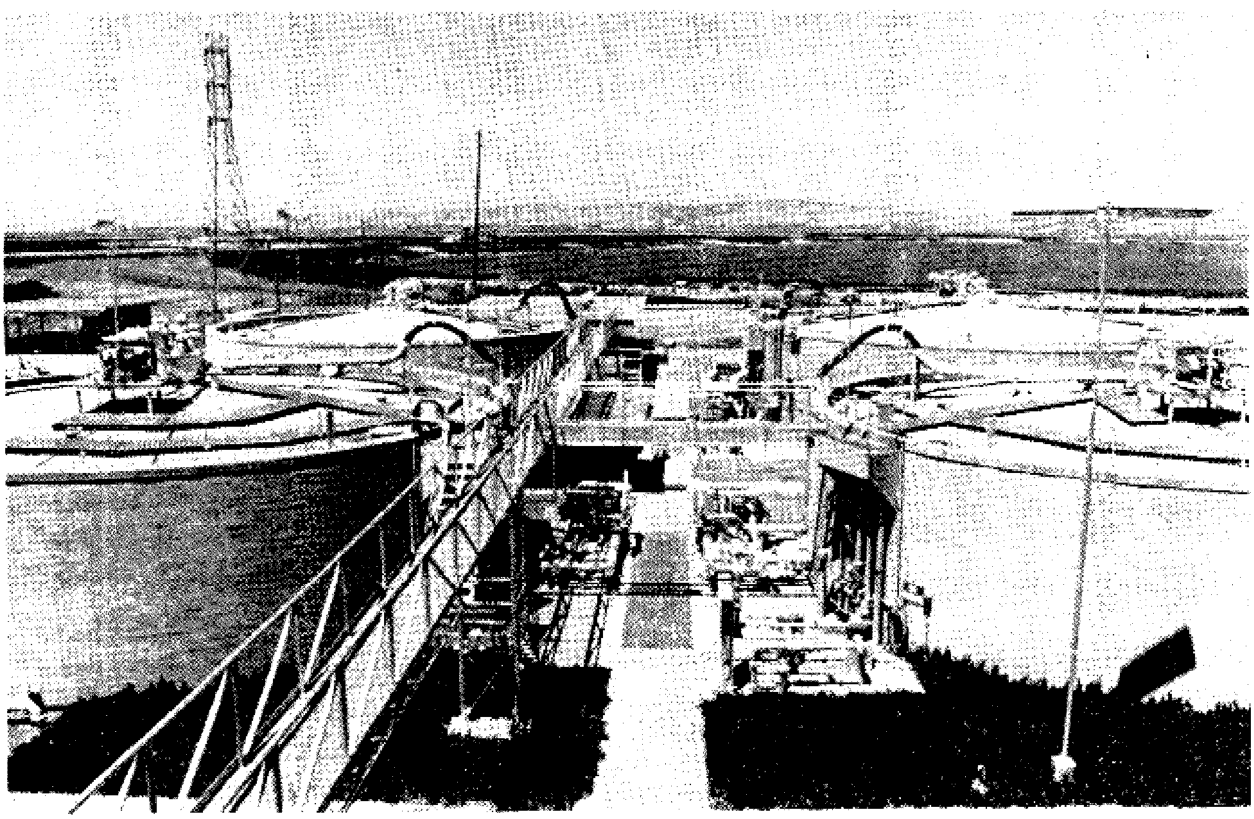


FIGURE 6-28

OVERALL VIEW OF FOUR DIGESTERS WITH DOWNES FLOATING COVERS AT SUNNYVALE, CALIFORNIA

6.2.6.5 Piping

The piping system for an anaerobic digester is an important component of the design. Many activities take place during the operation of a digester: feeding of raw sludge, circulation of sludge through the heat exchanger, withdrawal of digested sludge and supernatant, and collection of sludge gas. The piping system should be designed to allow these activities to occur concurrently, yet independently. Flexibility should also be built into the piping system to allow operation in a variety of modes and to ensure that digestion can be continued in the event of equipment breakdown or pipe clogging.

Feeding of incoming sludge into anaerobic digesters can be automated to load the tanks frequently and uniformly. Switching feeds between several tanks can be controlled based on either time, hydraulic flow, or solids flow. A time-controlled feed system uses a repeat-cycle timer to sequentially open and close the feed valve for each digester. Switching between digesters can occur every thirty minutes to four hours. A flow-controlled feed system uses a flowmeter on the raw sludge pipeline, in combination with a totalizer, to load preset volumes to each digester. These may or may not be equal depending on the individual characteristics of each digester. A feed control system based on solids flow requires the measurement of both raw sludge flow and density. Since density is correlated with the concentration of solids in sludge, these two signals can be combined to yield a measure of the solids mass being fed to the digesters. Selection of flowmeters and density meters for sludge is discussed in Chapter 17.

Raw sludge should enter the digester in the zone of intense mixing to disperse the undigested organics quickly. Raw sludge, before entering the digester, should be mixed with warm circulating sludge to seed the incoming sludge and avoid thermal shock. The introduction of cold feed sludge into regions where there is no local mixing results in the feed sludge sinking to the digester bottom and becoming an isolated mass.

Digested sludge is usually drawn off the bottom of the tank, although means to withdraw sludge from at least one other point should be provided in case the main line becomes plugged. A supernatant collection system, when required, should have drawoff points at three or more elevations to allow the operator to remove the clearest supernatant. An example of a supernatant collection system is shown on Figure 6-29. The telescopic valve is used to adjust the water surface level in the digester. An unvalved overflow with a vent as a siphon breaker is provided to ensure that the tank cannot be overfilled.

Special consideration should be given in the design of sludge-piping systems to prevent the deposition of grease and clogging with debris. Sludge piping generally has a minimum diameter of 6 inches (150 mm), except for pump discharge lines in small plants, where four-inch (100 mm) diameter pipes may be acceptable. Where possible, considering these minimum pipe size recommendations, velocities in sludge pipelines should be maintained above four feet per second (1.2 m/sec) to keep sludge solids in suspension. The hydraulics of sludge piping is described in detail elsewhere (84,160). Glass lining of cast iron and steel pipe will prevent the buildup of grease and is recommended for all pipes conveying scum and raw sludge. The grease content of sludge is typically reduced by 50 percent or more during digestion, so that glass lining is not warranted for pipes carrying digested or circulating sludge. Sludge piping is generally kept as short as practicable, with a minimum number of bends. Long radius elbows and sweep tees are preferred for changes in direction. Provisions are commonly made for cleaning sludge lines with steam, high pressure water, or mechanical devices. These provisions should include blind flanges, flushing cocks, and accommodation for thermal expansion.

A problem unique to anaerobic digestion systems is the buildup of crystalline inorganic phosphate deposits on the interior walls of the tank and downstream piping. This encrustation will increase pipeline friction, displace volume in the digestion tank, and foul downstream mechanical equipment (102). This chemical scale has formed not only in digested sludge lines, but also on mechanical aerators for facultative sludge lagoons and in pipes carrying either digester supernatant or filtrate/centrate. Laboratory analyses have identified this material as magnesium ammonium phosphate ($MgNH_4PO_4 \cdot 6\ H_2O$), more commonly known as guanite or struvite. It has a specific gravity of 1.7, decomposes when heated, and is readily soluble only in acid solutions. Methods successfully used to prevent this buildup include (161):

- Aerobic digestion of the sludge stream with the highest phosphate content
- Dilution of digested sludge flows to prevent supersaturation and to raise pipeline velocities
- Limiting magnesium ion concentration in the stream
- Substitution of PVC pipe for cast-iron pipe to reduce interior roughness

6.2.6.6 Cleaning

Anaerobic digestion tanks can become partially filled with a bottom layer of settled grit and a top layer of floating scum. These accumulations reduce the volume available for active digestion and thereby degrade the performance of the digesters. Periodically, the digestion tank must be drained and these deposits removed. This cleaning process is usually expensive and unpleasant. Furthermore, it can disrupt normal processing of sludge for as long as several months. Therefore, attention should be given during design to (1) reducing the rate at which grit and scum can accumulate, and (2) making it easy to clean the digester when it becomes necessary.

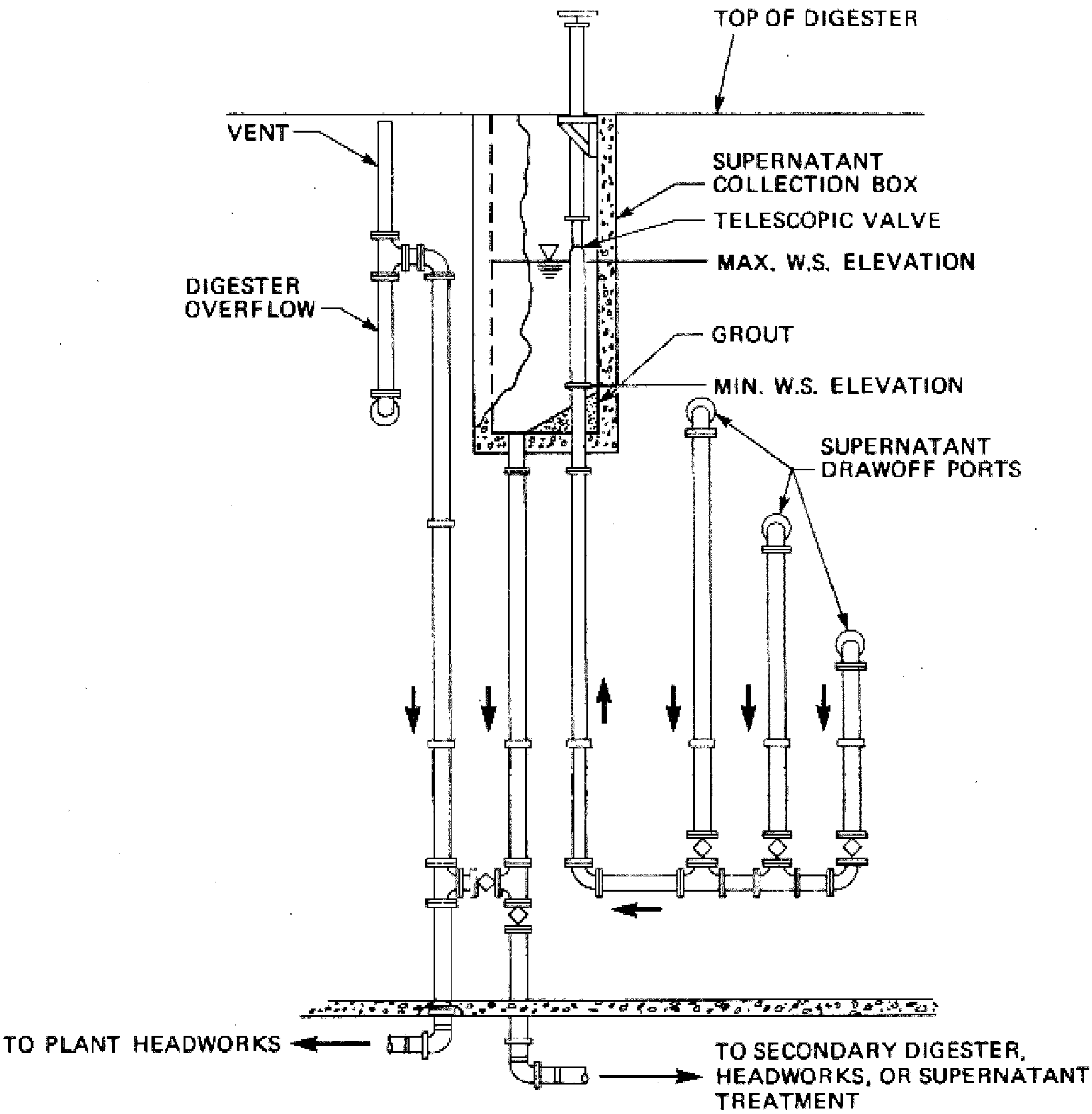


FIGURE 6-29

TYPICAL DIGESTER SUPERNATANT COLLECTION SYSTEM

Prevention of Grit and Scum Buildup

The most sensible approach to minimizing digester cleaning is to prevent grit and scum from entering the system. This can be accomplished through effective grit removal in the headworks of the plant coupled with separate processing of scum (for example, incineration or hauling to a rendering plant). A second mitigation measure, which is almost as effective, is to maintain a homogeneous mixture within the digester so that the grit and scum cannot separate out. This is best achieved by strong mixing and positive submergence of the liquid surface under a floating cover (refer to the preceding sections on mixers and covers).

Provisions can also be made to remove grit and scum easily from the digester while normal digestion continues. Grit removal from the digester can be improved by providing multiple withdrawal points, or steep floor slopes (as in a waffle bottom or egg-shaped digester). An access hatch in the digester cover, or pipes extending into the upper levels of the digesting sludge, can be used to remove floating material in the tank before it forms a mat. Strong mixing in the tank will carry floating material down into the zone of active digestion, where it will be broken down. Other methods of scum control in digesters are described in References 41 and 162.

Facilities for Digester Cleaning

Traditionally, digester cleaning has been a difficult, dirty task. As a result, it is often postponed until tank capacity is severely reduced. Cleaning then becomes even more onerous because of the increased urgency and scope of the operation. If a digester can be cleaned easily, it is much more likely that it will be cleaned regularly.

To ensure that the digesters can be easily cleaned, it is important for the designer to consider the following questions:

- What will be done with the raw sludge while the tank is out of service? Typically, raw sludge flow is distributed to the remaining tanks as long as there is adequate capacity. The problem, however, becomes much more serious in a plant with only one digester. Possibly, a temporary aerobic digester or an anaerobic lagoon can be devised, although odors may be a problem with the latter. Lime may be added to the raw sludge to disinfect it and control odors (see Section 6.4).

- How will the tank be drained? There is a risk of explosion during the period in which the tank is being emptied, making it important to speed this step in the cleaning process. Addition of a separate digester drain pump in the Sunnyvale treatment plant in California allows each tank to be emptied in less than two days. As shown on Figure 6-30, the intake of the drain pump is located below the low point on the digester floor, from where the pump draws. As a result, the pump also serves to remove the slurry of grit and washwater rapidly. The volume of washwater required has been greatly reduced by the addition of the drain pump. Four to 5 feet (1.2 to 1.5 m) of sand on the bottom can be washed from the tank with washwater amounting to less than a quarter of the total tank volume.

Traditionally, the volume of washwater is two to four times the tank volume. Once drained, the Sunnyvale digesters can be scrubbed down in one day, and start-up can begin the next day. Before the drain pump was installed, all material removed from the tank had been lifted out through the manholes in the sidewalls. Consequently, it took 30 to 60 days to drain and clean a digester. In either case, an additional month will be required to restore the biological process completely, unless it is seeded from other "healthy" digesters. Ten to fifteen percent of the digester's volume is usually required for adequate seeding. A seeded digester can be brought back into full biological activity in less than a week.

- Where will the contents of the tank and the washwater be taken? Placing these materials on a sand-drying bed or in an existing sludge lagoon are two simple solutions to the problem. Construction of a small earthen basin, specifically for use during digester cleaning, may be warranted. Hauling material in tank trucks to another treatment plant or to a suitable dispoal site is another option. Mechanical dewatering equipment may be used to reduce the volume for hauling, but the large proportion of abrasive material (grit) contained in the sludge and wash water may produce excessive wear.

At the Joint Water Pollution Control Plant, operated by the County Sanitation Districts of Los Angeles County, all washwater is treated in a separate digester cleaning facility. The washwater is first passed through sieve bend type (static) strainers and then pumped to cyclonic grit separators. The removed grit is cleaned in a helical screw grit washer and, along with the screenings, is transported by conveyor to storage hoppers. These hoppers are emptied daily and the material trucked to a sanitary landfill. Figure 6-31 shows the cyclonic grit separator and static screens at this plant. The liquid discharged from the cyclonic grit separators is further processed in dissolved air flotation tanks. Liquid underflow from these flotation tanks is diverted to the primary sedimentation tanks, while float and settled material are combined with digested sludge flow and fed to the plant's sludge dewatering system. The digester cleaning facility now serves 33 digesters with a combined capacity of 5.7 million cu ft (21,200 m^3). A full-time seven-man crew is required for digester cleaning, allowing a five-year cleaning cycle. New digester additions under construction in 1979 will lenghten this period to seven years. In 1973, the bid for construction of the digester cleaning facility was approximately $3,000,000.

- How will access be provided into the tank? Manholes should be provided through both the cover and the sidewalls of the tank to allow for ventilation, entrance of equipment and personnel, and removal of organic and inorganic debris. Often in the past, the number and size of these openings has not been sufficient for easy cleaning.

- Is there a source of water for washing the tank and refilling it for start-up? Washdown water should be air-gapped and capable of supplying a pressure in excess of 60 psi (414 kN/m^2) through a hose of at least one-inch (2.5 cm) diameter. Larger capacities are required for digesters greater than 55 feet (17 m) in diameter. Once the tank has been cleaned, start-up begins by filling the tank with either raw wastewater, primary effluent, or unchlorinated secondary effluent, and bringing the entire contents up to operating temperature. If seed sludge is to be used, it should be fed into the digester as soon as its liquid contents have achieved operating temperature.

Additional discussions of digester cleaning and start-up can be found in references 164 and 165.

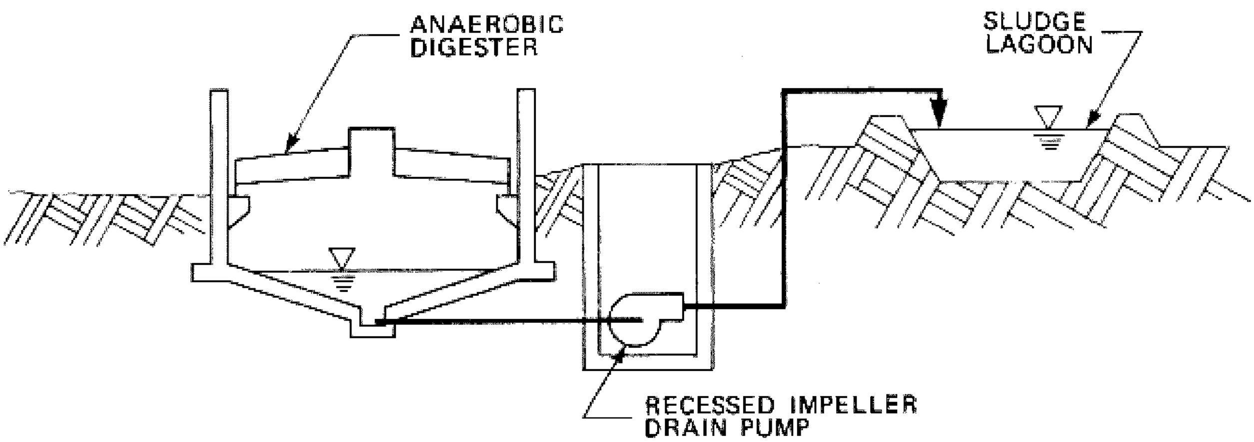


FIGURE 6-30

DIGESTER DRAIN SYSTEM

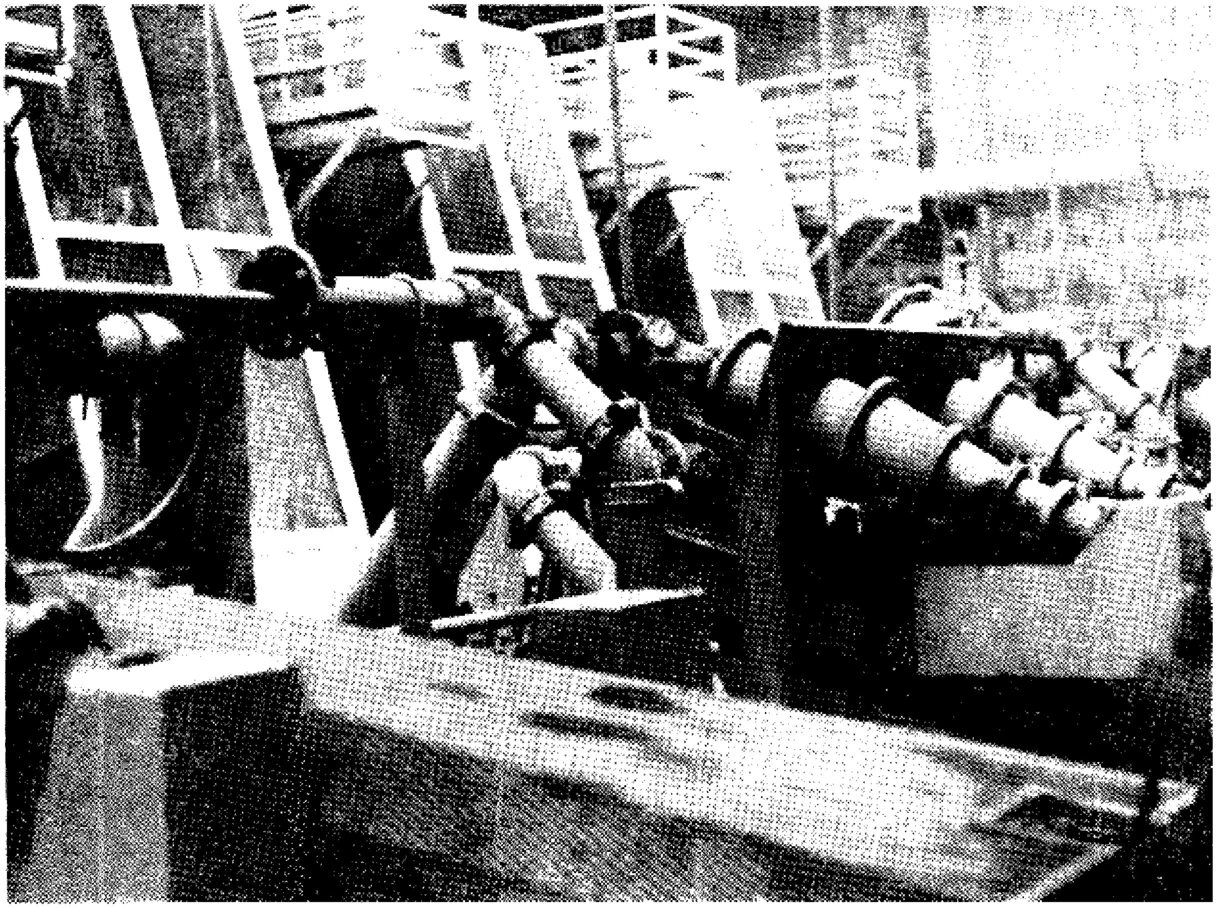
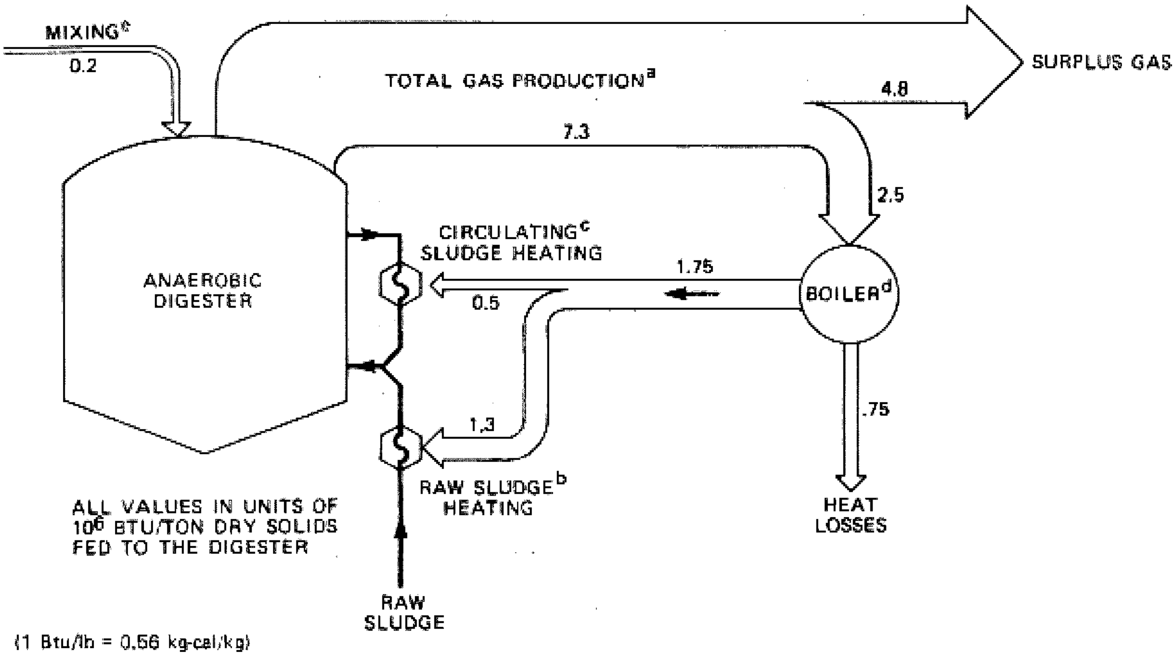


FIGURE 6-31

DIGESTER WASHWATER CLEANING BY CYCLONIC SEPARATORS, GRIT DEWATERERS, AND STATIC SCREENS AT LOS ANGELES COUNTY CARSON PLANT

6.2.7 Energy Usage

The flow of energy through a typical anaerobic digester system is displayed on Figure 6-32. In this simple system, a hot water boiler, fueled with sludge gas, is used to heat the digesters. The digestion system shown on Figure 6-32 produces more energy than it requires in the form of digester gas. The energy required for digestion is mainly to heat the sludge. The energy consumed in mixing the digester contents is very small in comparison. Surplus digester gas can be (1) burned in a boiler to produce heat for buildings in the plant, (2) used to power an engine to generate electricity or directly drive a pump, (3) sold to the local utility for use in the domestic gas supply, or (4) flared



[a]Raw sludge volatile solids contents, percent	75
Volatile solids reduction during digester, percent	50
Specific gas production, cu ft/lb VS reduced	15
Heat value of gas, Btu/cu ft	650

$$2{,}000\ \text{lb/ton}\ (.75)\ (.50)\ (15\ \frac{\text{cu ft}}{\text{lb}})\ (650\ \frac{\text{Btu}}{\text{cu ft}}) = 7.3 \times 10^6\ \text{Btu/ton}$$

[b]Feed solids concentration, percent
Specific heat of sludge, Btu/lb/°F
Rise in temperature, °F

$$\frac{2{,}000\ \text{lb/ton}}{0.04}\ (1\ \frac{\text{Btu}}{\text{lb-}^\circ\text{F}})\ (25^\circ\text{F}) = 1.3 \times 10^6\ \text{Btu/ton}$$

$$^{c}\ \frac{\text{Makeup Heat Requirement}}{\text{Raw Sludge Heat Requirement}} = 40\ \text{percent}$$

[d]Net boiler and heating system efficiency, percent	70
[e]Feed solids concentration, percent	4
Detention time, days	20
Mixing requirement, bhp/1,000 cu ft	0.25

$$\frac{2{,}000\ \text{lb/ton}}{(.04)\ 62.4\ \text{lb/cu ft}}\ (20\ \text{days})\ (24\ \frac{\text{hr}}{\text{day}})\ (0.25\ \frac{\text{bhp}}{1{,}000\ \text{cu ft}})\ (2{,}547\ \frac{\text{Btu}}{\text{bhp/hr}}) = 2.4 \times 10^5\ \text{Btu/ton}$$

FIGURE 6-32

ENERGY FLOW THROUGH AN ANAEROBIC SLUDGE DIGESTION SYSTEM

in a waste-gas burner. The energy flow through a more complex gas utilization system, in which gas is used to fuel an engine-generator, is described in Chapter 18.

The energy flow diagram shown on Figure 6-32 conveys very effectively the relative magnitude and direction of energy exchanges in an anaerobic digestion system. This type of diagram is helpful in the design of a gas utilization system. However, more detail must be added and the full range of expected conditions must be evaluated, rather than just the average conditions depicted for this case.

More complete discussions of digester gas utilization systems can be found in Chapter 18 and elsewhere (38,39).

6.2.8 Costs

Cost curves have been compiled that plot construction costs for anaerobic digestion systems versus either digester volume (166), sludge solids loading (167,168,169), or total treatment plant flow (170,171,172). However, these curves differ significantly, even when converted to a common cost index and plotted in terms of a single sizing parameter (Figure 6-33). Cost curves are generally constructed to allow comparison of equivalent alternatives and consequently do not always describe actual costs.

Estimated annual costs for operation and maintenance are shown in Figure 6-34. No credit has been given in this graph for the value of surplus sludge gas. In most cases, use of this gas requires construction of additional facilities for conditioning, compressing, and burning the gas. The cost for construction and operation of these systems (38) must be included in calculations of the net value of surplus sludge gas.

6.2.9 Design Example

This section illustrates the basic layout and sizing of the major components in an anaerobic sludge digestion system. For this example, it is assumed that the treatment plant provides activated sludge secondary treatment to a typical municipal wastewater. A mixture of primary sludge and thickened waste-activated sludge is to be anaerobically digested, held in a facultative sludge lagoon, and ultimately spread as a stabilized liquid onto land.

6.2.9.1 Design Loadings

Sludge production estimates for two flow conditions, average and peak day, are listed in Table 6-20 (see page 6-79). The peak loading is listed because several components must be sized to meet this critical condition. Refer to Chapter 4 for a discussion of the procedures to determine sludge production values. Sludge solids concentrations and the resulting sludge volumes are also included in Table 6-20.

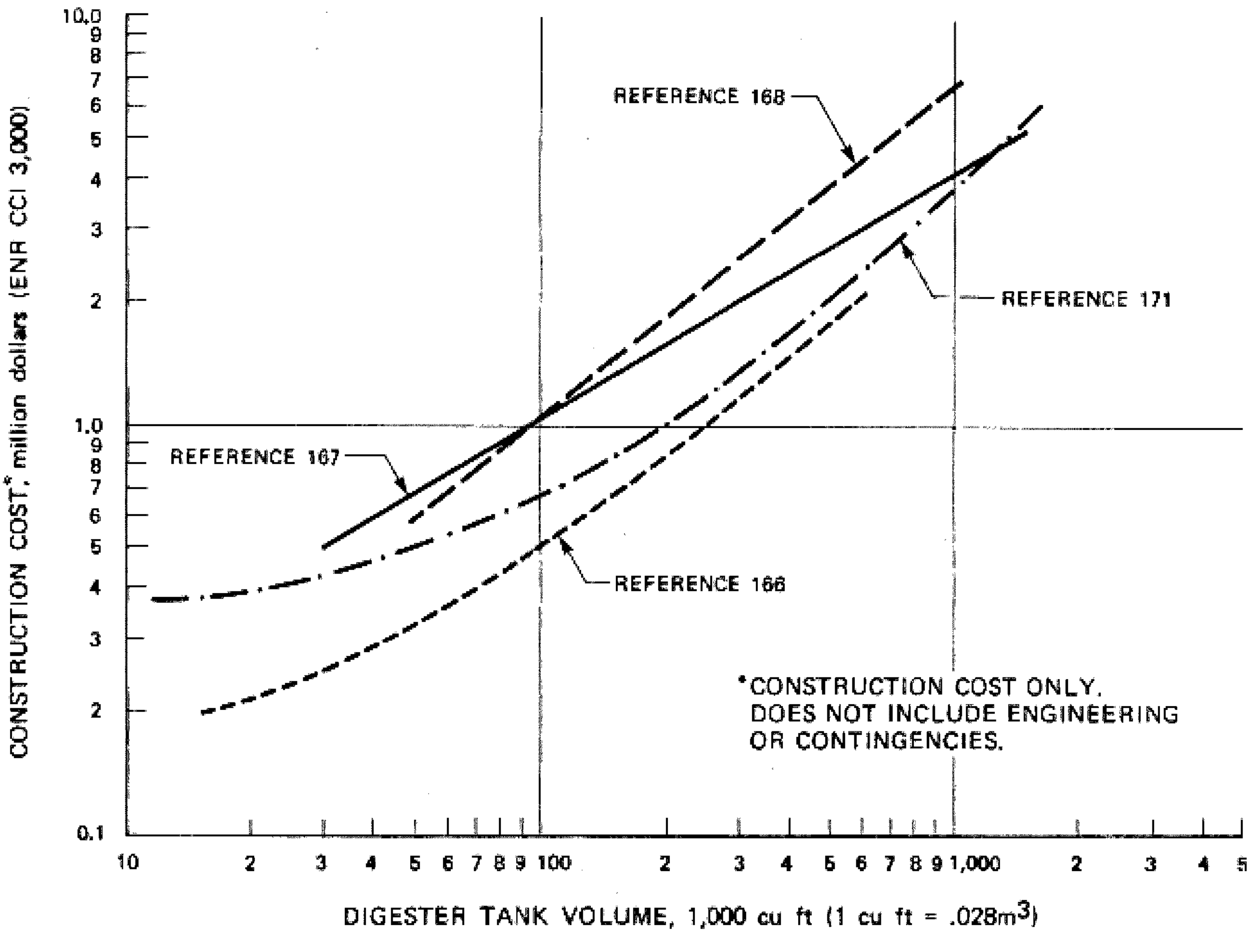


FIGURE 6-33

CONSTRUCTION COSTS FOR ANAEROBIC DIGESTION SYSTEMS (111-168,171)

6.2.9.2 System Description

The conceptual design for a high-rate anaerobic digestion system is presented on Figure 6-35 (see page 6-80). At the heart of the system are two cylindrical single-stage, high-rate digestion tanks operated in parallel. The contents of both digesters are heated to 95°F (35°C) and vigorously mixed with draft-tube gas mixers. Floating covers are used on both tanks to keep floating material soft and submerged, and to allow in-line storage of sludge in the digestion tanks.

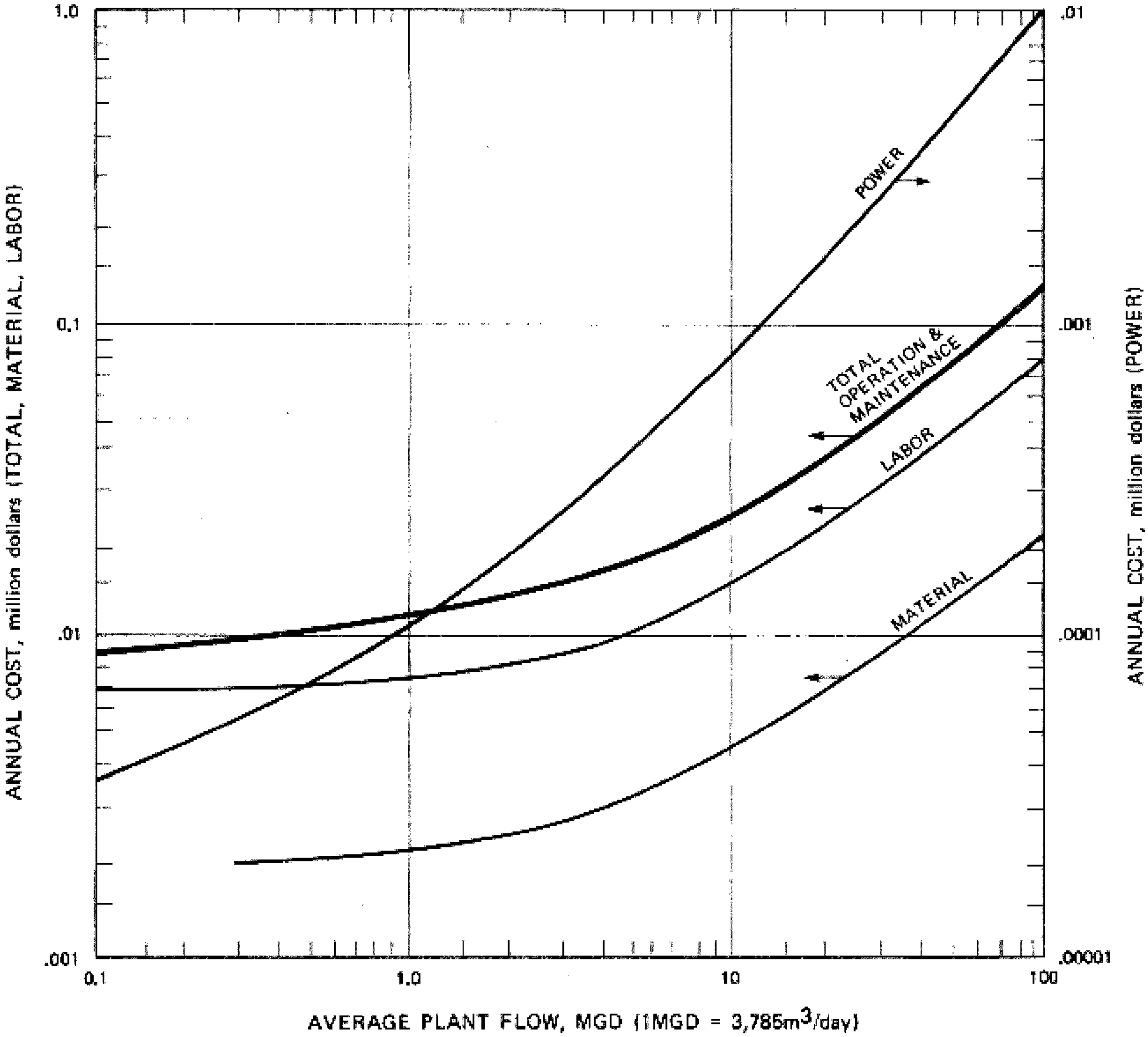


FIGURE 6-34

OPERATING, MAINTENANCE, AND ENERGY COSTS FOR ANAEROBIC SLUDGE DIGESTION SYSTEMS (171)

Raw primary and secondary sludges are first combined and then heated to 95°F (35°C) in a jacketed pipe heat exchanger. The rate of the raw sludge flow is measured with a magnetic flowmeter. The signal from this meter is integrated to indicate the hydraulic loading to digestion. This information is also used to indicate equal volumes of raw sludge for even distribution to each digester. The controls are set so that each digester is fed approximately ten times each day. Raw sludge is mixed with circulating sludge and added to the digester through the gas dome in the center of the cover. The operating temperature in the digester is maintained by circulating a small volume of sludge through an external spiral heat exchanger. Digested sludge is withdrawn daily from the bottom of the tank and transferred by gravity to facultative sludge lagoons. For monitoring purposes, a flowmeter is included in the digested sludge withdrawal line. This provides a means for evenly distributing the sludge to several lagoons. Both tanks are operated as completely mixed primary digesters without supernatant removal.

6.2.9.3 Component Sizing

Digestion Tanks

Sizing critera:

- $\geq$10 days solids retention time during the most critical expected condition to prevent process failure (See Section 6.2.3.3).
- $\geq$50 percent volatile solids reduction at average conditions to minimize odors from the facultative sludge lagoons.

Tank volume:

Raw sludge flow at peak conditions (Q_p)

--Assume peak day conditions (this is conservatively large but provides a margin of safety).

$$Q_p = 6,010 + 3,430 = 9,440 \text{ cu ft per day} \quad (267 \text{ m}^3/\text{day})$$

Active volume (V_a)

$$V_a = \frac{9,440 \text{ cu ft per day}}{2 \text{ tanks}} (10 \text{ days}) = 47,200 \text{ cu ft per tank}$$

Correction for volume displaced by grit and scum accumulations and floating cover level.

Assume:

4-ft grit deposit

2-ft scum blanket

2-ft cover below maximum

8-ft total displaced height

Therefore, if original sidewater depth of the tank is 30 feet, active volume is only $\frac{30 - 8}{30}$ = 0.73 of the total tanks volume.

Tank volume (V_t)

$$V_t = \frac{47{,}200 \text{ cu ft}}{\text{tank}} \left(\frac{1}{.73}\right)$$

= 64,700 cu ft per tank
Say 65,000 cu ft per tank = (1,800 m^3/tank)

Solids retention time at average conditions (SRT_a)

$$SRT_a = \frac{65{,}000 \text{ cu ft per tank (2 tanks)}}{3{,}200 \text{ cu ft per day} + 2{,}000 \text{ cu ft per day}}$$

= 25.0 days, based on total volume, 50 percent volatile solids reduction can be expected with this solids retention time (see Section 6.2.4.1).

Tank dimensions:

Diameter (D)

Assuming initially, a 30-foot sidewater height and neglecting the volume in the bottom cone:

$$D = \sqrt{\frac{4(65{,}000 \text{ cu ft})}{(30 \text{ ft})}} = 52.5 \text{ ft} = (16.0 \text{ m})$$

Sidewater height (h)

Since floating covers come in 5-foot diameter increments, enlarge diameter and adjust sidewater height:

$$h = \frac{4(65{,}000 \text{ cu ft})}{(55 \text{ ft})^2} = 27.4 \text{ ft} = (8.4 \text{ m})$$

Note: This adjustment increases displacement volume effect and reduces active volume to $\frac{27.4-8}{27.4}$ or 0.71. This is ignored in this example because of previous conservative assumptions.

TABLE 6-20

DESIGN LOADING ASSUMPTIONS

Parameter	Flow condition: Average	Flow condition: Peak day
Sludge production, lb dry solids/day		
Primary sludge	10,000	15,000
Waste activated sludge	5,000	7,500
Solids concentration, percent		
Primary sludge	5.0	4.0
Waste activated sludge	4.0	3.5
Sludge volume[a], cu ft/day		
Primary sludge	3,200	6,010
Waste activated sludge	2,000	3,430

[a]Sludge volume =

$$\frac{\text{sludge production}}{(\text{solids concentration})\ (\text{density of sludge})}$$

e.g., $\frac{10{,}000\ \text{lb/day}}{(.05)\ (62.4\ \text{lb/cu ft})} = 3{,}200$ cu ft/day.

1 lb/day = .454 kg/day
1 cu ft/day = .0283 m^3

Heat Exchangers - (See Section 6.2.6.2)

Raw sludge heat exchanger capacity (Q_s)

Assume:

- Peak day sludge loading
- Minimum temperature of raw sludge = 55°F

$$Q_s = \left(\frac{9{,}440\ \text{cu ft}}{\text{day}}\right)\left(\frac{62.4\ \text{lb}}{\text{cu ft}}\right)\left(\frac{1\ \text{day}}{24\ \text{hrs}}\right)\left(1\ \frac{\text{Btu}}{\text{lb - °F}}\right)(95°\text{F}-55°\text{F})$$

= 982,000 Btu/hr = (247,000 kg-cal/hr)

Makeup heat exchanger capacity (Q_m)

Assume:

- Tank completely buried but above water table, U = 0.06
- Bottom exposed to wet soil, U = 0.11
- Cover insulated, U = 0.16
- Minimum soil temperature = 40°F
- Minimum air temperature = 10°F

Q_m = heat loss through walls + bottom + top
= (0.06 Btu/sf/°F/hr)([2 ft]55 ft/4[27.4 ft])(95°F-40°F)
+ (0.11)([55 ft]^2/4](95°F-40°F)
+ (0.16)([55 ft]^2/4](95°F-10°F)
= 76,029 Btu/hr = (19.2 kg-kcal/hr)

The above calculated values are used for sizing equipment. Average heat requirements would be substantially less.

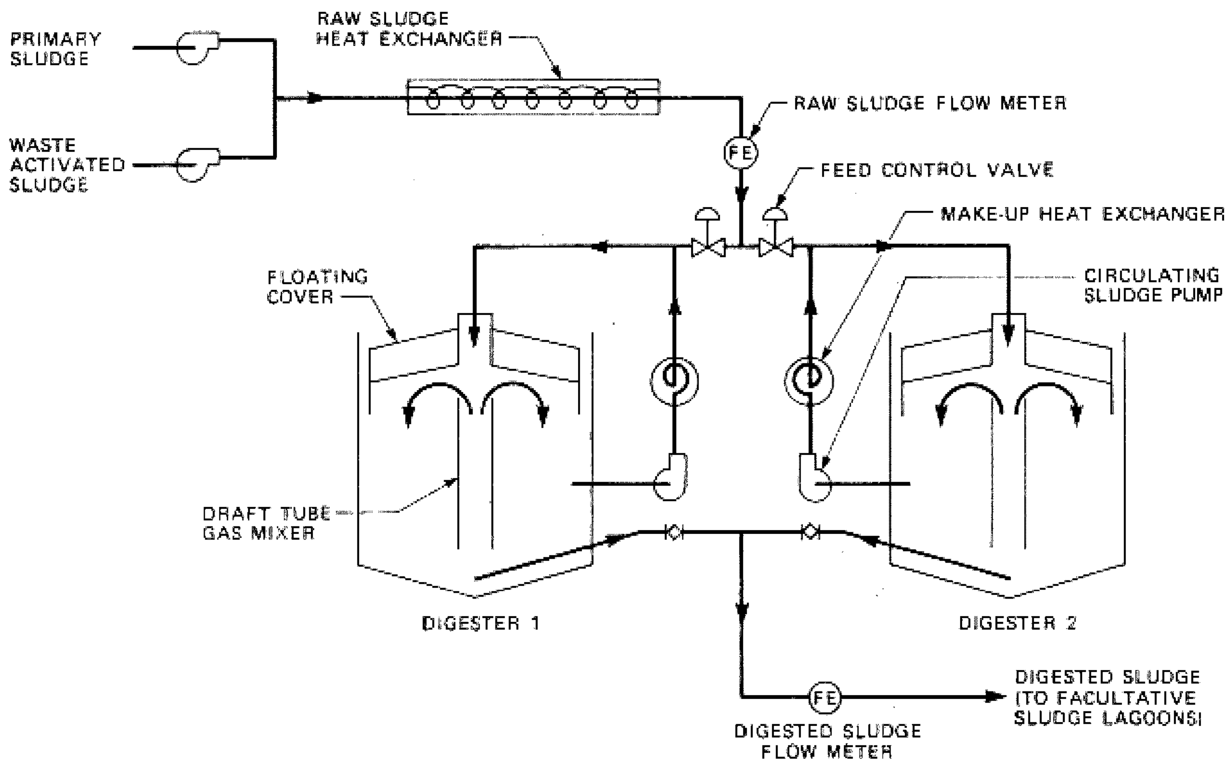


FIGURE 6-35

CONCEPTUAL DESIGN OF AN ANAEROBIC SLUDGE DIGESTION SYSTEM

Mixing (See Section 6.2.6.3)

Sizing criterion:

Assumptions:

- Velocity gradient (G) = 60 sec^{-1}
- Plant located at sea level P_1 = 14.7 psi
- Gas released 13 ft below the water surface P_2 = 14.7 + 0.434 (13) = 20.3 psi
- Viscosity of the digesting sludge is the same as for water at 95°F or 1.5×10^{-5} lb_f-sec/sq ft

Rate of energy transfer (E)

Combining Equations 6-5 and 6-6 and solving for E:

$$E = V \mu G^2$$

$$= 65{,}000 \text{ cu ft/tank } (1.5 \times 10^{-5} \text{ lb}_f - \text{sec/sq ft})(60 \text{ sec}^{-1})^2$$

$$= 3{,}510 \text{ ft lb}_f\text{/sec/tank} = (4.8 \text{ kW/tank})$$

This is the power delivered to the digester contents. Motor horsepower for the compressor will be substantially higher.

Gas Flow (Q) solving Equation 6-7 for Q.

$$Q = \frac{E}{2.4\ (P_1)\left(\ln \frac{P_2}{P_1}\right)} \qquad (6\text{-}8)$$

$$= \frac{3{,}510 \text{ ft-lb/sec/tank}}{2.4\ (14.7 \text{ psi})\left(\ln \frac{20.3 \text{ psi}}{14.7 \text{ psi}}\right)}$$

$$= 308 \text{ cfm/tank } (0.145 \text{ m}^3\text{/sec/tank})$$

6.3 Aerobic Digestion

Aerobic digestion is the biochemical oxidative stabilization of wastewater sludge in open or closed tanks that are separate from the liquid process system.

6.3.1 Process Description

6.3.1.1 History

Studies on aerobic digestion of municipal wastewater sludge have been conducted since the early 1950's (175,176). Early studies (177,178) indicated that aerobic digestion performed as well as, if not better than, anaerobic digestion in reducing volatile solids in sludge. Aerobic digestion processes were economical to construct, had fewer operating problems than anaerobic processes, and produced a digested sludge that drained well. By 1963, at least one major equipment supplier (179) had approximately 130 installations in plants with flow from 10,000 to 100,000 gallons per day (37.8 to 378 m^3/day). By the late 1960's and early 1970's, consulting engineers across the country were specifying aerobic digestion facilities for many of the plants they were designing.

6.3.1.2 Current Status

As of early 1979, numerous plants use aerobic digestion, and several of them are quite large (11). Because of significant improvements in design and control of anaerobic processes, coupled with the significant mid-1970 jump in energy costs, the continued use of aerobic digestion, except in the small facility, is much in doubt.

6.3.1.3 Applicability

Although numerous lab and pilot-scale studies have been conducted on a variety of municipal wastewater sludges, very few documented, full-scale studies have been reported in the literature. Table 6-21 lists some of these aerobic digestion studies and provides information on the type of sludge studied, temperature of digestion, scale of study, and literature reference.

6.3.1.4 Advantages and Disadvantages

Various advantages have been claimed (66,197) for aerobic digestion over other stabilization techniques, particularly anaerobic digestion. Based on all current knowledge, the following advantages can be cited for properly designed and operated aerobic digestion processes:

- Have capital costs generally lower than for anaerobic systems for plants under 5 MGD (220 l/s) (170).
- Are relatively easy to operate compared to anaerobic systems.

- Do not generate nuisance odors (199,200).
- Will produce a supernatant low in BOD_5, suspended solids, and ammonia nitrogen (199,200).
- Reduce the quantity of grease or hexane solubles in the sludge mass.
- Reduce the number of pathogens to a low level under normal design. Under auto-heated design, many systems provide 100 percent pathogen destruction (187).

TABLE 6-21

SELECTED AEROBIC DIGESTION STUDIES ON VARIOUS MUNICIPAL WASTEWATER SLUDGES

Sludge type	Studies under 50°F	Studies between 50°- 86°F	Studies over 86°F
Primary sludge	180	181, (182[a])	183, 184
Primary sludge plus			
waste-activated	187	187	(185)(186)(187)
lime		188	
iron		189	
alum		189,(190)	
waste-activated + iron		190	
trickling filter		181	
waste paper		191	
Contact stabilization sludge	192	192, 197, (199)	
Contact stabilization sludge plus			
iron		(190)	
alum		(190), (194)	
Waste-activated sludge		195	
Trickling filter sludge		181, 196	

[a]( ) indicates full-scale study results.

As with any process, there are also certain disadvantages. In aerobic digestion processes, the disadvantages are:

- Usually produce a digested sludge with very poor mechanical dewatering characteristics.
- Have high power costs to supply oxygen, even for very small plants.
- Are significantly influenced in performance by temperature, location, and type of tank material.

6.3.1.5 Microbiology

Aerobic digestion of municipal wastewater sludges is based on the principle that, when there is inadequate external substrate available, microorganisms metabolize their own celluar mass. In actual operation, aerobic digestion involves the direct oxidation of any biodegradable matter and the oxidation of microbial cellular material by organisms. These two steps are illustrated by the following reactions:

$$\text{Organic matter} + O_2 \xrightarrow{\text{Bacteria}} \text{Cellular material} + CO_2 + H_2O \qquad (6\text{-}9)$$

$$\text{Cellular material} + O_2 \longrightarrow \text{Digested sludge} + CO_2 + H_2O \qquad (6\text{-}10)$$

The process described by Equation 6-10 is referred to as "endogenous respiration"; this is normally the predominant reaction in aerobic digestion.

6.3.2 Process Variations

6.3.2.1 Conventional Semi-Batch Operation

Originally, aerobic digestion was designed as a semi-batch process, and this concept is still functional at many facilities. Solids are pumped directly from the clarifiers into the aerobic digester. The time required for filling the digester depends on available tank volume, volume of waste sludge, precipitation, and evaporation. During the filling operation, sludge undergoing digestion is continually aerated. When the tank is full, aeration continues for two to three weeks to assure that the solids are thoroughly stabilized. Aeration is then discontinued and the stabilized solids settled. Clarified liquid is decanted, and the thickened solids are removed at a concentration of between two and four percent. When a sufficient amount of stabilized sludge and/or supernatant have been removed, the cycle is repeated. Between cycles, it is customary to leave some stabilized sludge in the aerator to provide the necessary microbial population for degrading the wastewater solids. The aeration device need not operate for several days, provided no raw sludge is added.

Many engineers have tried to make the semi-batch process more continuous by installing stilling wells to act as clarifiers in part of the digester. This has not proven effective (200-202).

6.3.2.2 Conventional Continuous Operation

The conventional continuous aerobic digestion process closely resembles the activated sludge process as shown on (Figure 6-36). As in the semi-batch process, solids are pumped directly from

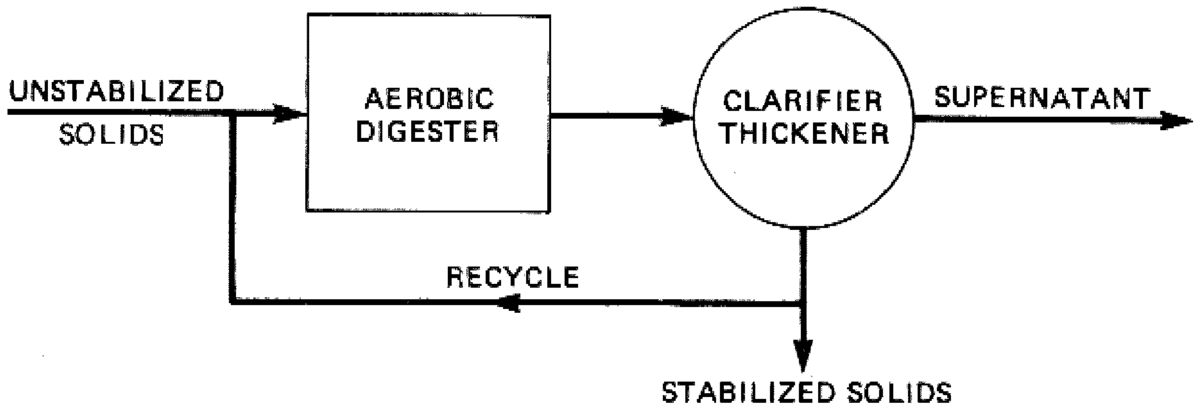


FIGURE 6-36

PROCESS FLOW DIAGRAM FOR A CONVENTIONAL CONTINUOUSLY OPERATED AEROBIC DIGESTER

clarifiers into the aerobic digester. The aerator operates at a fixed level, with the overflow going to a solids-liquid separator. Thickened and stabilized solids are either recycled back to the digestion tank or removed for further processing.

6.3.2.3 Auto-Heated Mode of Operation

A new concept that is receiving considerable attention in the United States is the auto-heated thermophilic aerobic digestion process (187,203). In this process, sludge from the clarifiers is usually thickened to provide a digester feed solids concentration of greater than four percent. The heat liberated in the biological degradation of the organic solids is sufficient to raise the liquid temperature in the digester to as high as 140°F (60°C) (187). Advantages claimed for this mode of operation are higher rates of organic solids destruction, hence smaller volume requirements; production of a pasteurized sludge; destruction of all weed seeds; 30 to 40 percent less oxygen requirement than for the mesophilic process, since few, if any, nitrifying bacteria exist in this temperature range; and improved solids-liquid separation through decreased liquid viscosity (187,203,204).

Disadvantages cited for this process are that it must incorporate a thickening operation, that mixing requirements are higher because of the higher solids content, and that non-oxygen aerated systems require extremely efficient aeration and insulated tanks.

6.3.3 Design Considerations

6.3.3.1 Temperature

Since the majority of aerobic digesters are open tanks, digester liquid temperatures are dependent on weather conditions and can fluctuate extensively. As with all biological systems, lower temperatures retard the process while higher temperatures speed it up. Table 6-21 lists studies on aerobic digestion of municipal sludges as a function of liquid temperature. When considering temperature effects in system design, one should design a system to minimize heat losses by using concrete instead of steel tanks, placing the tanks below rather than above grade, and using sub-surface instead of surface aeration. Design should allow for the necessary degree of sludge stabilization at the lowest expected liquid operating temperature, and should meet maximum oxygen requirements at the maximum expected liquid operating temperature.

6.3.3.2 Solids Reduction

A major objective of aerobic digestion is to reduce the mass of solids for disposal. This reduction is assumed to take place only with the biodegradable content of the sludge, though some studies (205,206) have shown that there may be destruction of the non-organics as well. In this discussion, solids reduction will pertain only to the biodegradable content of the sludge.

The change in biodegradable volatile solids can be represented by a first order biochemical reaction:

$$\frac{dM}{dt} = -K_d M \qquad (6\text{-}11)$$

where:

$\frac{dM}{dt}$ = rate of change of biodegradable volatile solids per unit of time - (Δ mass/time)

K_d = reaction rate constant - ($time^{-1}$)

M = concentration of biodegradable volatile solids remaining at time t in the aerobic digester - (mass/volume).

The time t in Equation 6-11 is actually the sludge age or solids residence time in the aerobic digester. Depending on how the aerobic digester is being operated, time t can be equal to or considerably greater than the theoretical hydraulic residence time. The reaction rate term K_d is a function of sludge type, temperature, and solids concentration. It is a pseudoconstant, since the term's value is the average result of many influences. Figure 6-37 shows a plot of various reported K_d values as a function of the digestion temperature. The data shown are for several different types of waste sludge, which partially explains the scatter. Furthermore, there has been no adjustment in the value of K_d for sludge age. At this time, not enough data are available to allow segregation of K_d by sludge type; therefore, the line drawn through the data points represents an overall average K_d value. Little research has been conducted on the effect of solids concentration on reaction rate K_d. The results of one study with waste-activated sludge at a temperature of 68°F (20°C) are shown on Figure 6-38, which indicates that K_d decreases with increasing solids concentration.

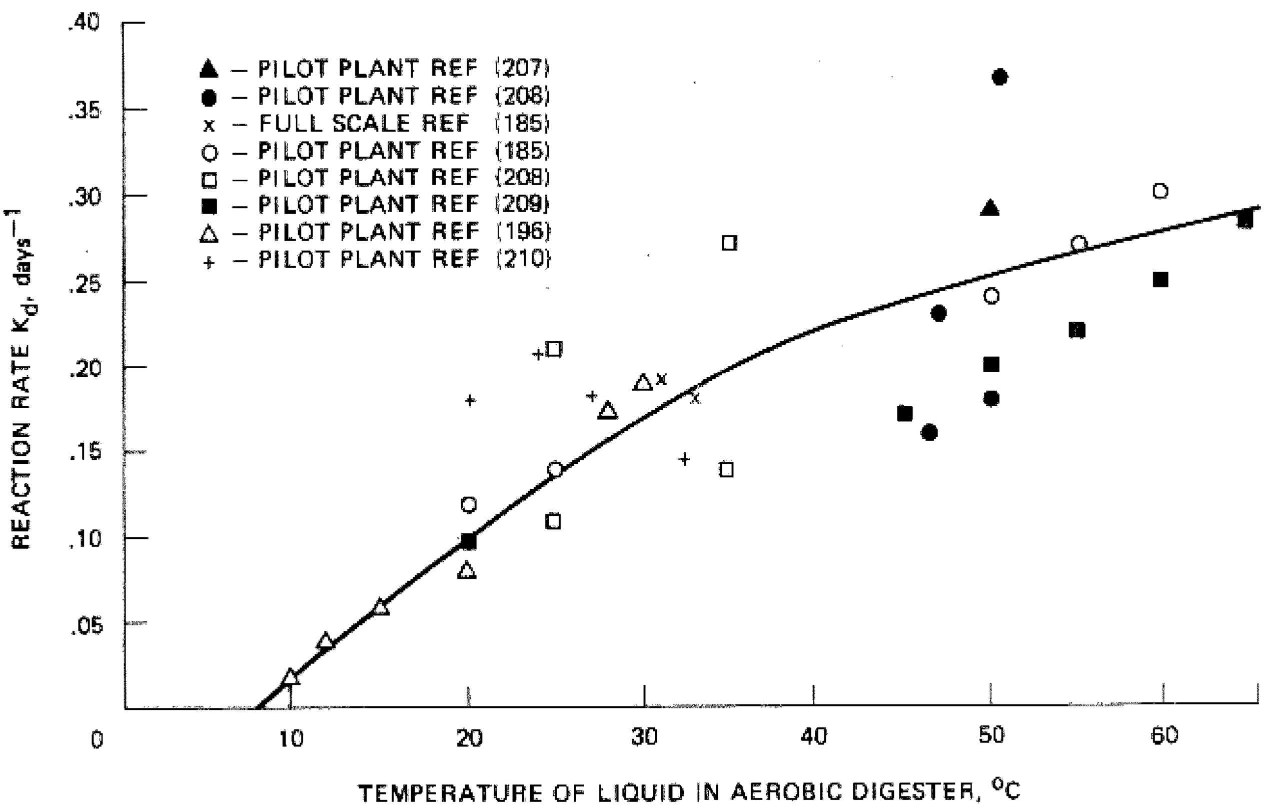


FIGURE 6-37

REACTION RATE K_d VERSUS AEROBIC DIGESTER LIQUID TEMPERATURES

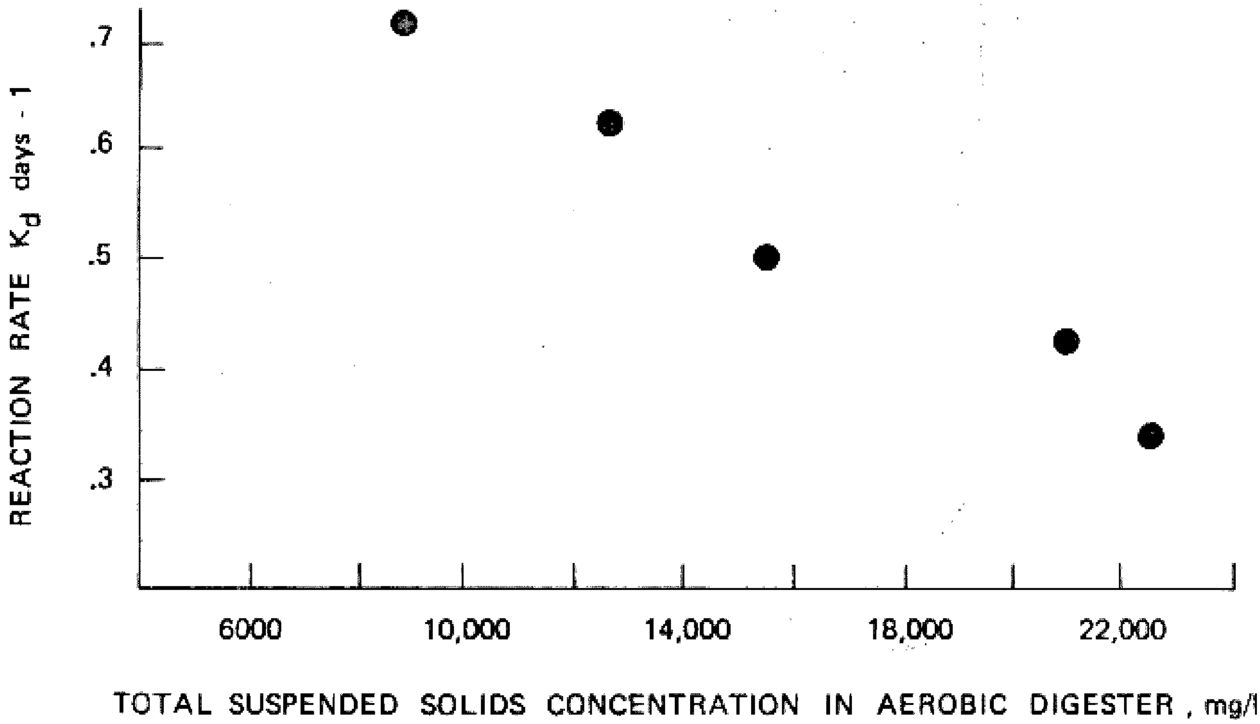


FIGURE 6-38

EFFECT OF SOLIDS CONCENTRATION ON REACTION RATE K_d (194)

6.3.3.3 Oxygen Requirements

Activated sludge biomass is most often represented by the empirical equation $C_5H_7NO_2$. Under the prolonged periods of aeration typical of the aerobic digestion process, Equation 6-10 can be written as follows:

$$C_5H_7NO_2 + 7O_2 \longrightarrow 5CO_2 + 3H_2O + H^+ + NO_3^- \qquad (6\text{-}12)$$

Hypothetically, this equation indicates that 1.98 pounds (0.898 kg) of oxygen are required to oxidize one pound (0.45 kg) of cell mass. From pilot and full-scale studies, however, the pounds of oxygen required to degrade a pound of volatile solids were found to be 1.74 to 2.07 (0.789 to 0.939 kg). For mesophilic systems, a design value of 2.0 is recommended. For auto-thermal systems, which have temperatures above 113°F (45°C), nitrification does not occur and a value of 1.45 is recommended (187,203,204).

The actual specific oxygen utilization rate, pounds oxygen per 1,000 pounds volatile solids per hour, is a function of total sludge age and liquid temperature (192,199,205). In one study, Ahlberg and Boyko (199) visited several operating installations and developed the relationship shown on Figure 6-39. Specific oxygen utilization is seen to decrease with increase in sludge age and decrease in digestion temperature.

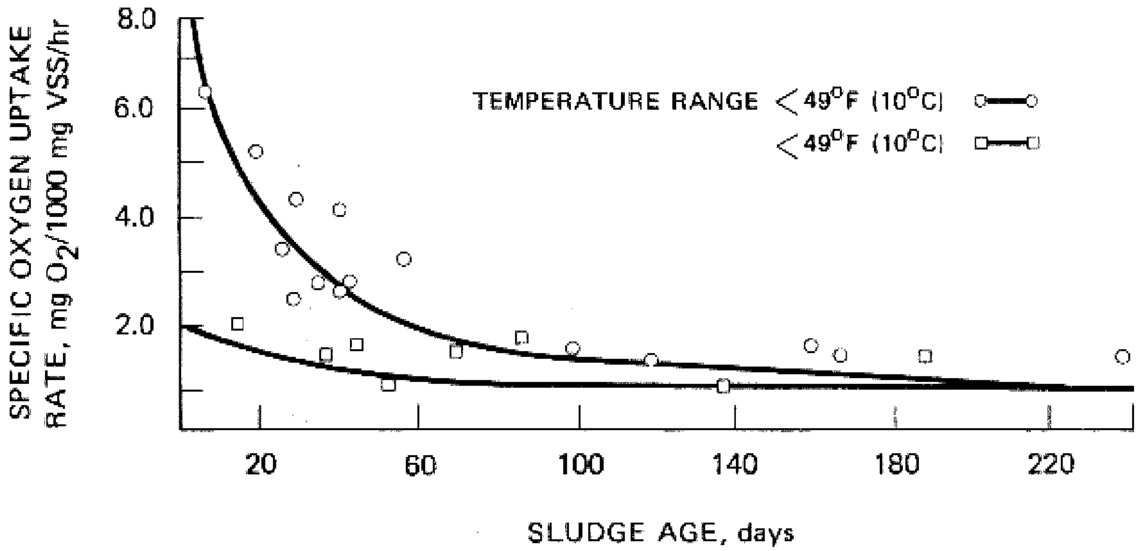


FIGURE 6-39

INFLUENCE OF SLUDGE AGE AND LIQUID TEMPERATURES ON THE OXYGEN UPTAKE RATES IN AEROBIC DIGESTERS (199)

Field studies have also indicated that a minimum value of 1.0 mg of oxygen per liter should be maintained in the digester at all times (199).

6.3.3.4 Mixing

Mixing is required in an aerobic digester to keep solids in suspension and to bring deoxygenated liquid continuously to the aeration device. Whichever of these two requirements needs the most mixing energy controls the design.

No published studies are available on field evaluation of horsepower requirements to maintain various levels of solids in suspension within aerobic digesters. According to past experience, levels ranging from 0.5 to 4.0 horsepower per 1,000 cubic feet of tank volume (13 to 106 Kw/1,000 m^3) were satisfactory. Designers should consult an experienced aeration equipment manufacturer for assistance in design.

Based on an analysis of over 15 years of data on the effect of tank geometry on mixing (211) charts have been developed that calculate the optimum energy requirements to meet oxygen needs of the process for a particular tank geometry. Figure 6-40 shows the chart developed by Envirex Incorporated for low speed mechanical aerators in noncircular basins. The use of this chart is explained in the design example in Section 6.3.5.

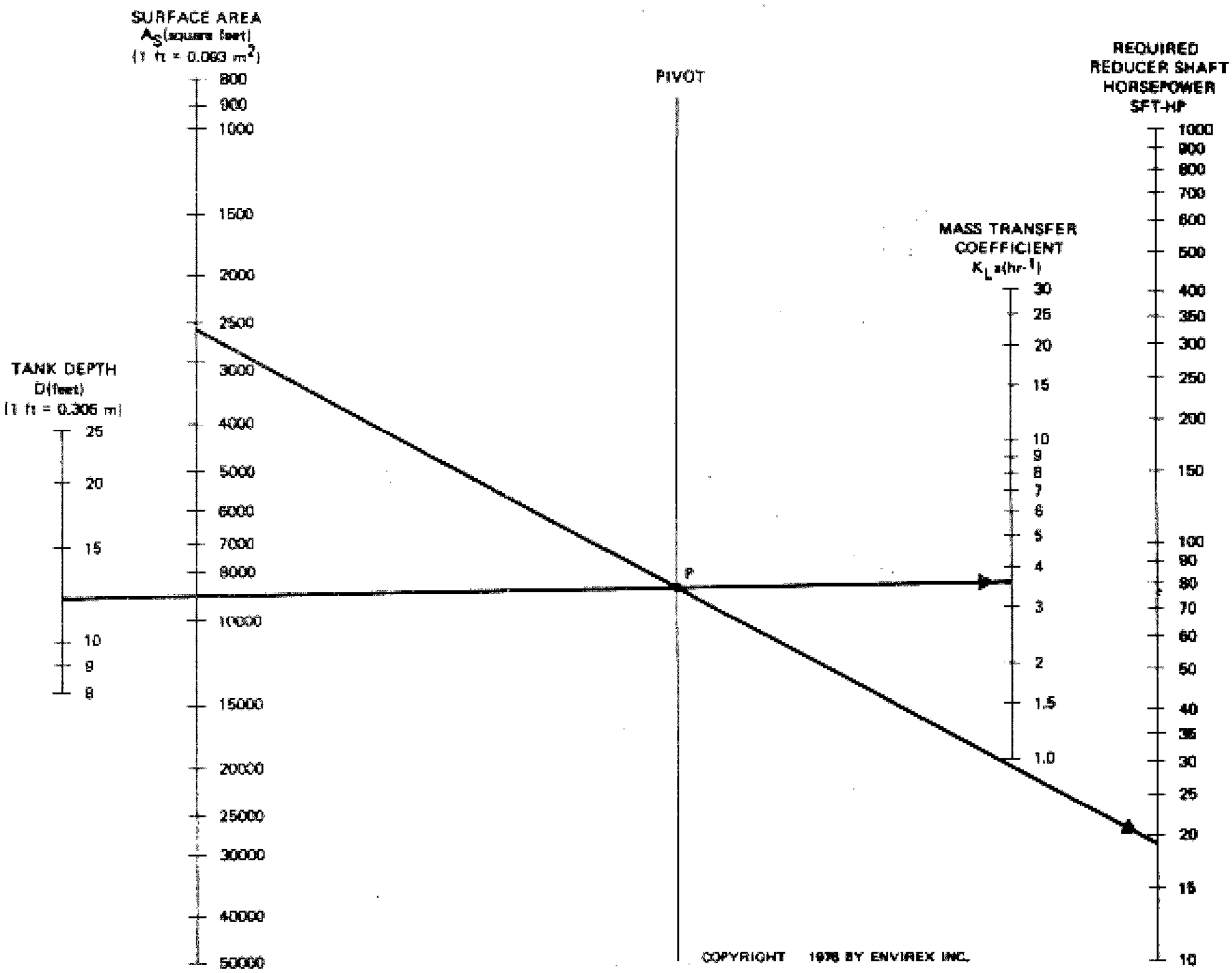


FIGURE 6-40

DESIGN CHART FOR LOW SPEED MECHANICAL AERATORS IN NON-CIRCULAR AERATION BASINS TO CALCULATE ENERGY REQUIREMENTS FOR MEETING OXYGEN REQUIREMENTS

6.3.3.5 pH Reduction

The effect of increasing detention time on pH of sludge in the aerobic digester during mesophilic temperature range operation is shown on Figure 6-41.

The drop in pH and alkalinity is caused by acid formation that occurs during nitrification. Although at one time the low pH was considered inhibitory to the process, it has been shown that the system will acclimate and perform just as well at the lower pH values (186,192,213). It should be noted that if nitrification does not take place, pH will drop little if at all. This could happen at low liquid temperatures and short sludge ages or in thermophilic operation (203). Nitrifying bacteria are sensitive to heat and do not survive in temperatures over 113°F (45°C) (214).

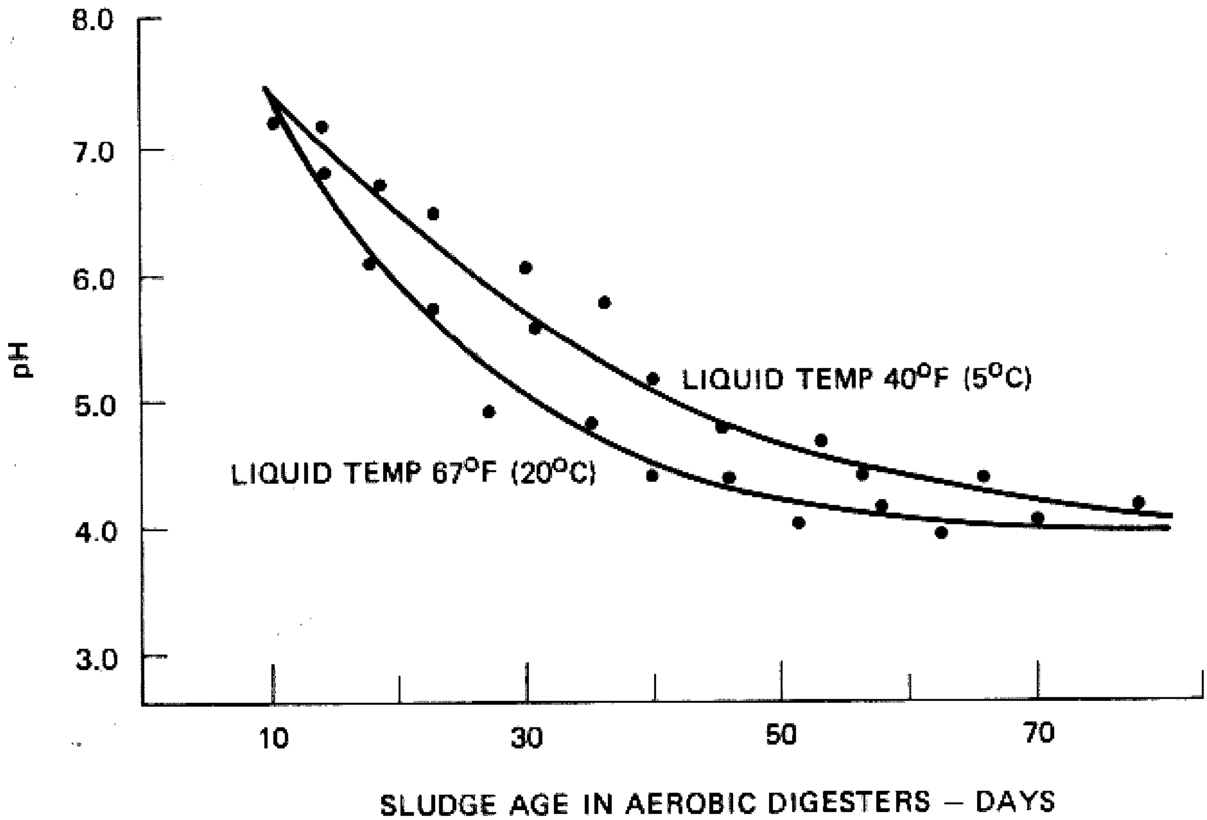


FIGURE 6-41

EFFECT OF SLUDGE AGE ON pH DURING AEROBIC DIGESTION

6.3.3.6 Dewatering

Although there are published reports of excellent operating systems (193) much of the literature on full-scale operations has indicated that mechanical dewatering of aerobically digested sludge is very difficult (182,189,215). Furthermore, in most recent investigations, it is agreed that the dewatering properties of aerobically digested sludge deteriorate with increasing sludge age (181,11,189,216). Unless pilot plant data indicate otherwise, it is recommended that conservative criteria be used for designing mechanical sludge dewatering facilities for aerobically digested sludge. As an example, a designer would probably consider designing a rotary vacuum filter for a production rate of 1.5 pounds of dry solids per square foot per hour (7.4 $kg/m^2/hr$), a cake solids concentration of 16 percent, with a $FeCl_3$ dose of 140 pounds (63.5 kg), and a lime dose (CaO) of 240 pounds (109 kg). This assumes an aerobic solids concentration of 2.5 percent solids. For more detailed information on results of various types of dewatering systems, see Chapter 9.

6.3.4 Process Performance

6.3.4.1 Total Volatile Solids Reduction

Solids destruction has been shown to be primarily a direct function of both basin liquid temperature and the length of time during which the sludge was in the digester. Figure 6-42 is a plot of volatile solids reduction versus the parameter degree-days. Data were taken from both pilot and full-scale studies on several types of municipal wastewater sludges. Figure 6-42 indicates that, for these sludges, volatile solids reductions of 40 to 50 percent are obtainable under normal aeration conditions.

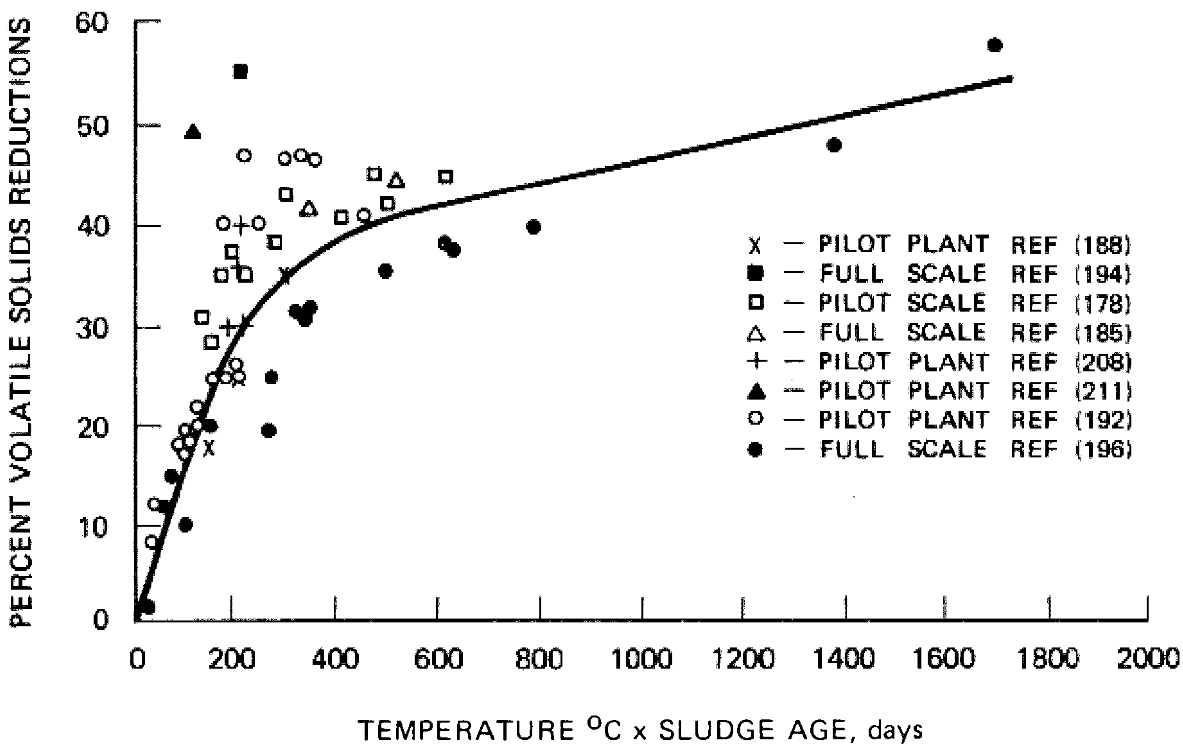


FIGURE 6-42

VOLATILE SOLIDS REDUCTION AS A FUNCTION OF DIGESTER LIQUID TEMPERATURE AND DIGESTER SLUDGE AGE

6.3.4.2 Supernatant Quality

The supernatant from aerobic digesters is normally returned to the head end of the treatment plant. Table 6-22 gives supernatant characteristics from several full-scale facilities operating in the mesophilic temperature range. Table 6-23 summarizes the current design criteria for aerobic digesters.

TABLE 6-22

CHARACTERISTICS OF MESOPHILIC AEROBIC DIGESTER SUPERNATANT

	Reference 196[a]	Reference 199[b]	Reference 213[c]
Turbidity - JTU	120	-	-
NO_3-N - mg/l	40	-	30
TKN - mg/l	115	2.9-1,350	-
COD - mg/l	700	24-25,500	-
PO_4-P - mg/l	70	2.1-930	35
Filtered P - mg/l	-	0.4-120	-
BOD_5 - mg/l	50	5-6,350	2-5
Filtered BOD_5 - mg/l	-	3-280	-
Suspended solids - mg/l	300	9-41,800	6.8
Alkalinity - mg/l $CaCO_3$	-	-	150
SO_4 - mg/l	-	-	70
Silica - mg/l	-	-	26
pH	6.8	5.7-8.0	6.8

[a]Average of 7 months of data.

[b]Range taken from 7 operating facilities.

[c]Average values.

6.3.5 Design Example

Given

Using the information provided in Chapter 4, a design engineer has determined that the following quantities of sludge will be produced at a 0.5-MGD (22 l/s) contact stabilization plant:

Total daily solids generation	1,262 pounds (572 kg)
Amount due to chemical sludge	0
Amount that will be volatile	985 pounds (447 kg)
Amount that will be non-volatile	277 pounds (125 kg)

In addition, the designer has the following information:

- Estimated minimum liquid temperature (winter) in digester is 50°F (10°C).
- Estimated maximum liquid temperature (summer) in digester is 77°F (25°C).

- System must achieve greater than 40 percent volatile solids reduction during the winter.

- A minimum of two continuously operated tanks are required (see Figure 6-36). (This is a state requirement for plants under 1 MGD [44 l/s]).

- Expected waste sludge solids concentration to the aerobic digester is 8,000 mg/l.

- Expected thickened solids concentration for the stabilized sludge is three percent (30,000 mg/l), based on designer's experience.

TABLE 6-23

SUMMARY OF CURRENT AEROBIC DIGESTER DESIGN CRITERIA

	Days	Liquid temperature
Solids residence time required to achieve 40 percent volatile solids reduction	108	40°F
	31	60°F
	18	80°F
55 percent volatile solids reduction	386	40°F
	109	60°F
	64	80°F
Oxygen requirements	2.0 pounds of oxygen per pound of volatile solids destroyed when liquid temperature 113°F or less 1.45 pounds of oxygen per pound of volatile solids destroyed when liquid temperature greater than 113°F	
Oxygen residual	1.0 mg/l of oxygen at worst design conditions	
Expected maximum solids concentration achievable with decanting	2.5 to 3.5 percent solids when dealing with a degritted sludge or one in which no chemicals have been added	
Mixing horsepower	Function of tank geometry and type of aeration equipment utilized. Should consult equipment manufacturer. Historical values have ranged from 0.5 to 4.0 horsepower per 1,000 cubic feet of tank volume	

1 lb = 0.454 kg
1 hp/1,000 cu ft - 26.6 kw/1,000 m^3

Sludge Age Required

Figure 6-42 (presented previously) offers a quick method for calculating the number of degree days required to achieve the 40 percent volatile solids reduction required. The result is 475 degree-days. At a basin temperature of 50°F (10°C) then:

$$\frac{475 \text{ degree-days}}{10 \text{ degrees}} = 47.5 \text{ days}$$

Therefore, the volume of the aerobic digester must be adequate to provide 47.5 days sludge age to meet minimum volatile solids reduction during the winter.

During the summer, the basin temperature will be 77°F (25°C): 25°C x 47.5 day sludge age = 1,175 degree-days.

From Figure 6-42, at 1,175 degree-days, there would be 49 percent volatile solids reduction.

Volatile Solids Reduction

For winter conditions, there would be a 40 percent volatile solids (VS) reduction. The actual pounds of solids reduced are:

$$\frac{985 \text{ lb VS}}{\text{day}} \times 0.4 = 394 \frac{\text{lb VS reduced}}{\text{day}} \text{ (179 kg/day)}$$

For summer conditions, there would be a 49 percent volatile solids reduction. The actual pounds of solids reduced are:

$$\frac{985 \text{ lb VS}}{\text{day}} \times 0.49 = 483 \frac{\text{lb VS reduced}}{\text{day}} \text{ (219 kg/day)}$$

Oxygen Requirements

Since nitrification is expected, provisions must be made to supply 2.0 pounds of oxygen per pound of volatile solids destroyed (2 kg O_2/kg volatile solids destroyed).

$$\text{Winter conditions: } 394 \frac{\text{lb VS dest}}{\text{day}} \times \frac{2.0 \text{ lbs } O_2}{\text{lb VS dest.}} = \frac{788 \text{ lbs } O_2}{\text{day}} \text{ (358 kg/day)}$$

$$\text{Summer conditions: } 483 \frac{\text{lb VS dest}}{\text{day}} \times \frac{2.0 \text{ lbs } O_2}{\text{lbs VS dest.}} = \frac{966 \text{ lbs } O_2}{\text{day}} \text{ (438 kg/day)}$$

During summer conditions, a minimum of 1.0 mg/l oxygen residual must be provided.

Calculating Tank Volume

Sludge age in an aerobic digester can be defined as follows:

$$\text{Sludge age} = \frac{\text{total lb SS aerobic digester}}{\text{total lb SS lost per day from aerobic digester}}$$

where SS = suspended solids.

The suspended solids concentration in the digester will range from the value of the influent suspended solids concentration or 8,000 mg/l to the maximum value of the thickened and stabilized solids concentration of 30,000 mg/l. On the average, the suspended solids concentration within the digester is equal to 70 percent of the thickened solids concentration, or 21,000 mg/l.

An average poundage of suspended solids in the supernatant can be approximated by the following equation.

$$(\text{SS concentration in supernatant})(1-f)(8.34)(\text{influent flow})$$

where f is the fraction of influent flow into the aerobic digester that is retained, and 1-f is the fraction that leaves as supernatant. The term f can be approximated by the following equation.

$$f = \frac{\text{influent SS concentration}}{\text{thickened SS concentration}} \times \text{fraction of solids not destroyed}$$

For winter conditions, the fraction of solids not destroyed is:

$$\frac{1{,}262 \text{ lb total solids} - 394 \text{ lb of solids reduced}}{1{,}262 \text{ lb total solids}} = 0.69$$

Then, the term f for this example, is:

$$\frac{8{,}000 \text{ mg/l}}{30{,}000 \text{ mg/l}} \times 0.69 = 0.18$$

Therefore, 18 percent of the influent flow into the aerobic digester will be retained, and 82 percent will leave as supernatant.

For a properly designed solids-liquid separator (under 200 gallons per day per sq ft [8.16 $m^3/day/m^2$] overflow rate), the suspended solids concentration would be approximately 300 mg/l.

The influent flow can be found by dividing the influent solids load (1,262 pounds per day [572 kg/day] by the influent solids concentration [8,000 mg/l]). The result is 18,914 gallons per day (71.5 m^3/day).

The pounds of suspended solids intentionally wasted per day from the aerobic digestion system can now be approximated from the following expression.

$$(\text{SS concentration in thickened sludge})(f)(8.34)(\text{influent flow}).$$

All the terms in the above equation have been previously defined.

It is now possible to solve for the required tank volume for any given sludge age. In this example, winter conditions govern, and it was previously calculated that a 47.5-day minimum was required. From the values previously discussed:

$$47.5 \text{ days} = \frac{(21{,}000 \text{ mg/l})(8.34)(\text{tank volume-million gallons})}{((300 \text{ mg/l})(1-0.18)+(30{,}000)(0.18))(8.34)(0.018915 \text{ mil gal})}$$

Tank volume = 0.233 million gallons (881 m^3)

Theoretical hydraulic detention time:

$$\frac{233{,}000 \text{ gallons}}{18{,}915 \text{ gallons per day}} = 12.3 \text{ days}$$

This is the minimum volume, to which must be added capacity for weekend storage and precipitation requirements. For this design, two tanks will be provided, each to have a volume capacity of 233,000 gallons (881 m^3)(100 percent stand-by capacity as per state requirements).

The actual dimensions of the tanks depend on the aeration equipment utilized and are discussed in the following section.

Power Requirements

The designer has decided to use low-speed mechanical aerators for mixing and oxygen transfer in the aerobic digester.

Previous calculations have indicated that the maximum oxygen requirement was 966 pounds oxygen per day (438 kg/day). After making corrections for plant elevation, alpha and beta factors, water temperature, and minimum residual requirements, the engineer calculated an overall mass transfer coefficient K_La of 3.53 hr^{-1}. From this value, in conjunction with Figure 6-7, power requirements will be calculated as follows.

Initially, a depth of 12 feet (3.65 m) is selected. Since each tank is to be 233,000 gallons (881 m^3), the surface area with a 12-foot (3.65 m) liquid depth would be 2,596 sq ft (241 m^2). A pivot point P is located by placing a straight-edge across scales D and K_La of Figure 6-40. Then a line is drawn through pivot point p connecting scale A_S, tank surface area, to the required reducer shaft horsepower scale. The required shaft horsepower for one tank would be 19 horsepower (14.1 kW). Assuming a motor reducer efficiency of 92 percent, total motor horsepower would equal 19 ÷ 0.92, or 20.6 horse-power (15.4 kW). The aerator manufacturer recommends that a minimum 10 horsepower unit (7.5 kW) will be required to mix the 12-foot (3.65 m) liquid depth. Each 10 horsepower unit (7.5 kW) could mix an area 40 feet by 40 feet (12.1 m by 12.1 m). After making some calculations, the designer decides to use two 10-horsepower (7.5 kW) units in each tank, each tank being 36 feet (10.9 m) wide by 72 feet (24.5 m) long and having a total tank depth of 14 feet (4.2 m) allowing 2 feet (0.61 m) of free board. Figure 6-43 shows a view of the plan.

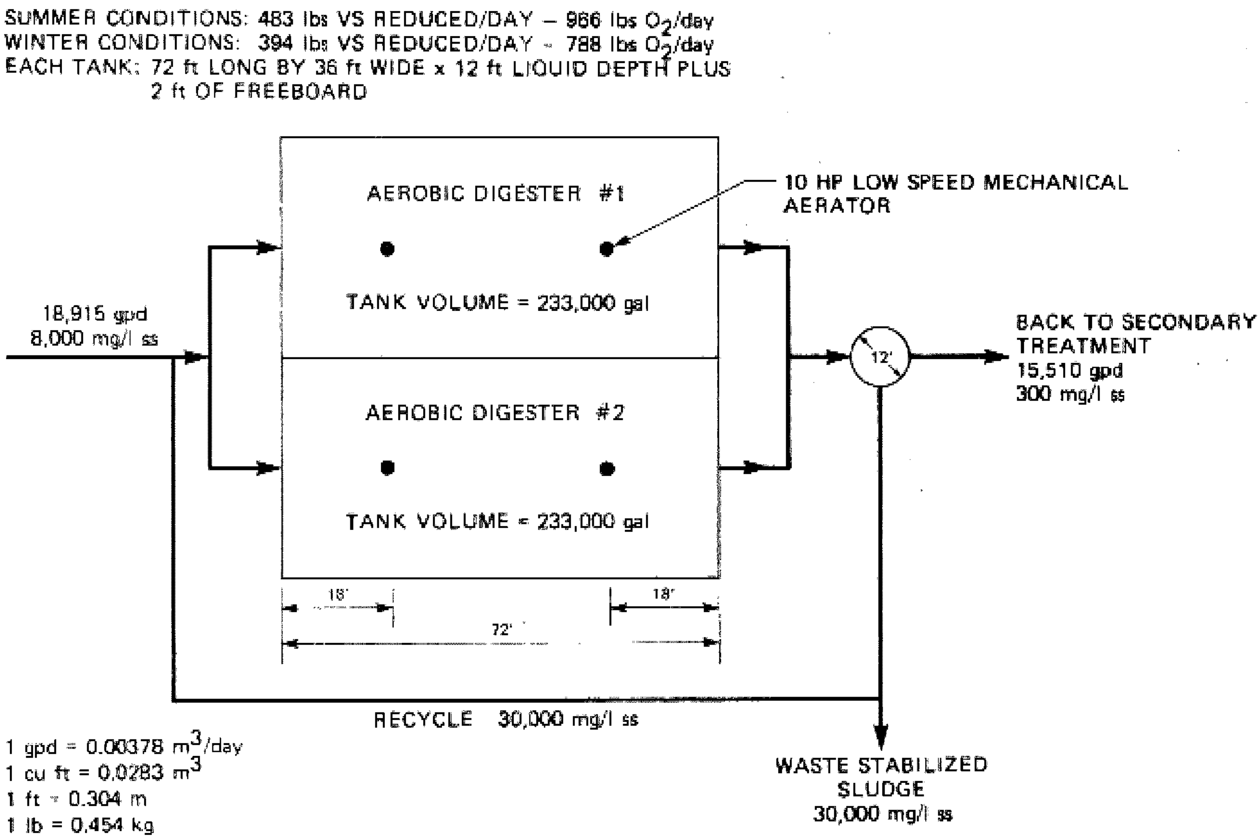


FIGURE 6-43

SUMMARY OF RESULTS FOR AEROBIC DIGESTION DESIGN EXAMPLE

Clarifier Surface Area

Surface area was based on an overflow rate of 200 gallons per square foot per day (8.16 $m^3/day/m^2$). At an influent flow of 18,915 gallons per day (71.5 m^3/day), the required surface area is 95 square feet (8.8 m^2). The designer selected a 12-foot (3.7 m) diameter clarifier.

Supernatant Flow

It was previously calculated that 82 percent of the influent to the aerobic digester would leave as supernatant. Based on an influent of 18,915 gallons per day (71.5 m^3/day), the supernatant flow will be 15,510 gallons per day (58.6 m^3/day), plus any precipitation.

6.3.6 Cost

6.3.6.1 Capital Cost

A regression analysis of construction bids from 1973-1977 indicated that, on the basis of USEPA Municipal Wastewater Treatment Plant Construction Cost Index - 2nd quarter 1977, the capital cost could be approximated by Equation 6-13 (198).

$$C = 1.47 \times 10^5 Q^{1.14} \qquad (6\text{-}13)$$

where:

C = capital cost of process in dollars

Q = plant design flow in million gallons of wastewater flow per day

The associated costs included those for excavation, process piping, equipment, concrete, and steel. In addition, such costs as those for administrating and engineering are equal to 0.2264 times Equation 6-13 (198).

6.3.6.2 Operation and Maintenance Cost

Although there are many items that contribute to operation and maintenance cost, in most aerobic digestion systems, the two most prevalent are staffing requirements and power usage.

Staffing Requirements

Table 6-24 lists labor requirements for both operation and maintenance. The labor indicated includes: checking mechanical equipment, taking dissolved oxygen and solids analyses, and general maintenance around the clarifier.

Power Requirements

In 1979, the cost of power for operating aeration equipment has become a significant factor. It is possible to minimize power consumption through two developments in environmental science.

- Make sure that the tank geometry and aeration equipment are compatible (212). The difference between optimized and unoptimized design can mean as much as a 50 percent difference in power consumption.
- Pace devices to control oxygen (power) input (218). Because of temperature effects, oxygen requirements for any given aerobic digestion system can vary as

much as 20 to 30 percent between summer and winter. One must design to meet the worst conditions (summer), for without some type of oxygen controller, considerable power is wasted during other times of the year.

TABLE 6-24

AEROBIC DIGESTION LABOR REQUIREMENTS (217)

Plant design flow, MGD	Labor, man hours per year		
	Operation	Maintenance	Total
0.5	100	20	120
1	160	30	190
2	260	50	310
5	500	100	600
10	800	160	960
25	1,500	300	1,800

1 MGD = 3,786 m^3/day

Other Requirements

Besides manpower and power cost, the designer must consider lubrication requirements. If mechanical aerators are being used, each unit needs to have an oil change once, and preferably twice, a year. Depending on horsepower size, this could be 5 to 40 gallons per unit per change (19-152 l/unit/change). Further, the designer must make sure an adequate inventory of spare parts are available.

6.4 Lime Stabilization

Lime stabilization is a very simple process. Its principal advantages over other stabilization processes are low cost and simplicity of operation. Evaluation of studies where lime stabilization was accomplished at pH ranges of 10-11, has shown that odors return during storage due to pH decay. To eliminate this problem and reduce pathogen levels, addition of sufficient quantities of lime to raise and maintain the sludge pH to 12.0 for two hours is required. The lime-stabilized sludge readily dewaters with mechanical equipment and is generally suitable for application onto agricultural land or disposal in a sanitary landfill.

No direct reduction of organic matter occurs in lime treatment. This has two important impacts. First, lime addition does not make sludges chemically stable; if the pH drops below 11.0, biological decomposition will resume, producing noxious odors. Second, the quantity of sludge for disposal is not reduced, as it is by biological stabilization methods. On the contrary, the mass of dry sludge solids is increased by the lime added and by the chemical precipitates that derive from this addition. Thus, because of the increased volumes, the costs for transport and ultimate disposal are often greater for lime-stabilized sludges than for sludge stabilized by other methods.

6.4.1 Process Description

6.4.1.1 History

Lime has been traditionally used to reduce odor nuisances from open pit privies and the graves of domestic animals. Lime has been used commonly in wastewater sludge treatment to raise the pH in stressed anaerobic digesters and to condition sludge prior to vacuum filtration. The original objective of lime conditioning was to improve sludge dewaterability but, in time, it was observed that odors and pathogen levels were also reduced. In 1954, T.R. Komline filed a patent (No. 2,852,584) for a method of processing raw sludge in which heavy dosages of hydrated lime (6 to 12 percent of total dry solids) were added specifically to cancel or inhibit odors. However, only recently has lime addition been considered a major sludge stabilization alternative.

Many studies describe the effectiveness of lime in reducing microbiological hazards in water and wastewater, but the bactericidal value of adding lime to sludge has been noted only recently (219-222). A report of operations at the Allentown, Pennsylvania wastewater treatment plant states that lime conditioning an anaerobically digested sludge to a pH of 10.2 to 11, and then vacuum filtering and storing the cake, destroyed all odors and pathogenic enteric bacteria (233). Kampelmacher and Jansen reported similar experiences (224). Evans noted that lime addition to sludge released ammonia and destroyed coliform bacteria and that the sludge cake was a good source of nitrogen and lime to the land (225).

Lime stabilization of raw sludges has been conducted in the laboratory and in full-scale plants. Farrell and others (226) reported that lime stabilization of a primary sludge reduced bacterial hazard to a negligible value, improved vacuum filter performance, and provided a satisfactory means of stabilizing sludge prior to ultimate disposal. Paulsrud and Eikum (227) determined the lime dosage required to prevent odors occurring during storage of sewage sludges. Primary biological sludges, septic tank sludges, and different chemical sludges were used in the study. An important finding was that lime dosages greater than those sufficient to initially raise the pH of the sludges were required to prevent pH decay and the return of odors during storage. Laboratory and pilot scale work by Counts and Shuckrow (228) on lime stabilization showed significant reductions in pathogen populations and obnoxious odors when the sludge pH was greater than 12. Counts conducted growth studies on greenhouse and outdoor plots which indicated that the disposal of lime-stabilized domestic sludge on cropland would have no detrimental effect on plant growth and soil characteristics. Disposal of the lime-stabilized domestic sludge at loading rates up to 100 tons dry solids per acre (224 t/ha) on green-house plots and 40 tons dry solids per acre (90 t/ha) on outdoor plots had no detrimentatal effect on plant growth and soil characteristics.

A full-scale lime stabilization facility was built as part of a 1-MGD (43.8 l/s) wastewater treatment plant in Lebanon, Ohio. Operation began in 1976. A case study of lime treatment and land application of sludge from this plant, along with a general economic comparison of lime stabilization with anaerobic digestion, is available (229).

6.4.1.2 Current Status

As of May 1978, lime treatment is being used to stabilize the sludge from at least 27 municipal wastewater treatment plants in Connecticut. Average wastewater flows treated at these plants vary from 0.1 to 31 MGD (4.4 to 1358 l/s). In most of the plants, incinerators have been either wholly or partially abandoned. While few chemical or bacterial data are available, qualitative observations indicate that treatment is satisfactory. Most of the communities have indicated that they will continue with lime stabilization.

Landfill burial is the most common means of disposal for lime-stabilized sludge. However, lime-treated sludge from eight of the plants in Connecticut is applied onto land. At Enfield, Connecticut, dewatered sludge is stockpiled in large mounds. The sludge is spread onto cornfields when application is compatible with crop cycles and weather conditions. Few nuisances are caused by the practice. Odors have not been a problem, even when piles have been opened for spreading of the sludge. In Willimantic, Connecticut, lime-stabilized sludge is mixed with leaves and grasses. After stockpiling, a portion of mixture is screened and distributed to local nurseries. The remainder is used as final cover for landfill.

6.4.1.3 Applicability

Lime stabilization can be an effective alternative when there is a need to provide:

- Backup for existing stabilization facilities. A lime stabilization system can be started (or stopped) quickly. Therefore, it can be used to supplement existing sludge processing facilities when sludge quantities exceed design levels, or to replace incineration during fuel shortages. Full sludge flows can be lime-treated when existing facilities are out of service for cleaning or repair.

- Interim sludge handling. Lime stabilization systems have a comparatively low capital cost and, therefore, may be cost effective if there are plans to abandon the plant or process within a few years.

- Expansion of existing facilities or construction of new facilities to improve odor and pathogen control. Lime stabilization is particularly applicable in small plants or when the plant will be loaded only seasonally.

In all cases, a suitable site for disposal or use of stabilized sludge is required.

6.4.1.4 Theory of the Process

Lime addition to sludge reduces odors and pathogen levels by creating a high pH environment hostile to biological activity. Gases containing nitrogen and sulfur that are evolved during anaerobic decomposition of organic matter are the principal source of odors in sludge (228). When lime is added, the microorganisms involved in this decomposition are strongly inhibited or destroyed in the highly alkaline environment. Similarly, pathogens are inactivated or destroyed by lime addition.

High lime dosing of sludge also affects the chemical and physical characteristics of sludge. Although the complex chemical reactions between lime and sludge are not well understood, it is likely that mild reactions, such as the splitting of complex molecules by hydrolysis, saponification, and acid neutralization, occur in the high pH environments created in lime stabilization (228). These reactions reduce the fertilizer value of the stabilized sludge, improve its dewaterability, and change the character of liquid sidestreams. The nature of these chemical changes is described in Section 6.4.3.4.

6.4.2 Design Criteria

Three fundamental design parameters must be considered in the design of a lime stabilization system: pH, contact time, and lime dosage. At this early stage in the development of the process, the selection of the levels of these parameters has been largely empirical. The results of earlier studies now can be used as a starting point, but because of the complexity of chemical interactions that apparently occur in lime treatment of sludge, bench-scale and pilot studies are recommended as part of designing a large-scale system, particularly if substantial departures from these conditions are contemplated.

6.4.2.1 pH and Contact Time

The primary objective of lime stabilization is to inhibit bacterial decomposition and inactivate pathogenic organisms. The extensive use of lime is medicinal; the masking of noxious odors from decaying substances permits uncritical acceptance of its use for sludge treatment. Nevertheless, evidence is needed of its value and of the necessary dose levels and contact times for effective treatment.

The effective factor in lime treatment is evidently the pH level and not just the dose of lime. As with most disinfection processes, the time of exposure (the extensive factor) is equally as important as the pH (the intensive factor). Investigations by Farrell and others (226), Counts and Shuckrow (228), and Noland and others (229), have established time, pH, and processing conditions for producing satisfactory lime stabilization. Process performance is discussed in a subsequent section (Section 6.4.3).

The design objective is to maintain pH above 12 for about two hours to ensure pathogen destruction, and to provide enough residual alkalinity so that the pH does not drop below 11 for several days, allowing sufficient time for disposal or use without the possibility of renewed putrefaction. The recommended design criteria for accomplishing these objectives are:

- Treat sludge in the liquid state.
- Bring the sludge to pH 12.5 by lime addition and maintain pH above 12.5 for 30 minutes (which keeps pH >12 for two hours).

Farrell and others (226) attempted to determine whether the additions of lime that would occur in conditioning of sludge for dewatering would produce adequate stabilization. They mixed liquid sludge with lime for two minutes, and then dewatered the sludge on a Buchner funnel. Their results indicated inadequate bacteriological destruction. Later results by Strauch and others (230) in Denmark and unpublished results at Downington, Pennsylvania (See Section 6.4.4.1) indicate that special reaction conditions or intense mixing of sludge cake with lime can produce satisfactory results.

6.4.2.2 Lime Dosage

The amount of lime required to stabilize sludge is determined by the type of sludge, its chemical composition, and the solids concentration. Table 6-25 summarizes the results of plant-scale tests at Lebanon, Ohio, and shows that lime additions ranging from 6 to 51 percent of the total dry solids in the sludge were required to raise the pH to the levels indicated in the table. These lime dosages were sufficient to keep the sludge pH above

12.0 for 30 minutes. Primary sludges required the lowest dosages, while the highest average dosages were required to raise the pH level of waste-activated sludges. The results of studies conducted by Paulsrud and Eikum (227) agree generally with the Lebanon tests and are displayed in Table 6-26. Iron and alum sludges required the highest dosages. Farrell, and others (226) also found that alum additionally increased the lime requirement and suggested that part of the lime added to alum sludge may be bound as a calcium-aluminum compound.

TABLE 6-25

LIME REQUIREMENT TO ATTAIN pH 12 FOR 30 MINUTES AT LEBANON, OHIO (228)

Sludge type	Solids concentration, percent		Lime dosage, lb $Ca(OH)_2$/lb dry solids		pH, average	
	Range	Average	Range	Average	Initial	Final
Primary sludge[a]	3-6	4.3	0.06-0.17	0.12	6.7	12.7
Waste activated sludge	1-1.5	1.3	0.21-0.43	0.30	7.1	12.6
Anaerobically digested mixed sludge	6-7	5.5	0.14-0.25	0.19	7.2	12.4
Septage	1-4.5	2.7	0.09-0.51	0.20	7.3	12.7

[a]Includes some portion of waste activated-sludge.

1 lb/lb = 1 kg/kg.

TABLE 6-26

LIME DOSES REQUIRED TO KEEP pH ABOVE 11.0 AT LEAST 14 DAYS (226)

Type of sludge	Lime dose, lb $Ca(OH)_2$/lb suspended solids
Primary sludge	0.10 - 0.15
Activated sludge	0.30 - 0.50
Septage	0.10 - 0.30
Alum-sludge[a]	0.40 - 0.60
Alum-sludge[a] plus primary sludge[b]	0.25 - 0.40
Iron-sludge[a]	0.35 - 0.60

[a]Precipitation of primary treated effluent.

[b]Equal proportions by weight of each type of sludge.

1 lb/lb = 1 kg/kg.

Figure 6-44 displays the general relationship between lime dosage and pH for a typical municipal sludge at several solids concentrations. Table 6-26 calculated from data on Figure 6-44, shows that the lime dose per unit mass of sludge solids required to attain a particular pH level is relatively constant. That is, lime requirements are more closely related to the total mass of sludge solids, rather than the sludge volume. Consequently, reduction in volume by thickening may have little or no effect on the amount of lime required, because the mass of sludge solids is not changed.

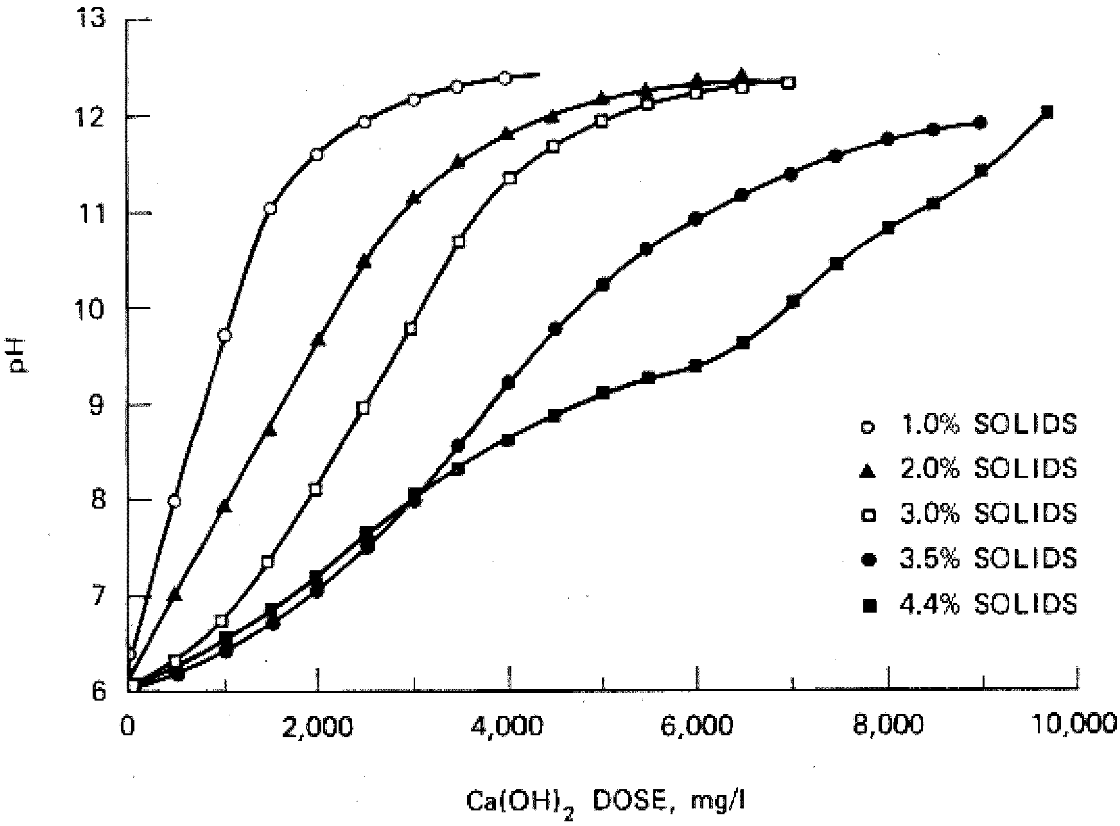


FIGURE 6-44

LIME DOSES REQUIRED TO RAISE pH OF A MIXTURE OF PRIMARY SLUDGE AND TRICKLING FILTER HUMUS AT DIFFERENT SOLIDS CONCENTRATIONS (228)

Lime additions must be sufficient to ensure that the pH of sludge does not drop below the desired level after prolonged storage. If insufficient lime is added, the pH will decay as the treated sludge ages (227-229). This phenomenon is displayed on Figure 6-45. Notice that higher lime dosages not only raise the initial pH but, more importantly, prevent, or at least delay, the drop in pH levels. Consequently, in practice, lime doses must be greater than that sufficient to raise the pH to the desired value. In most cases, significant pH decay will not occur if enough lime is added to raise the sludge pH to 12.5 and maintain that value for at least 30 minutes (229).

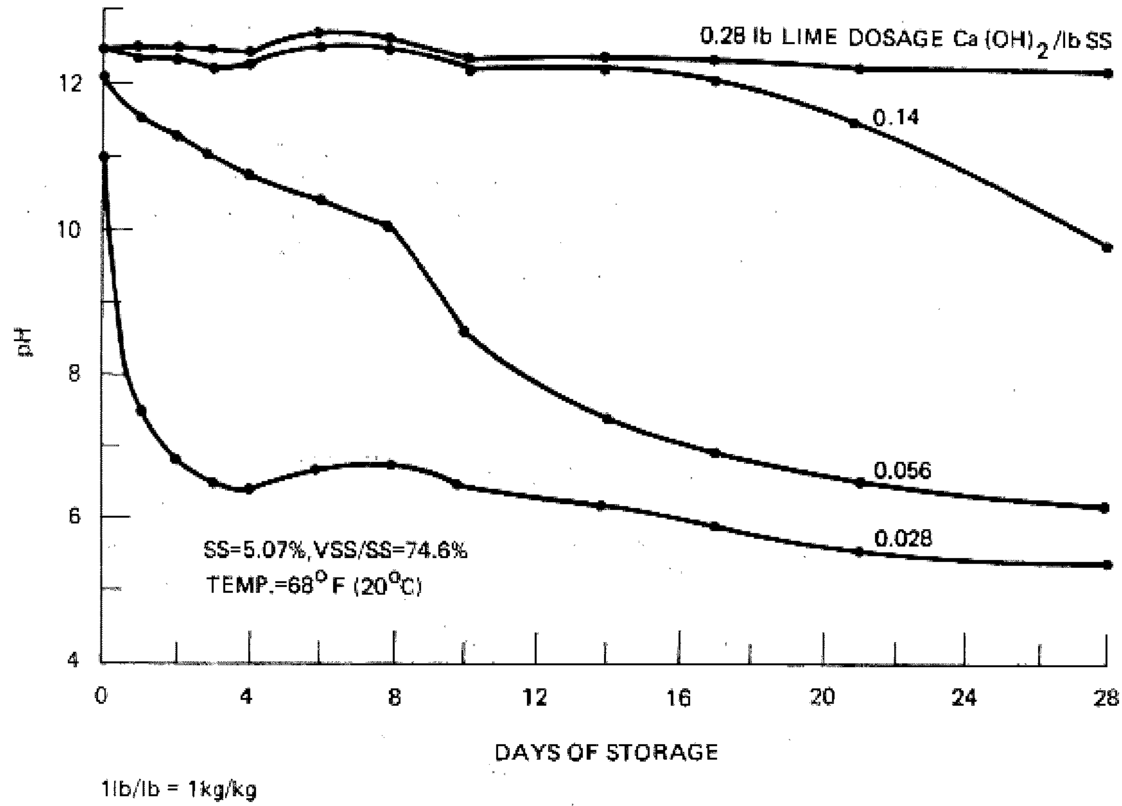


FIGURE 6-45

CHANGE IN pH DURING STORAGE OF PRIMARY SLUDGE USING DIFFERENT LIME DOSAGES

Several mechanisms of pH decay have been proposed and some have been documented (227,228). The initial pH drop results from the uptake of atmospheric CO_2 and slow reactions of hydroxyl ions with sludge solids. The rate of pH reduction is accelerated once the pH reaches a point at which bacterial action can resume production of organic acids through anaerobic microbial degradation.

The foregoing discussion makes it clear that a dose level cannot be defined without reference to the specific sludge. Actual dose levels will have to be determined in bench-scale tests. Approximate levels can be selected from the information above in order to establish size of equipment and to estimate costs.

6.4.3 Process Peformance

Lime stabilization reduces odors and odor production potential in sludge, reduces pathogen levels, and alters dewatering, settling, and chemical characteristics of the sludge. The nature and extent of the effects produced are described in the following paragraphs.

6.4.3.1 Odor Control

Lime treatment deodorizes sludge by creating a high pH environment in the sludge, thus eliminating or suppressing the growth of microorganisms that produce malodorous gases. In one laboratory study (228), the threshhold odor number of raw mixed primary and trickling filter sludges was 8,000, while that of lime-treated sludges ranged between 800 and 1300. The threshold odor number defines the greatest dilution of the sample with odor-free water to yield the least definitely perceptible odor (231). Sufficient lime must be added to retard pH decay because odor generation will generally resume once the pH of the sludge falls below pH 11.0 (220,228).

Hydrogen sulfide (H_2S), a malodorous gas present in dissolved form in sludge, is a major cause of sludge odors. Figure 6-46 shows that, as the pH of sludge is raised, the fraction of total sulfide in the H_2S form decreases from about 50 percent at pH 7 to essentially zero at pH 9. Consequently, above this pH, there is no longer any H_2S odor.

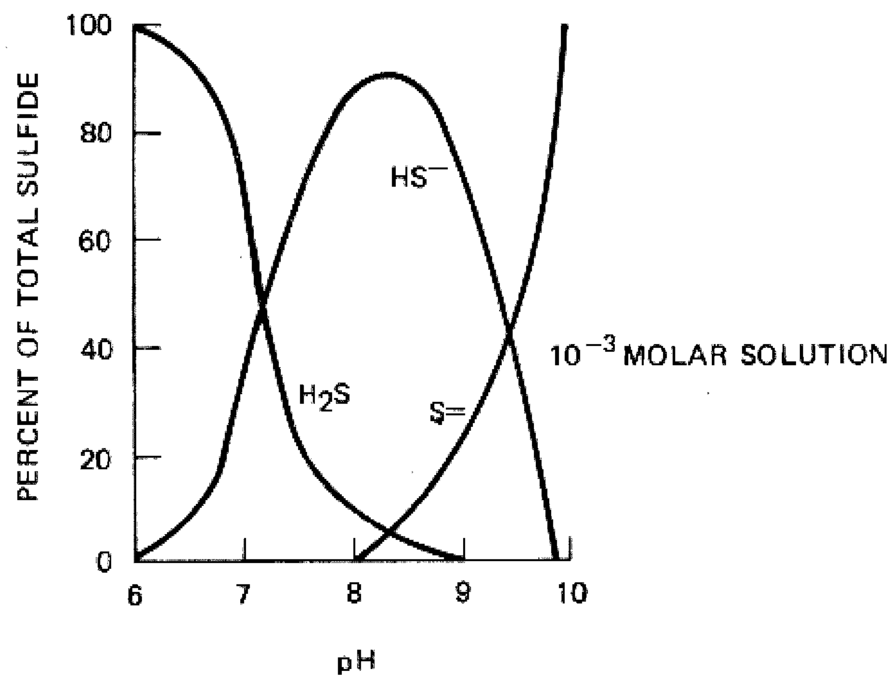


FIGURE 6-46

EFFECT OF pH ON HYDROGEN SULFIDE-SULFIDE EQUILIBRIUM

During full-scale operations at the Lebanon plant (229), odor was intense when septic raw sludge was first pumped to the lime stabilization mixing tank. Odor intensity increased when diffused air was applied for mixing. When lime was added, the sludge odor was masked by the odor of ammonia, which was stripped from the sludge by the air bubbled through the mixture. The ammonia odor was most intense with anaerobically digested sludge and was strong enough to cause nasal irritation. As mixing proceeded, the treated sludge acquired a musty, mucus-like odor.

6.4.3.2 Pathogen Reduction

Significant pathogen reductions can be achieved in sludges that have been lime-treated to pH 12.0 (228,229). Table 6-27 lists bacteria levels measured during the full-scale studies at Lebanon and shows that lime stabilization of raw sludges reduced total coliform, fecal coliform, and fecal streptococci concentrations by more than 99.9 percent. The numbers of Salmonella and Pseudomonas aeruginosa were reduced below the level of detection. Table 6-27 also shows that pathogen concentrations in lime-stabilized sludges ranged from 10 to 1,000 times less than those in anaerobically digested sludge from the same plant.

TABLE 6-27

BACTERIA IN RAW, ANAEROBICALLY DIGESTED, AND LIME STABILIZED SLUDGES AT LEBANON, OHIO (228)

	Bacterial density, number/100 ml				
Sludge type	Total coliform[a]	Fecal coliform[a]	Fecal streptococci	Salmonella[c]	Ps. aeruginasa
Raw					
Primary	2.9×10^9	8.3×10^8	3.9×10^7	62	195
Waste-activated	8.3×10^8	2.7×10^7	$1.0 \times$ [illegible]	6	5.5×10^3
Septage	2.9×10^8	1.5×10^7	6.7×10^5	6	754
Anaerobically digested					
Mixed primary and waste-activated	2.8×10^7	1.5×10^6	2.7×10^5	6	42
Lime stabilized[b]					
Primary	1.2×10^5	5.9×10^3	1.6×10^4	<3	<3
Waste-activated	2.2×10^5	1.6×10^4	6.8×10^3	<3	13
Septage	2.1×10^3	265	665	<3	<3
Anaerobically digested	18	18	8.6×10^3	<3	<3

[a]Millipore filter technique used for waste-activated sludge and septage. MPN technique used for other sludges.

[b]To pH equal to or greater than 12.0.

[c]Detection limit = 3.

Information on virus destruction in sludge by lime stabilization is scant. There are numerous investigations on removal of viruses from wastewater by lime flocculation but little on destruction of viruses by elevated pH. A study by Berg (233) measured the structure of a polio virus in water by pH adjustment alone, and indicate very rapid destruction above pH 11. Similar effects would be expected for other animal viruses.

Qualitative observation under a microscope has shown substantial survival of higher organisms, such as hookworms, amoebic cysts, and *Ascaris* ova, after contact times of 24 hours at high pH (226). It is not known whether long-term contact would eventually destroy these organisms. A more complete discussion of sludge disinfection is contained in Chapter 7.

6.4.3.3 Dewatering and Settling Characteristics

Lime has been used extensively as a conditioning agent to improve the dewaterability of sludge. Trubnick and Mueller (234) presented detailed procedures to be followed in conditioning sludge for filtration, using lime with and without ferric chloride. Sontheimer (235) described the improvements in sludge filterability produced by lime addition. A more detailed discussion of lime conditioning is contained in Chapter 8.

The addition of lime has been shown to improve the filterability of alum and iron primary sludges (226). Specific resistance was reduced by a factor of approximately four, and filter yield was increased by a factor of two when lime conditioning was used. Counts and Shuckrow (228) studied the effect of lime treatment on the filterability of primary sludge and trickling filter sludge but could not detect any consistent trend.

The impact of lime stabilization on sand bed drying of sludge has been examined by several researchers (226,228,229). Lime additions to raw sludge increased the rate of drying at least initially and, in one study, produced a drier final cake. However, lime-treated primary sludge did not dry as fast as either lime-treated or untreated anaerobically digested sludge (229).

The settling of lime-stabilized primary and mixed sludges was enhanced in one study (228), indicating that gravity thickening after lime treatment may be used to reduce the volume of sludge to be dewatered.

6.4.3.4 Chemical Characteristics

Lime stabilization causes chemical changes in the sludge. The nature of these changes is illustrated in Tables 6-28 and 6-29, which compile chemical data from two studies. The general effect of lime addition is a reduction in component concentration. This is caused by both dilution with lime slurry and loss of some volatile sludge components to the atmosphere.

Lime-stabilized sludges have lower concentrations of soluble phosphate, ammonia nitrogen, and total Kjeldahl nitrogen than anaerobically digested sludge from the same plant, as shown in Table 6-28. These lower nutrient levels reduce the agricultural value of the sludge but, assuming nitrogen limits the rate at which sludge can be applied, would allow more sludge to be applied per acre of land. A reduction in the soluble (filterable) phosphate concentration is caused by the reaction between lime and dissolved orthophosphate to form calcium-phosphate precipitate. For this reason, residual phosphate in the supernatant/filtrate after lime treatment is believed to be largely organic in nature (228). Nitrogen levels can be reduced during lime stabilization if gaseous ammonia is stripped during air mixing of the treated sludge. As the pH of the sludge increases from near neutral to 12, the predominant form of ammonia shifts from the ammonium ion (NH_4^+) to dissolved ammonia gas (NH_3). Some of this gas is carried off by the air bubbled through the sludge for mixing.

TABLE 6-28

CHEMICAL COMPOSITION OF SLUDGES AT LEBANON, OHIO, BEFORE AND AFTER LIME STABILIZATION (228)

	Concentration, average, mg/l								
Sludge type	Alkalinity	Total COD	Soluble COD	Total phosphate	Soluble phosphate	Total Kjeldahl nitrogen	Ammonia nitrogen	Total suspended solids	Volatile suspended solids
Primary									
Before lime addition	1,885	54,146	3,046	350	69	1,656	223	48,700	36,100
After lime addition	4,313	41,180	3,556	283	36	1,374	145	38,370	23,480
Waste activated									
Before lime addition	1,265	12,810	1,043	218	85	711	51	12,350	10,000
After lime addition	5,000	14,700	1,618	263	25	1,034	64	10,700	7,136
Anaerobically digested mixed sludge									
Before lime addition	3,593	66,372	1,011	580	15	2,731	709	61,140	33,316
After lime addition	8,467	58,670	1,809	381	2.9	1,780	494	66,350	26,375
Septage									
Before lime addition	1,897	24,940	1,223	172	25	820	92	21,120	12,600
After lime addition	3,475	17,520	1,537	134	2.4	597	110	23,190	11,390

A direct result of adding lime to sludge is that the total alkalinity will rise to a high value. This can affect the suitability of the treated sludge for land application. The input can be positive or negative, depending on soil conditions at the application site. Data in Table 6-28 indicates the magnitude of change in alkalinity.

Biochemical oxygen demand, chemical oxygen demand, and total organic carbon concentrations increase in the liquid fraction of wastewater sludges when lime is added (228,229). Organic matter is dissolved in the high pH environment. Possible reactions involved include saponification of fats and oils, hydrolysis and dissolution of proteins, and decomposition of proteins to form methanol (228).

Lime stabilization usually does not produce the substantial reductions in volatile matter associated with anaerobic and aerobic sludge digestion. However, volatile solids concentrations decreased by 10 to 35 percent after lime additions in the plant-scale studies at Lebanon (229), as shown in Table 6-28. Reductions in total solids concentration after lime stabilization were measured by Counts and Shunckrow (228). These reductions, displayed in Table 6-29, are greater than can be accounted for simply by dilution with lime slurry. It may be simply that the lime interfered with the volatile solids analysis. However, reactions between lime and nitrogenous organic matter may cause a loss of sludge solids. Hydrolysis of proteins and destruction of amino acids are known to occur by reaction with strong bases. Volatile substances such as ammonia, water, and low molecular weight amines or other volatile organics may possibly be formed and lost to the atmosphere.

6.4.4 Process Design

A lime stabilization operation is divided into two operations: lime handling and sludge mixing. Lime handling comprises facilities for receiving storing, transporting, feeding, and "slurrying" of the lime. The sludge mixing operation consists of a holding tank provided with mixing. A discussion of design considerations for these two operations follows.

6.4.4.1 Design of Lime Handling Facilities

Lime, in its various forms, is the principal and lowest cost alkali used in industry and wastewater treatment. As a result, a substantial body of knowledge has evolved concerning the most efficient handling of lime. Only the basic elements of lime system design are described in this manual. Detailed information is contained in several references that focus on the selection, handling, and use of lime (236-239).

Lime Characteristics

Lime is a general term applied to several chemical compounds that share the common characteristic of being highly alkaline. The two forms commercially available are quicklime (CaO) and hydrated lime ($Ca(OH)_2$). The characteristics of these two chemicals are summarized in Table 6-30. Lime is a caustic material and can cause severe injury to tissue, particularly to eyes. Equipment must be designed with safe handling in mind; eyewash fountains and safety showers should be provided, and operating procedures should mandate use of proper handling procedures and protective clothing.

Quicklime is derived from limestone by a high temperature calcination process. It consists primarily of the oxides of calcium and magnesium. The grade of quicklime most commonly used in wastewater treatment contains 85 to 90 percent CaO.

TABLE 6-29

CHEMICAL COMPOSITION OF SLUDGE AND SUPERNATANT BEFORE AND AFTER LIME STABILIZATION[a] (227)

Parameter	Primary sludge	Trickling filter humus	Mixed sludge
Whole sludge			
pH			
Before lime addition	6.0	6.3	6.1
After lime addition	12.1	12.3	12.0
Total solids (wt percent)			
Before lime treatment	3.6	3.0	3.6
After lime treatment	3.2	2.7	3.3
Total alkalinity (mg/l as $CaCO_3$)			
Before lime addition	1,141	1,151	1,213
After lime addition	6,920	6,240	5,760
Ammonia nitrogen (mg N/l)			
Before lime addition	211	274	192
After lime addition	91	148	87
Organic nitrogen (mg N/l)			
Before lime addition	1,066	1,179	1,231
After lime addition	1,146	995	1,099
Nitrate nitrogen (mg N/l)			
Before lime addition	3	7	16
After lime addition	25	22	31
Total phosphate (mg P/l)			
Before lime addition	342	305	468
After lime addition	302	235	337
Filterable phosphate (mg P/l)			
Before lime addition	92	96	80
After lime addition	32	17	31
Supernatant			
TOC (mg/l)			
Before lime addition	1,000	917	1,175
After lime addition	2,083	1,883	2,250
BOD (mg/l)			
Before lime addition	1,120	964	1,137
After lime addition	1,875	1,981	2,102
Threshhold odor number[b]			
Before lime addition	4,889	5,333	933
After lime addition	467	333	67
Total solids (wt percent)			
Before lime addition	0.1	0.1	0.2
After lime addition	0.6	0.5	0.7

[a]Values in this table are averages of three tests for each sludge type.

[b]The greatest dilution with odor-free water to yield the least perceptible odor.

Quicklime is rarely applied directly (that is, in a dry condition) to the sludge. First it is converted to hydrated lime by reaction with water in an exothermic reaction called slaking.

$$CaO + H_2O \longrightarrow Ca(OH)_2 + \text{Heat}$$

During slaking, the generally coarse CaO particles are ruptured, splitting into microparticles of $Ca(OH)_2$. These smaller particles have a large total surface area and are highly reactive. The slaking reaction is carried out under closely controlled conditions to promote maximum lime reactivity.

TABLE 6-30

CHARACTERISTICS OF QUICKLIME AND HYDRATED LIME

Common name/ formula	Available forms	Containers and requirements	Appearance and properties	Weight, lb/cu ft (bulk density)	Commercial strength	Solubility in water
Quicklime/ CaO	Pebble Crushed Lump Ground Pulverized	80-100 lb moisture-proof bags, wooden barrels, and carloads. Store dry; maximum 60 days in tight container - 3 months in moisture-proof bag.	White (light grey, tan) lumps to powder. Unstable, caustic irritant. Slakes to hydroxide slurry evolving heat (490 Btu/lb). Air slakes to $CaCO_3$. Sat. sol. approximately pH 12.5	55 to 75; to calculate hopper capacity - use 55; Sp. G., 3.2-3.4.	70 to 96 percent CaO (Below 88 percent can be poor quality)	Reacts to form $Ca(OH)_2$ each lb of quicklime will form 1.16 to 1.32 lb of $Ca(OH)_2$, with 2 to 12 percent grit, depending on purity.
Hydrated lime/ $Ca(OH)_2$	Powder (Passes 200 mesh)	50 lb bags, 100 lb barrels, and carloads. Store dry; maximum one year.	White, 200-400 mesh; powder free of lumps; caustic, dusty irritant; absorbs H_2O and CO_2 from air to form $Ca(HCO_3)_2$. Sat. sol. approximately pH 12.4.	25-40; to calculate hopper capacity - use 30; Sp. G., 2.3-2.4	$Ca(OH)_2$ - 82 to 98 percent; CaO - 62 to 74 percent (Std. 70 percent)	10 lb/1,000 gal at 70°F 5.6 lb/1,000 gal at 175°F

1 lb = 0.454 kg
100 Btu/lb = 55 kg-cal/kg
1 lb/cu ft = 16 kg/m^3
1 lb/1,000 gal = 0.120 g/l

If slaking is done by the lime manufacturer, hydrated lime is delivered to the wastewater treatment plant. The manufacturer adds only enough water for hydration, producing a dry $Ca(OH)_2$ powder. At the waste treatment plant, the powder is then slurried with more water prior to mixing with sludge. Alternatively, slaking may be carried out at the wastewater treatment plant; the delivered product is, therefore, quicklime. In this case, the lime is slaked, then diluted (if necessary) prior to process application.

Direct addition of dry quicklime to sludge and without the use of a separate slaker, is practiced in Denmark in at least ten Swedish treatment plants. Potential advantages are the elimination of slaking equipment and the generation of heat, which can improve pathogen reduction and speed dewatering through evaporation. In one case (230), direct additions of dry quicklime were made to raise sludge pH above 13.0 and bring the temperature to 176°F (80°C). Salmonella and intestinal parasites were killed within two hours. Heat generated by slaking of quicklime does not raise temperature significantly unless the sludge is dewatered and the lime dose is high--on the order of 400 to 800 lb per ton dry solids (200-400 kg/t).

The decision whether to purchase quicklime or hydrated lime in a particular situation is influenced by a number of factors such as size of treatment facility, material cost, and storage requirements. The cost of hydrated lime is about 30 percent greater than the cost of quicklime with an equivalent calcium oxide content. The difference is due to the higher production and transportation costs for hydrated lime. Nevertheless, hydrated lime is preferred for small-scale operations mainly because its use eliminates the labor and equipment required for slaking. Hydrated lime is also more stable and therefore is easier to handle and to store. When lime use exceeds three to four tons per day (3,000-4,000 kg/day), quicklime should be considered because of its inherent economy (236). Selection of the type of lime to be used should be based on a detailed economic analysis, taking into account all the unique factors of the particular application.

Both quicklime and hydrated lime react spontaneously with atmospheric CO_2.

$$CaO + CO_2 \longrightarrow CaCO_3$$

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

In addition, quicklime can be slaked by the water vapor in the air.

These reactions cause two problems:

- Lime quality is degraded because the reaction product, $CaCO_3$, is ineffective in raising pH.
- The partial reaction with CO_2, and in the case of CaO, with water vapor, causes caking. This interferes with lime slaking and feeding.

Thus, lime storage, slaking, and feeding equipment should be sealed to as great a degree as possible to prevent contact of lime with atmospheric CO_2 and water vapor.

Delivery and Storage of Lime

Lime can be delivered either in bags or in bulk. The choice depends mostly on the rate of chemical use at the treatment plant. Bagged lime costs about 20 percent more than bulk lime, but it is generally preferred where daily requirements are less than 1000 to 1500 pounds of lime per day (236). At this small scale, handling and storage of bagged lime is relatively simple, involving manual labor or simple mechanical aids. As the scale of operation increases, it becomes more efficient and economical to use bulk lime, which can be delivered in large quantities, transported in mechanical or pneumatic conveying systems, and stored in weather-tight bins or silos.

Bagged lime must be stored under cover to prevent rain from wetting the bags. Proper handling is especially important when quicklime is used, because it is highly reactive with water, producing heat and swelling that can cause the bags to burst. Because heat can be generated during accidental slaking of quicklime, bags should never be stored close to combustible materials.

Hydrated lime may be stored under dry conditions for periods up to a year without serious deterioration by reaction with atmospheric CO_2 (recarbonation). Quicklime deteriorates more rapidly. Under good storage conditions, with multiwall moisture-proofed bags, quicklime may be held as long as six months, but in general should not be stored for more than three months (236).

Bulk quicklime and hydrated lime can be stored in conventional steel or concrete silos or bins. The storage facilities must be airtight to prevent slaking and recarbonation. Pebble quicklime is free-flowing and will discharge readily from storage bins if the hopper bottoms have a minimum slope of 60 degrees from the horizontal. Pulverized quicklime and especially hydrated lime have a tendency to arch and therefore require some type of mechanical or aeration agitation to ensure uniform discharge from storage bins. Detailed descriptions of the various types of flow-aiding devices can be found elsewhere (236,240).

Storage facilities should be sized on daily lime demand, type and reliability of delivery, future chemical requirements, and an allowance for flexibility and expansion. As a minimum, storage should be provided to supply a seven-day lime demand; however, sufficient storage to supply lime for two to three weeks is desirable. In any case, the total storage volume should be at least 50 percent greater than the capacity of the delivery railcar or truck to ensure adequate lime supply between shipments (236).

Lime Feeding

Lime is nearly always delivered to the sludge mixing vessel as a $Ca(OH)_2$ slurry (milk-of-lime). This facilitates transport to the point of application and improves lime dispersion and reaction efficiency. The exact series of steps through which dry lime is wetted and introduced to the sludge varies according to such factors as the scale of the operation, the type of lime purchased, and the method of storage. The following paragraphs outline the basic lime-feeding schemes. The discussion is largely derived from a bulletin published by the National Lime Association (236), which should be referred to for more detail.

Feeding of Hydrated Lime - In small treatment plants where bagged hydrated lime is purchased, the dry chemical is simply mixed with water in a batch tank and metered to the sludge mixing tank as required. Solutions of lime are not corrosive, so that an unlined steel tank is sufficient for mixing and storage of the slurry. Hydrated lime is fed as a 6 to 18 percent $Ca(OH)_2$ slurry by weight, the percentage depending on the application and on operator preference. The milk-of-lime can be discharged to the sludge in one batch or metered continuously to the basin through a solution feeder.

In larger operations, where hydrated lime is stored in bulk, a more automated mixing and feeding scheme is appropriate. A dry chemical feeder is used for continuous delivery of a measured amount of dry lime to a dilution tank. The feeder is often positioned directly at the base of the bulk storage bin to minimize dry lime transport distance.

Two general types of automated dry feeders are available:

- Volumetric feeders, which deliver a constant, preset volume of chemical in a unit of time, regardless of changes in material density.

- Gravimetric feeders, which discharge a constant weight of chemical in a unit of time.

Gravimetric feeders cost roughly twice as much as volumetric feeders with an equivalent capacity and require more maintenance, but they are more accurate. Most manufacturers of gravimetric feeders will guarantee a minimum accuracy of within one percent, by weight, of the set rate. Volumetric feeders, on the other hand, may have an error of 30 percent by weight, due to the varying bulk density of hydrated lime. Gravimetric feeders are preferred because of their greater accuracy and dependability, but the less expensive volumetric type may be sufficient when limited funds are available, when greater chemical feeding accuracy is not required, or when a reduced degree of maintenance is desirable.

Dry hydrated lime is delivered to a dilution tank that is often fitted directly onto the feeder. The tank is agitated by either compressed air, water jets, or impeller type mixers. The lime slurry is then transferred to the sludge mixing basins. This transfer operation is the most troublesome single operation in the lime handling process. The milk-of-lime reacts with atmospheric CO_2 or carbonates in the dilution water to form hard, tenacious $CaCO_3$ scales, which, with time, can plug the transfer line. Because the magnitude of this problem is in direct proportion to the distance over which the slurry must be transferred, lime feeder facilities should be located as close as possible to the lime/ sludge mixing tanks. Pumping of the lime slurry should be avoided (if possible, gravity transfer should be used), and all apparatus should be accessible for cleaning. Scaling in lime slurry systems has been prevented through the use of a chemical additive that interfers with crystal formation. Design features and operating techniques used successfully for milk-of-lime transfer are described in detail in reference 236.

Direct addition of dry hydrated lime to centrifuge cake was tested in a pilot-scale study at the wastewater treatment plant in Downington, Pennsylvania. An undigested mixture of primary and secondary sludges was dewatered to a solids concentration of 20 percent, and then blended with powdered $Ca(OH)_2$ for ten minutes in a twin-paddle mixer. Addition of 200 pounds of hydrated lime per ton dry (100 kg/t) raised sludge pH to 11.8, reduced pathogen levels to below the detection limit, and controlled odor and fly problems.

Slaking and Feeding of Quicklime - Feeding of quicklime is similar to that for hydrated lime, except that there is an additional step, slaking, in which the quicklime reacts spontaneously with water to form hydrated lime. Bagged quicklime can be slaked in batches by simply mixing one part quicklime with two to three parts water in a steel trough while blending with a hoe. Proportions should be adjusted so that the heat of the reaction maintains the temperature of the reacting mass near 200°F (93°C). The resulting thin paste should be held for 30 minutes after mixing to complete hydration. Manually operated batch slaking is a potentially hazardous operation and should be avoided if possible. Uneven distribution of water can produce explosive boiling and splattering of lime slurry. Use of protective equipment should be mandatory. For small plants, the potential gain in using the lower-priced quicklime is smaller, because lime consumption is smaller. Use of slaked lime is safer, simpler, and requires less labor.

Continuous slaking is accomplished in automated machines that also dilute and degrit the lime slurry. Several types of continuous slakers are available. They vary mainly in the proportion of lime to water mixed initially. A volumetric or gravimetric dry chemical feeder is used to measure quicklime as it is moved from bulk storage to the slaker. Since quicklime is available in a wide range of particle sizes, it is important to match the dry feeder with the type of quicklime to be used in the particular application.

6.4.4.2 Mixing Tank Design

A tank must be provided for mixing raw sludge with lime slurry and then holding the mixture for a minimum contact time. Many of the currently operating lime stabilization facilities do not have tanks with sufficient capacity to hold sludge for more than a few minutes. Although these operations generally have been successful, the acceptability of very short detention times has not been conclusively demonstrated. Because of the uncertainty surrounding this practice, it is recommended that all lime stabilization facilities include a tank large enough to hold the lime sludge mixture for 30 minutes. The pH of the reacted mixture should exceed 12.5 during this period.

The following paragraphs discuss two aspects of mixing tank design - tank sizing and mixing. To determine tank size, a designer must first select a flow mode. The following section on tank sizing describes flow modes. The subsequent section on tank mixing covers the general types of mixers and suggests criteria for sizing mixing systems.

Tank Sizing Considerations

Mixing tanks can be operated as either a batch process or continuous flow process. In the batch mode, the tank is filled with sludge, and then sufficient lime is added to maintain the pH of the sludge-lime mixture above 12.5 for the next 30 minutes. After this minimum contact time, the stabilized sludge can be transferred to dewatering facilities or to either tank trucks or a pipeline for land application. Once the holding tank is emptied, the cycle begins again.

In the continuous flow mode, the pH and volume of sludge in the holding tank are held constant. Entering raw sludge displaces an equal volume of treated sludge. Lime is added continuously, in proportion to the flow of incoming raw sludge, and thus, the holding time would vary. The lime dose must be sufficient to keep the contents of the tank at a pH of 12.5. Often the daily cycle of sludge production does not match the pattern of sludge disposal. In this case, a system could be operated on a semi-continuous basis, where the quantity of sludge in the tank fluctuates through the day. Here the treatment tank would be used as a buffer between sludge production and disposal.

It is most common to operate lime stabilization systems in the batch flow mode. Batch operations are very simple and are well suited for small-scale, manually operated systems. When adequate capacity is provided, the mixing tanks can also be used to gravity thicken the lime-treated sludge before disposal. In very small treatment plants, tank capacity should be adequate to treat the maximum-day sludge production in one batch. This is because small plants are generally operated only during the day, and it is usually desirable to stabilize the entire day's sludge in one batch. Larger plants are more likely to be manned round-the-clock. Because sludge can be processed over the whole day, stabilization tanks can be relatively smaller.

Continuous-flow stabilization systems require automated control of lime feeding and therefore are usually not cost-effective for small-scale operations. The primary advantage of continuous-flow systems over batch systems is that a smaller tank size may be possible. Capacity does not have to be provided for storage of sludge between batches. Instead, the mixing tank must only be large enough to ensure that all sludge particles are held at high pH for a contact time sufficient to destroy odor and disease-producing organisms.

The most important design parameter for a continuous flow, well-mixed reactor is the nominal detention time (defined as tank volume divided by volumetric input flow rate). Unlike a batch tank, where contact time of all particles is the same, some particles in a well-mixed, continuously fed tank escape after relatively short contact. Thus, 30 minutes of pH at 12.5 in a batch mixer might not be the same as 30 minutes residence time in a well-mixed, continuously fed reactor.

In making a recommendation for detention time, the nature of the treatment that occurs must be considered. Unlike some treatments, such as irradiation, the treatment does not stop after the treated sludge leaves the vessel. If pH is 12.5 as the sludge leaves the mixing tank, it remains at this pH after leaving. Consequently, a 30-minute detention time in a continuously fed, well-mixed reactor is adequate, provided the pH is measured in an exit line. If pH of the limed sludge appears to fall too rapidly upon standing, it is a simple matter to move the pH sensor and to control lime feed rate to a position further downstream.

Thickening of raw sludge before lime addition will reduce the mixing tank capacity requirement in direct proportion to the reduction in sludge volume. However, the lime requirement will be reduced only slightly by prethickening, since most of the lime demand is associated with the solids (227), and total solids mass is not changed by thickening.

Tank Mixing

Lime/sludge mixtures can be mixed with either diffused air or mechanical mixers. The agitation should be great enough to keep sludge solids suspended and to distribute the lime slurry evenly and rapidly. Both diffused air and mechanical systems can provide adequate mixing, although the former has been more commonly used in pilot studies and full scale operations. In addition to their mixing function, sparger air systems supply oxygen and, thereby, can be used for sludge aeration before the sludge is dosed with lime. If storage of unlimed sludge is contemplated, the designer should check that the air requirement for mixing is sufficient to meet the oxygen demand of the sludge. Oxygen requirements are discussed in the section on aerobic digestion.

There are disadvantages to both types of mixing systems. Mechanical mixers are subject to fouling with rags, string, and other debris in the sludge. Although air spargers may clog, fouling problems are greatly reduced by mixing with air. Ammonia will be stripped from the sludge when mixing is done with diffused air, producing odors and reducing the fertilizer value of the treated sludge. However, if nitrogen levels limit land application rates, this stripping of ammonia will reduce land requirements for disposal. A further, although probably minor, problem with air mixing is that CO_2 is absorbed by the sludge/lime mixture, tending to raise the quantity of lime required to reach the desired pH. The selection of the method of mixing should be based on the factors described above, coupled with an economic evaluation.

With air mixing, coarse bubble diffusers should be used, mounted along one of the tank walls to induce a spiral-roll mixing pattern. An air supply of 20 to 30 scfm per 1,000 cubic feet (20-30 m^3/min /1,000 m^3) is required for adequate mixing (241). If the mixing tank is enclosed, ventilation should be sufficient to remove odorous gases stripped from the sludge during mixing. In many cases, these gases should be treated in an odor control unit before being discharged into the atmosphere.

Mechanical mixer specifications for various tank sizes are presented in Table 6-31. Sizing is based on two criteria: maintaining the bulk fluid velocity (defined as the turbine agitator pumping capacity divided by the cross sectional area of the mixing vessel) above 26 feet per minute (8.5 m/min), and using an impeller Reynolds number greater than 1,000. The tank/mixer combinations in Table 6-31 are adequate for mixing sludges with up to 10 percent dry solids and viscosity of 1,000 cp. Impellers on mechanical mixers should be designed to minimize fouling with debris in the sludge.

6.4.5 Costs and Energy Usage

Engineering decisions are commonly based on a comparison of costs for feasible solutions. Energy considerations are now also becoming important in the decision-making process. This section discusses costs and energy usage for lime stabilization systems.

6.4.5.1 Capital and Operating Costs

Cost estimates for the construction and operation of three different size lime stabilization systems are summarized in Table 6-32. A comparison of these costs shows that there is a large economy of scale, especially for the capital costs. Operation and maintenance expenses, particularly those for lime, are more closely related to the quantity of sludge treated.

Comparisons of the cost of lime treatment with other stabilization methods must take into account that the addition of lime increases the quantity of solids to be handled after stabilization. In contrast, sludge solids actually decrease during anaerobic and aerobic digestion. This difference between stabilization methods can have an important effect on costs for final disposal of sludge. The magnitude of this cost differential is site-specific and depends on such factors as the method of disposal and the distance to the disposal site.

TABLE 6-31

MECHANICAL MIXER SPECIFICATIONS FOR SLUDGE SLURRIES (228)

Tank size, gal	Tank diameter, ft	Motor size, hp	Shaft speed, rpm	Turbine diameter, ft
5,000	9.5	7.5	125	2.7
		5	84	3.2
		3	56	3.6
15,000	13.7	20	100	3.7
		15	68	4.4
		10	45	5.3
		7.5	37	5.6
30,000	17.2	40	84	4.8
		30	68	5.1
		25	56	5.5
		20	37	6.8
75,000	23.4	100	100	5.2
		75	68	6.2
		60	56	6.6
		50	45	7.3
100,000	25.7	125	84	6.0
		100	68	6.5
		75	45	7.8

Assumptions:
- Bulk fluid velocity >26 ft/min. (8.5 m/min.).
- Impeller Reynolds number >1,000.
- Mixing tank configuration.
  - Liquid depth equals tank diameter.
  - Baffles with a width of 1/12 the tank diameter, placed at 90 degrees spacing.

Mixing theory and equations after References 155 and 242.

1 gal = 3.785 l
1 ft = 0.305 m
1 hp = 0.746 kW

6.4.5.2 Energy Usage

Energy is required during both the construction and operation of a lime stabilization system. During operation of a lime stabilization facility, the principal direct use of energy is electricity for mixing the lime/sludge mixture. A rough estimate of the annual energy requirement for mixing with diffused air is 290 kWh per year per cfm of blower capacity (based on continuous duty). This estimate was made assuming a six psig (0.4 kg/m^2) pressure boost, standard inlet conditions, and an overall compressor/motor efficiency of 60 percent. One horsepower of mechanical mixing requires about 6,500 kWhr of electricity per year. These mixing energy demands can be expressed in terms of a primary fuel requirement (that is, fuel oil, coal, natural gas) by applying a conversion factor of 10,700 Btu (2,700 kg-cal) per kWh of electricity. This factor assumes a fuel conversion efficiency of 35 percent at the power plant and a transmission efficiency of 91 percent.

TABLE 6-32

ESTIMATED AVERAGE ANNUAL COSTS FOR LIME STABILIZATION FACILITIES[a] (228)

Item	Treatment plant capacity, mgd		
	1	4	40[e]
Capital[b]	10,500	30,100	87,200
Operation and maintenance[c]	12,600	35,900	257,400
Total	23,100	66,000	344,600
Unit cost[d], (dollars/ton dry sludge solids)	54.17	39.27	20.51

[a]All costs expressed in 1978 dollars.

[b]Amortized over 30 years at 7 percent. Includes cost of all buildings, equipment, and piping for lime storage and funding, and for sludge mixing and lagoon storage, except as noted.

[c]Average lime dose of 0.2 lb $Ca(OH)_2$/lb dry solids. Hydrated lime (47 percent CaO, \$44.50/ton) used in the 1-mgd system, otherwise, quicklime (85 percent CaO, \$40/ton). All labor at \$6.50/hr. Does not include cost for transport and disposal.

[d]Primary plus waste-activated sludge, 2,300 lb dry sludge solids produced/mil gal of wastewater treated (1.20×10^{-4} Kg/m^3).

[e]Includes sludge thickening but not lagoon storage.

Large amounts of energy are used in the production of quicklime. Quicklime (CaO) is produced by burning limestone ($CaCO_3$) in kilns. This process, termed calcination, is illustrated in the following reaction:

$$CaCO_3 \xrightarrow{\text{heat}} CaO + CO_2$$

The current national average energy consumption for all quicklime production is about 7.0 million Btu per ton of quicklime (1.9×10^6 kg-cal/metric ton) (243). This figure is decreasing since modern plants, using large and more efficient kilns, should be able to produce one ton of quicklime with about 5.5 million Btu (1.5×10^6 kg-cal/metric ton).

6.4.6 Design Example

This section illustrates the layout and sizing of the major components in a lime stabilization system. For this example, it is assumed that the treatment plant has a capacity of approximately 8 MGD (350 l/s) and provides secondary treatment to typical municipal wastewater. A mixture of primary sludge and thickened waste-activated sludge is to be stabilized with lime, then mechanically dewatered, and ultimately spread onto land.

6.4.6.1 Design Loading

Sludge production estimates for two flow conditions, average and peak day, are listed in Table 6-20 (provided previously in the anaerobic digestion section). The peak-loading is listed because critical components must be sized to meet this critical condition. Chapter 4 provides a discussion of the procedure to determine sludge production values. Sludge solids concentrations and the resulting sludge volumes are also included in Table 6-20.

6.4.6.2 System Description

The conceptual design for the lime stabilization system is presented on Figure 6-47. Prior to stabilization, all sludge is passed through an in-line grinder. This conditioning improves sludge mixing and flow characteristics, protects downstream pumping and dewatering equipment, and eliminates unsightly conditions (such as rags, sticks, plastic) at the disposal site. Two batch mixing tanks are provided, each with the capacity to treat the total sludge produced in an eight-hour shift during peak day conditions. While one tank is filling, sludge in the other is dosed with lime, mixed for 30 minutes, and then discharged to the dewatering equipment. Since the mixing tanks are sized for peak conditions, they can provide some short-term storage for treated sludge during periods of lower loading. Design of an actual facility should take into consideration the operating schedule for dewatering and disposal.

In this example, it is assumed that dewatering is operated continuously and therefore only minimal inline storage is required. However, if dewatering equipment was operated for two shifts, and serviced during the third, at least eight hours of storage would be required.

Air discharged through coarse bubble diffusers is used to mix the sludge with the lime slurry. Air mixing is started as raw sludge is first added to the tank to keep the sludge from turning septic and producing odors. When the tank is filled, lime is added and mixing is continued for at least 30 minutes.

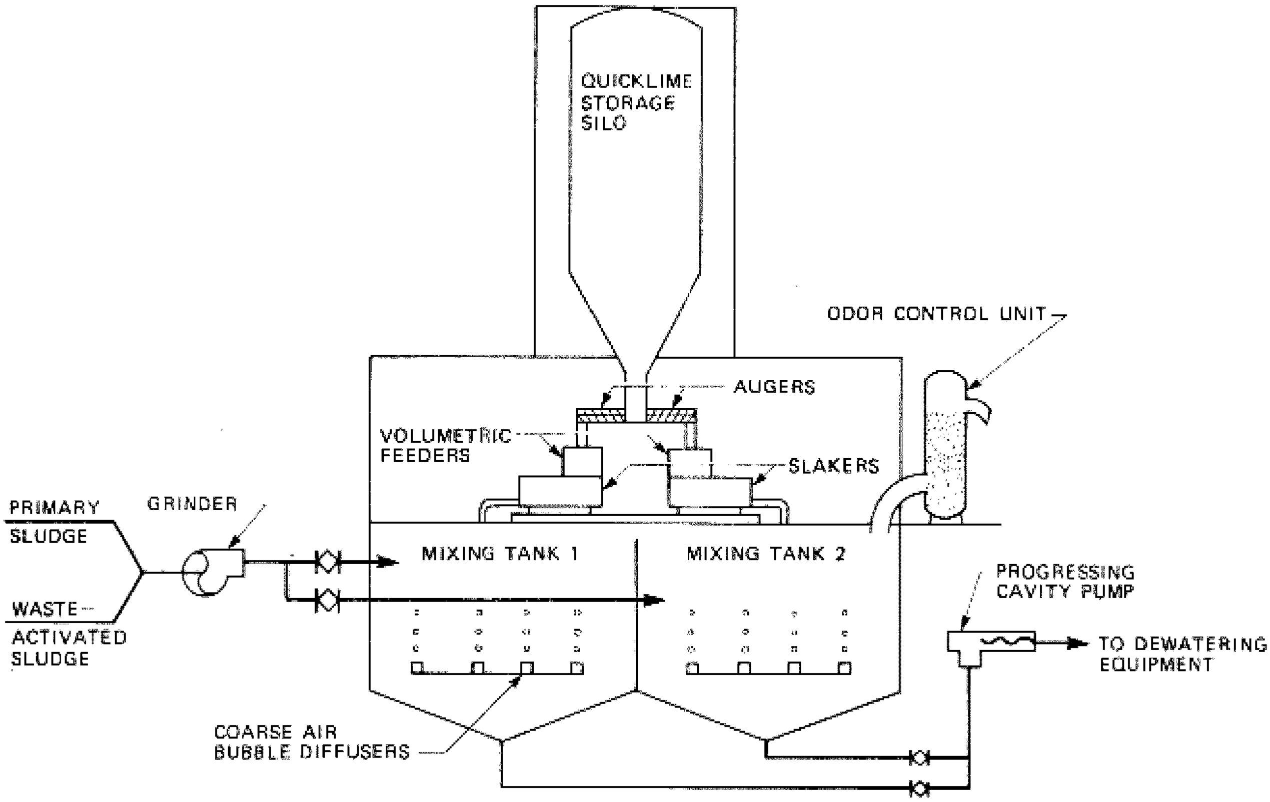


FIGURE 6-47

CONCEPTUAL DESIGN FOR A LIME STABILIZATION FACILITY

To reduce odors, the mixing tanks are covered, and gases stripped from the sludge during mixing are removed in an odor control unit. This unit is a packed bed scrubber. The scrubbing solution is dilute sulfuric acid. Ammonia gas is absorbed by the sulfuric acid solution. All wetted parts are constructed of acid-resistant materials.

Quicklime is used in this installation. A bulk storage silo, with capacity to hold a 30-day lime requirement under average conditions, supplies lime to two volumetric feeders. Each feeder measures out quicklime to a slaker, where the lime is hydrated, slurried, and discharged into the mixing tank. The lime dose is sufficient to maintain the sludge above pH 12.5 for 30 minutes.

6.4.6.3 Component Sizing

Mixing Tank

Sizing criterion:

Conditions.

Volume requirement (V):

Peak-day sludge production shown in Table 6-21.

$$V = \frac{8 \text{ hr/tank}}{24 \text{ hr/day}} (6010 \text{ cu ft/day} + 3430 \text{ cu ft/day})$$
$$= 3{,}150 \text{ cu ft/tank}$$
$$= (89 \text{ m}^3\text{/tank})$$

Tank surface area (A):
(Assume 10 feet liquid depth)

$$A = \frac{3{,}150 \text{ cu ft}}{10 \text{ ft}} = 315 \text{ ft}^2$$
$$= 39.3 \text{ m}^2$$

Tank dimensions:
(Assume 2 feet freeboard)
18 ft x 18 ft x 12 ft
(5.4 m x 5.4 m x 3.7 m)

Air mixing system

Sizing criterion:

30 cfm/1,000 cu ft

Blower capacity (Q):
(One blower per tank)

$$Q = \frac{(3{,}150 \text{ cu ft})}{\text{tank}} (30 \text{ cfm/1,000 cu ft})$$
$$= 95 \text{ cfm/blower}$$
$$= (2.6 \text{ m}^3\text{/min/blower})$$

Lime Storage

Sizing criterion:

30-day storage during average loading.

Quicklime characteristics:

Purity -	90 percent CaO
Bulk density -	55 lb/cu ft

Lime dosage:

Primary sludge - 0.12 lb $Ca(OH)_2$/lb dry solids
Activated sludge - 0.30 lb $Ca(OH)_2$/lb dry solids

Average daily lime requirement (W):

Expressed as hydrated lime -

$$W_{CaOH_2} = (10{,}000 \text{ lb/day})\left(.12 \frac{\text{lb}}{\text{lb}}\right) + (5{,}000 \text{ lb/day})\left(\frac{.30 \text{ lb}}{\text{lb}}\right)$$

$$= 2{,}700 \text{ lb } Ca(OH)_2\text{/day}$$

$$= (1{,}230 \text{ kg/day})$$

Expressed as purchased quicklime (90 percent purity) -

$$W_{CaO} = (2{,}700 \text{ lb } Ca(OH)_2 \text{ day})\left(\frac{56 \text{ lb CaO/Mole}}{74 \text{ lb } Ca(OH)_2\text{/mole}}\right)\left(\frac{100}{90}\right)$$

$$= 2{,}270 \text{ lb CaO/day}$$

$$= (1{,}030 \text{ kg/day})$$

Storage requirement (V_s):

$$V_s = \frac{2{,}270 \text{ lb/day}}{55 \text{ lb/cu ft}} (30 \text{ days})$$

$$= 1{,}240 \text{ cu ft}$$

$$= (35 \text{ m}^3)$$

Slaker:

Sizing criterion:

Ability to dose one batch in 15 minutes.

Slaker capacity (C):

$$C = \frac{2{,}270 \text{ lb CaO/day}}{3 \text{ batchs/day}} \frac{(1 \text{ batch})}{(15 \text{ min})}$$

$$= 50 \text{ lb CaO/min}$$

$$= (23 \text{ kg/min})$$

6.5 Chlorine Stabilization

Stabilization by chlorine addition was developed as a proprietary process and is marketed under the registered trademark "Purifax." The chlorine stabilization process is applied to wastewater treatment plant sludges and sidestreams to reduce putrescibility and pathogen concentration. The process has also been used to improve the dewaterability of digested sludge and to reduce the impact of recycled digester supernatant on the wastewater treatment systems. Because chlorine reactions with sludge are very rapid, reactor volumes are relatively small, reduced system size and initial costs. The process results in no appreciable destruction of volatile solids, and unlike anaerobic digestion, yields no methane gas for energy generation and little sludge mass reduction.

Chlorine-stabilized sludges are buff-colored, weak in odor, sterile, and generally easy to dewater, either mechanically or on drying beds. The stabilized sludge has been used as a soil conditioner. However, there is concern about its use on cropland and its disposal in landfills because of its high acidity, high chloride content, and potential for releasing chlorinated hydrocarbons and heavy metals. The stabilized sludges are corrosive unless pH has been adjusted. Process equipment that comes into contact with sludges that have not been neutralized must be constructed of acid-resistant materials or be coated with protective films.

6.5.1 Process Description

Chlorine treatment stabilizes sludge by both reducing the number of organisms available to create unpleasant or malodorous conditions and making organic substrates less suitable for bacterial metabolism and growth. Some of the mechanisms responsible are oxidation, addition of chlorine to unsaturated compounds, and displacement of hydrogen by chlorine.

The immediate reaction from addition of gaseous chlorine to water is shown below:

$$Cl_2 + H_2O \longrightarrow HOCl + H^+ Cl^- \qquad (6\text{-}14)$$

In the chlorine stabilization process, sufficient acid is produced to reduce the pH of the sludge to a range of 2 to 3. Dissociation of HOCl to H^+ and OCl^- is suppressed by low pH and therefore is not significant. Cl_2 and HOCl are highly reactive and powerful bactericides and viricides. The chloride ion has no disinfection capability.

The process stream immediately following the chlorine addition is substantially a chlorine solution containing sludge. The solution contains (in molecular form) as much as ten percent of the total chlorine species present. The predominant species in solution is undissociated HOCl. HOCl and Cl_2 react with sludge to oxidize ammonia to chloramines and organic nitrogen to organic chloramines. Other reduced ions, such as Fe^{+2} and S^{-2}, are oxidized at the same time. Some of the oxidized end products, such as chloramines and organic chloramines, are germicidal and viricidal (244).

The chlorine stabilization unit consists of a disintegrator, a recirculation pump, two reaction tanks, a chlorine eductor, and a pressure control pump. A chlorine evaporator and/or a chlorinator, feed pump, and inlet flow meter can be purchased with the unit or separately. The unit is often supplied by the manufacturer as a complete package mounted on a skid plate and ready for installation. A detailed diagram of the unit is shown on Figure 6-48.

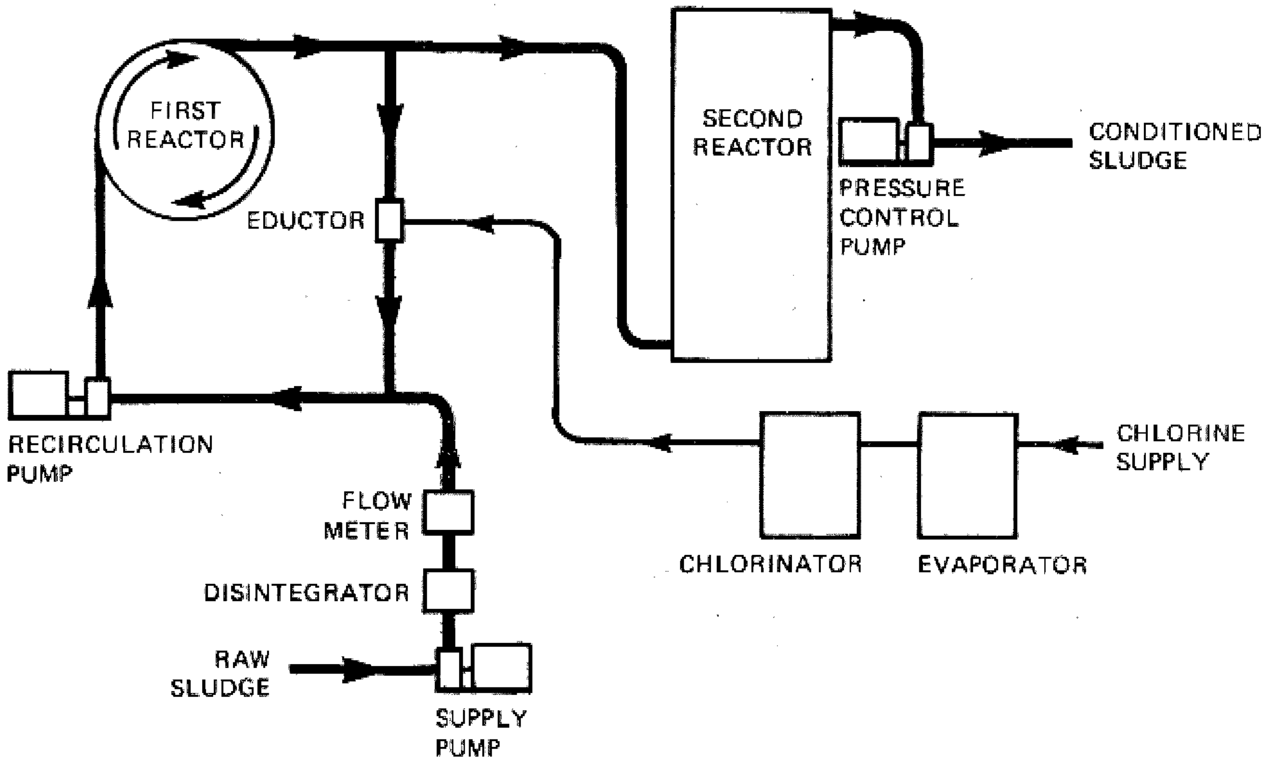


FIGURE 6-48

SCHEMATIC DIAGRAM OF A CHLORINE OXIDATION SYSTEM

In the first operating step, sludge is pumped through a disintegrator which reduces particle size and therefore, provides greater sludge surface area for contact with the chlorine. Chlorinated sludge from the first reactor is mixed with raw sludge just prior to reaching the recirculation pump. The combined flow then passes through the first reaction tank. Chlorine is added via an eductor located in the recirculating loop. Recirculation aids mixing and efficient chlorine use. The ratio of recirculated reacted product to raw sludge at design capacity is about 7 to 1. System pressure is maintained in the 30 to 35 psi (210 to 240 kN/cm^2) range, by a pressure control pump located at the discharge of the second reactor. The pressure provides a driving force to ensure penetration of chlorine into the sludge particles. The second reactor tank increases system detention time, allowing a more complete reaction between the sludge and the chlorine.

Flow patterns within the two reactor tanks are high, in the form of velocity spirals, with tangential discharges. The tanks are oriented with the spiral axis of the first in a horizontal plane and the second in a vertical plane. Solids that settle during periods of non-operation are easily resuspended when the process is started again. The system is neither drained nor cleaned between operating periods. A holding tank should be provided for feed storage and for flow equalization. Blending done in the tank also helps to maintain feed uniformity, thus providing sludge of uniform chlorine demand and minimizing the need to frequently adjust chlorine dose. Sludge blending is particularly valuable for processing of primary sludges, which tend to be more concentrated when initially pumped from the sedimentation tank than at the end of the pumping cycle. Similarly, where primary and secondary sludges are treated together, blending can be accomplished in the holding tank. Continuously wasted activated sludge, however, may be adequately treated without prior blending, provided that solids concentration is nearly constant with time. Mixing is usually done by mechanical or air agitation. Air mixing is preferable, because it enhances aerobic conditions, reduces odors, and averts problems with fouling of the impellers by rags and strings. Odor can be controlled in the holding tank if a portion of the filtrate or supernatant from the dewatering process is returned to it.

If the chlorine demand of the liquid fraction of the sludge is high, separation of some of the liquid from solids by thickening prior to chlorination may substantially reduce total sludge chlorine demand. If, however, the chlorine demand is low, thickening will not be beneficial. For more detailed discussion of chlorine demands exerted by sludge solids and liquid fractions, see Section 6.5.3. Solids concentrations above certain defined limits should not be exceeded, because the diffusion rate of chlorine through the sludge is hindered and processing rates must be reduced to provide additional time for the chlorine to reach reaction sites. Normally, processing rates are not affected if solids concentrations are below the following values:

- Primary sludge or primary plus trickling filter humus - four percent.
- Primary plus waste-activated sludge - four percent.
- Waste-activated sludge - 1.5 percent.

Processing rates for higher concentrations must be determined on a case-by-case basis.

Use of a holding tank downstream of the chlorine oxidation process allows subsequent processes to run independently and at their own best rate. Solids settling may occur in the tank after an initial period of flotation. The tank can, therefore, be used to separate the solid and liquid fractions of the stabilized product.

6.5.2 Uses, Advantages, and Disadvantages

Chlorine oxidation has been used to treat raw and digested primary sludge, raw and digested secondary sludges, septage, digester supernatants, and sidestreams from dewatering processes.

The chlorine stabilization process has several attractive features. It can be operated intermittently, so long as sufficient storage volume is available prior to and following the unit. Unlike biological sludge processing systems, the process can be started up, run for a few hours, and turned off. A constant supply of process feed is not required. As a result, operating costs are directly dependent upon production rates, and costs attributable to overcapacity are eliminated.

Chlorine oxidation is a chemical process and is thus operationally insensitive to factors such as toxic materials in the sludge, which adversely affect biological stabilization systems. It can also process feed streams of widely varying character, such as digested sludge and digester supernatant, within a short period of time. This flexibility is not characteristic of anaerobic or aerobic digestion processes.

Disadvantages of the chlorine stabilization process center on chemical, operational, and environmental factors. From a chemical standpoint, the low pH of chlorine-stabilized sludge may require the sludge to be partially neutralized prior to mechanical dewatering or before being applied to acid soils. Costs of neutralization are in addition to chlorine costs. These are discussed in Section 6.5.5.1. As mentioned earlier, chlorine stabilization does not reduce sludge mass nor produce methane gas as a by-product for energy generation. The process consumes relatively large amounts of chlorine. Special safety and handling precautions must be used when handling this gas. If high alkalinity wastes--for example, digested sludge, digester supernatants--are processed, CO_2 generated during chlorination may promote cavitation in downstream pumps.

There is concern that chlorine oxidation of sludges, septage, and sidestreams from sludge treatment processes could result in increased levels of toxic chlorinated organics in the treated materials (245). Data available are inconclusive. Investigations are underway that will help clarify this issue. In the meantime, measures should be taken to mitigate environmental concerns when the chlorine oxidation processes is used. These are:

- Provisions should be made to deal with the filtrate, centrate, or decant from the process, including return to the wastewater treatment plant, unless this practice leads to wastewater treatment plant upset or to violations of effluent standards; or to treat by activated carbon absorption or other means.

- If the treated sludge leaving the pressurized chlorinator is discharged to a tank sparged with air, the gases from the tank should be vented away from workers.

- Treated solids should be disposed of with care. Consideration should be given to:

  1. Using secured landfills or landfills located at hydrogeographically isolated sites.

  2. Treating leachates from secured landfills to prevent contamination of surface or groundwaters.

  3. Directly incorporating the solids into soils at rates sufficiently low to minimize leachate production. Direct incorporation as opposed to surface spreading should be used to prevent consumption of solids by grazing animals.

  4. Using erosion control measures to prevent runoff contaminated with toxic chlorinated compounds from entering surface waters.

  5. Providing adequate monitoring of facilities to assure detection of unexpected problems.

6.5.3 Chlorine Requirements

Chlorine demand varies with the characteristics of each waste stream. Demand can be estimated from Table 6-33 for cases in which a combination of sludges and/or sidestreams makes up the process feed. The demand of a sludge produced by combining two streams is the weighted average of the demands of the individual streams. For example, using Table 6-33 one estimates that the demand of a sludge composed of five volumes of 0.7 percent waste-activated sludge and one volume of four percent primary sludge is about (17 + 5[7])/6 = 9 pounds per thousand gallons (1 kg/1,000 l).

If a chlorine residual is desired to provide added protection against septicity, then additional chlorine should be added in an amount equal to the required residual. For instance, if a residual of 200 mg/l chlorine is required for the waste-activated/primary sludge combination just discussed, then an additional $(200 \text{ mg/l})(0.00834 \frac{\text{lb/thousand gal}}{\text{mg/l}}) = 1.7$ pounds of chlorine per 1,000 gallons of sludge (0.20 kg/1,000 l) should be added, bringing the total chlorine addition to 10 to 11 pounds per 1,000 gallons (1.2 to 1.3 kg/1,000 l) of sludge.

BIF Division of General Signal (246) states that, for solids concentrations other than those shown, the chlorine demand per gallon varies in proportion to the solids concentration. For example, if the solids concentration were to double, chlorine demand would also double.

TABLE 6-33

ESTIMATED CHLORINE REQUIREMENTS FOR SLUDGE AND SIDESTREAM PROCESSING[a]

Feed stream	Suspended solids, percent	Chlorine requirement, lb/1,000 gal
Primary sludge	4.0	17
Waste-activated sludge		
With prior primary treatment	0.7	7
No primary treatment	0.7	7
From contact stabilization	0.7	7
Sludge from low and high rate trickling filters	1.0	10
Digester supernatant	0.3	2 - 10
Septage	1.2	6

[a]Information obtained from R. C. Neal of BIF.

1 lb/1,000 gal = 0.12 kg/l

6.5.4 Characteristics of Chlorine-Stabilized Materials

6.5.4.1 Stabilized Sludge

Characteristics of freshly treated sludge are a pH of 2 to 3 and a chlorine residual of approximately 200 mg/l. Retention in a downstream holding tank allows the chlorine residual to drop to zero and the pH to rise to between 4.5 and 6.5. Normally, a slight medicinal odor is present. After adequate addition of chlorine, the color of the sludge changes from black to light brown.

Chlorine oxidation generally improves the sand bed dewaterability of many sludges and septages. If properly chlorinated, the sludges are stable and do not undergo anaerobic activity for at least 20 days. When properly disposed in landfills or on the soil, the chlorinated sludge does not exhibit septicity during handling and disposal. If stored in lagoons, the sludge-liquid mixture must be sufficiently aerated to avoid odor and septicity problems, especially in warm weather.

Production of chlorinated hydrocarbons by the chlorine stabilization process has been the subject of research efforts since the process was conceived. Early studies (1971) by Metcalf and Eddy, for the BIF Company by then-current technology were aimed at the detection of specific objectionable compounds. This work indicated that, rather than producing the compounds, chlorine stabilization actually seemed to lower their concentrations in most instances. Later work (1978) using more advanced gas chromatograph-mass spectrometry techniques has revealed the production of 0.9 to 1 percent by weight organic chlorine in several sludges stabilized by the chlorine oxidation process

(245). These results indicate that as much as 10 to 20 percent of initial sludge solids had chemically reacted with the chlorine. Additional studies by ASTRE for the BIF Company suggested that total identifiable chlorinated organic compounds nearly doubled when the particular raw sludges studied were treated by a chlorine oxidation process. A six-fold increase was found in the amount of chlorinated organic Consent Decree toxics (see 43 FR 4109, January 31, 1978 for Consent Decree list of toxic substances) following chlorine oxidation and an eight-fold increase in the amount of total organic Consent Decree toxics.

6.5.4.2 Supernatant/Filtrate/Subnatant Quality

These process streams are produced by thickening and/or dewatering operations after chlorine treatment. Filtrates from sandbed dewatering are typically clear and colorless. The pH varies from 4 to 6, and no residual chlorine remains. Filtrate from chlorine-treated sludge generally contains lower suspended solids and BOD_5 than the filtrate produced when filtering digested sludges. Typical filtrate composition is 50-150 mg/l suspended solids and 100-300 mg/l BOD_5 with low turbidity and color.

In bench-scale studies simulating the chlorine oxidation process, Olver, and others found that acidic conditions enhanced the release of heavy metals from sludges (247).

Sukenik and others (248) noted an increase in supernatant chemical oxygen demand (COD) after sludge treatment by chlorine oxidation. Though the reason for the increase is undetermined, the suggestion was made that chlorine may solubilize the oxygen-demanding material rather than oxidize it. Biochemical oxygen demand of the supernatant is generally comparable to that of raw wastewater. Data collected at Alma, Michigan, indicates that chemically precipitated phosphate is not redissolved by the chlorine oxidation process (246).

A 1978 report indicated that chlorinated organics were present in the centrate from several chlorinated sludge samples (245). Although less than one half of one percent of the organic compounds assumed to be present could be identified, eight chlorinated compounds on the Consent Decree list of toxic substances were detected, including three known or suspected carcinogens.

6.5.5 Costs

Data reported herein were derived by Purifax from actual installations.

6.5.5.1 Operating Costs

Because the chlorine stabilization process can be operated intermittently, annual operating costs are proportional to the quantity of material processed. Table 6-34 displays operating cost data. Chlorine, the major expense factor, historically has cost between 9 and 14 cents per pound (19.8 to 30.9 cents per kg). Chlorine unit costs vary with annual usage, method of transportation and transportation distances, and competition. In the last few years, prices have decreased because of an increased demand for sodium hydroxide (chlorine is a by-product of sodium hydroxide production).

TABLE 6-34

ACTUAL OPERATING COSTS FOR CHLORINE STABILIZATION SYSTEM[a]

Process stream and year reported	Chlorine		Cost, dollars/ton of dry solids		
	Dosage, lb/ton of dry solids	Cost, cents/lb	Chlorine	Power[b]	Chlorine and power
Primary and waste-activated sludge					
Ravena-Coeymans, NY, 1974	167	11.35	18.95	1.90	20.85
Plainfield, CT, 1973	148	14.00	20.72	2.07	22.79
Extended aeration					
Plainfield, CT, 1975	180	14.00	25.20	2.52	27.72
Waste-activated sludge only					
Fair Lawn, NJ	211	9.85	20.78	2.08	22.86

[a]Information obtained from D. L. Moffat of BIF.

[b]Estimated at 10 percent of chlorine cost.

Note: Estimated operation and maintenance (6).
Operation - 2 hr/shift.
Maintenance - $200/yr.

1 lb/ton = 0.504 kg/tonne
1 cent/lb = 2.20 cents/kg
1 dollar/ton = 1.10 dollars/tonne

Although it is not related to the cost of chlorine stabilization of sludge, additional chemical costs can result if chemical conditioning is necessary prior to mechanical dewatering. Chemical conditioning of chlorine-stabilized sludge consists of adding sodium hydroxide or lime to raise the pH to between 4.5 and 5.5 and then adding the proper dosage of an appropriate coagulant. Although more expensive, sodum hydroxide is generally preferred to lime because it reacts faster. Neutralizing can be done in-line, without need of an intermediate detention tank. Sodium hydroxide requirements range from 20 to 30 pounds per ton of dry solids (10 to 15 kg/t) for primary sludge to 10 to 20 pounds per ton of dry solids (5 to 10 kg/t) for secondary sludge. At a 1976 cost of eight cents per pound (18 cents/kg) this is equivalent to a cost \$0.80 to \$2.40 per ton (\$0.88 to \$2.65/t) of dry solids. Polymer costs are equivalent to those required for dewatering of sludges stabilized by other means and are generally greater than the cost of pH adjustment. (See Chapter 8).

Costs for neutralizing chlorine-stabilized sludge prior to spreading it on acid soils are about \$0.60 to \$0.90/ton (\$0.66 to \$0.99/t), assuming that 20 to 30 pounds of $Ca(OH)_2$ are required per ton (10 to 15 kg/t) of stabilized sludge solids and $Ca(OH)_2$ costs are \$0.03 per pound (\$0.07/kg).

Power costs of operating the stabilization system are estimated at ten percent of chlorine costs. Additional power costs are incurred if mixing is used in the holding tank upstream from the stabilization process.

Labor costs are incurred only for daily start-up, shutdown, periodic checks, and maintenance, and are small in comparison to other operating costs.

6.5.5.2 Capital Costs

Capital costs for chlorine stabilization systems tend to be less than for conventional anaerobic digestion systems of equal capacity. Normally, the system is furnished by the manufacturer on a skid-plate and in a ready-to-install condition. Table 6-35 shows actual 1979 capital costs for systems of specified capacity for two different feed sludges.

TABLE 6-35

CHLORINE STABILIZATION CAPITAL COSTS, 1979[a]

Capacity, gal/hr		
Primary and waste-activated sludge[b]	Waste-activated sludge only[c]	Budgetary cost,[d] dollars
660	960	82,000
1,320	1,800	137,000
2,940	4,200	175,000
5,880	8,520	228,000
13,080	18,300	307,000[e]

[a]Information obtained from R. C. Neal of BIF.

[b]Solids concentration 3 percent by weight.

[c]Solids concentration 1.5 percent by weight.

[d]Budgetary costs based on an ENR 20 cities average construction cost index of 2869 for December 1978. Costs include chemical oxidizer, sludge macerator, sludge feed pump, motor starters, vacuum-type chlorinator, freight and start-up service.

[e]Budgetary cost includes chlorine evaporator.

1 gal/hr = 3.79 l/hr

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PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 7. Disinfection

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
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CHAPTER 7

DISINFECTION

7.1 Introduction

Wastewater sludge disinfection, the destruction or inactivation of pathogenic organisms in the sludge, is carried out principally to minimize public health concerns. Destruction is the physical disruption or disintegration of a pathogenic organism, while inactivation, as used here, is the removal of a pathogen's ability to infect. An important but secondary concern may be to minimize the exposure of domestic animals to pathogens in the sludge. At the present time in the United States, the use of procedures to reduce the number of pathogenic organisms is a requirement before sale of sludge or sludge-containing products to the public as a soil amendment, or before recycling sludge directly to croplands, forests, or parks. Since the final use or disposal of sludge may differ greatly with respect to public health concerns, and since a great number of treatment options effecting various degrees of pathogen reduction are available, the system chosen for reduction of pathogens should be tailored to the demands of the particular situation.

This chapter identifies the major pathogenic organisms found in wastewater sludges; briefly describes the pathogen characteristics, including size, life and reproductive requirements, occurrence in sludge, and survival under different environmental conditions; and discusses methods for reducing the number of pathogenic organisms in sludge. The effect of conventional sludge treatment processes on pathogen reduction will be reviewed. Two types of processes designed specifically for the reduction of pathogenic organisms in sludge are heat pasteurization and high-energy irradiation, and they will be developed in detail. Other processes such as long-term storage and composting will also be discussed.

7.2 Pathogenic Organisms

A pathogen or pathogenic agent is any biological species that can cause disease in the host organism. The discussions in this chapter will be confined to pathogens that produce disease in man and complete their life cycles in North America. These organisms or agents fall into four broad categories: viruses, bacteria, parasites, and fungi. Within the parasite category, there are protozoa, nematodes, and helminths. Viruses, bacteria, and parasites are primary pathogens that are present at some level in sludge as a result of human activity upstream from the wastewater treatment plant. Fungi are secondary pathogens and are only numerous in sludge when given the opportunity to grow during some treatment or storage process.

7.2.1 Pathogen Sources

Pathogens enter wastewater treatment systems from a number of sources:

- Human wastes, including feces, urine, and oral and nasal discharges.
- Food wastes from homes and commercial establishments.
- Industrial wastes from food processing, particularly meat packing plants.
- Domestic pet feces and urine.
- Biological laboratory wastes such as those from hospitals.

In addition, where combined sewer systems are used, ground surface and street runoff materials, especially animal wastes, may enter the sewers as storm flow. Vectors such as rats that inhabit some sewer systems may also add a substantial number of pathogens.

7.2.2 Pathogen Characteristics

Viruses, bacteria, parasites, and fungi differ in size, physical composition, reproductive requirements, occurrence in the United States population, and prevalence in wastewater.

7.2.2.1 Viruses

Viruses are obligate parasites and can only reproduce by dominating the internal processes of host cells and using the host's resources to produce more viruses. Viruses are very small particles whose protein surface charge changes in magnitude and sign with pH. In the natural pH range of wastewater and sludges, most viruses have a negative surface charge. Thus, they will adsorb to a variety of material under appropriate chemical conditions. Different viruses show varying resistance to environmental factors such as heat and moisture. Enteric viruses are acid-resistant and many show tolerance to temperatures as high as 140 °F (60° C).

Many of the viruses that cause disease in man enter the sewers with feces or other discharges and have been identified, or are suspected of being, in sludge. The major virus subtypes transmitted in feces are listed in Table 7-1 together with the disease they cause. Viruses are excreted by man in numbers several orders of magnitude lower than bacteria. Typical total virus concentrations in untreated wastewaters are 1,000 to 10,000 plaque-forming units (PFU) per 100 ml; effluent concentrations are 10 to 300 PFU per 100 ml. Wastewater treatment, particularly chemical coagulation or biological processes followed by sedimentation, concentrates viruses in sludge. Raw primary and waste-activated sludges contain 10,000 to 100,000 PFU per 100 ml.

TABLE 7-1

PATHOGENIC HUMAN VIRUSES POTENTIALLY IN WASTEWATER SLUDGE

Name	Disease
Adenoviruses	Adenovirus infection
Coxsackie virus, Group A	Coxsackie infection; viral meningitis; AFRI[a], hand, foot, and mouth disease
Coxsackie virus, Group B	Coxsackie infection, viral meningitis; viral carditis, endemic pleurodynia, AFRI[a]
ECHO virus, (30 types)	ECHO virus infection; aseptic meningitis; AFRI[a]
Poliovirus (3 types)	Poliomyelitis
Reoviruses	Reovirus infection
Hepatitis virus A	Viral hepatitis
Norwalk agent	Sporadic viral gastroenteritis
Rotavirus	Winter vomiting disease

[a]AFRI is acute febrile respiratory illness.

7.2.2.2 Bacteria

Bacteria are single-celled organisms that range in size from slightly less than one micron (μ) in diameter to 5μ wide by 15μ long. Among the primary pathogens, only bacteria are able to reproduce outside the host organism. They can grow and reproduce under a variety of environmental conditions. Low temperatures cause dormancy, often for long periods. High temperatures are more effective for inactivation, although some species form heat-resistant spores. Pathogenic bacterial species are heterotrophic and generally grow best at a pH between 6.5 and 7.5. The ability of bacteria to reproduce outside a host is an important factor. Although sludge may be disinfected, it can be reinoculated and recontaminated.

Bacteria are numerous in the human digestive tract; man excretes up to 10^{13} coliform and 10^{16} other bacteria in his feces every day. The most important of the pathogenic bacteria are listed in Table 7-2, together with the diseases they cause.

TABLE 7-2

PATHOGENIC HUMAN BACTERIA POTENTIALLY IN WASTEWATER SLUDGE

Species	Disease
Arizona hinshawii	Arizona infection
Bacillus cereus	*B. cereus* gastroenteritis; food poisoning
Vibrio cholerae	Cholera
Clostridium perfringens	C. perfringens gastroenteritis; food poisoning
Clostridium tetani	Tetanus
Escherichia coli	Enteropathogenic E. coli infection; acute diarrhea
Leptospira sp	Leptospirosis; Swineherd's disease
Mycobacterium tuberculosis	Tuberculosis
Salmonella paratyphi, A, B, C	Paratyphoid fever
Salmonella sendai	Paratyphoid fever
Salmonella sp (over 1,500 serotypes)	Salmonellosis; acute diarrhea
Salmonella typhi	Typhoid fever
Shigella sp	Shigellosis; bacillary dysentery; acute diarrhea
Yersinia enterocolitica	Yersinia gastroenteritis
Yersinia pseudotuberculosis	Mesenteric lymphadenopathy

7.2.2.3 Parasites

Parasites include protozoa, nematodes, and helminths. Pathogenic protozoa are single-celled animals that range in size from 8μ to 25μ. Protozoa are transmitted by cysts, the nonactive and environmentally insensitive form of the organism. Their life cycles require that a cyst be ingested by man or another host. The cyst is transformed into an active organism in the intestines, where it matures and reproduces, releasing cysts in the feces. Pathogenic protozoa are listed in Table 7-3, together with the diseases they cause.

Nematodes are roundworms and hookworms that may reach sizes up to 14 inches (36 cm) in the human intestines (1). The more common roundworms found in man and the diseases they cause are listed in

Table 7-3. They may invade tissues other than the intestine. This situation is especially common when man ingests the ova of a roundworm common to another species such as the dog. The nematode does not stay in the intestine but migrates to other body tissue such as the eye and encysts. The cyst, similar to that formed by protozoa, causes inflammation and fibrosis in the host tissue. Pathogenic nematodes cannot spread directly from man to man. The ova discharged in feces must first embryonate at ambient temperature, usually in the soil, for at least two weeks.

TABLE 7-3

PATHOGENIC HUMAN AND ANIMAL PARASITES POTENTIALLY IN WASTEWATER SLUDGE

Species	Disease
A. Protozoa	
Acanthamoeba sp	Amoebic meningoencephalitis
Balantidium coli	Balantidiasis, Balantidial dysentery
Dientamoeba fragilis	Dientamoeba infection
Entamoeba histolytica	Amoebiasis; amoebic dysentery
Giardia lamblia	Giardiasis
Isospora bella	Coccidiosis
Naegleria fowleri	Amoebic meningoencephalitis
Toxoplasma gordii	Toxoplasmosis
B. Nematodes	
Ancyclostoma dirodenale	Ancylostomiasis; hookworm disease
Ancyclostoma sp	Cutaneous larva migrans
Ascaris lumbricoides	Ascariasis; roundworm disease; Ascaris pneumonia
Enterobius vermicularis	Oxyuriasis; pinworm disease
Necator americanus	Necatoriasis; hookworm disease
Strongyloides stercoralis	Strongyloidiasis; hookworm disease
Toxocara canis	Dog roundworm disease, visceral larva migrans
Toxocara cati	Cat roundworm disease; visceral larva migrans
Trichusis trichiura	Trichuriasis; whipworm disease
C. Helminths	
Diphyllobothrium latum	Fish tapeworm disease
Echinococcus granulosis	Hydated disease
Echinococcus multilocularis	Aleveolar hydatid disease
Hymenolepis diminuta	Rat tapeworm disease
Tymenolepis nana	Dwarf tapeworm disease
Taenia saginata	Taeniasis; beef tapeworm disease
Taenia solium	Cysticercosis; pork tapeworm disease

Helminths are flatworms, such as tapeworms, that may be more than 12 inches (30 cm) in length. The most common types in the United States (listed in Table 7-3) are associated with beef, pork, and rats. Transmission occurs when man ingests raw or inadequately cooked meat or the eggs of the tapeworm. In the less serious form, the tapeworm develops in the intestine, maturing and releasing eggs. In the more serious form, it localizes in the ear, eye, heart, or central nervous system.

7.2.2.4 Fungi

Fungi are single-celled non-photosynthesizing plants that reproduce by developing spores, which form new colonies when released. Spores range in size from 10 to 100 . They are secondary pathogens in wastewater sludge, and large numbers have been found growing in compost (2). The pathogenic fungi, listed in Table 7-4, are most dangerous when the spores are inhaled by people whose systems are already stressed by a disease such as diabetes, or by immunosuppressive drugs. Fungi spores, especially those of *Aspergillus fumigatus*, are ubiquitous in the environment and have been found in pasture lands, hay stacks, manure piles, and the basements of most homes (2).

TABLE 7-4

PATHOGENIC FUNGI POTENTIALLY IN WASTEWATER SLUDGE

Species	
Actinomyces sp	Actinomycosis
Aspergillus sp	Aspergillosis; Aspergillus pneumonia otomycosis
Candida albicans	Moniliasis; candidiasis oral thrush

7.2.3 Pathogen Occurrence in the United States

Information on pathogen occurrence and associated morbidity and mortality data vary greatly with pathogenic species. Available data, complied by the Center for Disease Control (CDC) of the United States Public Health Service, indicates that enteric viral, bacterial, and parasitic infections annually affect tens of thousands of people in the United States (3-7). Data on the occurrence of bacterial disease in the United States are scarce. However, the frequent detection of enteropathic bacteria (bacteria which affect the intestinal tract), such as *E. coli*, *Salmonella*, fecal streptococci, *Shigella*, and others in untreated wastewater and wastewater sludges indicates that these pathogens and their associated diseases are endemic to the United States.

As recently as 1977, over 12 percent of stool samples checked by state and territorial public health laboratories were positive for one or more pathogenic parasites. A. lumbricoides, which produces a resistant ova, was found in over two percent of the samples (6,7).

The frequent occurrence of enteric pathogens in the United States population indicates that pathogens should be expected in all wastewaters and sludges.

7.3 Pathogen Survival During Sludge Stabilization Processes

Sludge stabilization processes are ideally intended to reduce putrescibility, decrease mass, and improve treatment characteristics such as dewaterability. Many stabilization processes also accomplish substantial reductions in pathogen concentrations.

7.3.1 Pathogen Reduction During Digestion

Sludge digestion is one of the major methods for sludge stabilization in the United States. Well-operated digesters can substantially reduce virus and bacteria levels but are less effective against parasitic cysts.

7.3.1.1 Viruses

Viruses are removed most readily in wastewater treatment processes when attached to larger particles such as chemical or biological flocs. Sagik has reported primary treatment virus removal from three percent to extensive (8). Metcalf has measured primary treatment removals of 60 to 95 percent with a one-hour detention time (9). Sagik and Moore have reported 70 to 99 percent removals with activated sludge (8,10).

Virus concentration ranges for raw and anaerobically digested sludges are given in Table 7-5. The large difference between the high and low value for the number of viruses in untreated sludge results from several factors, including variation in virus occurrence in the human population, differing treatment plant removal efficiencies, and disparity in viral preconcentration and assay techniques. Anaerobic digestion has been shown to reduce the concentration of detectable viruses by one to several orders of magnitude. Moore and others reported a reduction by four orders of magnitude for poliovirus by anaerobic digestion for 30 days at 85°F (30°C) (10). Ward and Ashley reported four log inactivation of poliovirus in four days at 82°F (28°C) (17). Ward also found that naturally occurring ammonia (NH_3) was a viricidal agent for poliovirus, Coxsackie, and ECHO (18). However, it was less effective against reoviruses. Digester detention time, operating temperature, and method of operation are apparently the most important factors affecting virus removal. Stern and Farrell report almost 50 percent virus inactivation with sludge storage at 67°F (20°C) for two weeks under laboratory conditions (11). Reduction continued with longer storage. Increased operating temperature also improves reduction.

TABLE 7-5

PATHOGEN OCCURRENCE IN LIQUID WASTEWATER SLUDGES

Pathogen	Name or species	Concentration, number/100 ml: Unstabilized raw sludge[a]	Concentration, number/100 ml: Digested sludge[a,b]	Reference
Virus	Various	$2.5 \times 10^3 - 7 \times 10^4$	$100 - 10^3$	9, 10, 11
Bacteria	Clostridia sp	6×10^6	2×10^7	12
Bacteria	Fecal coliform	10^9	$3 \times 10^4 - 6 \times 10^6$	13, 12
Bacteria	Salmonella sp.	8×10^3	BDL[c] - 62	11
Bacteria	Streptococcus faecalis	3×10^7	$4 \times 10^4 - 2 \times 10^6$	11
Bacteria	Total coliforms	5×10^9	$6 \times 10^4 - 7 \times 10^7$	11
Bacteria	Mycobacterium tuberculosis	10^7	10^6	14
Parasites	Ascaris lumbricoides	200 - 1,000	0 - 1,000	15
Parasites	Helminth eggs	200 - 700	30 - 70	16

[a]Type of sludge usually unspecified.

[b]Anaerobic digestion; temperature and detention times varied.

[c]BDL is below detection limits, <3/100 ml.

Thermophilic anaerobic digestion of sludge at a temperature of 121°F (50°C) with a 20-day retention time at the City of Los Angeles Hyperion Treatment Plant showed a two log greater virus reduction than for comparable mesophilic digestion at a temperature of 94°F (35°C) and the same time period (19). Half the thermophilic samples, however, still showed measurable viruses, which was unexpected; this may be due to the way that digesters are operated. Plant-scale digesters are usually operated on a fill-and-draw basis. If the digesters are mixed continuously, the daily fraction of sludge which is removed to make room for the addition of raw sludge will contain sludge that has been in the process for only a short time. Considering this fact, the appearance of viable pathogens in digested sludge is not surprising.

7.3.1.2 Bacteria

Most bacteria in wastewater are readily sampled and measured. Commonly found concentrations and types of bacteria are shown in Table 7-5. The sensitivity of assay techniques for different bacterial species do vary, from 3 MPN per 100 ml for Salmonella to 1,000 MPN per 100 ml for total coliform, fecal coliform, and fecal streptococcus. In general, anaerobic digestion reduces bacterial counts by one to four logs. Work conducted at Hyperion, in parallel with the virus studies discussed previously, showed thermophilic anaerobic digestion of sludge decreased bacterial counts by two to three logs over mesophilic digestion (19). Increasing both the temperature and the detention time increases bacterial inactivation. Fill-and-draw operation, however, prevents digestion from removing as large a fraction of the bacteria as it might in another operating mode.

Farrell and Stern reported the following bacterial concentrations in an aerobically digested waste-activated sludge (13):

fecal coliform	7×10^7 MPN per 100 ml
Salmonella	1.5×10^4 MPN per 100 ml

The Salmonella values are higher than the upper end of the typical range of values given for anaerobically digested sludge in Table 7-5.

For thermophilic oxygen-aerobic digestion, Ornevich and Smith reported that increasing temperature decreased the time required for bacteria inactivation (20). At 113°F (45°C) Salmonella and Pseudomonas were reduced to below detectable limits in 24 hours; at 140°F (60°C), the time was reduced to 30 minutes.

7.3.1.3 Parasites

There is a wide variation in the apparent level of parasite infestation from region to region in the United States (6,7,21). Protozoa cysts should not survive anaerobic digestion, but helminth ova definitely do and should be expected in digested wastewater sludge unless testing proves the contrary.

The data for parasite occurrence and persistence during wastewater treatment are much more limited than those for bacteria. Cysts of the protozoa Entamoeba histolytica, have been reported at about four per liter in untreated wastewater (16). Protozoan cysts have a low specific gravity and are not likely to be removed to any great degree in primary sedimentation. Secondary treatment by the activated sludge process is reported to incompletely remove all cysts. Trickling filters can remove up to 75 percent of cysts (8). E. histolytica are easily inactivated by well-operated mesophilic sludge digestion.

Data for helminths are also sparse; limited data for sludges, reported in Table 7-5, indicate that digestion can cause some ova reduction. Stern and Farrell reported that Ascaris ova survived thermophilic (121°F, [50°C]) digestion at the Hyperion Treatment Plant (11).

7.3.2 Long Term Storage

Pathogen reduction has been recognized for years as a side benefit of sludge storage in lagoons. Hinesley and others have reported 99.9 percent reduction in fecal coliform density after 30-days storage (22). For an anaerobically digested sludge stored in anaerobic conditions for 24 weeks at 39°F (4°C), Stern and Farrell reported major reductions in fecal coliform, total coliform, and Salmonella bacteria (11). In similar tests at 68°F (20°C), the same bacteria could not be measured after 24 weeks. Viruses were reduced by 67 percent at 39°F (4°C) and to below detectable limits at 68°F (20°C) in the same time period. Recent work by Storm and others showed fecal coliform reductions of one to three orders of magnitude during long-term storage of an anaerobically digested mixture of primary and waste-activated sludge in facultative lagoons (23).

7.3.3 Chemical Disinfection

A number of chemicals used for wastewater sludge stabilization, including lime and chlorine, also reduce the number of pathogenic organisms in sludge.

7.3.3.1 Lime

Lime treatment of wastewater sludge is discussed in detail in Chapter 6. Plant-scale liming of wastewater sludge was evaluated at Lebanon, Ohio (24). Two chemical-primary sludges, one with alum and one with ferric chloride, were limed to pH 11.5 and placed on drying beds. After one month, Salmonella sp. and Pseudomonas aeruginosa were undetectable. Bench testing was also conducted on ferric chloride-treated wastewater raw sludges that were limed to pH 10.5, 11.5 and 12.5; these sludges were sampled after 0.5 hours and 24 hours and bacterial tests performed (24). Pathogenic bacteria reduction improved with time and was substantially better at pH values of 11.5 and 12.5. Qualitative checks for higher life forms such as Ascaris ova indicated that they survived 24 hours at a pH greater than 11.0. Virus studies on limed sludges have not been reported, but a pH in excess of 11.5 should inactivate known viruses (11).

7.3.3.2 Chlorine

Chlorine is a strong oxidizing chemical used for disinfecting drinking water and wastewater effluents. It is effective for bacteria and virus inactivation if applied in sufficient quantity to develop a free chlorine residual in the solution being treated. Chlorine is less effective in disinfecting solutions with a high suspended solids concentration. Cysts and ova of parasites are very resistant to chlorine. The use of chlorine for wastewater sludge treatment is presented in Chapter 6. Few data are available on the potential of chlorine for reducing the number of pathogenic organisms in sludge. Some samples of sludge treated with large doses of chlorine in South Miami, Florida, and Hartland, Wisconsin, showed large reductions in bacteria and coliphages (25). Chlorine doses of 1,000 mg/l applied to waste-activated sludge (WAS) with a 0.5 percent solids concentration reduced total bacteria counts by four to seven logs and coliform bacteria and coliphage to below detection limits. Primary sludge with a 0.5 to 0.85 percent solids concentration was treated with 1,000 mg/l chlorine, and total and fecal coliform counts were reduced below detectable limits.

7.3.3.3 Other Chemicals

Other strong oxidizing chemicals such as ozone are sometimes used for drinking water and wastewater disinfection. While they may prove useful for sludge disinfection, they are as yet untried.

7.4 Pathogen Survival in the Soil

An objective of reducing the number of pathogens in wastewater treatment plant sludge is to produce a product that may be beneficially utilized. As such, the behavior of sludge pathogens in the soil is important. Sludge is returned to the soil by spray irrigation, surface flooding, wet or dry surface spreading, or subsurface injection. These techniques expose the sludge to the sun, air, water, and soil in different ways that may strongly affect pathogen survival.

7.4.1 Viruses

Data for the survival of viruses, bacteria, and parasites in soil are summarized in Table 7-6. Factors that have been found to affect survival include soil temperature, pH, clay concentration, cation exchange capacity, specific surface area, and organic content. Virus adsorption to soil particles is the chief mechanism for their retention when applied to the land. Virus adsorption in soil is reversible. Viruses survive best at slightly alkaline pH's. Cooler temperatures prolong virus infectiveness, as does a moisture content between 15 and 25 percent (8).

7.4.2 Bacteria

Maximum recorded bacterial survival times vary with species, from a little over one month to almost a year, as shown in Table 7-6. The important variables in bacteria survival are moisture content, moisture holding capacity, temperature, pH, sunlight, organic matter, and competition or predation (26). Moisture content is most important, since desiccation often leads to cellular death. Lower temperatures prolong survival, and a lower pH increases the rate of inactivation. The presence of organics may promote survival or even regrowth.

TABLE 7-6

PATHOGEN SURVIVAL IN SOILS

Pathogen type	Name or species	Length of survival, days	Reference
Virus	Poliovirus	Up to 84	8
Virus	Poliovirus 1	Up to 170	10
Virus	ECHO 7	Up to 170	10
Virus	ECHO 9	Up to 170	10
Virus	Coxsackie B3	Up to 170	10
Bacteria	Clostridium sp	Up to 210	15
Bacteria	Leptospira sp	Up to 43	27
Bacteria	Mycobacterium tuberculosis	More than 180	27
Bacteria	Salmonella sp.	Up to 570	28
Bacteria	Salmonella typhi	Up to 120	27
Bacteria	Shigella sp.	Up to 210	15
Bacteria	Streptococcus faecalis	Up to 210	15
Bacteria	Total coliform	Up to 210	
Parasite	Entamoeba histolytica	Up to 8	27
Parasite	Ascaris lumbricoides	Up to 2,550	27
Parasite	Hookworm larvae	Up to 42	27

Burge reported that sludge applied by subsurface injection tends to maintain its identity in clumps (29). Since bacteria and viruses in sludge are associated with the solids, they may be protected from natural predation and other environmental factors in the sludge. Burge also stated that ammonia in sludge may be bactericidal.

If sludge is applied by a surface method and allowed to dry before incorporation into the soil, considerable bacterial reduction can be achieved. This potential advantage of surface applications must be weighed against the associated odor risk and the cost of subsurface injection.

7.4.3 Parasites

Protozoa cysts are reported to be destroyed in eight days after land application. Helminth ova, however, are very durable and may survive up to seven years. Hookworm larvae may be viable for over a month.

7.5 Potential Human Exposure to Pathogens

Man may be exposed to pathogens in wastewater sludge in a variety of ways and at greatly varying concentrations. Figure 7-1 lays out in simplified form some of the potential pathways. There is no firm scientific evidence to document a single confirmed case where human disease is directly linked to exposure to pathogens from wastewater sludge. Viable pathogens have, however, been isolated from intermediate points in the sludge management system, such as from surface runoff from sludge treated fields. These factors should be considered in the selection and design of a process for reducing the number of pathogenic organisms.

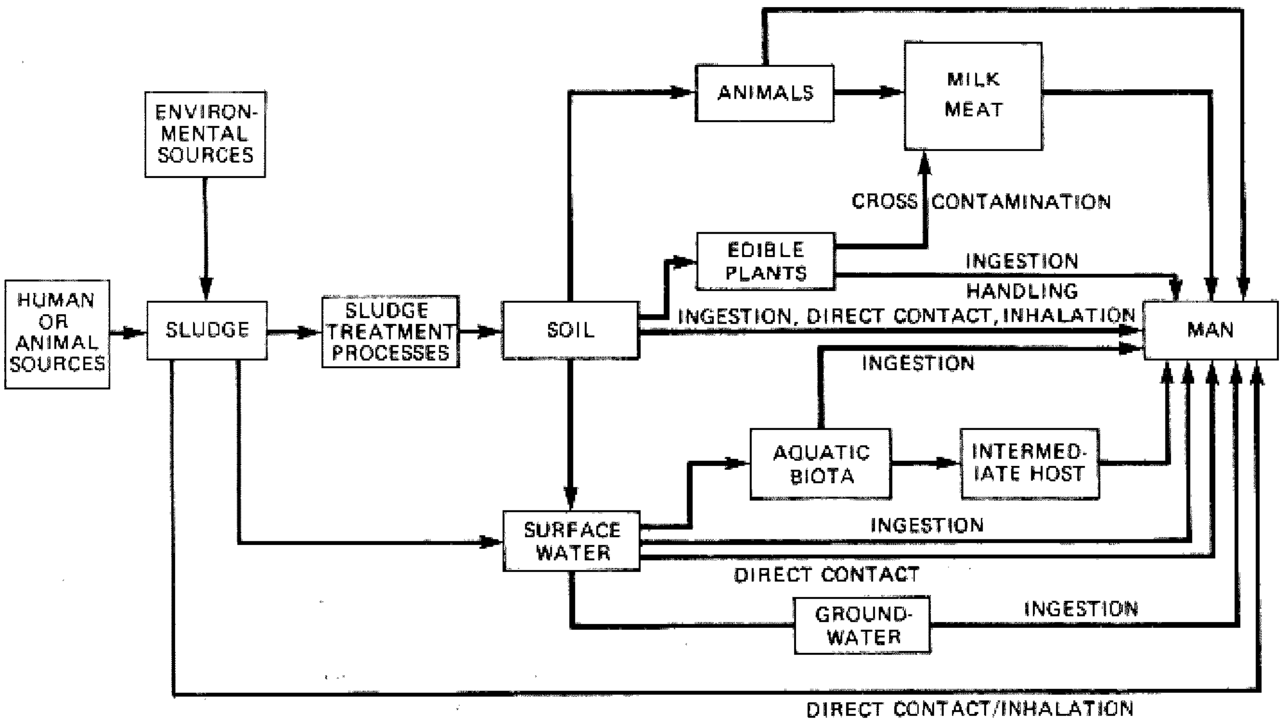

FIGURE 7-1

POTENTIAL PATHOGEN PATHWAYS TO MAN

7.6 Heat Disinfection Processes

The number of pathogenic organisms in wastewater sludge can be effectively reduced by applying heat to untreated or digested sludges. Heat may be used solely for pathogen reduction as in pasteurization or as one step in a processes designed to stabilize sludge, improve treatability or reduce mass. The focus of this section will be on sludge pasteurization. Other heating processes, such as thermal processing and incineration, are developed in Chapters 8 and 11 and will only be reviewed briefly here.

7.6.1 Sludge Pasteurization

Man has recognized for many years that heat will inactivate microorganisms as well as the eggs and cysts of parasites. Different species and their subspecies show different sensitivities to elevated temperatures and duration of exposure. Roediger, Stern, and Ward and Brandon have determined the time-temperature relationships for disinfection of wet sludges with heat (30-32). Their results, summarized for a number of microorganisms in Table 7-7, indicate that pasteurization at 158°F (70°C) for 30 minutes inactivates parasite ova and cysts and reduces population of measurable pathogenic viruses and bacteria below detectable levels. For bacteria, Ward and Brandon found that fecal streptococci were most heat-resistant. followed by coliforms and then Salmonella (32). Nicholson indicates that a higher temperature for a shorter time period (195°F [91°C], 10 minutes) also destroys all pathogens (33).

TABLE 7-7

TIME AND TEMPERATURE TOLERANCE FOR PATHOGENS IN SLUDGE (30, 31, 32)

Species	Exposure time for organism inactivation, min				
	Temperature, °C				
	50	55	60	65	70
Viruses					25
Mycobacterium tuberculosis					20
Micrococcus pygogenes					20
Escherichi coli			60		5
Salmonella typhi			30		4
Fecal streptococci					60
Fecal coliforms					60
Corynebacterium diptheriae		45			4
Brucella abortus		60		3	
Cysts of Entamoeba histolytica	5				
Eggs of Ascaris lumbricoides	60	7			
Aspergillus flavus conidia			60		

°F = 1.8 °C + 32

7.6.1.1 Process Description

The critical requirement for pasteurization is that all sludge be held above a predetermined temperature for a minimum time period. Heat transfer can be accomplished by steam injection or with external or internal heat exchangers. Steam injection is preferred because heat transfer through the sludge slurry is slow and undependable. Incomplete mixing will either increase heating time, reduce process effectiveness, or both. Overheating or extra detention are not desirable, however, because trace metal mobilization may be increased, odor problems will be exacerbated, and unneeded energy will be expended. Batch processing is preferable to avoid reinoculations if short circuiting occurs.

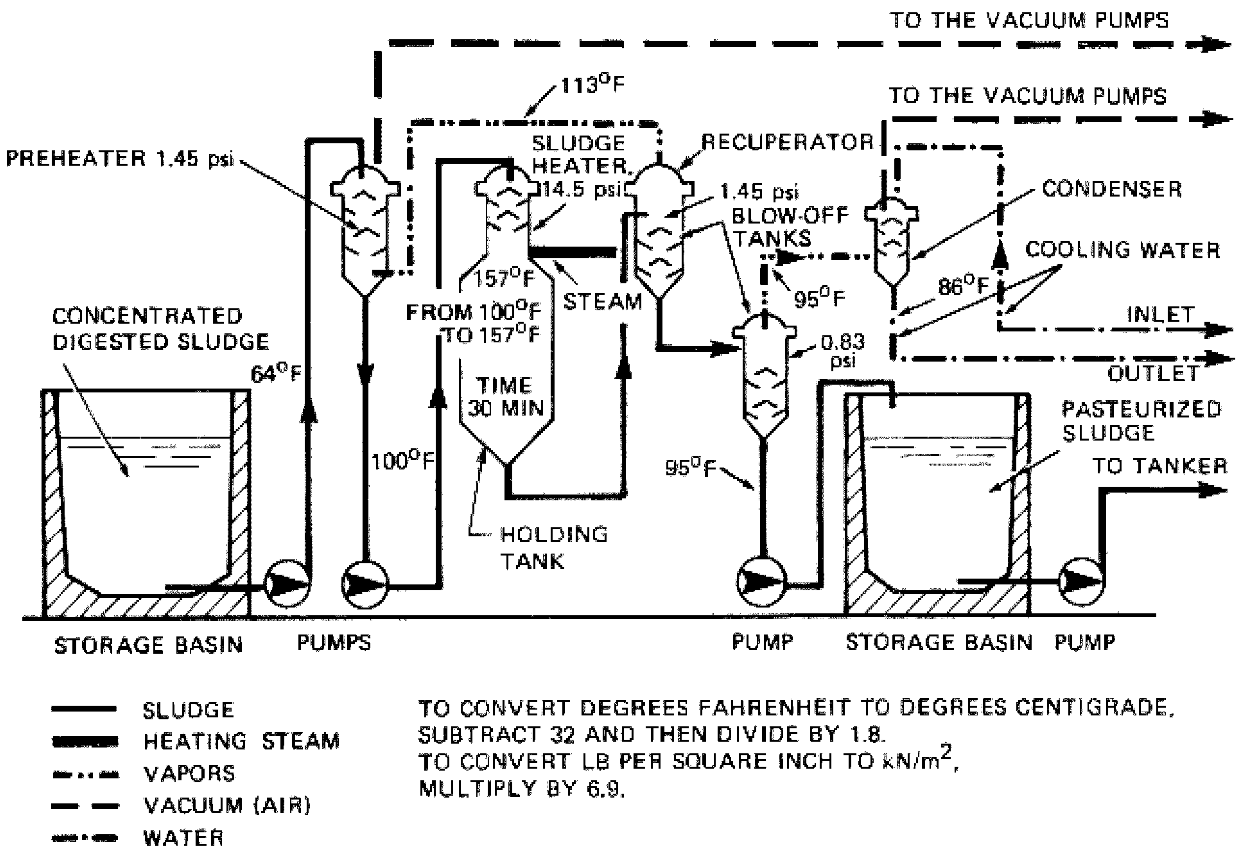

FIGURE 7-2

FLOW SCHEME FOR SLUDGE PASTEURIZATION WITH SINGLE-STAGE HEAT RECUPERATION (11)

The flow scheme for a typical European sludge pasteurization system with a one-stage heat recuperation system is shown on Figure 7-2. Principal system components include a steam boiler, a preheater, a sludge heater, a high-temperature holding tank, blowoff tanks, and storage basins for the untreated and treated sludge. Sludge for pasteurization enters the preheater where the temperature is raised from 64 to 100°F (18 to 38°C) by vapors from the blow-off tank; 30 to 40 percent of the total required heat is thus provided by recovery. Next, direct steam injection raises the temperature to 157°F (70°C) in the pasteurizer where the sludge resides for at least 30 minutes. Finally the sludge is transferred to the blow-off tanks, where it is cooled first to 113°F (45°C) at 1.45 pounds per square inch (10 kN/m^2) and then to 98°F (35°C) at 0.73 pounds per square inch (5 kN/m^2) (31).

For sludge flows of 0.05 to 0.07 MGD (2 to 3 l/s), a single-stage heat recuperation system is considered economical. In the 0.11 to 0.13 MGD (4.8 to 5.7 l/s) flow range a two-stage heat recuperator is considered economical. For flows over 0.26 MGD (11 l/s), a three-stage heat recuperation is considered economically attractive.

7.6.1.2 Current Status

There is only one operating municipal sludge pasteurization facility in the United States today, a heat conditioning system converted for pasteurization. Pasteurization is often used in Europe and is required in Germany and Switzerland before application of sludge to pasture lands during the spring-summer growing season. Based on European experience, heat pasteurization is a proven technology, requiring skills such as boiler operation and understanding of high temperature and pressure processes. Pasteurization can be applied to either untreated or digested sludge with minimal pretreatment. Digester gas, available in many plants, is an ideal fuel and is usually produced in sufficient quantities to disinfect locally produced sludge. Potential disadvantages include odor problems and the need for storage facilities following the process--where bacterial pathogens may regrow if sludge is reinoculated.

7.6.1.3 Design Criteria

A pasteurization system should be designed to provide a uniform minimum temperature of 157°F (70°C) for at least 30 minutes. Batch processing is necessary to prevent short circuiting and recontamination, especially by bacteria. In-line mixing of steam and sludge should be considered as a possible aid to increase heat transfer efficiency and assure uniform heating. In-line mixing will also eliminate the need to mix the sludge while it is held at the pasteurization temperature. The system should be sized to handle peak flows or sludge storage should be used to reduce peak flows. Sizing of storage capacity and the pasteurization system will depend on the type of sludge treated, the average sludge flow, and the end use of the sludge. If digested sludge is to be pasteurized, the digesters may have sufficient volume to hold sludge during minor mechanical breakdowns or when inclement weather prevents an end use such as land application. If sludge is to be stored after treatment and prior to pasteurization, a minimum storage volume should be two days average flow. Storage facilities must be equipped for odor control or with aeration capacity to prevent septic conditions. Storage capacity for pasteurized sludge should be adequate to hold at least four days' amount of processed sludge at average flow. Odor control must be provided, and pilot-scale testing may be needed to determine the best odor control process design. Sludge thickening prior to pasteurization may be cost-effective for increasing overall energy efficiency, but the value of thickening should be determined on a case-by-case basis. Piping, pumps, valves, heat exchangers, flow meters, and other mechanical equipment should, at a minimum, be comparable to those for thermophilic digesters. The tanks for holding sludge during pasteurization should be corrosion-resistant.

7.6.1.4 Instrumentation and Operational Considerations

Temperature monitoring at several points in each pasteurization system is a minimum requirement. Flow metering devices, boiler controls, emergency pressure relief valves, and level sensors in tanks should also be considered (see Chapter 17, Instrumentation).

Heat pasteurization has flexibility to respond to variable solids concentrations and flow rates, provided there is enough basic system capacity. Expansion of facilities with parallel modules should work well; multiple modules also improve system reliability.

7.6.1.5 Energy Impacts

Pasteurization requires both electricity for pumping and fuel for heating the sludge. Energy requirements for pasteurization processes, with and without heat recovery, have been estimated for secondary activated sludge plants where either raw or digested sludge is pasteurized (34). A combination of primary and waste-activated sludge with 4,800 gallons of untreated sludge per 1,000,000 gallons (4.8 l/m^3) raw sewage or with 3,100 gallons of digested sludge per 1,000,000 gallons (3.1 l/m^3) raw sewage, with a solids content of five percent and a specific heat of one Btu per °F (1900 J/°C) were assumed. The process allowed for 10 percent heat loss and a 100 to 125 pounds per square inch (690 to 860 kN/m^2) boiler with an 80 percent efficiency. Steam injection heats the sludge to 157°F (70°C), where it is held for 45 minutes with steam reinjection to maintain the temperature. The energy requirements for processes with a range of wastewater flows are summarized on Figure 7-3.

7.6.1.6 Cost Information

The only sludge pasteurization process operating in the United States was not initially designed for pasteurization. Thus no actual cost data are available. Costs have been estimated for the processes discussed under "Energy Impacts" (34). It was assumed that the processes would have parallel pasteurization reactors and four-day storage volume for the pasteurized sludge. The use (volume of throughput per given size) for the processes increases with increasing system size.

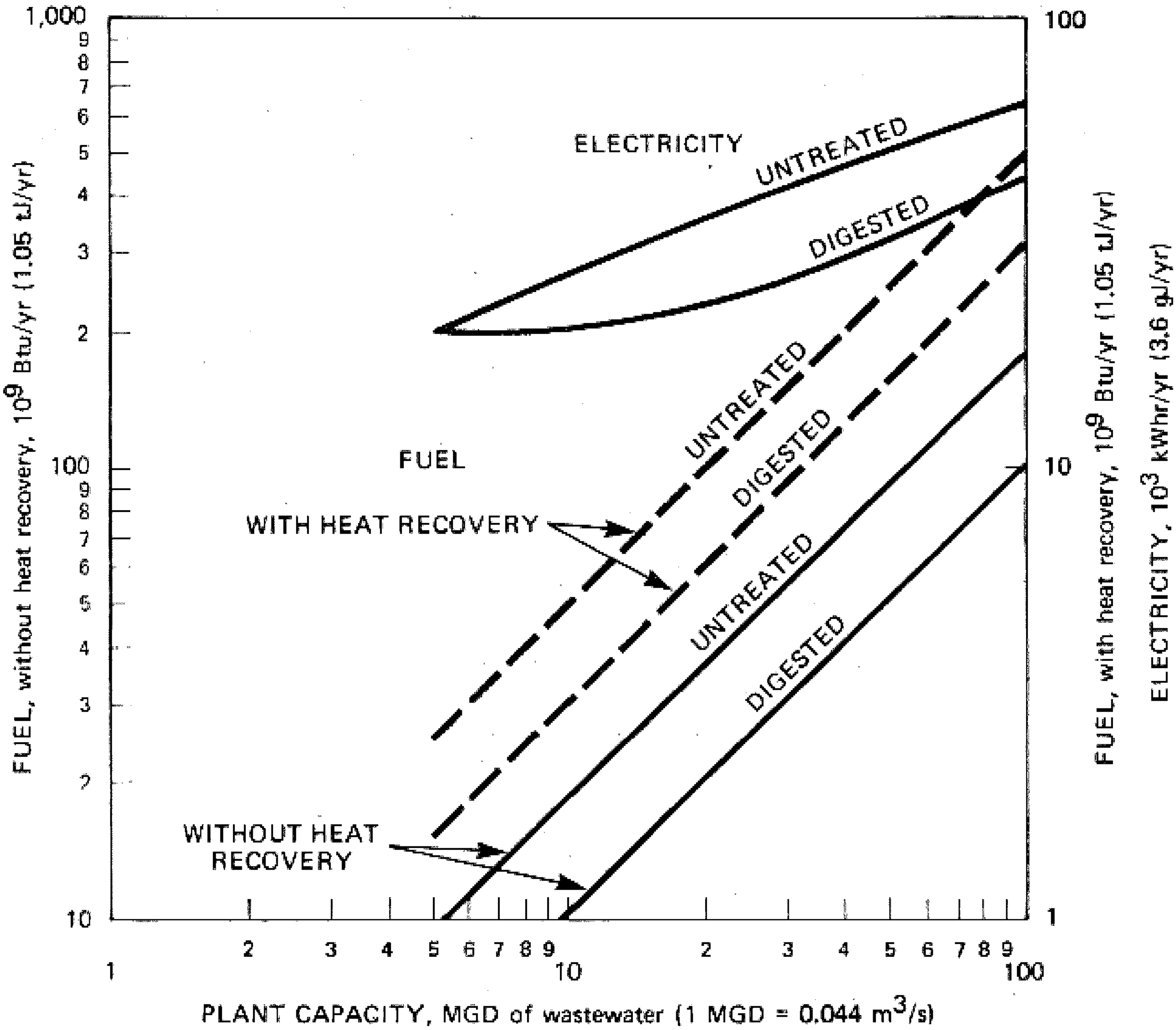

FIGURE 7-3

ENERGY REQUIREMENTS FOR SLUDGE PASTEURIZATION SYSTEMS (34)

Cost estimates were made in June 1977 for construction materials, labor, equipment, normal excavation, contractor overhead and profit, operating and maintenance labor, materials and supplies, and energy. Summary graphs for these estimates are given on Figures 7-4 through 7-7.

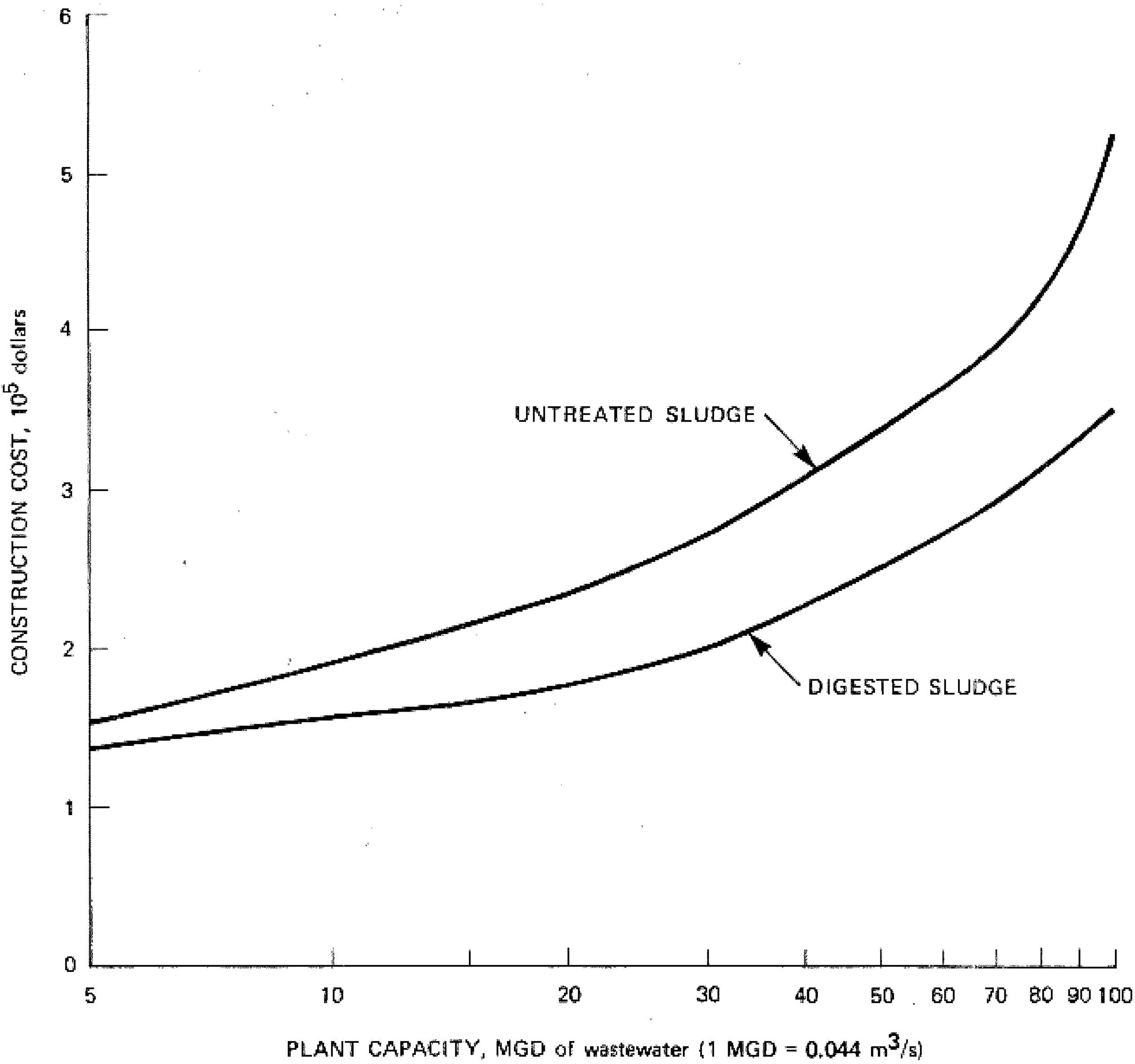

FIGURE 7-4

CONSTRUCTION COSTS FOR SLUDGE PASTEURIZATION SYSTEMS WITHOUT HEAT RECOVERY (34)

These graphs were used to estimate unit pasteurization costs for a 50-MGD (2.2-m^3/s) secondary wastewater treatment plant. Additional assumptions made were that yard piping for the system would cost 15 percent of the total construction cost, electricity would cost three cents per kilowatt hour, fuel would cost $3.00 per million Btu's ($2.84/GJ), labor would cost $10.00 per hour, and capital was amortized over 20 years at seven percent. The resulting pasteurization cost was $15.00 per ton ($16.50/t) of dry solids with heat recovery. A similar calculation was made for a 10-MGD (0.44-m^3/s) secondary plant with no heat recovery, a cost of $33.00 per ton ($36.40/t) of dry solids was estimated.

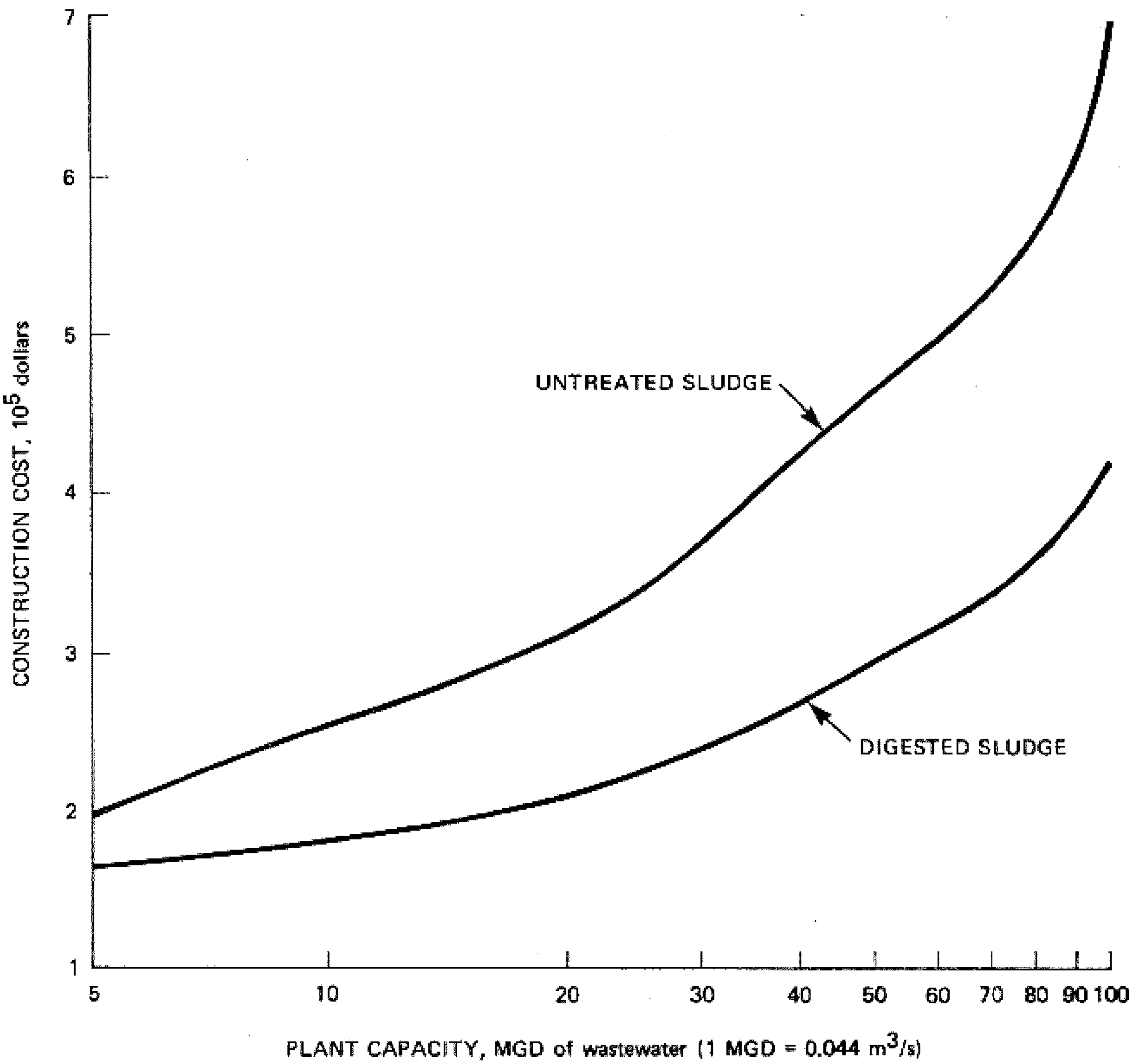

FIGURE 7-5

CONSTRUCTION COSTS FOR SLUDGE PASTEURIZATION SYSTEMS WITH HEAT RECOVERY (34)

7.6.1.7 Design Example

To establish the equipment requirements and layout for a typical pasteurization system, digested combined primary and waste-activated sludge from a 50-MGD (2.2 m^3/s) activated sludge plant are to be pasteurized prior to reuse by direct injection. If the sludge is produced at a rate of 2,000 pounds of solids per million gallons (0.24 kg/m^3), and 40 percent of the solids are destroyed during digestion, the resulting digested sludge has 2.4 percent solids. The sludge flow rate is about 4,800 gallons per million gallons (4.8 l/m^3). For the 50-MGD (2.2 m^3/s) plant, the flow rate is 0.3-MGD (13.0 l/s). If the pasteurization facility is run 24 hours per day, five days per week, the flow rate is 0.42 MGD (18.9 l/s) or about 300 gallons per minute (18.9 l/s).

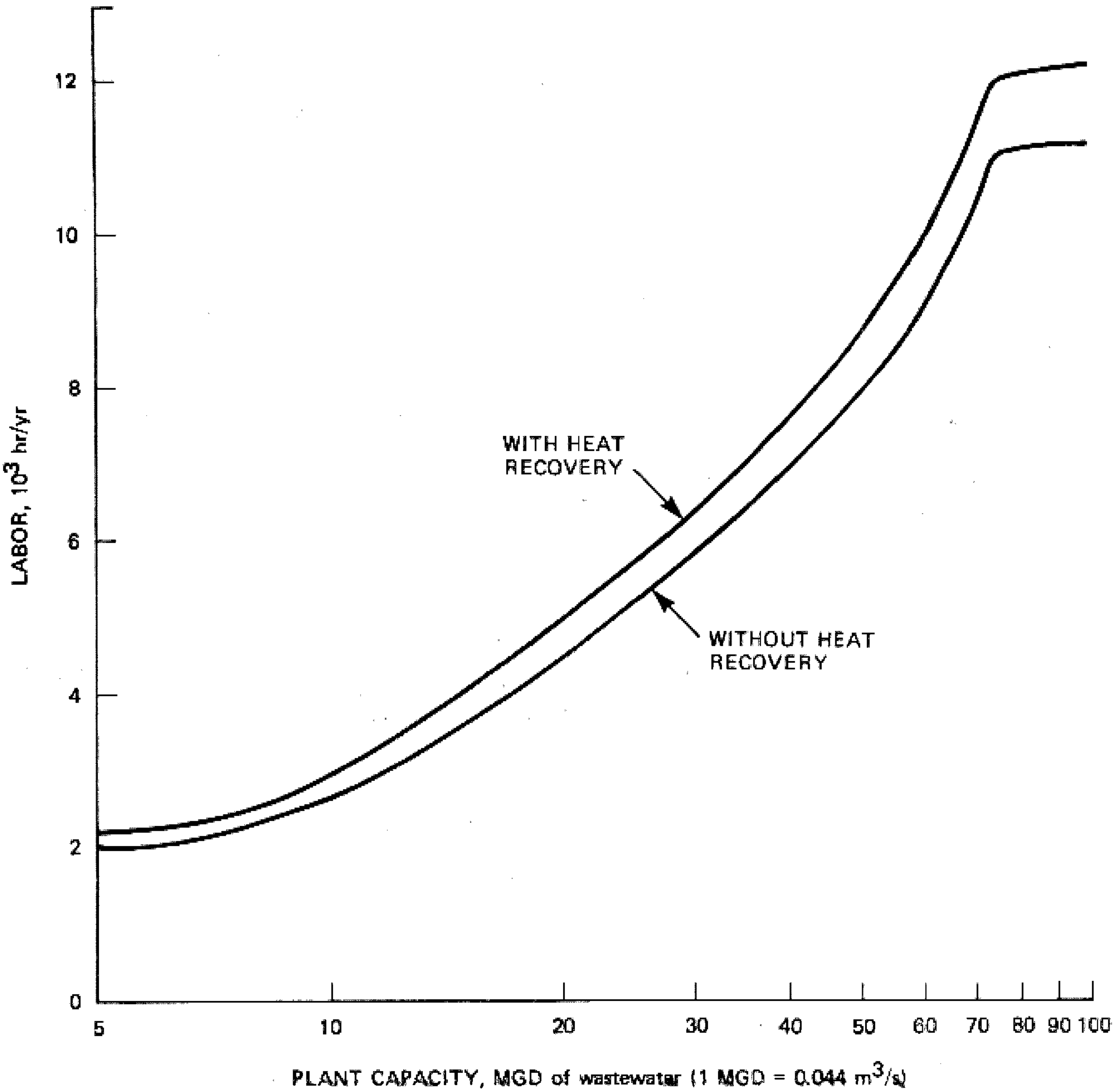

FIGURE 7-6

LABOR REQUIREMENTS FOR SLUDGE PASTEURIZATION SYSTEMS (34)

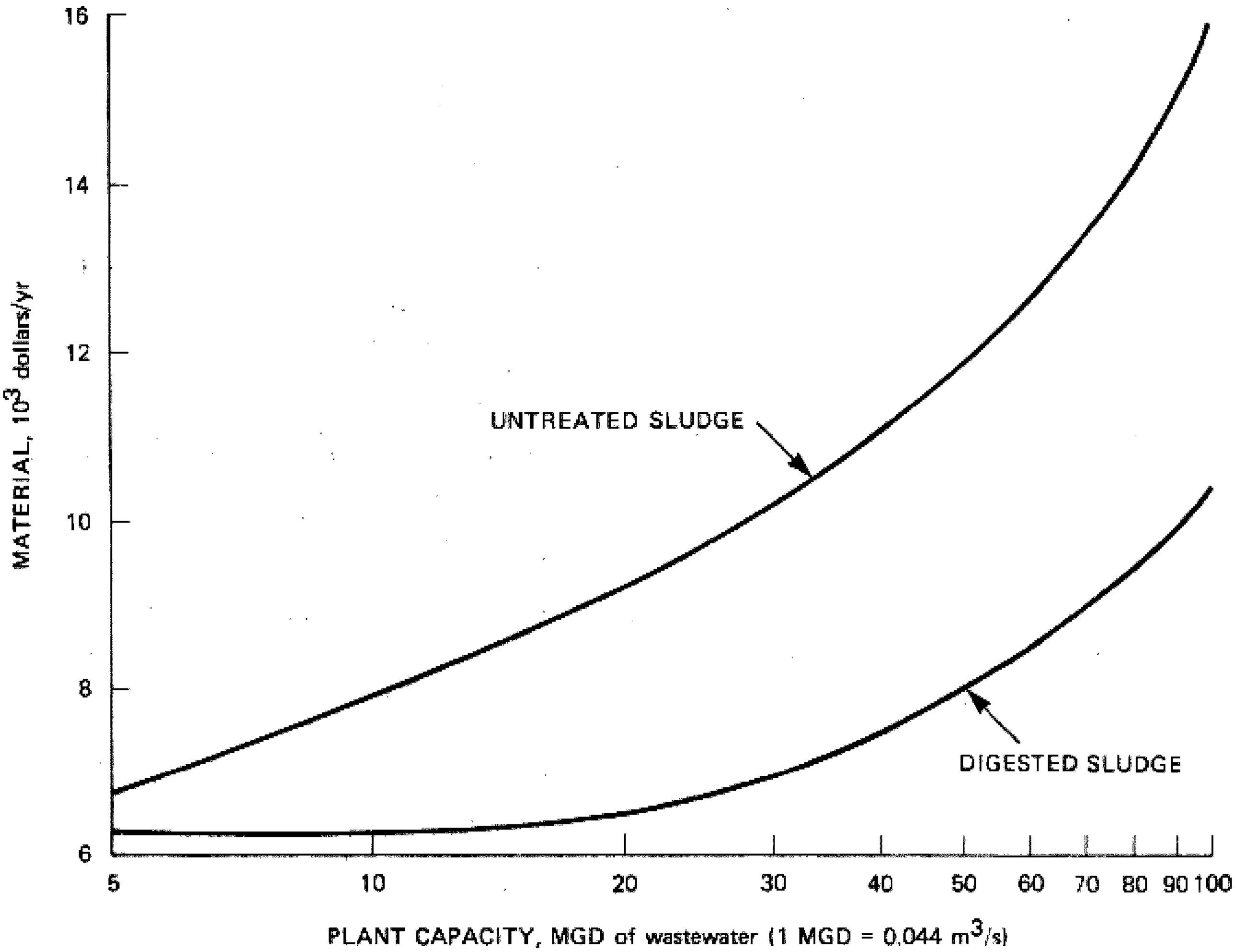

FIGURE 7-7

MAINTENANCE MATERIAL COSTS FOR SLUDGE PASTEURIZATION SYSTEMS (34)

To select the reactor size, assume that there are two parallel units and each can be charged, held, and emptied, in 1.5 hours. Determining the volume per reactor:

$$V = \frac{SC}{NH}$$

where:

S = total sludge volume per week, gallons;

C = cycle time, hours;

N = number of reactors/cycle;

H = total operating hours.

For this example,

$$V = \frac{(2.1 \times 10^6 \text{ gallons})(1.5 \text{ hr/cycle})}{(2 \text{ reactors/cycle})(120 \text{ hr})} = 13{,}125 \text{ gallons } (49.7 \text{ m}^3)$$

Assume a 13,500 gallon (51 m^3) storage tank will be used to store this sludge. Set prepasteurization storage at 2.5 times the average daily flow, or at one million gallons (3780 m^3). Set post pasteurization storage at four times the average daily flow or 1.7 million gallons (6350 m^3). Three heat exchangers in series heat the digested sludge from 68°F to 131°F (20° to 55°C); the boiler supplies steam to raise the temperature to 157°F (70°C). The heat exchangers can be either sludge to sludge or sludge to water to sludge. Sludge-to-sludge exchangers should be carefully specified as they have a history of fouling.

The sludge pumps should be sized and piped either to fill or empty a 13,500 gallon tank (51 m^3) in 30 minutes, equivalent to 450 gallons per minute (28 l/s). At least three pumps are needed; providing one pump on standby.

The required boiler capacity is calculated with the equation:

$$E = \frac{\Delta T \; h \; W}{e \;\; t}$$

where:

E = energy required in Btu per hour

ΔT = the temperature difference between sludge from the heat exchanger and sludge in the reactor;

h = heat capacity of the sludge, Btu/lb°F;

W = wet sludge weight, lb;

t = time for heating;

e = boiler conversion efficiency.

If h is one Btu per lb °F (864 J/kg°C); e = 80 percent; T = 63°F (35°C); W = 112,600 lb (51,200 kg); and t = 0.5 hr; then,

$$E = \frac{(63)(1)(112{,}600)}{(0.5)(0.8)} = 17{,}700{,}000 \text{ Btu/hr } (3.9 \text{ GJ/hr})$$

An additional allowance of ten percent should be added to maintain the reactor temperature for 30 minutes, giving a total of 19.5 million Btu/hr (4.3 GJ/hr) or about 600 horsepower.

Figure 7-8 provides a schematic layout for the major process components.

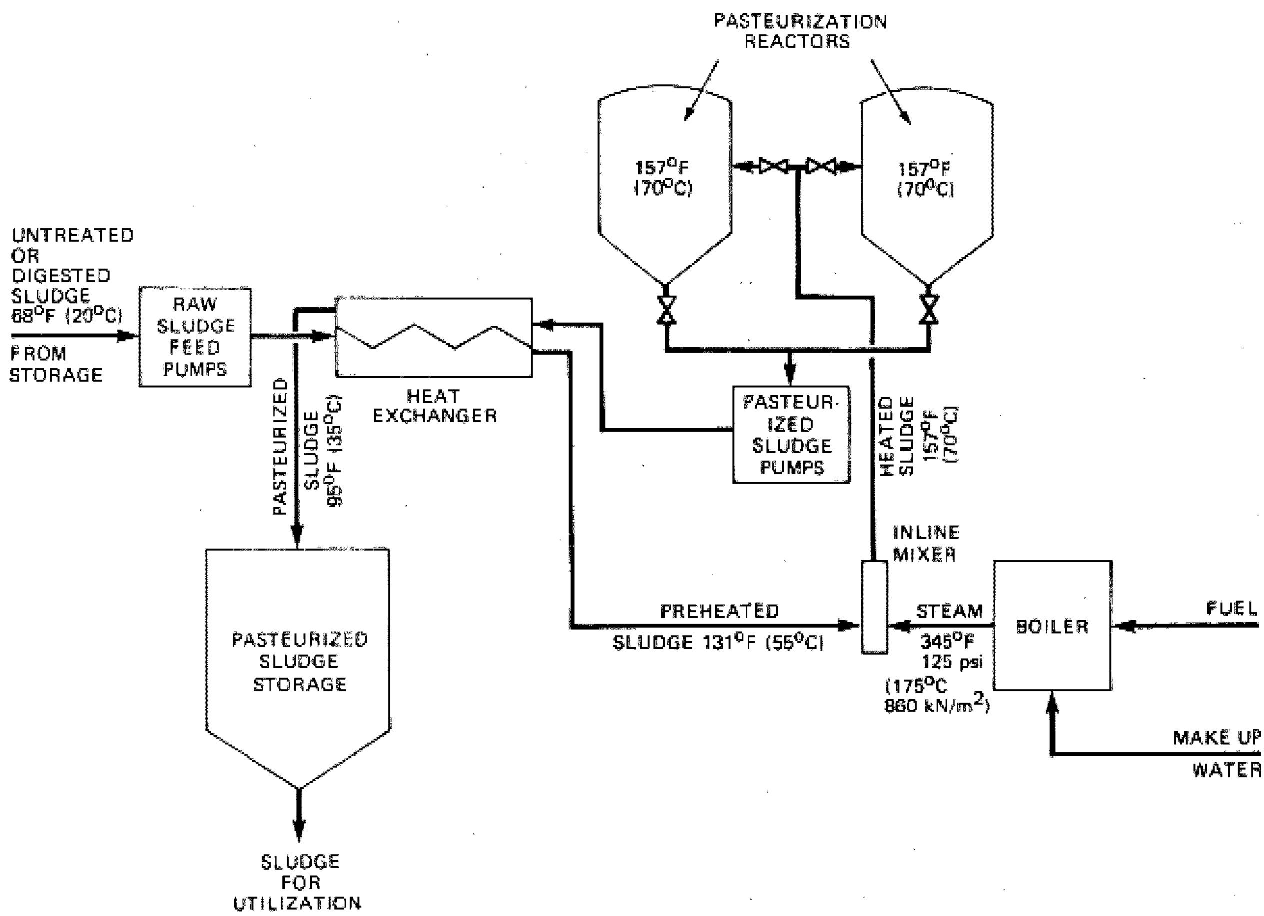

FIGURE 7-8

SYSTEM COMPONENT LAYOUT FOR SLUDGE PASTEURIZATION WITH HEAT RECOVERY

7.6.2 Other Heat Processes

The reduction of pathogenic organisms in sludge may be an added benefit of other sludge treatment processes. In this chapter heat processes are subdivided into heat-conditioning, heat-drying, high temperature combustion, and composting.

7.6.2.1 Heat-Conditioning

Heat-conditioning includes processes where wet wastewater sludge is pressurized with or without oxygen and the temperature is raised to 350° to 400°F (177° to 240 °C) and held for 15 to 40 minutes. These processes destroy all pathogens in sludge, and are discussed in detail in Chapter 8.

7.6.2.2 Heat-Drying

Heat-drying is generally done with a flash drier or a rotary kiln. Limited data from analyses on Milwaukee, Wisconsin's dried sludge, Milorganite, produced with a direct-indirect rotary counterflow kiln type dryer, indicates it is bacteriologically sterile (13). Data on samples of flash-dried sludge taken in Houston, Chicago, Baltimore, and Galveston, showed no coliform bacteria in the Houston sludge and no greater than 17 MPN/gm dry sludge in the other sludges. Total non-confirming lactose fermenters (spore formers) ranged from 14 MPN to 240,000 MPN per gm (35). No tests were made for viruses or parasites; other pathogens may also survive if some bacteria do.

Data for the Carver-Greenfield process gathered during testing by LA/OMA showed a seven order of magnitude reduction for total and fecal coliform, to a detectable level of less than one organism per gram (36). Fecal streptococci were reduced six orders of magnitude to two MPN per gram and Salmonella from 50,000 MPN per gram to less than 0.2 MPN per gram. Ascaris ova were reduced to less than 0.2 ova per gram.

7.6.2.3 High Temperature Processes

High temperature processes include incineration, pyrolysis, or a combination thereof (starved-air combustion). These processes raise the sludge temperature above 930°F (500°C) destroying the physical structure of all sludge pathogens and effectively sterilizing the sludge. The product of a high temperature process is sterile unless shortcircuiting occurs within the process.

7.6.2.4 Composting

Composting is considered here as a heat process because a major aim of sludge composting operations is to produce a pathogen-free compost by achieving and holding a thermophilic temperature. Available data indicate that a well-run composting process greatly reduces the numbers of primary pathogens (37-40). However, windrow or aerated pile operations have not achieved a sufficiently uniform internal temperature to inactivate all pathogens. Adverse environmental conditions, particularly heavy rains, can significantly lower composting temperatures. An additional problem with composting is the potential regrowth of bacteria. This is particularly true with windrows where mixing moves material from the outside of the mound to the center (40). However, storage of compost for several months following windrow or pile composting helps to further reduce pathogen levels.

Secondary pathogens, particularly heat-resistant fungi such as Aspergillus, have been found to propagate rapidly during the composting of wastewater sludges. Aspergillus apparently will die out during storage of several months or more (22).

Enclosed mechanical composting systems may achieve sufficient temperature, 157°F (70°C) or greater, for an adequate time; more research can verify the efficiency of mechanical systems for pathogen reduction.

7.7 Pathogen Reduction With High-Energy Radiation

The use of high-energy radiation for wastewater sludge disinfection has been considered for over 25 years. Two energy sources, beta and gamma rays, offer the best potential system performance. Beta rays are high-energy electrons, generated with an accelerator for use in disinfection, while gamma rays are high-energy photons emitted from atomic nuclei. Both types of rays induce secondary ionizations in sludge as they penetrate. Secondary ionizations directly inactivate pathogens and produce oxidizing and reducing compounds that in turn attack pathogens.

7.7.1 Reduction of Pathogens in Sludge With Electron Irradiation

High-energy electrons, projected through wastewater sludge by an appropriate generator, are being pilot tested as a means for inactivating or destroying pathogens in sludge at the Deer Island Wastewater Treatment Plant in Boston, Massachusetts (41). The electrons produce both biological and chemical effects as they scatter off material in the sludge. Direct ionization by the electrons may damage molecules of the pathogen, particularly the DNA in bacteria cell nuclei and the DNA or RNA of the viruses. The electrons also cause indirect action by producing e^-_{aq} (hydrated electrons) and H and OH free radicals that react with oxygen and other molecules to produce ozone and hydroperoxides. These compounds then attack organics in the sludge--including pathogens--promoting oxidation, reduction, dissociation, and other forms of degradation.

The pathogen-reducing power of the electron beam (e-beam) depends on the number and the energy of electrons impacting the sludge. E-beam dose rates are measured in rads; one rad is equal to the absorption of 4.3×10^{-6} Btu per pound (100 ergs/gm) of material. Since the radiation distributes energy throughout the volume of material regardless of the material penetrated, the degree of disinfection with an irradiation system is essentially independent of the sludge solids concentration within the maximum effective penetration depth of the radiation. The penetrating power of electrons is limited, with a maximum range of 0.2 inches (0.5 cm) in water or sludge slurries, when the electrons have been accelerated by a potential of one million volts (MeV).

For e-beam disinfection to be effective, some minimum dosage must be achieved for all sludge being treated. This effect is attained by dosing above the average dosage desired for disinfection. One method used to ensure adequate disinfection is to limit the thickness of the sludge layer radiated so that ionization intensity of electrons exiting the treated sludge is about 50 percent of the maximum initial intensity. For the 0.85 MeV electrons used in the existing facility, this constraint limits sludge layer thickness to about 0.08 inches (0.2 cm).

Accelerated electrons can induce radioactivity in substances which they impact. However, the electron energy levels for sludge irradiation, up to about 2 MeV, are well below the 10 MeV needed to induce significant radioactivity with electrons.

7.7.1.1 Process Description

Disinfection with an e-beam has been proposed for use on both untreated and digested sludges. The major system components of the Deer Island facility shown on Figure 7-9 include the sludge screener, sludge grinder, sludge feed pump, sludge spreader, electron beam power supply, electron accelerator, electron beam scanner, and sludge removal pump. A concrete vault houses the electron beam, providing shielding for the workers from stray irradiation, especially x-rays. X-rays are produced by the interaction of the electrons with the nucleus of atoms in the mechanical equipment and in the sludge. The pumps must be progressive cavity or similar types to assure smooth sludge feed. Screening and grinding of sludge prior to irradiation is necessary to assure that a uniform layer of sludge is passed under the e-beam.

At Deer Island, sludge from the feed pump discharges into the constant head tank (see Figure 7-10), which is equipped with an underflow discharge weir. Sludge is discharged under the weir in a thin stream and then flows down an inclined ramp. At the bottom of the ramp, it moves by free-fall into the receiving tank.

The electrons are first accelerated. They leave the accelerator in a continuous beam that is scanned back and forth at 400 times per second across the sludge as it falls free in a thin film from the end of the inclined ramp. The dosage is varied by adjusting the height of the underflow weir and hence the sludge flow rate.

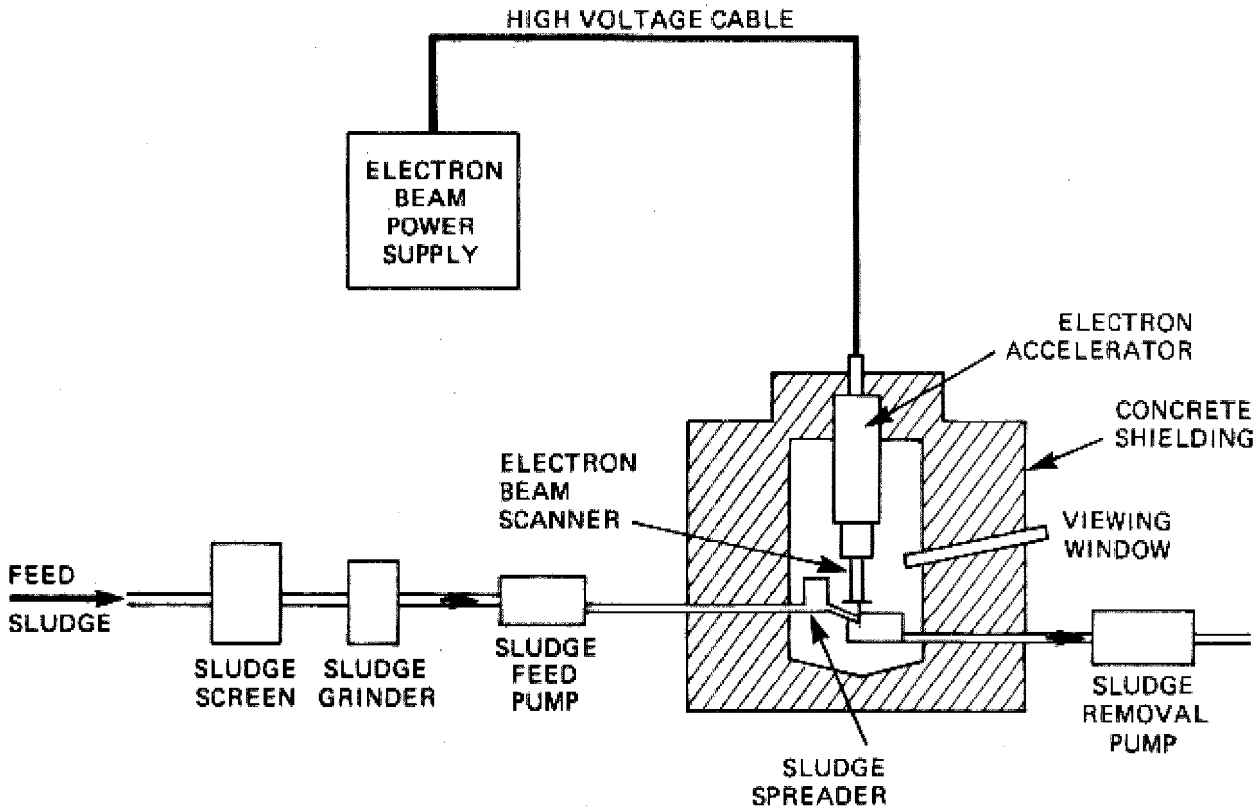

FIGURE 7-9

EQUIPMENT LAYOUT FOR ELECTRON BEAM FACILITY (41)

7.7.1.2 Status

E-beam sludge irradiation must be considered a developing technology. The Deer Island irradiation facility, as of August 1979, is the only e-beam facility now operated in the United States for sludge disinfection. This pilot project is designed to treat 0.1 MGD (4 l/s) sludge at up to eight percent solids with a dosage of 400,000 rads. According to Shah, the facility has been operated about 700 hours since it was brought on line in 1976, with the longest continuous on-line time being eight hours (42).

7.7.1.3 Design Considerations

Design criteria for an e-beam sludge facility are difficult to establish because operational data are available from only one pilot facility. However, the work at Deer Island provides good baseline information. A minimum level of electron irradiation should be 400,000 rads, which can best be supplied with a one to two MeV electron accelerator. This energy level provides good penetration for 0.2-inch (0.5-cm) thick sludge layers, making the achievement of a uniform sludge layer less important than with lower energy electrons. However, screening and grinding of sludge before disinfection are still necessary to ensure uniform spreading by this feed mechanism. The high-energy electrons, combined with a short spacing of about 2.75 inches (7 cm) between the scanner window and the sludge film, ensure efficient energy transfer in the system.

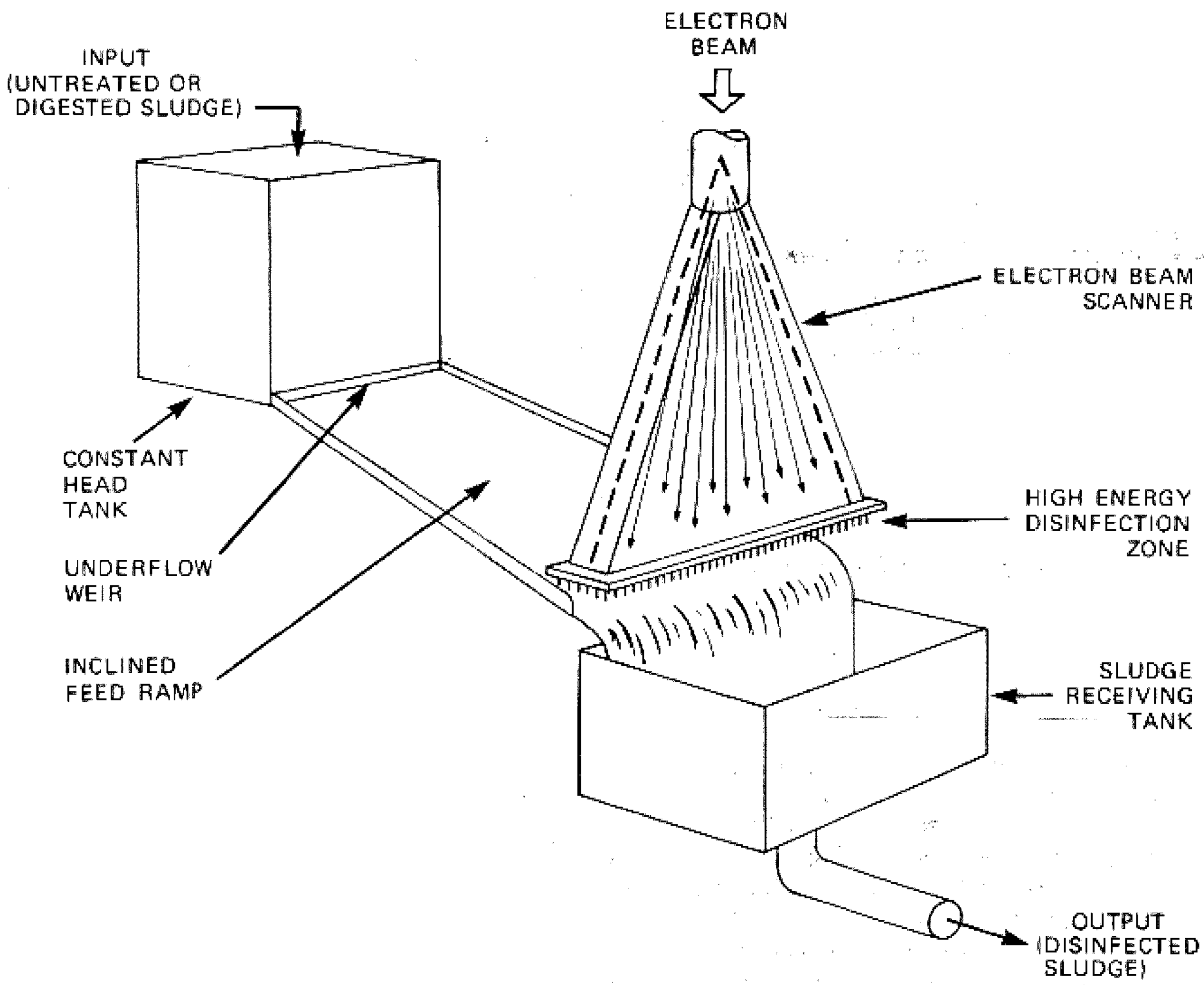

FIGURE 7-10

ELECTRON BEAM SCANNER AND SLUDGE SPREADER

Only digested sludge has been irradiated at Deer Island. Nonstabilized sludge disinfection by e-beam irradiation still requires pilot-scale testing before any design is considered.

Owing to the limited penetrating power of high energy electrons, this method of treatment is probably only feasible for liquid sludge. Piping pumps, valves, and flow meters should be specified as equal to those used for anaerobic sludge digestion systems.

7.7.1.4 Instrumentation and Operational Considerations

Instrumentation needs for an e-beam facility should include flow measurement of and temperature probes in the sludge streams entering and leaving the irradiator. Alarms as well as monitoring should be used to indicate variation in sludge flow and high or low radiation doses.

Sludge disinfection by e-beam irradiation has large inherent flexibility. The radiation source (the e-beam) can be switched on and off as easily as an electric motor. The unit can be run as needed, up to its maximum throughput capacity. Electron accelerators have a proven record for reliability over at least 20 years in industrial applications and should prove dependable in wastewater treatment applications. According to Haas, the reliability of the electron beam generator and associated electronics presently used for medical and industrial applications is comparable to that for the microwave radar systems at major airports (43). Accelerators for sludge disinfection would use the same basic components and would have similar reliability. Other system components--pumps, screens, and grinders--are all in common use in waste treatment plants. Cooling air for the scanner must be provided at several hundred cfm (about 10 m^3/s). This constant introduction of cooling air leads to the generation of ozone in the shielding vault around the accelerator. If the ozone were vented into the plant or into the atmosphere, some air pollution would result. At Deer Island, this problem is avoided by venting the cooling air through the sludge, where the ozone is consumed by chemical reduction. These reactions provide a small amount of additional disinfection and COD reduction.

7.7.1.5 Energy Impacts

Energy use for e-beam facilities has been estimated for the equipment used at Deer Island. A facility with a 50-kW (50-kJ/s) beam would require about 100 kW (100kJ/s) of total electrical power including 25 kW (25 kJ/s) for screening, grinding, and pumping, 10 kW for (10 kJ/s) window cooling, and 12 kW (12 kJ/s) for electrical conversion losses. Energy requirements for 0.1 MGD (4 l/m^3) are 6 kWhr per ton (24 MJ/t) of wet sludge at five percent solids or 120 kWhr per dry ton (480 MJ/t) (41).

7.7.1.6 Performance Data

Data for e-beam disinfection of both untreated and digested sludges are available as a result of laboratory testing done prior to the operation of the Deer Island facility. For untreated primary sludge, a dose of 400 kilorads (krads) with 3 MeV electrons reduced total bacteria count by five logs, total coliform by more than six logs, below detectable limits, and total Salmonella by over four logs, also below detectable limits. Fecal streptococci were only reduced by two logs with data indicating that some fecal streptococci are sensitive to radiation while others are resistant.

For samples of anaerobically digested sludge irradiated at Deer Island with 0.85 MeV electrons, total bacteria were reduced by four logs at a dose of 280 krads, total coliform by five to six logs at a dose of 150 to 200 krads; a dose of 400 krads reduced fecal streptococci by 3.6 logs.

Virus inactivation has also been measured. A dose of 400 krads will apparently reduce the total virus measured as plaque forming units (PFU) by one to two logs. Laboratory batch irradiation of five enteric viruses showed about two logs reduction at a dose of 400 krads; Coxsackie virus were most resistant while Adeno virus were least resistant. These results correlate directly with virus size. Larger viruses are larger targets and hence more susceptible to electron "hits" (41).

Data for parasite reduction are scarce but 400 krads will apparently destroy all Ascaris ova (41). Comparing these performance data with information from Table 7-5 on the quantity of pathogens in sludge indicate that a dose of 400 krads may be adequate to disinfect anaerobically digested sludge, but raw sludge or aerobic sludge may require higher doses.

7.7.1.7 Product Production and Properties

Odor problems are dramatically lower for irradiated sludge as compared with pasteurized sludge (41). Irradiation of digested sludge with an e-beam may also improve sludge dewaterability and destroy some synthetic organic chemicals, as well as reduce pathogen levels. Irradiation has reduced specific resistance of sludge by up to 50 percent at a dose of 400 krads (41). Since specific resistance is normally measured on a log scale, a 50 percent reduction may indicate minimal improvement in sludge dewaterability.

7.7.1.8 Cost Information

The only cost estimates available on e-beam sludge treatment process result from work done at Deer Island. The hypothetical facility used for the cost estimate had the following characteristics:

- Electron beam power of 75 kW (75 kJ/s).
- Accelerator voltage of 1.5 MeV.

- Disinfection dose of 400 krad.

- Yearly throughput of 50 million gallons (190,000 m^3) with process operating 300 days per year. This throughput is equivalent to the raw sludge from a 25-MGD (1.1-m^3/s) activated sludge plant or the digested sludge from a 35-MGD (1.5-m^3/s) activated sludge plant.

The total capital cost was $600,000. The cost included the following: accelerator component with scanner--$350,000; automatic controls--$30,000; sludge handling equipment--$100,000; and building construction and facility installation--$120,000. Annual costs were as follows: capital (20 years at 10 percent) $30,000; depreciation--$30,000; operation and maintenance--$40,000; electric power at three cents per kWhr (.83 cents per mJ) $28,000; and water--$2,000. This cost estimate was carried out in Boston in late 1977. At that time the ENR construction cost index was about 2,650. The net cost was $2.53 per 1,000 gallons ($0.67/m^3) of liquid sludge treated.

The energy requirements (fuel and electricity) for an irradiation system are estimated to be 90 to 98 percent less than those for heat pasteurization.

7.7.2 Disinfection With Gamma Irradiation

Gamma irradiation produces effects similar to those from an electron beam. However, gamma rays differ from electrons in two major ways. First, they are very penetrating; a layer of water 25 inches (64 cm) thick is required to stop 90 percent of the rays from a cobalt-60 (Co-60) source; in comparison, a 1-MeV electron can only penetrate about 0.4 inches (1 cm) of water. Second, gamma rays result from decay of a radioactive isotope. Decay from a source is continuous and uncontrolled; it cannot be turned off and on. The energy level (or levels) of the typical gamma ray from a given radioactive isotope are also relatively constant. Once an isotope is chosen for use as a source, the applied energy can only be varied with exposure time.

Two isotopes, Cs-137 and Co-60, have been considered as "fuel" sources for sludge irradiators. Cs-137 has a half life of 30 years and emits a 0.660 MeV gamma ray. In the late 1970's, it was available in the United States as a by-product from the processing of nuclear weapons wastes. If the United States establishes a nuclear reactor spent-fuel rod reprocessing program, it would also be available at a rate of about 2 pounds per ton (1 kg/t) of fuel. Co-60 has a half life of five years and emits two gamma rays with an average energy of 1.2 MeV. It is made by bombarding normal cobalt metal, which is stable cobalt isotope 59, with neutrons.

7.7.2.1 Process Description

Two general types of gamma systems have been proposed for wastewater sludge disinfection. The first is a batch-type system for liquid sludge, where the sludge is circulated in a closed vessel surrounding the gamma ray source. Dosage is regulated by detention and source strength. The second system is for dried or composted sludge. A special hopper conveyor is used to carry the material for irradiation to the gamma ray source. Conveyor speed is used to control the dosage.

7.7.2.2 Current Status - Liquid Sludge

The only gamma ray system in active operation is a liquid sludge facility at Geiselbullach (near Munich) in West Germany. Sludge has been treated in a demonstration-scale facility since 1973. The design capacity is 0.04 MGD (2.0 l/s) but the initial Co-60 charge only provided radiation to treat 0.008 MGD (0.3 l/s). The basic flow scheme is shown on Figure 7-11. Digested sludge is pumped or otherwise moved into the vault with the Co source and circulated until the desired dosage is reached. The chamber is then completely emptied and recharged.

Wizigmann and Wuersching (45) reported on the efficiency of the Geiselbullach facility when the applied dose was 260 krads in 210 minutes. Bacterial tests were made on samples of processed sludge and showed a two-log reduction in total bacterial count, an Enterococcus reduction of two logs, and an Enterobacteriaceae reduction of four to five logs. Two of 40 samples were positive for _Salmonella_. Bacterial regrowth was measured in sludge-drying beds where the sludge was placed after irradiation.

Plastic encapsulated bacteria samples were also irradiated in the system to a dosage of 260 krads. Two of nine _E. coli_ strains were radiation-resistant and reduced five to six logs; three strains were totally inactivated, and four strains were reduced six to eight logs. Tests on ten strains of _Salmonella_ in 170 samples showed four to seven log reduction, with 85 percent of the samples over five logs and 61 percent over six logs. Klebsiella were reduced six to eight logs. Gram-negative species were more sensitive to gamma radiation than gram-positive ones, and spores were more resistant than vegetative forms. A comparison of the disinfection results of the real sludge samples and the plastic encapsulated cultures indicates that circulation in the sludge system apparently did not result in a very uniform dose exposure.

Parasite ova (_Ascaris suum_) circulated through the system in plastic capsules failed to develop during three weeks of incubation. This observation period was not adequate, however, to assure that long-term recovery would not take place.

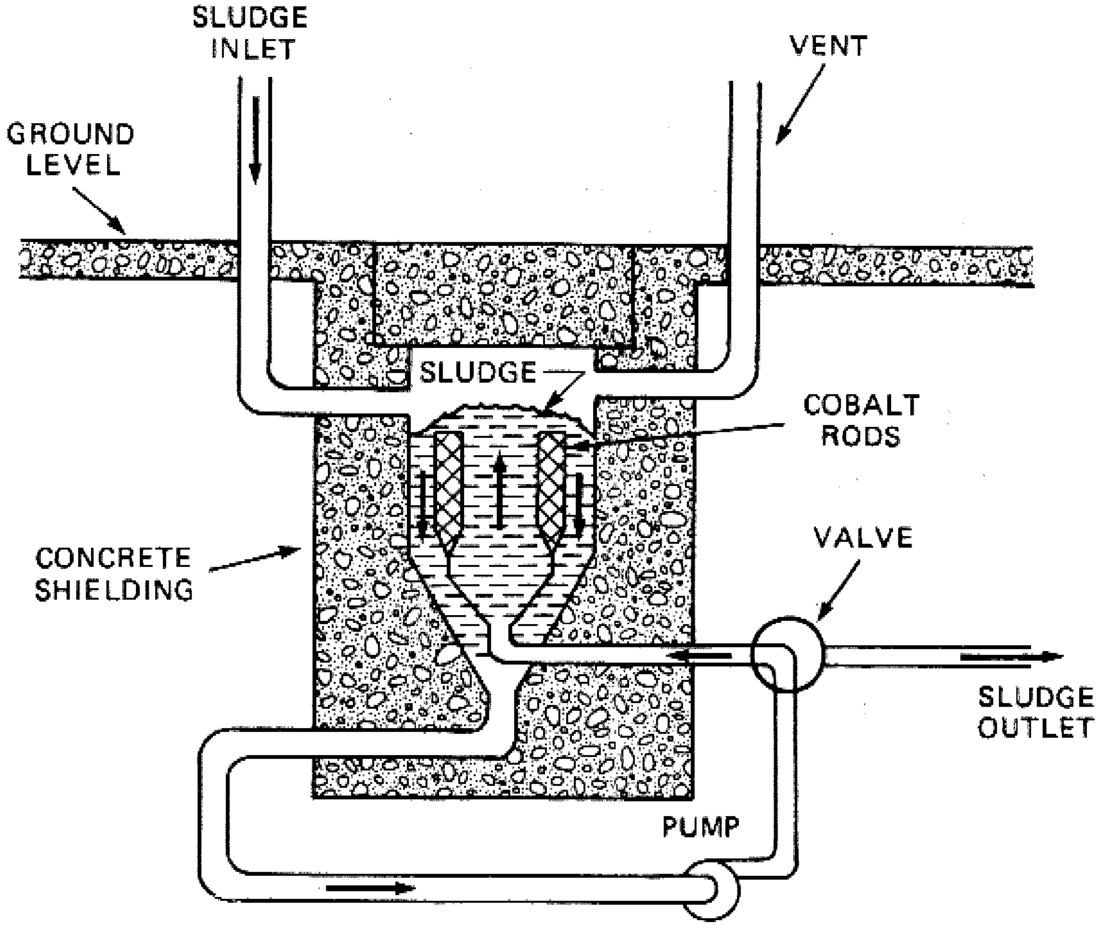

FIGURE 7-11

SCHEMATIC REPRESENTATION OF COBALT-60
IRRADIATION FACILITY AT GEISELBULLACH, WEST GERMANY (44)

According to the latest available reports, land spreading of the sludges treated at Geiselbullach has been well received by local farmers and the general public. No radiation hazards have resulted and the treated sludges satisfy disinfection requirements. The competing system in Germany, heat pasteurization, requires more energy and produces an odorous product that is more difficult to handle.

7.7.2.3 Current Status - Dried or Composted Sludge

A dry sludge irradiation system using a gamma source is being developed by Sandia Laboratories in Albuquerque, New Mexico. The eight-ton-per-day (7.2 t/day) demonstration facility, containing about one million Curie of Cs-137, underwent final testing and start-up in June 1979. The facility will be used to irradiate bagged composted sludge for agricultural experiments and bagged dried raw primary sludge for testing as a cattle-feed supplement.

Owing to the high cost of Co-60, the overall viability of any sludge irradiation facility in the United States depends on Cs-137 supplies. Cs-137 will be available in quantity only if the political and technical difficulties associated with power plant fuel rod reprocessing can be resolved. About 200 megacuries of Cs-137 could be available from processing wastes from weapons manufacture and could be used for further testing.

7.7.2.4 Design Criteria

The design criteria for gamma irradiation facilities depend on the type of wastewater sludge treated. Current literature discussions suggest a dose of 400 krads but this level does not ensure complete virus removal (41). The dose level should probably be varied in relation to other treatments the sludge receives. A composted, bagged product with an 80 percent solids content needs a lower dose than a mixture of raw primary and waste-activated sludge because the dried product already has a reduced pathogen level owing to the drying process. Data from the demonstration facility at Sandia Laboratory for design of a dry facility should be available by late 1979. For a liquid sludge facility, data on dose-response and pathogen levels (Table 7-5 and Section 7.7.2.2) can be combined with information from Geiselbullach to set the required radiation doses. The storage capacity for both untreated and irradiated sludge should be equal to that for a pasteurization facility of similar size (see Section 7.6.1.7).

When a dry system radiation source is not in use, it should be shielded in a steel-lined concrete vault. The vault should be designed to be flooded with water during loading and unloading of the radiation source, to shield workers from radiation. Provision must be made for pool water treatment in the event that the radiation source leaks. Cooling air is circulated around the source both during system operation and down times. This air must be filtered to prevent a radioactive air release. Since the dried sludge is a flammable material, there must be smoke and/or heat detection and a fire suppression system. For a liquid storage system the treatment vessel serves as a radiation source storage vault.

7.7.2.5 Instrumentation and Operational Considerations

Instrumentation should include radiation detectors and flow metering for the wet sludge system. When either facility is operating, arrangements must be made for periodic radiation safety inspection. The disinfection effectiveness should also be tested by periodic sampling of the sludge before and after disinfection.

7.7.2.6 Energy Impacts

In May 1977, Ahlstrom and McGuire (46) projected annual energy requirements for both wet and dry gamma irradiation facilities, using a dose rate of 1,000 krads. Their results are summarized on Figures 7-12 and 7-13. For a 0.1-MGD (4-l/s) facility treating sludge with five percent solids, 300 days per year, the unit energy use is about 5.2 kWhr per 1,000 gallons (5 MJ/m^3) or 25 kWhr per ton (100 MJ/ton) dry solids. For a plant treating 35 tons per day (32 t/day) at 60 percent solids, 300 days per year (equivalent to the solids from the previous example), the energy use is 5.6 kWhr per ton dry (22 MJ/t) solids, almost 80 percent less than the facility treating five percent solids. These energy uses should be compared to 120 kWhr per dry ton (450 MJ/t) for an e-beam system.

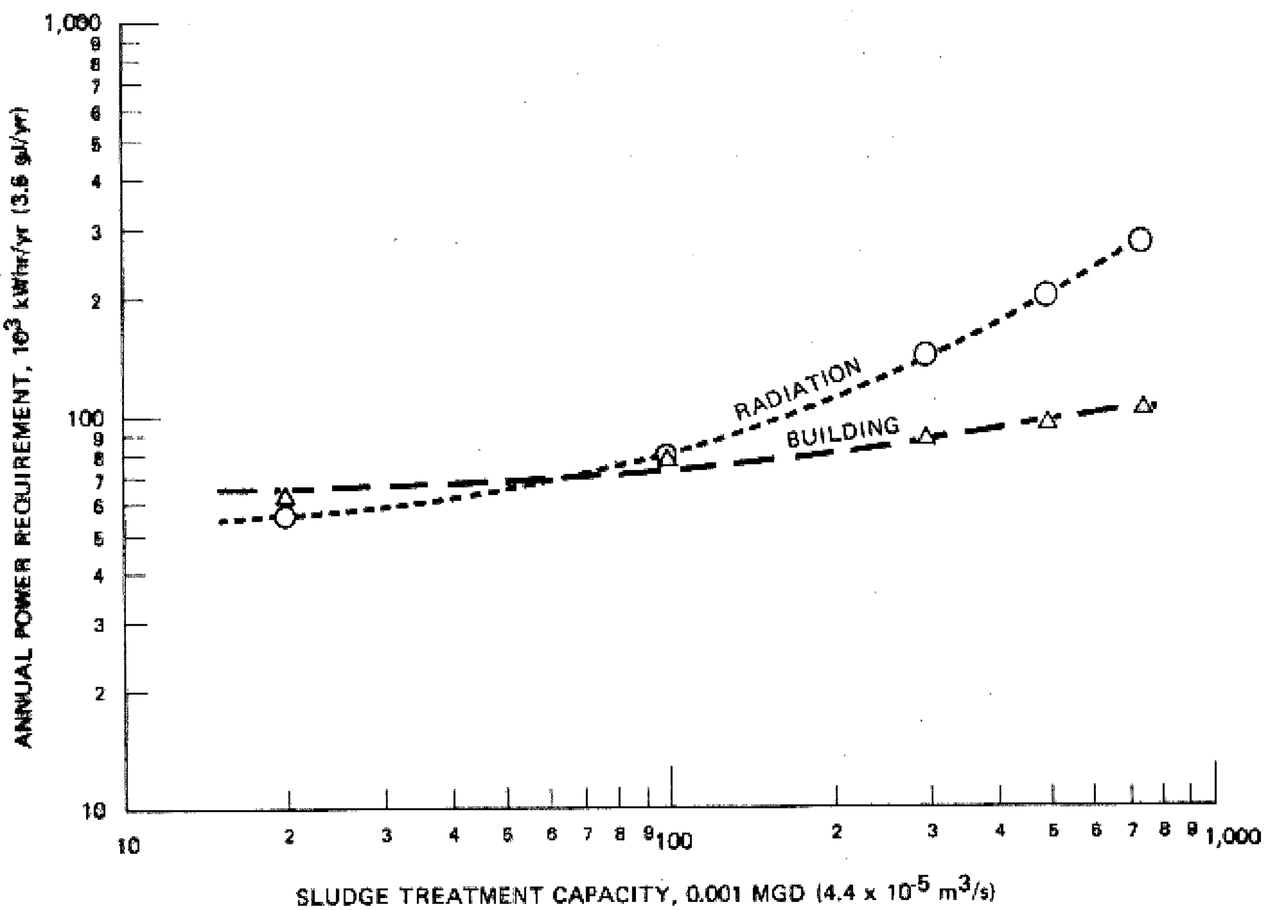

FIGURE 7-12

GAMMA RADIATION TREATMENT OF LIQUID SLUDGE POWER REQUIREMENTS (46)

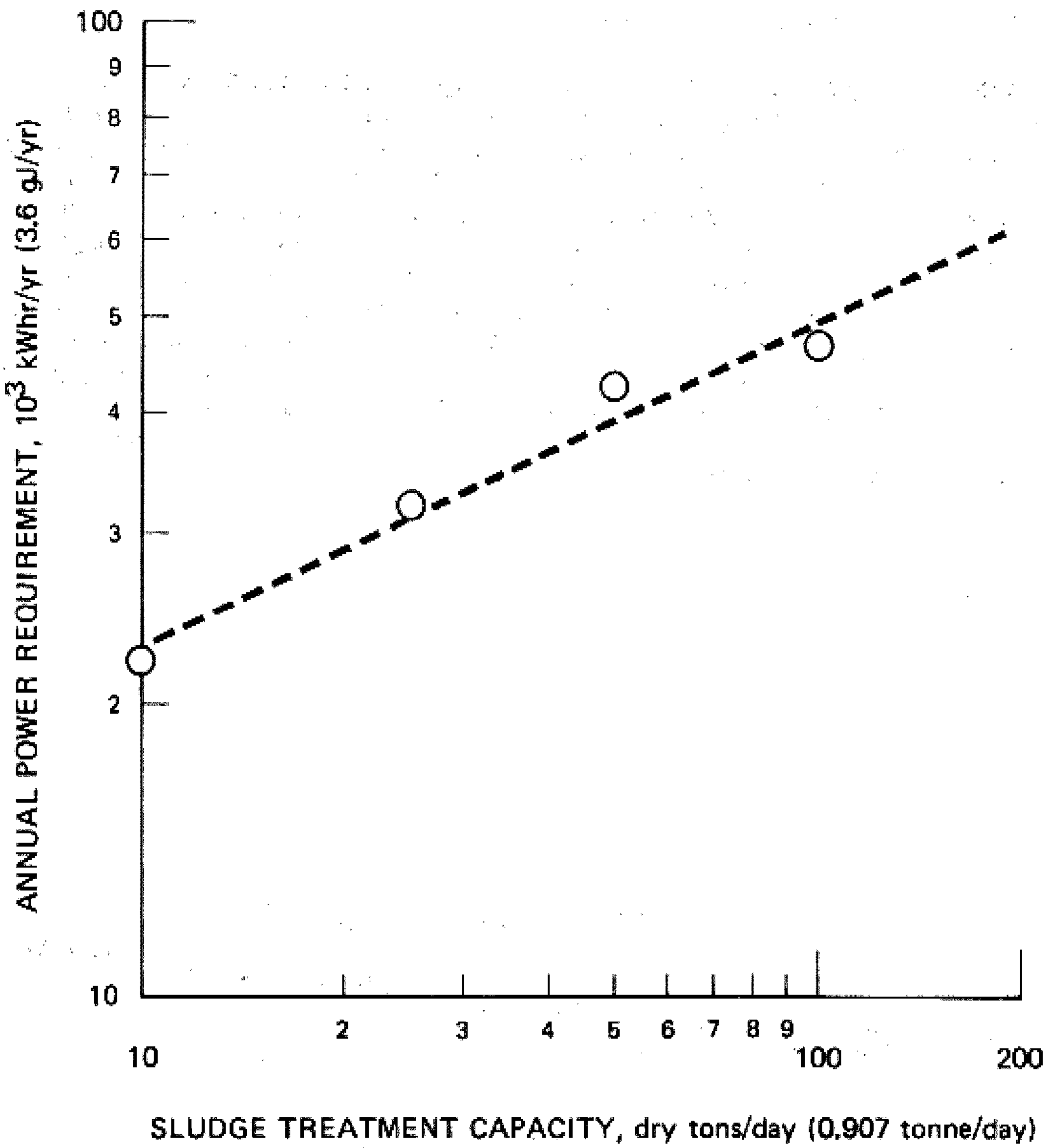

FIGURE 7-13

RADIATION TREATMENT OF DEWATERED SLUDGE - POWER REQUIREMENTS (46)

It is important to note that the liquid system would require a much larger Cs-137 charge since it would be treating almost 12 times the volume of material at the same dose level. However, the rod configuration for a dry facility would be much less efficient in terms of radiation transfer than a liquid one.

7.7.2.7 Performance Data

In June 1979 no performance data for the Sandia facility were yet available. Data for the Geiselbullach facility are summarized in Section 7.7.2.2.

7.7.2.8 Cost Information

Cost estimates for both liquid and dry facilities were developed together with the energy data of Section 7.7.2.6. The liquid facility included the following components:

- Insulated concrete building with 25-foot (7.6-m) ceiling.
- Equalization sludge storage tank.
- Emergency water dump tank (for source shielding water).
- Irradiating capsules (radiation source).
- Steel-lined source handling pool.
- Deionizer.
- Data aquisition and control system.
- Oxygen injection facility.
- Pumps, piping, and flow meters.
- Radiation alarm.
- Fire suppression system.

A capital cost graph for the wet facility is given on Figure 7-14; the estimates were made in May 1977. Graphs for labor hours per year and operations and maintenance materials and supplies are given on Figure 7-15 and 7-16, respectively. The additional operating cost is \$2.00 per 1000 gallons (\$0.53/m^3) for the Cs-137 (the irradiator).

The dry system uses a bucket conveyor to move the sludge past the radiation source (see Figure 7-17). This dry system would include the following:

- Loading and unloading conveyors.
- Concrete shielding.
- Source-handling pool.
- Holder for the Cs-137 capsules.
- Holder moving mechanism.
- Steel building.
- Pumps.
- Ventilators.

- Filters.
- Hoists.
- Radiation alarm system.
- Pool water testing tank.
- Fire suppression system.

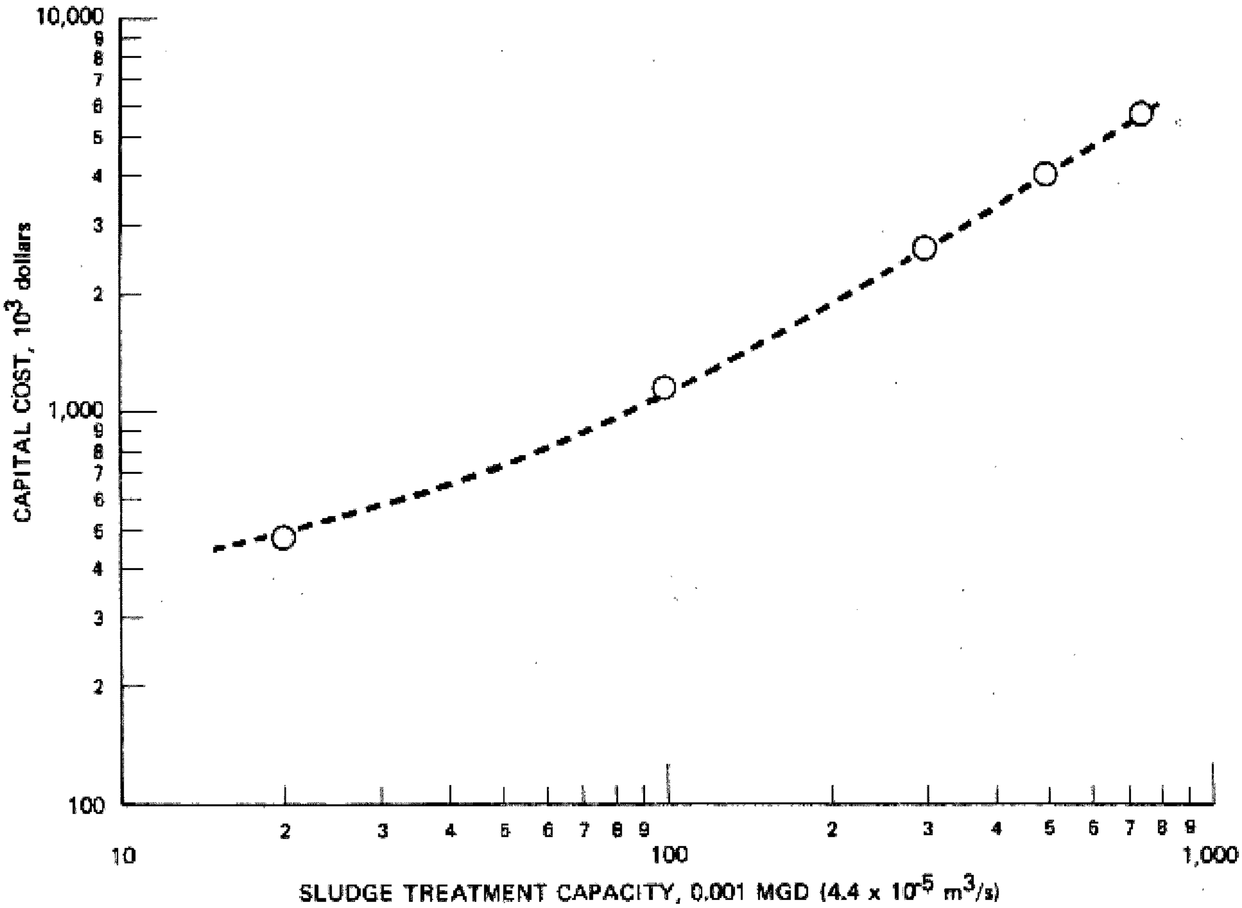

FIGURE 7-14

GAMMA RADIATION TREATMENT OF LIQUID SLUDGE - CAPITAL COSTS (46)

The capital costs for the dry system are summarized on Figure 7-18; these costs were also calculated in May 1977. Figure 7-19 and 7-20 present labor hours, materials ,and operations and maintenance supplies, respectively. The Cs-137 source is estimated to cost $1.55 per ton ($1.70/t) for a 10-ton-per-day (9.1-t/d) capacity facility and $1.22 per ton ($1.35/t) for facilities of 50 ton per day (45 t/d) and larger.

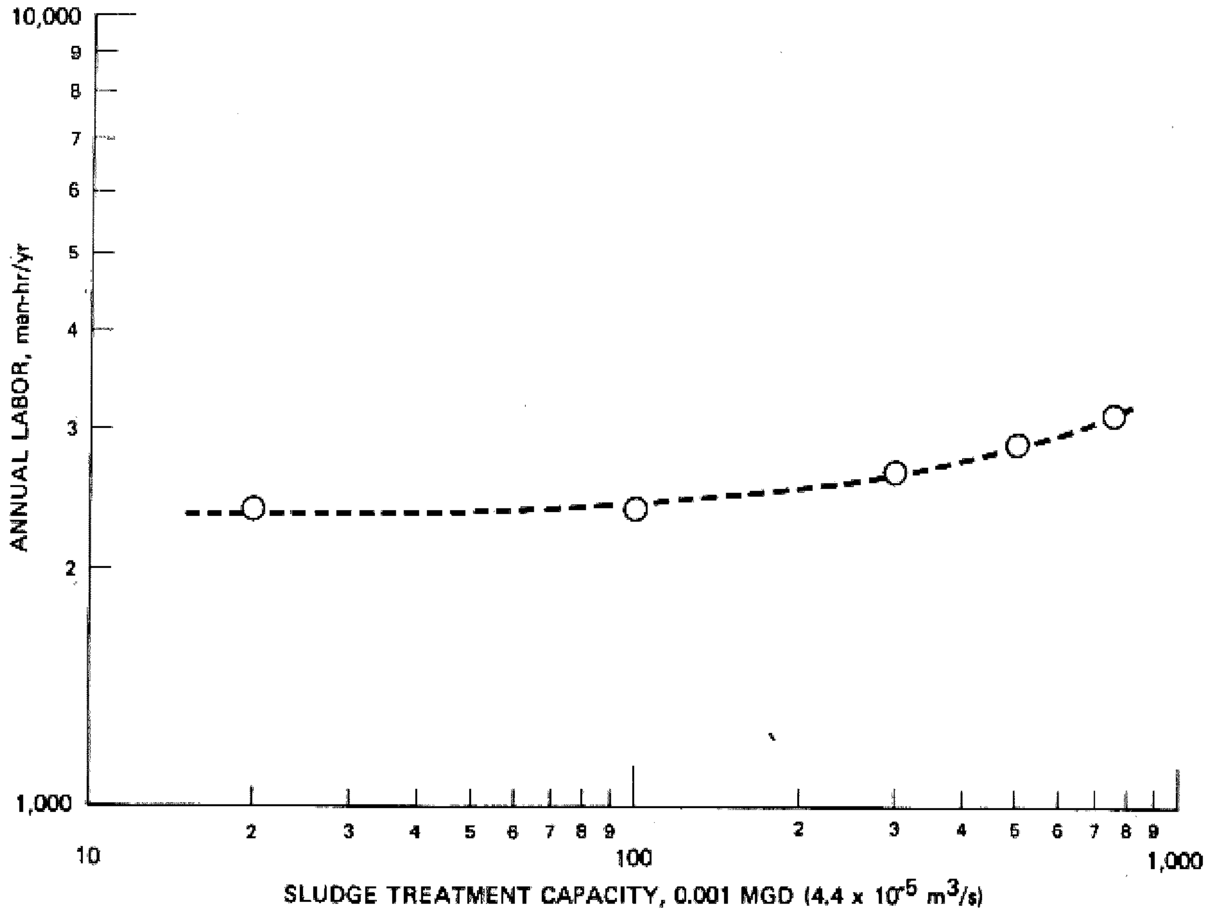

FIGURE 7-15

GAMMA RADIATION TREATMENT OF LIQUID SLUDGE LABOR REQUIREMENTS (46)

If labor plus overhead is $20.00 per hour, power is three cents per kWhr, ($0.33/GJ) and capital is amortized over 20 years at 8 percent, the cost for a 0.1-MGD (4-l/s) liquid system is $38.50 per ton ($42.40/t) dry solids. A dry system costs $24.00 per ton ($26.50/t) dry solids. Both these costs are considerably higher than those for e-beam irradiation and similar to those for heat pasteurization.

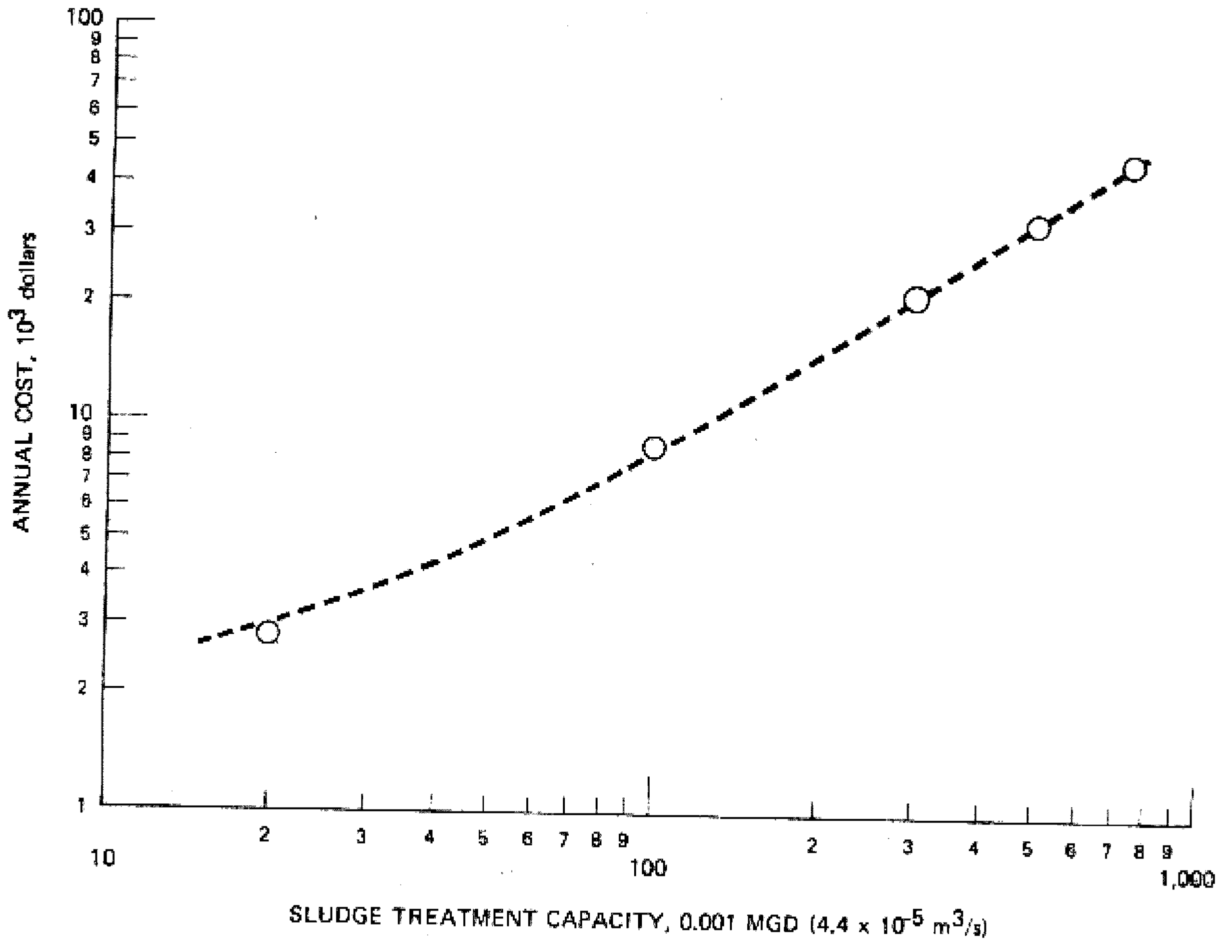

FIGURE 7-16

GAMMA RADIATION TREATMENT OF LIQUID SLUDGE
MAINTENANCE MATERIAL SUPPLIES COSTS (46)

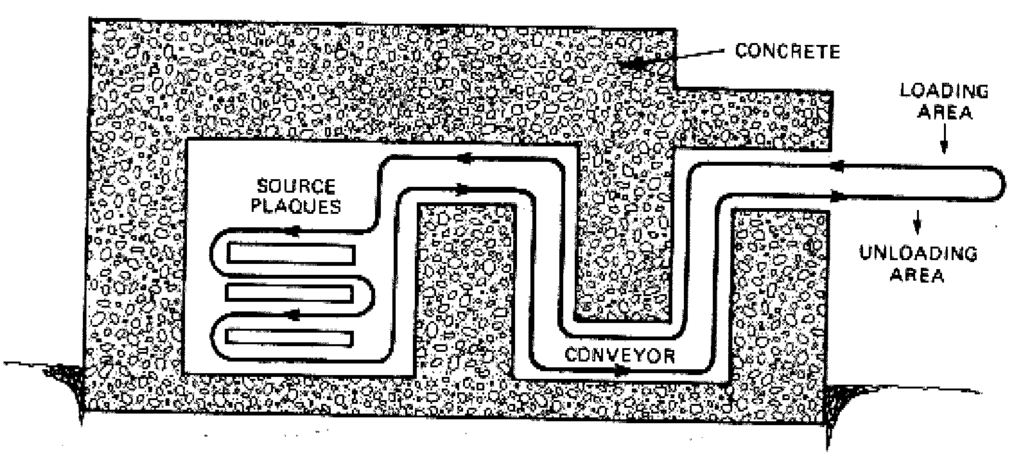

FIGURE 7-17

GAMMA RADIATION TREATMENT FACILITY FOR HANDLING
25 TONS PER DAY OR MORE OF DEWATERED SLUDGE

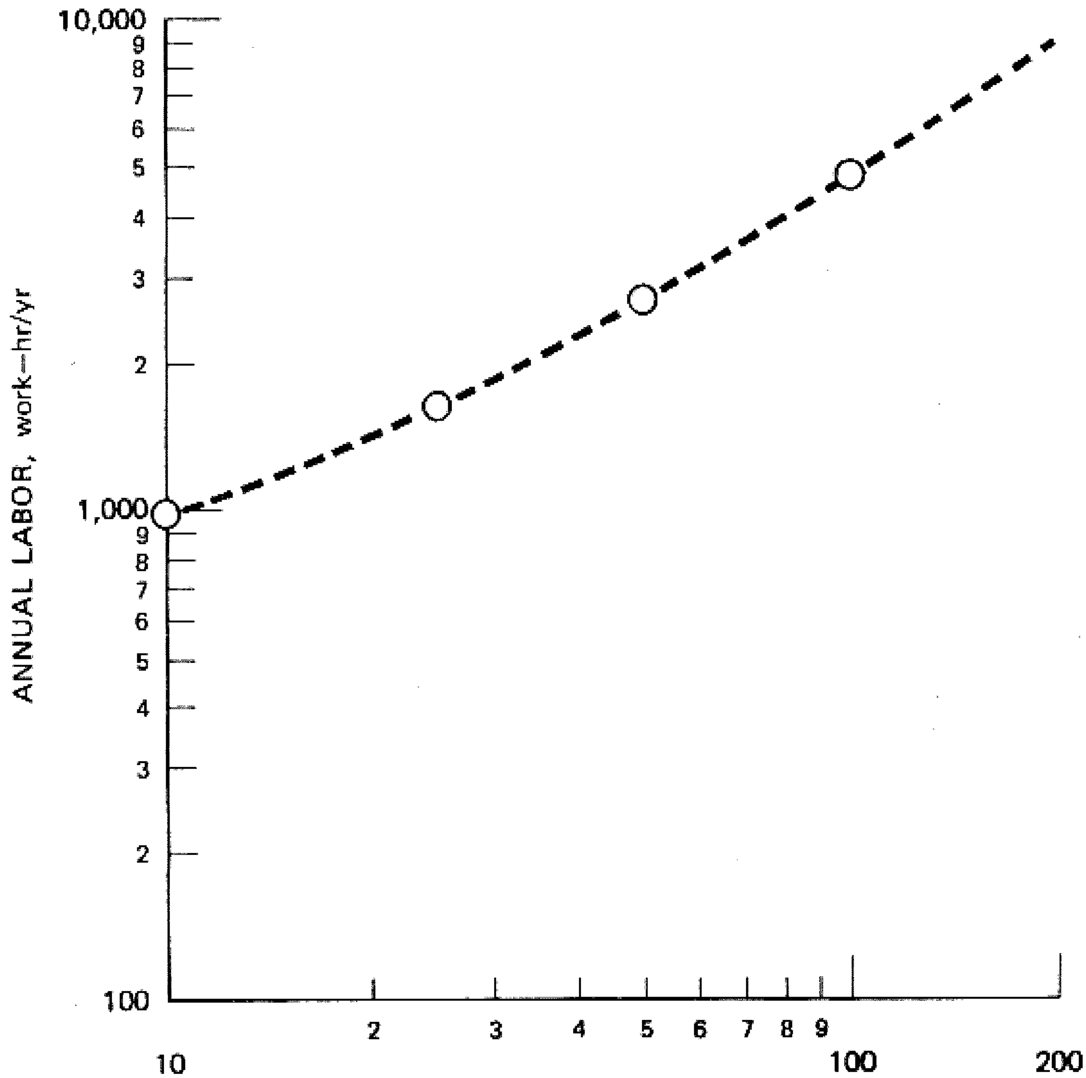

FIGURE 7-18

GAMMA RADIATION TREATMENT OF DEWATERED SLUDGE
CAPITAL COST (46)

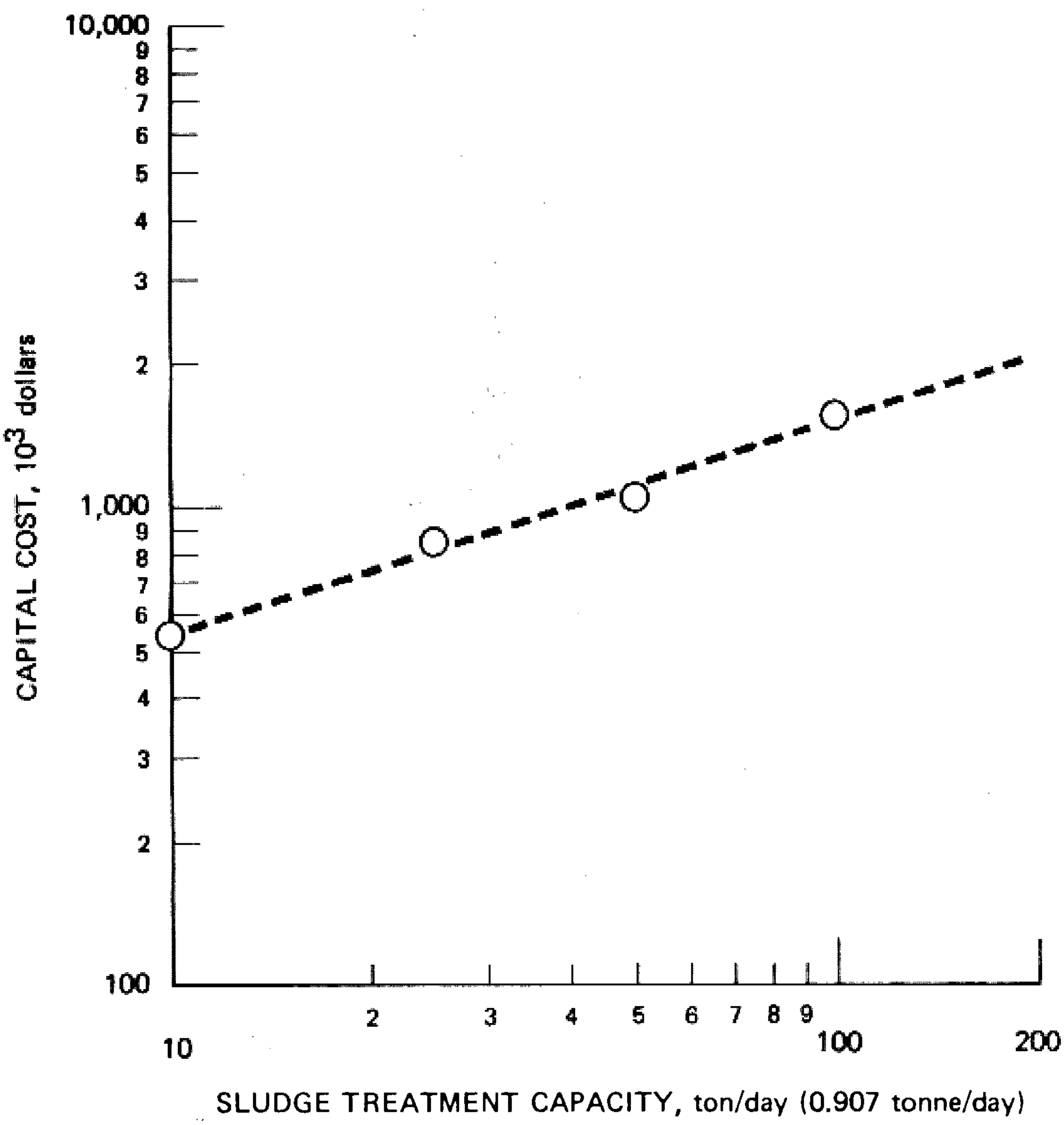

FIGURE 7-19

GAMMA RADIATION TREATMENT OF DEWATERED SLUDGE -
LABOR REQUIREMENTS (46)

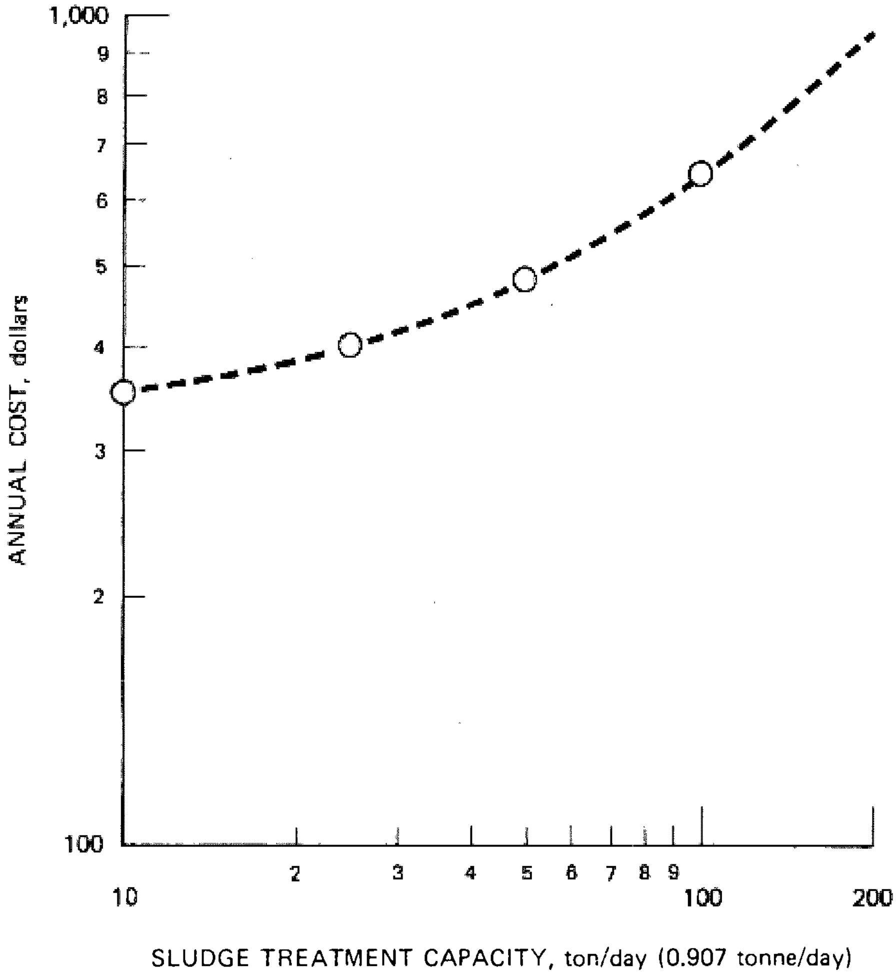

FIGURE 7-20

GAMMA RADIATION TREATMENT OF DEWATERED MAINTENANCE MATERIALS AND SUPPLIES COST (46)

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 8. Conditioning

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

September 1979

CHAPTER 8

CONDITIONING

8.1 Introduction

Conditioning involves the biological, chemical, and/or physical treatment of a sludge stream to enhance water removal. In addition, some conditioning processes also disinfect wastewater solids, affect wastewater solids odors, alter the wastewater solids physically, provide limited solids destruction or addition, and improve solids recovery.

8.2 Selecting a Conditioning Process

Conditioning always has an effect on the efficiency of the thickening or dewatering process that follows (1-3). Any evaluation of the conditioning process must therefore take into consideration capital, operating and maintenance costs for the entire system and the impact of sidestreams on other plant processes, the plant effluent, and resultant air quality.

Figure 8-1 shows how the evaluation would look in a quantified flow diagram.

This type of analysis is necessary because conditioning processes differ and, therefore, produce differing consequences for the total system. For instance, Table 8-1 compares the effects expected with no conditioning as opposed to those expected with polyelectrolyte conditioning or thermal conditioning prior to gravity thickening.

8.3 Factors Affecting Wastewater Solids Conditioning

8.3.1 General Wastewater Solids Properties

Wastewater solids are composed of screenings, grit, scum and wastewater sludges. Wastewater sludges consist of primary, secondary, and/or chemical solids with various organic and inorganic particles of mixed sizes; the sludges each have various internal water contents, degrees of hydration, and surface chemistry. Sludge characteristics that affect thickening or dewatering and for which conditioning is employed are particle size and distribution, surface charge and degree of hydration, and particle interaction.

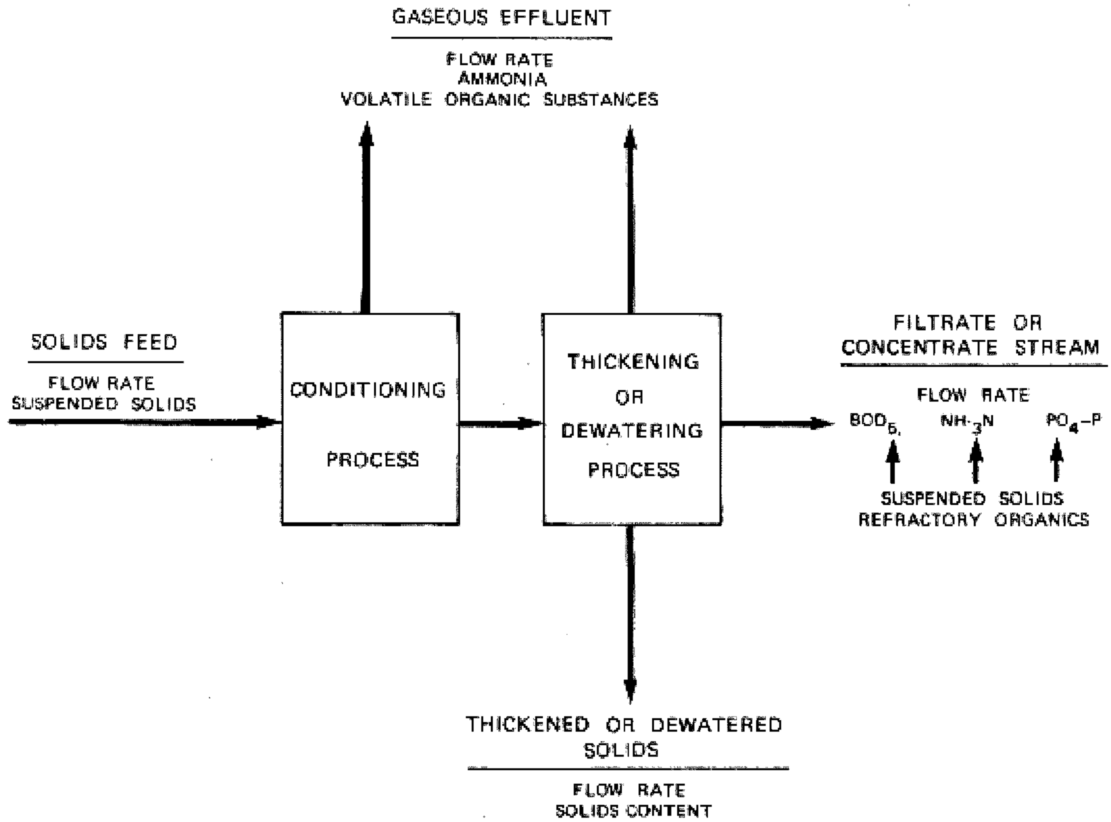


FIGURE 8-1

BASIC PARAMETERS FOR EVALUATION OF A SLUDGE CONDITIONING SYSTEM

TABLE 8-1

EFFECTS OF EITHER POLYELECTROLYTE CONDITIONING OR THERMAL CONDITIONING VERSUS NO CONDITIONING ON A MIXTURE OF PRIMARY AND WASTE-ACTIVATED SLUDGE PRIOR TO GRAVITY THICKENING[a]

	Polyelectrolyte conditioning	Thermal conditioning
Conditioning mechanism	Flocculation	Alters surface properties and ruptures biomass cells, releases chemical - water bonds - hydrolysis
Effect on allowable solids and hydraulic loading rates	Will increase	Will significantly increase
Effects of supernatant stream	Will improve suspended solids capture	Will cause significant increase in color, suspended solids, soluble BOD_5, COD and NH_3-N. Improve suspended solids capture
Effects on underflow concentration	May increase	Will significantly increase
Effects on manpower	Little to none	Requires higher skilled operators and strong preventive maintenance program

[a]It is assumed that the processes involved will work well.

8.3.1.1 Particle Size and Distribution

Particle size is considered to be the single most important factor influencing sludge dewaterability (4-7). As the average particle size decreases, primarily from mixing or shear, the surface/volume ratio increases exponentially (8). Increased surface area means greater hydration, higher chemical demand, and increased resistance to dewatering. Figure 8-2 shows relative particle sizes of common sludge materials.

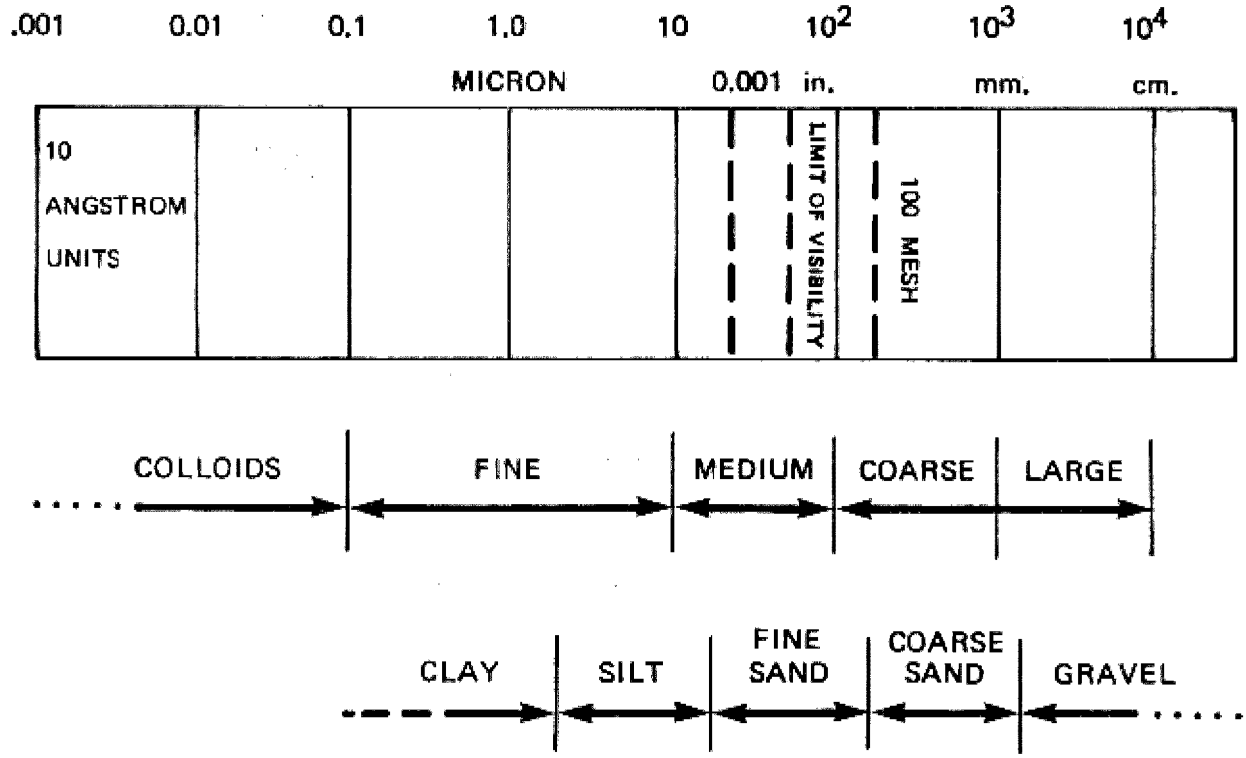


FIGURE 8-2

PARTICLE SIZE DISTRIBUTION OF COMMON MATERIALS

Raw municipal wastewaters contain significant quantities of colloids and fines, which, because of their size (1 to 10 microns), will almost all escape capture in primary clarifiers if coagulation and flocculation are not employed. Secondary biological processes, in addition to removing dissolved BOD, also partially remove these colloids and fines from wastewater. Because of this, biological sludges, especially waste-activated sludges are difficult to thicken or dewater and also have a high demand for conditioning chemicals.

A primary objective of conditioning is to increase particle size by combining the small particles into larger aggregates.

8.3.1.2 Surface Charge and Degree of Hydration

For the most part, sludge particles repel, rather than attract one another. This repulsion, or stability, may be due to hydration or electrical effects. With hydration, a layer or layers of water bind to the particle surface, providing a buffer, which prevents close particle approach. In addition, sewage solids are negatively charged and thus tend to be mutually repulsive. Conditioning is used to overcome the effects of hydration and electrostatic repulsion.

Conditioning is a two-step process consisting of destabilization and flocculation. In destabilization, the surface characteristics of the particles are altered so that they will adhere to one another. This desirable change is brought about through the use of natural polymeric material excreted by the activated sludge organism, synthetic organic polymer, or inorganic metal salts. Flocculation is the process of providing contact opportunities, by means of mild agitation, so the destabilized particles may come together.

Destabilization either with synthetic organic polyelectrolyte or with inorganic metal salt is readily available to the plant operator, but it represents an increase in operating cost. The degree to which natural flocculation is available is difficult to predict since it is dependent on the type of activated sludge or the attached-growth biological process that has been designed into the plant.

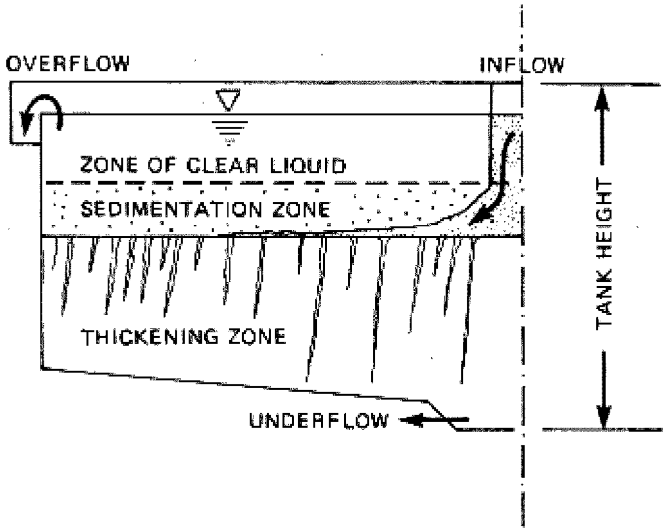
8.3.1.3 Particle Interaction

Municipal wastewater sludges contain large numbers of colloidal and agglomerated particles, which have large specific surface areas. Initially these particles behave in a discrete manner with little interaction. As the concentration of sludge is increased by the separational process, interaction increases. As shown on Figure 8-3 this flocculant behavior results in three distinct zones for a gravity thickener.

Conditioning can increase the rate of settling in the sedimentation zone, and compression thickening in the thickening zone; it can also improve the quality of the overflow. These improvements result from the ability of the conditioner to neutralize or overcome the surface charge, which in turn allows the particles to adhere to one another, thus preserving the dimensional integrity of the sludge matrix in the thickening zone.

8.3.2 Physical Factors

The amount of conditioning required for sludges is dependent on the processing conditions to which the sludge has been subjected and on the mechanics of the conditioning process available.



C_i - INFLOW SOLIDS CONCENTRATION
C_b - LOWEST CONCENTRATION AT WHICH FLOCCULANT SUSPENSION IS IN THE FORM OF POROUS MEDIUM
C_u - UNDERFLOW CONCENTRATION FROM GRAVITY THICKENER

FIGURE 8-3

TYPICAL CONCENTRATION PROFILE OF MUNICIPAL WASTEWATER SLUDGE IN A CONTINUOUSLY OPERATING GRAVITY THICKENER (12)

8.3.2.1 Effect of Processing Prior to Conditioning

Both the degree of hydration and fines content of a sludge stream can be materially increased by exposure to shear, heat, or storage. For example, pipeline transport of sludge to central processing facilities, weekend storage of sludge prior to mechanical dewatering, and storage of sludges for long periods of time have been shown to increase the demand for conditioning chemicals in all types of dewatering and should be accounted for in the design of the dewatering facility (10-13).

8.3.2.2 Conditioner Application

The optimum sequence for adding conditioner is best determined by trial and error, when two or more conditioners are used. With ferric chloride and lime, the ferric chloride is normally added first. In addition, it has been shown that deterioration of the floc after conditioning (due to both time and high shear mixing) can be a major determinant of chemical requirement (13). When a combination of anionic and cationic polymer is needed, anionic polymer is added first.

In order to minimize floc shearing, mixing should provide just enough energy to disperse the conditioner throughout the sludge. In dewatering applications, consideration should be given to providing individual conditioning for each dewatering unit, since it is not always economical to provide one common conditioning unit for several dewatering units. Problems can arise in balancing the flow rates of the various streams when starting up or shutting down individual units. The location of the conditioning unit relative to each dewatering device requires optimization.

Many types of conditioning units are available. Recent USEPA publications (14,15) describe the more common designs, design layouts, and operating problems. Additional information can be obtained from thickening and dewatering equipment suppliers.

8.4 Inorganic Chemical Conditioning

8.4.1 Introduction

Inorganic chemical conditioning is associated principally with mechanical sludge dewatering, and vacuum filtration is the most common application. The chemicals normally used in the conditioning of municipal wastewater sludges are lime and ferric chloride, although ferrous sulfate has also been used.

Ferric chloride is added first. It hydroylzes in water, forming positively charged soluble iron complexes which neutralize the negatively charge sludge solids, thus causing them to aggregate. Ferric chloride also reacts with the bicarbonate alkalinity in the sludge to form hydroxides that act as flocculants. The following equation shows the reaction of ferric chloride with bicarbonate alkalinity:

$$2FeCl_3 + 3Ca(HCO_3)_2 \longrightarrow 2Fe(OH)_3 + 3CaCl_2 + 6CO_2$$

Hydrated lime is usually used in conjunction with ferric iron salts. Although lime has some slight dehydration effects on colloids, it is chosen for conditioning principally because it provides pH control, odor reduction and disinfection. $CaCO_3$, formed by the reaction of lime and bicarbonate, provides a granular structure which increases sludge porosity and reduces sludge compressibility.

8.4.2 Dosage Requirements

Iron salts are usually added at a dosage rate of 40 to 125 pounds per ton (20 to 63 kg/t) of dry solids in the sludge feed, whether or not lime is used. Lime dosage usually varies from 150 to 550 pounds per ton (75 to 277 kg/t) of dry sludge solids fed. Table 8-2 lists typical ferric chloride and lime dosages for various sludges.

TABLE 8-2

TYPICAL CONDITIONING DOSAGES OF FERRIC CHLORIDE ($FeCl_3$) AND LIME (CaO) FOR MUNICIPAL WASTEWATER SLUDGES[a] (16)

	Vacuum filter		Recessed plate pressure filters	
Sludge type	$FeCl_3$	CaO	$FeCl_3$	CaO
Raw primary	40-80	160-200	80-120	220-280
Raw waste-activated sludge (WAS)-air	120-200	0-320	140-200	400-500
Raw (primary + trickling filter)	40-80	180-240		
Raw (primary + WAS)	50-120	180-320		
Raw (primary + WAS + septic)	50-80	240-300		
Raw (primary + WAS + lime)	30-50	none		
Elutriated anaerobically digested				
primary	50-80	0-100		
primary + WAS (air)	60-120	0-150		
Thermal conditioned sludges	none	none	none	none
Anaerobically digested sludges				
primary	60-100	200-260		
primary + trickling filter	80-120	250-350		
primary + WAS (air)	60-120	300-420	80-200	220-600

[a]All values shown are for pounds of either $FeCl_3$ or CaO per ton of dry solids pumped to the dewatering unit.

1 lb/ton = 0.5 kg/t

Inorganic chemical conditioning increases sludge mass. A designer should expect one pound of additional sludge for every pound of lime and ferric chloride added (13). This increases the amount of sludge for disposal and lowers the fuel value for incineration. Nevertheless, the presence of lime can be beneficial because of its sludge stabilization effects. The use of polyvalent metal salts and lime offers advantages over other methods, because the combination can better condition sludge which has extreme variations in quality.

8.4.3 Availability

Ferric chloride, the most widely used polyvalent metal salt conditioner, is available in dry or liquid form, with the liquid form being the most common. In the past, most ferric chloride has been made from scrap metal and chlorine, but during the past decade, much larger quantities have been made available through conversion of waste acids from large industrial pigment producers. It is supplied as either a 30 or 40 percent by weight solution.

Liquid ferrous sulfate, a by-product of certain industrial processes, is not generally available in large quantities. If availability is not at issue and testing proves it capable of conditioning the sludge, liquid ferrous sulfate can be used like ferric chloride.

Lime is purchased in dry form. It is readily available and comes in many forms. Pebble quicklime (CaO) and hydrated lime ($Ca(OH)_2$) are most often used for sludge conditioning.

8.4.4 Storage, Preparation, and Application Equipment

There have been numerous problems such as lime scaling and $FeCl_3$ corrosion with in-plant storage, preparation, and application of both lime and ferric chloride. Two excellent references deal with lime problems and how to solve them (17,18). Information on ferric chloride can be found in USEPA's Process Design Manual for Suspended Solids Removal (15).

8.4.5 Design Example

A designer has calculated that the rotary drum, cloth belt, vacuum filter that will be utilized at the plant, must be capable of dewatering a maximum of 600 pounds (272 kg) per hour of sludge. The sludge will be a mixture of 40 percent primary and 60 percent waste-activated sludge, which will be anaerobically digested. The vacuum filter will operate seven hours per day, five days per week.

To design for a margin of safety in the chemical feed equipment, the designer has used the higher values shown in Table 8-2. Chemical feeders should be capable of adding 120 pounds per ton (60 kg/t) of $FeCl_3$ and 420 pounds per ton (210 kg/t) of CaO.

Maximum daily amount of sludge to be dewatered is:

$$\frac{600 \text{ lb sludge}}{\text{hr}} \times \frac{7 \text{ hr}}{\text{day}} = 4{,}200 \text{ lb sludge per day } (1{,}905 \text{ kg/day})$$

Maximum amount of $FeCl_3$ required per day is:

$$\frac{4{,}200 \text{ lb sludge}}{\text{day}} \times \frac{120 \text{ lb } FeCl_3}{2{,}000 \text{ lb sludge}} = 252 \text{ lb } FeCl_3 \text{ per day } (114 \text{ kg/day})$$

The $FeCl_3$ is available at a 40 percent solution (4.72 pounds $FeCl_3$ per gallon (0.567 kg/l) of solution).

$$\frac{252 \text{ lb } FeCl_3}{\text{day}} \times \frac{1 \text{ gallon of product}}{4.72 \text{ lb } FeCl_3} = 53.4 \text{ gallons of solution per day}$$

(202 l/day)

Maximum amount of CaO required per day is:

$$\frac{4{,}200 \text{ lb sludge}}{\text{day}} \times \frac{420 \text{ lb CaO}}{2{,}000 \text{ lb sludge}} = 882 \text{ lb CaO per day (400 kg/day)}$$

The pebble quicklime is available at 90 percent CaO:

$$\frac{882 \text{ lb CaO}}{\text{day}} \times \frac{\text{lb pebble quicklime}}{0.9 \text{ lb CaO}} = 980 \text{ lb pebble quicklime per day}$$

(45 kg/day)

The amount of extra sludge produced due to chemical addition is estimated at one pound (0.45 kg) for every pound of $FeCl_3$ and pebble quicklime added. Therefore, total maximum daily dry solids to be disposed of are:

4,200 lb sludge + 252 lb $FeCl_3$ + 980 lb quicklime

which are equal to 5,432 pounds (2,464 kg) of solids. This is the equivalent of 27,160 pounds (12,320 kg) of wet sludge at a minimum of 20 percent solids.

8.4.6 Cost

8.4.6.1 Capital Cost

Figure 8-4 shows the relationship between construction costs of ferric chloride storage and feed facilities and installed capacity. For example, if a designer needed to feed 100 pounds (45.4 kg) per hour of ferric chloride the estimated cost would be $330,000. Since cost are given in June 1975 dollars, the cost must be adjusted to the proper time period. Costs for Figure 8-4 are estimated on the basis of liquid ferric chloride use. Chemical feed equipment was sized for a peak feed rate of twice the average. At least 15 days of storage was provided at the average feed rate. Piping and buildings provided to house the feeding equipment are included.

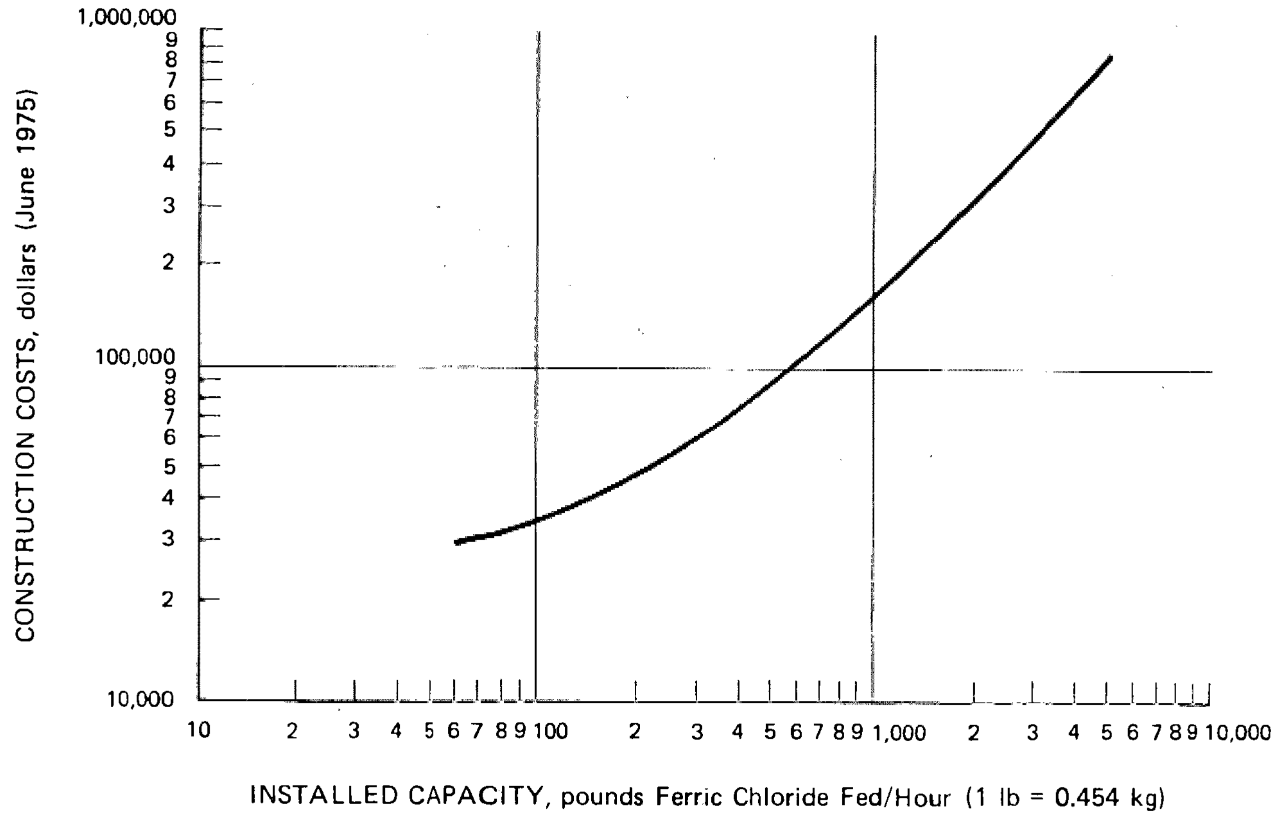


FIGURE 8-4

CAPITAL COST OF FERRIC CHLORIDE STORAGE AND FEEDING FACILITIES (22)

Figure 8-5 gives construction costs of lime storage and feeding facilities as a function of installed capacity. Cost estimates shown on Figure 8-5 are based on the use of hydrated lime in small plants (50 pounds per hour [22.7 kg/hr] or less) and pebble quicklime in larger plants. Allowances for peak rates of twice the average are built into the lime feed rates. At least 15 days of storage is provided for at the average rate. Storage time varies from installation to installation because it is dependent upon the relative distance to and reliability of the chemical supply. Piping and buildings to house the feeding equipment are included in the estimates. Estimated costs of steel bins with dust collector vents and filling accessories are also included.

8.4.6.2 Operation and Maintenance Cost

Figure 8-6 indicates the relationship between man-hours spent annually for operation and maintenance and pounds of $FeCl_3$ fed per hour. The labor includes unloading the ferric chloride and the operation and maintenance of the chemical feed equipment. Unloading requirements are as follows: for a 4,000-gallon (15.1 m^3) truck--1.5 man-hours; for 50-gallon (0.19 m^3) barrels, 72 per truck--9 man-hours. These requirements are shown

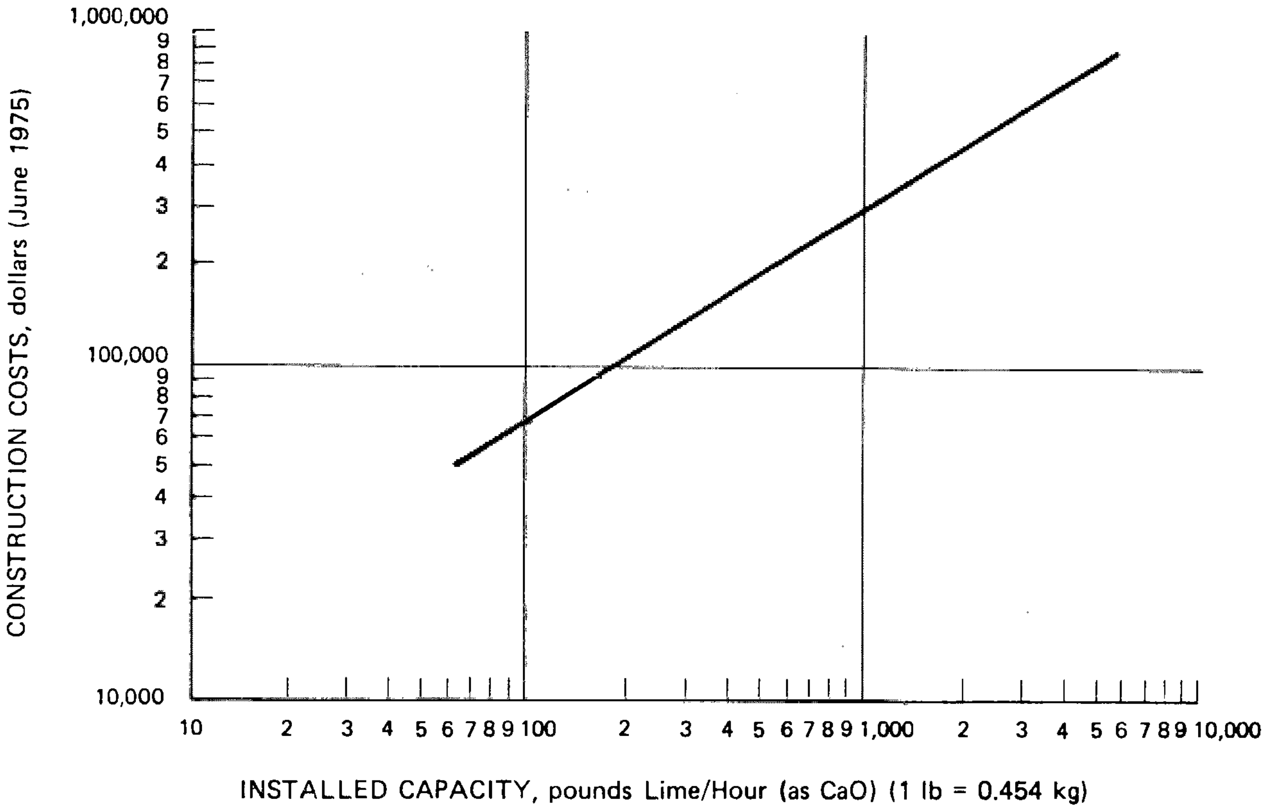


FIGURE 8-5

CAPITAL COST OF LIME STORAGE AND FEEDING FACILITIES (22)

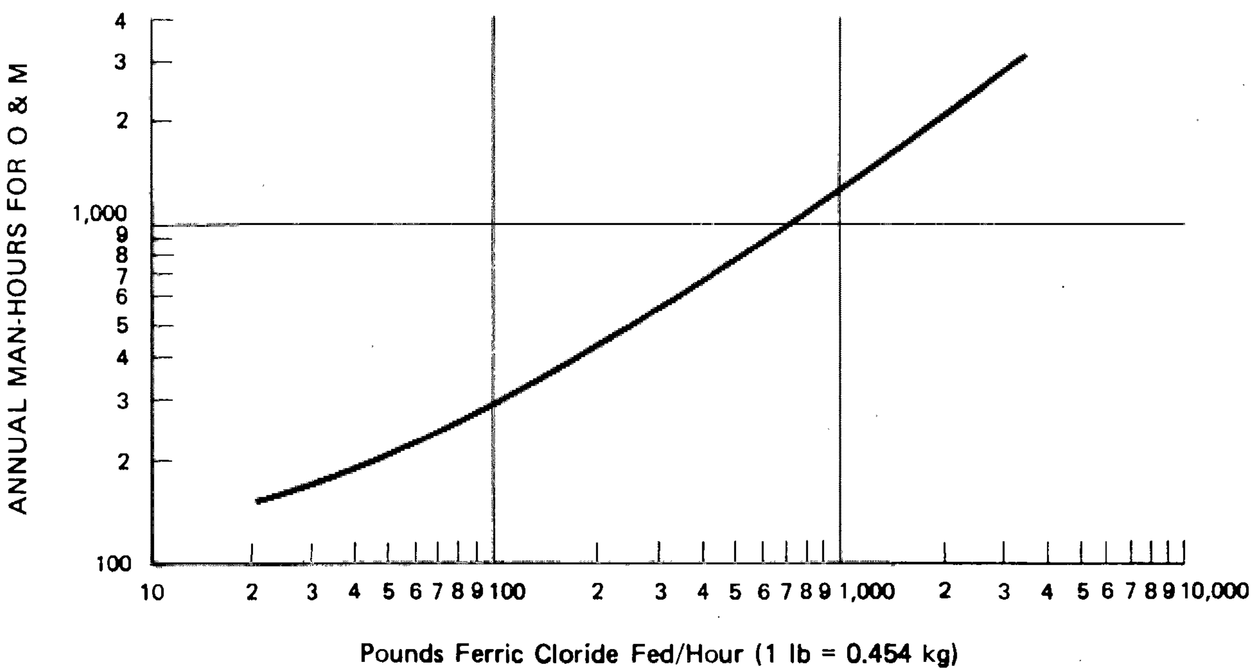


FIGURE 8-6

FERRIC CHLORIDE STORAGE AND FEEDING OPERATING AND MAINTENANCE WORK-HOUR REQUIREMENTS (22)

as man-hours per pound of chemicals fed to the process. Metering pump operations and maintenance is estimated at five minutes per pump per shift.

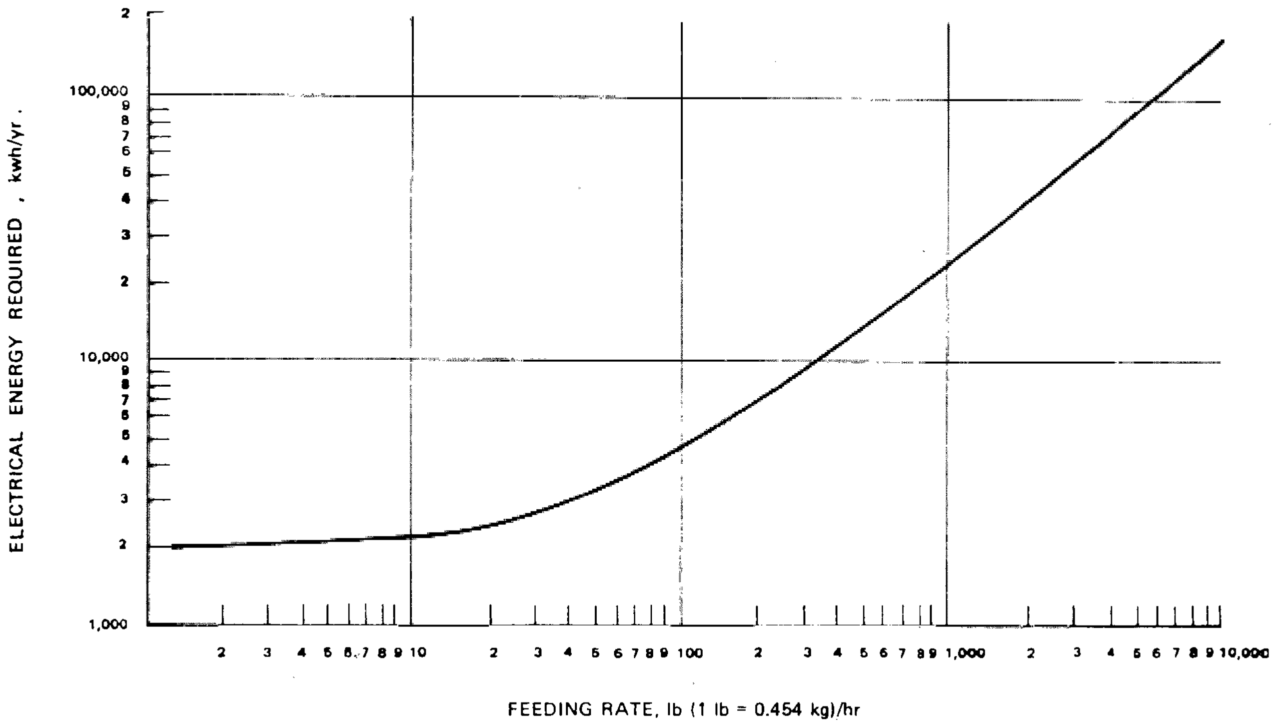


FIGURE 8-7

ELECTRICAL ENERGY REQUIREMENTS FOR A FERRIC CHLORIDE CHEMICAL FEED SYSTEM (23)

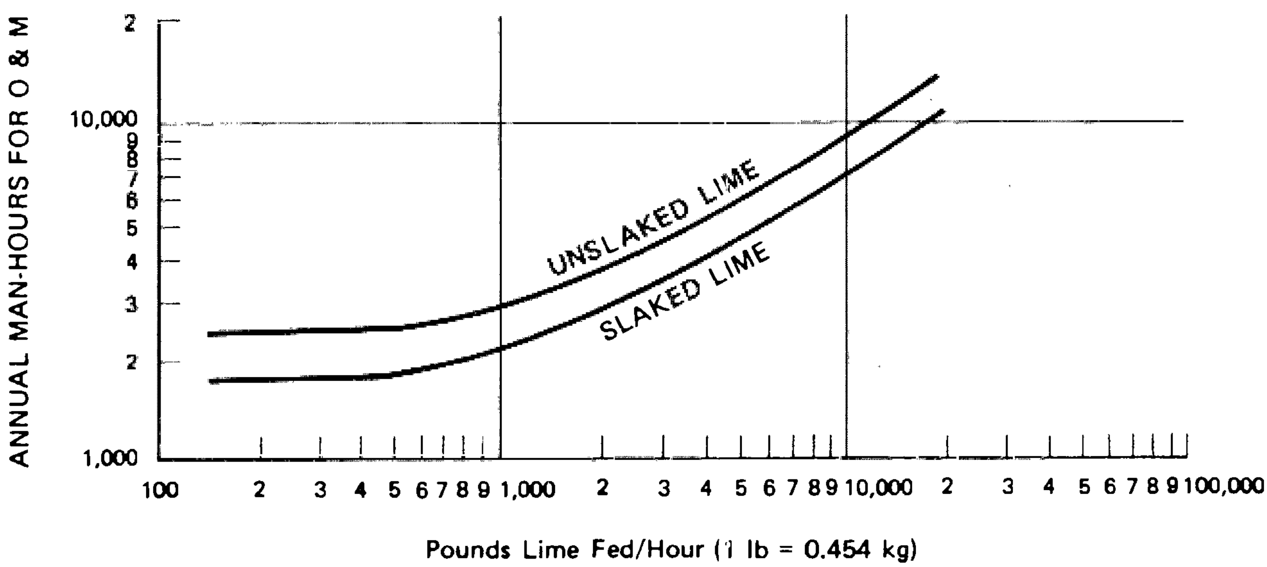


FIGURE 8-8

LIME STORAGE AND FEEDING OPERATION AND MAINTENANCE WORK-HOUR REQUIREMENTS (22)

Figure 8-7 indicates annual electric power requirements for a ferric chloride chemical feed system.

Annual maintenance material costs are typically 3 to 5 percent of the total chemical feed system equipment cost.

Figure 8-8 indicates man-hours for operation and maintenance as a function of pounds of lime fed per hour. The curve consists of lime unloading requirements and labor related to operation and maintenance of the slaking and feeding equipment. These requirements are summarized as follows: slaker--one hour per eight-hour shift per slaker in use; feeder--ten minutes per hour per feeder; slurry pot-feed line (for slaked lime)--four hours per week.

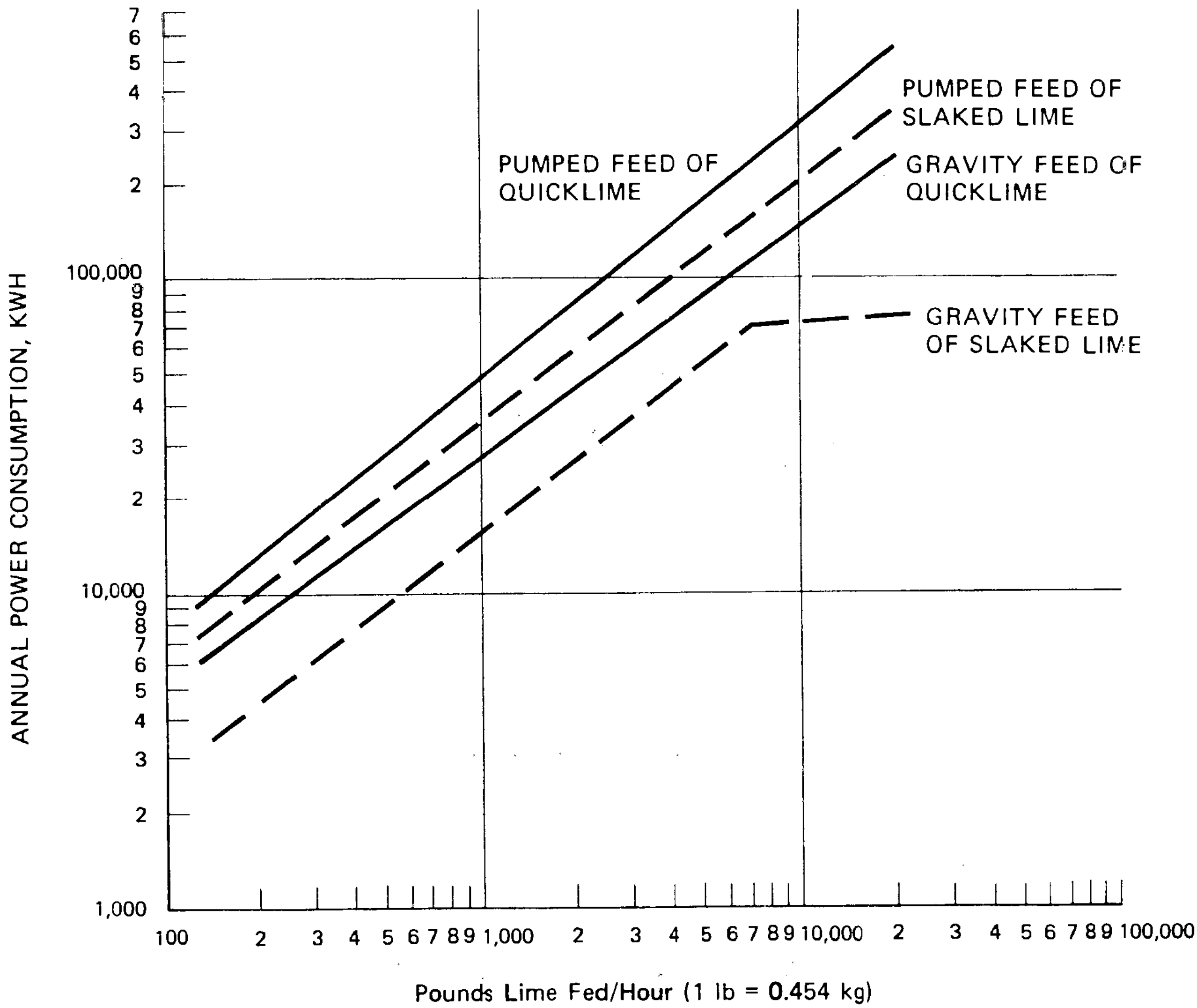


FIGURE 8-9

ELECTRICAL ENERGY REQUIREMENTS FOR A LIME FEED SYSTEM (22)

Figure 8-9 shows annual electric power requirements for a lime feed system. The major components and the values used in the curves, all expressed kilowatts per hour per 1,000 pounds (454 kg) of lime fed are: slakers--1.6 to 0.8; bin activators--2.7 to 0.36; grit conveyors--0.45 to 0.06; dust collection fans--0.04 to 0.02; slurry mixers--0.027 to 0.020; slurry feed pumps--2.2 to 1.4.

Annual maintenance material costs are typically 0.5 to 1.5 percent of the total lime feed system equipment cost.

8.5 Chemical Conditioning With Polyelectrolytes

8.5.1 Introduction

During the past decade, important advances have been made in the manufacture of polyelectrolytes for use in wastewater sludge treatment. Polyelectrolytes are now widely used in sludge conditioning and as indicated in Table 8-3, a large variety are available. It is important to understand that these materials differ greatly in chemical composition, functional effectiveness, and cost-effectiveness.

TABLE 8-3

SUPPLIERS OF POLYELECTROLYTES

Company	Number of grades and types	Company	Number of grades and types
American Cyanamid	40	Dow	33
Allied Colloids	34	Drew	8
Betz	7	Hercules	29
Calgon	18	Nalco	43
		Rohm & Hass	4

Selection of the correct polyelectrolyte requires that the designer work with polyelectrolyte suppliers, equipment suppliers, and plant operating personnel. Evaluations should be made on site and with the sludges to be conditioned. Since new types and grades of polymers are continually being introduced, the evaluation process is an ongoing one.

8.5.2 Background on Polyelectrolytes

8.5.2.1 Composition and Physical Form

Polyelectrolytes are long chain, water soluble, specialty chemicals. They can be either completely synthesized from individual monomers, or they can be made by the chemical addition of functional monomers, or groups, to naturally occurring polymers. A monomer is the subunit from which polymers are made through various types of polymerization reactions. The backbone monomer most widely used in synthetic organic polyelectrolytes is acrylamide. As of 1979 the completely synthesized polymers are most widely used. Polyacrylamide, created when the monomers combine to form a long, thread-like molecule with a molecular weight in the millions, is shown on Figure 8-10. In the form shown polyacrylamide is essentially non-ionic. That is to say it carries no net electrical charge in aqueous solutions. However, under certain conditions and with some solids, the polyacrylamide can be sufficiently surface-active to perform as a flocculant.

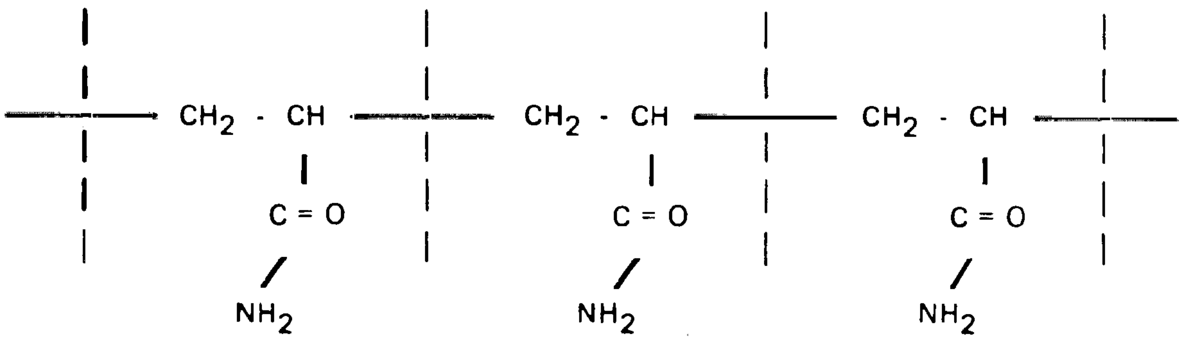


FIGURE 8-10

POLYACRYLAMIDE MOLECULE - BACKBONE OF THE SYNTHETIC ORGANIC POLYELECTROLYTES

Anionic-type polyacrylamide flocculants carry a negative electrical charge in aqueous solutions and are made by either hydrolyzing the amide group (NH_2) or combining the acrylamide polymer with an anionic monomer. Cationic polyacrylamides carry a positive electrical charge in aqueous solutions and can be prepared by chemical modification of essentially non-ionic-polyacrylamide or by combining the cationic monomer with acrylamide. When cationic monomers are copolymerized with acrylamide in varying proportions, a family of cationic polyelectrolytes with varying degrees of charge is produced. These polyelectrolytes are the most widely used polymers for sludge conditioning, since most sludge solids carry a negative charge. The characteristics of the sludge to be processed and the type of thickening or dewatering device used will determine which of the cationic polyelectrolytes will work best and still be cost-effective. For example, an increasing degree of charge is required when sludge particles become finer, when hydration increases, and when relative surface charge increases.

Cationic polyelectrolytes are available as dry powders or liquids. The liquids come as water solutions or emulsions. The shelf life of the dry powders is usually several years, whereas most of the liquids have shelf lives of two to six months and must be protected from wide ambient temperature variations in storage. Representative dry cationic polyelectrolytes are described in Table 8-4. This table does not list the myriad of available types but does show some of the differences in the materials. The original dry materials introduced in the 1960s were of relatively low cationic functionality or positive charge and high molecular weight. They were produced for the conditioning of primary sludges or easy-to-condition mixed sludges. The incentive to produce polymers of higher positive charge resulted largely from efforts to cope with mixed sludges containing large quantities of biomass.

TABLE 8-4

REPRESENTATIVE DRY POWDER CATIONIC POLYELECTROLYTES

Type	Relative cationic density	Molecular weight	Approximate dosage, lb/ton dry solids
Polyacrylamide copolymer	Low	Very high	0.5 - 10
Polyacrylamide copolymer	Medium	High	2 - 10
Polyacrylamide copolymer	High	Medium high	2 - 10
Polyamine homopolymer	Complete	High	2 - 10

Relatively low molecular weight liquid cationics with a 30 to 50 percent solids content were also available in the 1960s. They were, however, largely displaced by the higher cationic functionality, high molecular weight and newer, less costly liquid cationics. The various liquid cationics, in either dissolved or emulsion form, are described in representative fashion only, in Table 8-5. These liquid cationics eliminate the dustiness inherent in some dry powders but also require much more storage space. The selection of a dry, liquid, or emulsion form material usually depends on a comparison of cost-effectiveness, ease of handling, and storage requirements.

TABLE 8-5

REPRESENTATIVE LIQUID CATIONIC POLYELECTROLYTES

Type	Molecular weight	Percent solids
Mannich product	Low	20
Tertiary polyamine	Low	30
Quaternary polyamine	Very low	50
Cationic homopolymer	Low to medium	16 - 20
Emulsion copolymer	Low to medium	25 - 35

8.5.2.2 Structure in Solution

Organic polyelectrolytes dissolve in water to form solutions of varying viscosity. The resulting viscosity depends on their molecular weight and degree of ionic charge. At infinite dilution, the molecule assumes the form of an extended rod because of the repulsive effect of the adjacent-charged sites along the length of the polymer chain. At normal concentrations the long thread-like charged cationic polyelectrolyte assumes the shape of a random coil, as shown on Figure 8-11. This simplified drawing, however, neither shows the tremendous length of the polymeric molecular chain nor does it illustrate the very large number of active polymer chains that are available in a polymer solution. It has been estimated that a dosage of 0.2 mg/l of polyelectrolyte having a molecular weight of 100,000 would provide 120 trillion active chains per liter of water treated.

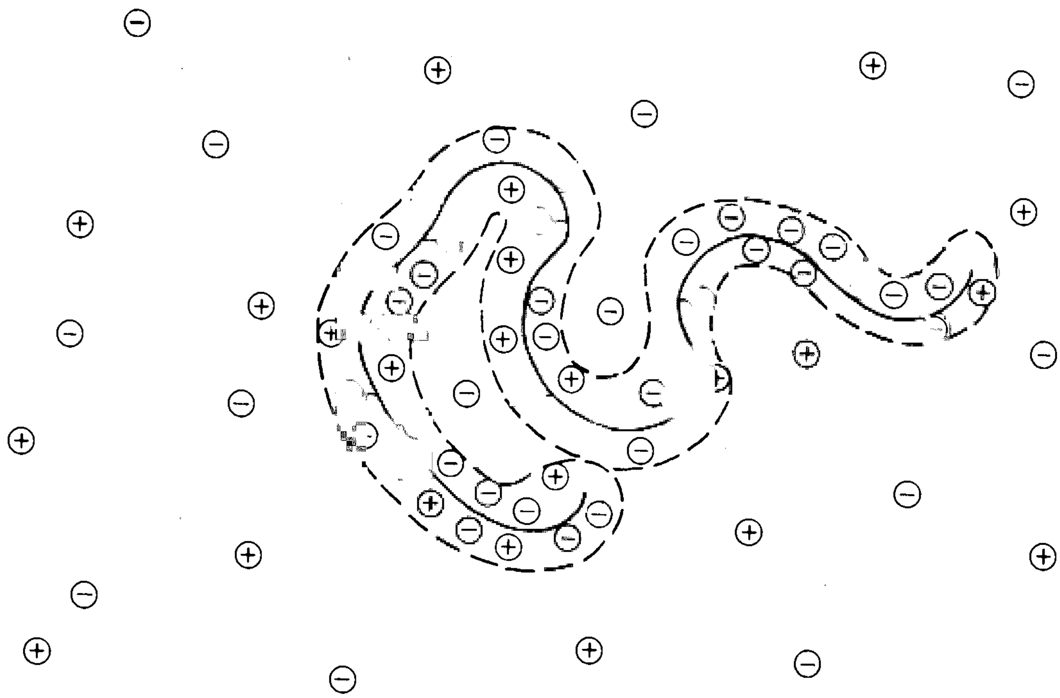


FIGURE 8-11

TYPICAL CONFIGURATION OF A CATIONIC POLYELECTROLYTE IN SOLUTION

8.5.2.3 How Polyelectrolyte Conditioning Works

Thickening and dewatering are inhibited by the sludge particles, chemical characteristics, and physical configurations. Polyelectrolytes in solution act by adhering to the sludge particle surfaces thus causing:

- Desorption of bound surface water.

- Charge neutralization.

- Agglomerization of small particulates by bridging between particles.

The result is the formation of a permeable sludge cake matrix which is able to release water. Figure 8-12 illustrates the polyelectrolyte-solid attachment mechanisn. The first two reactions noted on Figure 8-12 are the desirable ones and represent what occurs in normal practice. The other four reactions represent what can occur from over-dosage or too much shear of flocculated sludge. The problems reflected in reactions three through six rarely occur with a well-designed process.

8.5.3 Conditioning for Thickening

The various methods for thickening sludge are discussed in detail in Chapter 5.

8.5.3.1 Gravity Thickening

Normally, the addition of polyelectrolyte is not considered in the original design because of operating cost, but it has been used to upgrade existing facilities (21,22). Experience to date has indicated that the addition of polyelectrolyte to a gravity thickener will:

- Give a higher solids capture than a unit not receiving polymer addition.

- Allow a solids loading rate two to four times greater than a unit not receiving polymer addition.

- Maintain the same underflow solids concentration as a unit not receiving polymer addition.

When polyelectrolyte is used to condition sludge for gravity thickening, it should be added into the sludge feed line. The point of addition should provide good mixing and not cause excessive shear before the conditioned sludge discharges into the sludge feed well.

8.5.3.2 Dissolved Air Flotation Thickening

The effects of polyelectrolyte addition on solids capture, float concentration, solids loading rate, and hydraulic loading rate are covered in detail in Chapter 5.

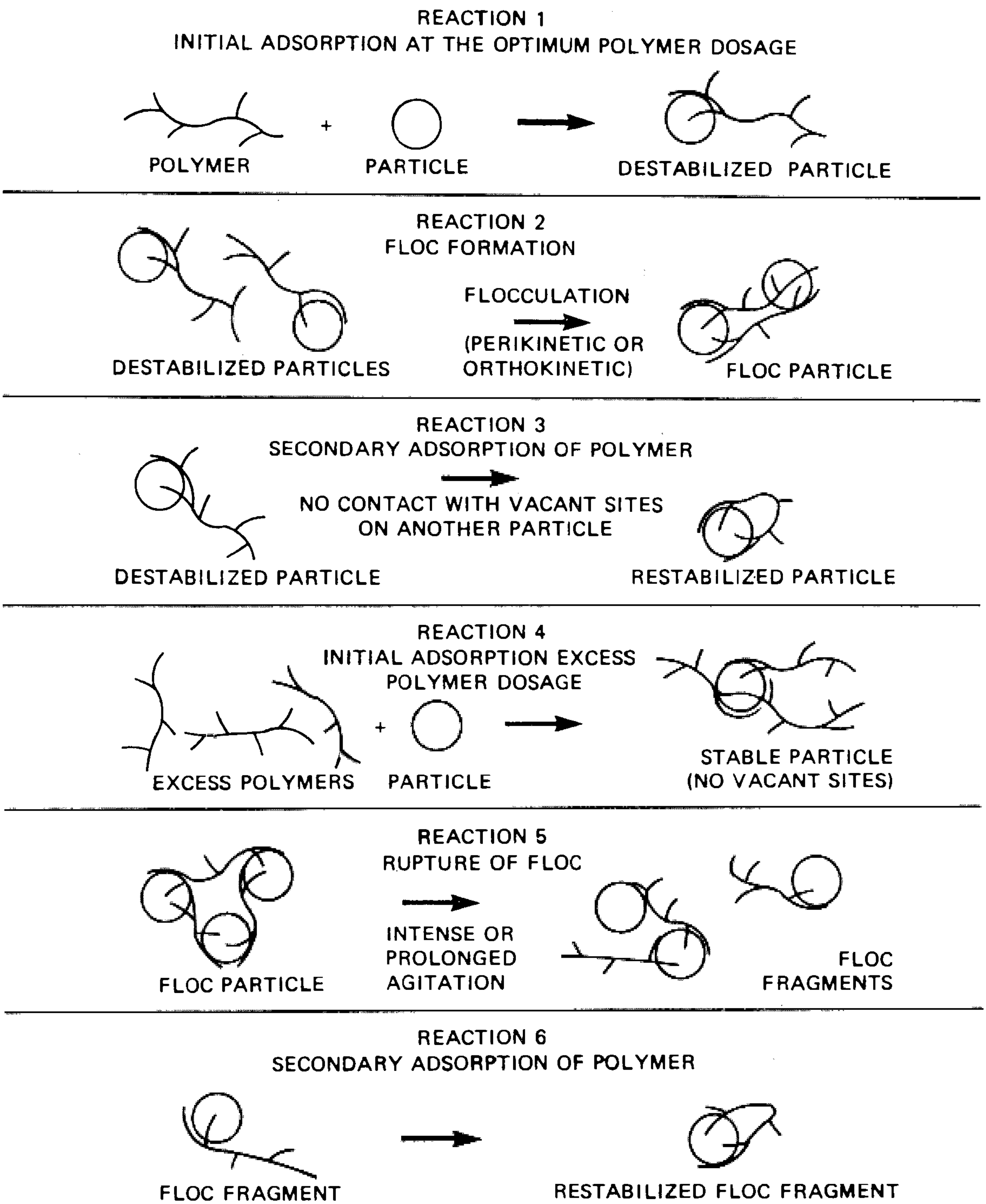


FIGURE 8-12

SCHEMATIC REPRESENTATION OF THE BRIDGING MODEL FOR THE DESTABILIZATION OF COLLOIDS BY POLYMERS (24)

8.5.3.3 Centrifugal Thickening

Centrifugal thickening includes thickening by disc nozzle, imperforate basket, and solid bowl decanter centrifuges. The disc nozzle unit does not utilize polyelectrolyte sludge conditioning, as it depends solely on centrifugal force (G = 3,000 to 5,000) to achieve solids-liquid separation. The imperforate basket centrifuge may or may not use polyelectrolyte addition. If polymer is added, it is in the range of one to three pounds of dry polymer per ton of feed solids (0.5 to 1.5 kg/t). This addition allows higher hydraulic feed rates and sometimes gives better solids recovery. It does not change the thickened solids concentration.

Solid bowl decanter centrifuges normally require as much as 20 pounds of dry polymer per ton of feed solids (10 kg/t) for thickening of a sludge, especially a waste-activated sludge. A new solid bowl unit has been developed for both thickening waste-activated sludge and obtaining an 85 to 95 percent solids capture with only 0 to 6 pounds of dry polymer per ton of feed solids (0 to 3 kg/t).

When polyelectrolyte conditioning is used with centrifugal thickening of sludge, several points of addition should be provided. The optimum point of addition is influenced by differences in polymer charge densities, required polymer sludge reaction times, and sludge characteristics. Recommended points of addition are:

- Directly before the inlet side of the sludge feed pump.
- Immediately downstream of the sludge feed pump.
- To the centrifuges' sludge feed line and just before its connection to the centrifuge.

8.5.4 Conditioning for Dewatering

The various dewatering methods are discussed in detail in Chapter 9. Polyelectrolytes were originally used to condition primary sludges and easy-to-dewater mixtures of primary and secondary sludges for dewatering by rotary vacuum filters or solid bowl decanter centrifuges. Improvement in the effectiveness of polyelectrolytes has led to their increasing use with all types of dewatering processes. Reasons for selecting polyelectrolytes over inorganic chemical conditioners are:

- Little additional sludge mass is produced. Inorganic chemical conditioners typically increase sludge mass by 15 to 30 percent.

- If dewatered sludge is to be used as a fuel for incineration, polyelectrolytes do not lower the fuel value.

- They allow for cleaner material-handling operations.

- They reduce operation and maintenance problems.

8.5.4.1 Drying Beds

Polyelectrolyte conditioning is not widely practiced. Indications are, however, that adding 0.5 to 2.0 pounds of dry polymer per ton of dry solids (0.25 to 1 kg/t) can increase dewatering rates by two to four times (23,24).

8.5.4.2 Vacuum Filters

The majority of municipal vacuum filtration processes in the United States still dewater sludge conditioned with ferric chloride and lime. Several facilities have, however, begun using polyelectrolytes for conditioning and have realized cost savings (4) due to less equipment maintenance, fewer materials handling problems, and reduction of cost in downstream sludge processing operations (1,2,4). Table 8-6 shows addition levels of dry polyelectrolyte used in conditioning different types of sludge for vacuum filtration. When using polyelectrolyte conditioning prior to vacuum filtration, the designer should be aware that sludge formation properties can be quite different from those of inorganic chemical conditioners. More operator attention may be required to obtain good cake release from the cloth. Cake dryness will probably be 10 to 15 percent lower and the volatile content of the dry cake will be significantly higher than if the sludge had been conditioned with ferric chloride and lime.

TABLE 8-6

TYPICAL POLYELECTROLYTE ADDITIONS FOR VARIOUS SLUDGES[a]

Sludge type	Pounds of dry polymer added per ton of dry solids
Raw primary	0.5 - 1.0
Waste-activated	8 - 15
Anaerobically digested primary	1.5 - 4
Primary plus trickling filter	2.5 - 5
Primary plus air waste-activated	4 - 10
Primary plus oxygen waste-activated	4 - 8
Anaerobically digested (primary plus air waste-activated)	5 - 12

[a]Data supplied by equipment manufacturers.

1 lb/ton = 0.5 kg/t

8.5.4.3 Recessed Plate Pressure Filters

No published information could be found on operating experience in the United States with polyelectrolyte conditioning of municipal wastewater sludge prior to pressure filtration. Several English studies indicated that polyelectrolyte conditioning can be effectively used with pressure filtration if done with care. Dosage must be optimized and carefully controlled for optimum cake solids concentration, solids capture, and ability to release the cake (25). A comprehensive study on filter press operating experience in the North American pulp and paper industry was recently published and gives some insight to the use of polymers for conditioning (26). Excerpts from the study are given below.

"Many existing pulp and paper industry installations have been conducting polyelectrolyte evaluations on their own with, what initially appeared to be, very encouraging results. The polymers that have met with greatest success are those which form what can be best described as strong 'pin-floc.' An array of low molecular weight cationic polymers have been cited as providing acceptable press performance. The reasons for adopting polymer as a conditioning agent have included (a) reduced conditioning costs; (b) reduced quantities of solids for handling due to the avoidance of large amounts of inorganics; and, (c) elimination of those problems in final disposal operations that have been associated with inorganic conditioning agents. Projected polymer requirements vary from 3 to 30 pounds of polymer per ton of sludge solids."

Several mills have identified special considerations associated with polyelectrolyte conditioning. In one instance, the polymer conditioned cakes are discharging less readily than those with inorganic conditioning. However, several other mills report no noticeable difference in discharge characteristics. It is generally observed that both cake consistencies and densities are lower when using polymer conditioning. However, in several instances, the difference is felt to be associated with the bulk of the inorganic conditioning added as dry solids before pressing."

"The handling of polymer-conditioned sludge prior to pressing has been identified as important. Complete initial mixing of the sludge and polymer is crucial and subsequent handling should involve a minimum of shear. It has been proposed that mixing be accomplished by injecting the polymer into the suction side of a positive displacement pump or the discharge side of a centrifugal pump. Mills have indicated the existence of an optimum flocculation time between conditioning and pressing. One mill reports that at the discharge of the press feed pump, the floc is sufficiently sheared to render it very difficult to dewater but that in the remaining 30 feet of pipe to the press, virtually complete reflocculation occurs. At the other extreme, several instances of intermittent sludge septicity demonstrated that extended sludge storage can be detrimental." Caution should be exercised in extrapolating paper mill data to municipal sludge.

8.5.4.4 Belt Filter Presses

Operating experience indicates that all belt presses require the use of polyelectrolyte conditioning to make them work. Compared to other mechanical dewatering processes, belt presses seem to have the greatest need for optimizing the polymer dosage as a function of the incoming sludge's characteristics (27). Underconditioning results in inadequate dewatering in the initial drainage section(s), causing either extrusion of inadequately drained solids from the press section(s), or in extreme instances, an uncontrolled overflow of sludge from the drainage section(s). Underconditioned biological solids can also blind or clog the fine mesh filter media. Overconditioning can also be a problem. Too much polyelectrolyte can cause cake doctoring or removal difficulties and aggravate media-blinding problems. The type of polymer also influences the tendency of a media to blind. In addition, overflocculated sludge may drain so rapidly that the solids are not distributed across the media.

Table 8-7 lists typical levels of dry polyelectrolyte addition to condition sludges for dewatering on belt presses. The big spread in polymer addition requirements is attributable to the percentage of biological solids present in the total waste sludge stream. Figure 8-13 is the result of one study and indicates that as the percent of biological solids increases so do the polymer requirements (27).

TABLE 8-7

TYPICAL LEVELS OF DRY POLYELECTROLYTE ADDITION FOR BELT FILTER PRESSES[a]

Sludge type	Pounds of dry polymer added per ton of dry solids
Raw primary	4 - 8
Primary plus trickling filter	3 - 10
Primary plus waste-activated (air)	4 - 10
Waste-activated (air)	8 - 12
Waste-activated (oxygen)	8 - 12
Aerobically digested (primary plus waste-activated {air})	4 - 10
Anaerobically digested primary	2 - 6
Anaerobically digested (primary plus waste-activated {air})	3 - 9

[a]Data supplied by equipment manufacturers.

1 lb/ton = 0.5 kg/t

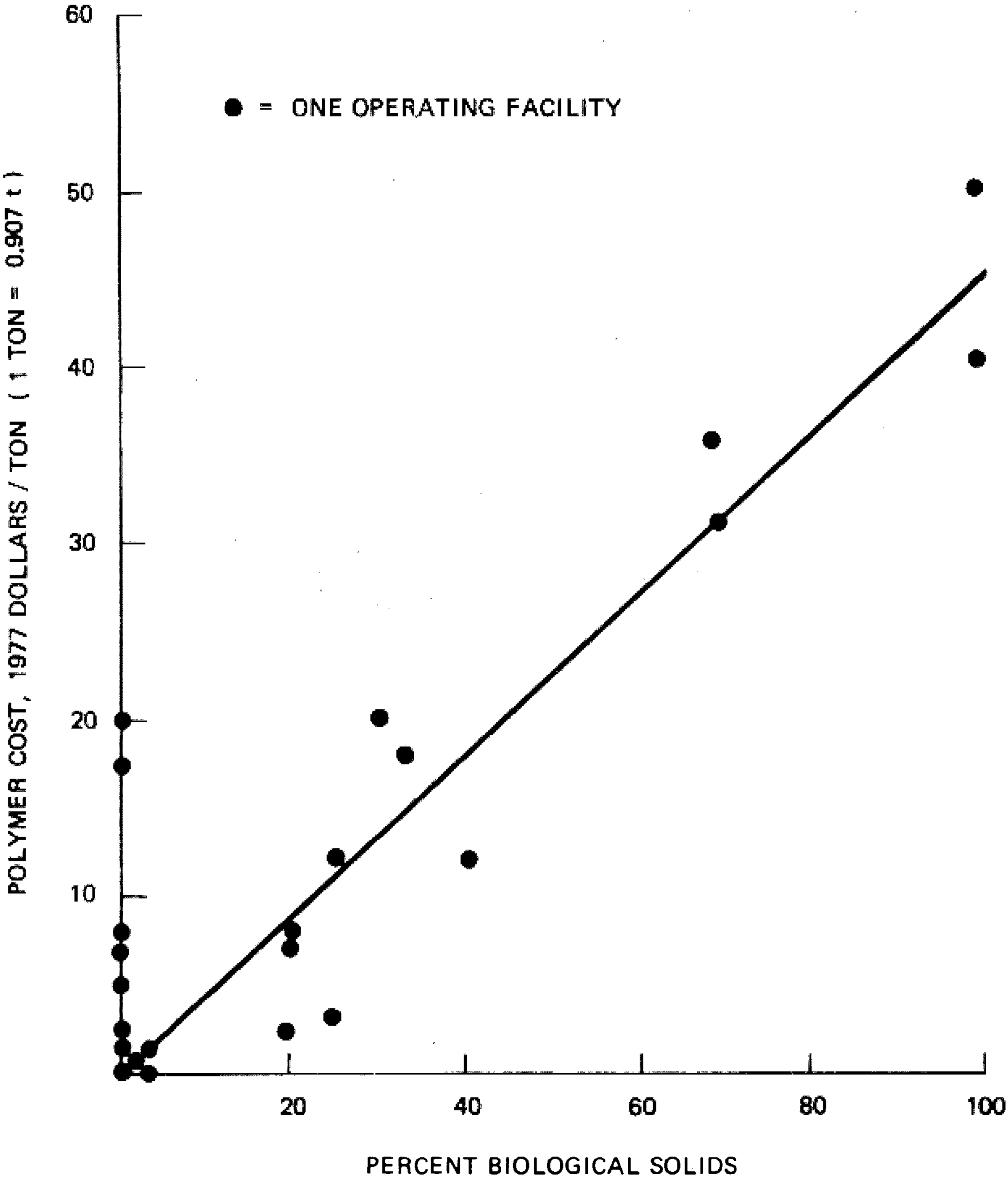


FIGURE 8-13

EFFECT OF BIOLOGICAL SOLIDS ON POLYMER REQUIREMENTS IN BELT PRESS DEWATERING (32)

8.5.4.5 Centrifuges

As was noted in the detailed discussion in Chapter 9, two types of centrifuges can be used for dewatering: imperforate baskets and solid bowl decanters. Although many imperforate basket centrifuges do not use polyelectrolytes for sludge conditioning prior to dewatering, the addition of 1 to 3 pounds of dry polymer per ton of dry feed solids (0.5 to 1.5 kg/t) can greatly reduce overall operating cost. The reason for this reduction is that basket centrifuges are used for dilute, difficult-to-dewater sludges such as aerobically digested, extended aeration, and nitrification sludges. Since the cost of polymer is offset by the reduction in operating time, a decision is normally made in favor of adding polymer.

Solid bowl decanter centrifuges usually require polyelectrolytes to obtain good performance on municipal wastewater sludges. Table 8-8 lists typical levels of dry polyelectrolyte addition to various sludges for conditioning prior to dewatering by solid bowl decanter centrifugation.

TABLE 8-8

TYPICAL LEVELS OF DRY POLYELECTROLYTE ADDITION FOR SOLID BOWL DECANTER CENTRIFUGES CONDITIONING VARIOUS SLUDGES[a]

Sludge type	Pounds of dry polymer added per ton of dry solids
Raw primary	2 - 5
Raw primary plus WAS (air)	4 - 10
Thermal conditioned (primary plus WAS (air))	3 - 5
Thermal conditioned (primary plus trickling filter)	2 - 4
Anaerobically digested	
Primary	6 - 10
Primary plus WAS (air)	7 - 10

[a]Data supplied by equipment manufacturers.

1 lb/ton = 0.5 kg/t

8.5.5 Storage, Preparation, and Application Equipment

Storage, preparation, and application equipment for both dry and liquid polymers are discussed in great detail in two current USEPA publications (15,28).

8.5.6 Case History

The following summarizes the conversion of the sludge conditioning process for the vacuum filters at the Bissell Point, St. Louis treatment plant from an inorganic chemical to an organic chemical process (29). The Bissell Point plant dewaters and incinerates 35,000 dry tons (31,745 dry) of raw primary sludge per year. Conditioning of the sludge before vacuum filtration was with ferric chloride and lime until July 1976. Table 8-9 summarizes the solids handling systems performance from 1972-1976.

TABLE 8-9

PERFORMANCE OF SOLIDS HANDLING SYSTEM AT BISSELL POINT, ST. LOUIS STP 1972-1976 (29)

Item	Usage	Cost, dollars/dry ton[a,b]
Lime dosage, lb/dry ton[b]	352	6.90
Ferric chloride dosage, lb/dry ton[b]	64	5.09
Auxiliary fuel (natural gas), therms/ dry ton[b]	62	12.75
Total annual cost	-	34.74
Yield (average), lb/sq ft/hr	7.1	-
Solids content, percent	30	-
Volatile solids fraction, percent	42	-

[a]All costs are adjusted to a July 1978 value.

[b]All tons (tonnes) are net dry tons (tonnes). This is defined as the dry tons (tonnes) of filter cake produced less the dry quantities of chemicals required to produce the cake.

1 lb = 0.454 kg
1 therm = 0.116 GJ
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 ton = 0.907 t

Since plant startup in 1970, numerous problems have developed from the use of ferric chloride and lime. The major problems were:

- Lime coating of filter cloths and grid work.
- Scale buildup in filtrate and plant drainage lines.
- Constant cleanup of lime spills.

In July 1976, after six months of planning and experimentation, the conditioning process was converted from ferric chloride and lime to a dual polymer process utilizing either anionic or cationic polymers. Several equipment modifications and operator training programs had to be undertaken in order to make the system work properly.

Grease Separation. The mixing of primary tank skimmings with the raw sludge caused blinding of the filter cloth. The large volume of skimmings also influenced the solids concentration. The skimmings did not upset the ferric chloride- and lime-conditioned sludge filters as much as they did the polymer-conditioned sludge filters. The solution employed was to separate the skimmings and sludge and treat each separately. Skimmings were dewatered by a modified grit dewatering screw and then fed directly into the incinerator.

Cloth-Washing Equipment. For polyelectrolytes to be effective, it is mandatory that the filter cloth be cleaned continuously. The original filter spray water system included one spray nozzle strainer. When this strainer had to be cleaned, the unit had to be stopped. To correct the problem, the one strainer was replaced with a duplex-type strainer which allowed switching of the strainers with no change in the filter operation.

Miscellaneous Filter Improvements. Several modifications were necessary to improve cake removal from the media. The doctor blades were modified to fit together and against the cloth media. Operating with polymers was found best at low vat levels. To avoid loss of vacuum when running at low levels, bridge blocks in the vacuum valve were installed to modify the pickup zone.

Operator Education. It was necessary to convince the plant operators that polymer usage would be beneficial to them. An extensive educating process was conducted for several months informing the operators of the benefits they would obtain using polyelectrolytes.

The conversion was considered very successful. Table 8-10 summarizes performance information for the solids handling processes after implementation of the polyelectrolytes conditioning process for 1977-1978. Comparison of the performance data in Tables 8-9 and 8-10 shows that the use of organic polymers in place of inorganic conditioners reduced auxiliary fuel requirements by 26 percent and conditioner cost by 53 percent. Overall annual cost per dry ton of solids was reduced by 56 percent.

8.5.7 Cost

8.5.7.1 Capital Cost

Figure 8-14 gives construction costs for polymer storage and feed facilities as a function of installed capacity. Cost estimates were based on the use of dry polymer. Chemical feed equipment was chosen specifically for a 0.25 percent stock solution. Piping and buildings to house the feeding equipment and store the bags were included. For example, for an installed capacity of 10 pounds (4.5 kg) of dry polymer per hour, the approximate June 1975 cost was $110,000. The cost would need to be adjusted to the current design period.

TABLE 8-10

PERFORMANCE OF SOLIDS HANDLING SYSTEM AT BISSELL POINT, ST. LOUIS STP 1977-1978 (29)

Item	Usage	Cost, dollars/dry ton[a,b]
Anionic dosage, lb/dry ton[b]	0.34	0.42
Cationic dosage, lb/dry ton[b]	65	5.25
Auxiliary fuel (natural gas), therms/ dry ton[b]	46	9.52
Total annual cost	-	15.19
Yield (average), lb/sq ft/hr	7.8	-
Solids content, percent	28	-
Volatile solids fraction, percent	56	-

[a]All costs are adjusted to a July 1978 value.

[b]All tons (tonnes) are net dry tons (tonnes). This is defined as the dry tons (tonnes) of filter cake produced less the dry quantities of chemicals required to produce the cake.

1 lb = 0.454 kg
1 therm = 0.116 GJ
1 lb/sq ft/hr = 4.9 kg/m^2/hr
1 ton = 0.907 t

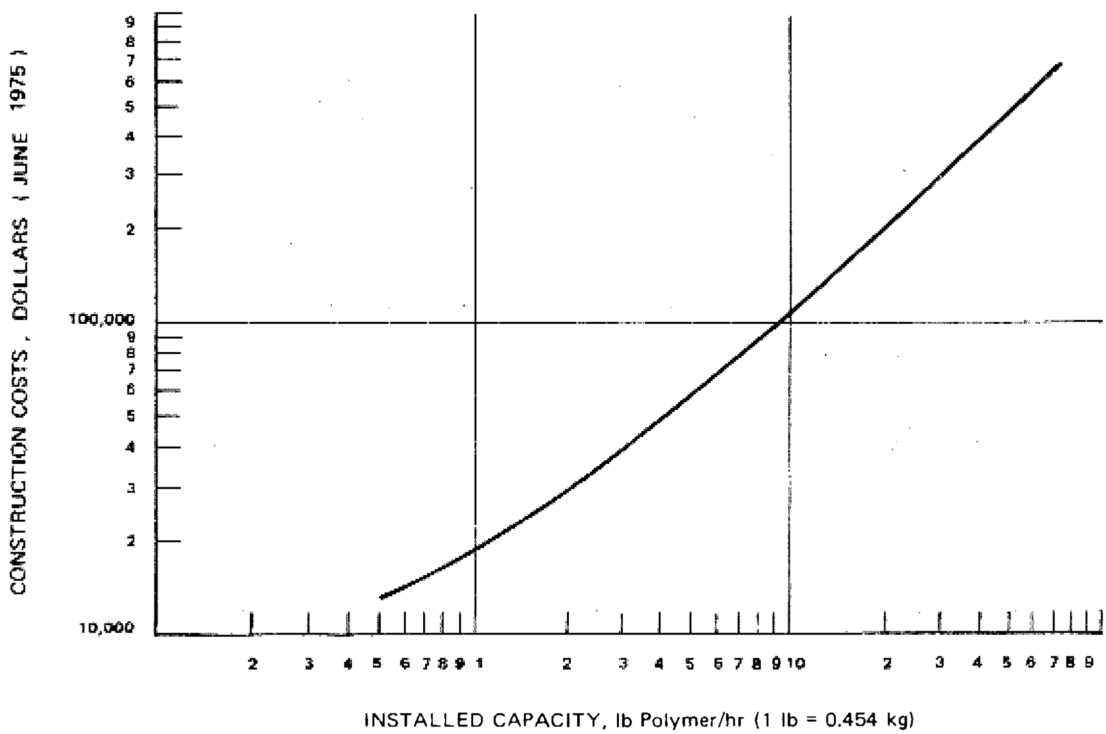


FIGURE 8-14

RELATIVE INFLUENCE OF POLYMER ADDITION ON IMPERFORATE BASKET CENTRIFUGE PROCESS VARIABLES (22)

8.5.7.2 Operation and Maintenance Cost

Figure 8-15 gives man-hours for operation and maintenance of a dry polymer feed system as a function of pounds of chemicals fed per hour. Unloading requirements are 16 minutes for 10- to 50-pound (4.5 to 22.6 kg) bags. Mixing labor was estimated at ten man-hours per 1,000 pounds (453.5 kg) of polymer under a wastewater flow of 10 MGD (26.2 m^3/s) and three hours per 1,000 pounds (453.5 kg) of polymer for wastewater flows over 10 MGD (26.2 m^3/s). Operation and maintenance requirements were taken as 385 man-hours per year per feeder.

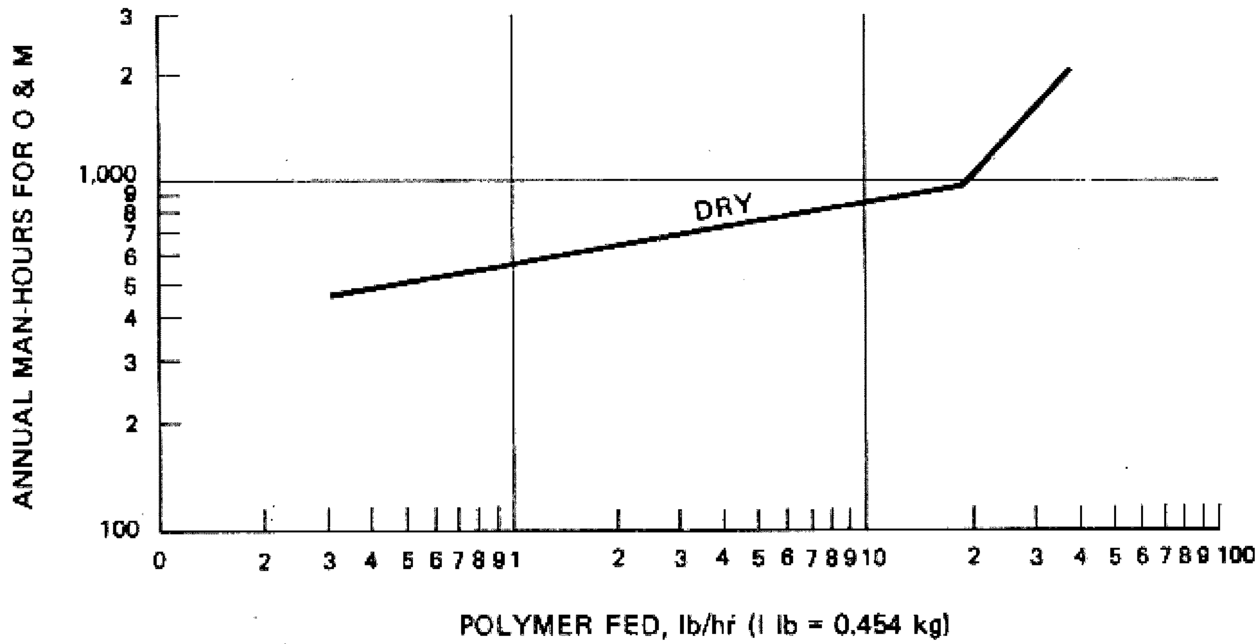


FIGURE 8-15

POLYMER STORAGE AND FEEDING OPERATION AND MAINTENANCE WORK-HOUR REQUIREMENTS (22)

Figure 8-16 gives annual electrical power requirements for a polymer feed system. The graph was based on the use of plunger metering pumps and 6.4 hp hour (4.7 kWhr) for mixing of 100 pounds (45.4 kg) of polymer.

Annual maintenance material costs are typically 0.5 to 1.5 percent of the total polymer feed system equipment cost.

8.6 Non-Chemical Additions

Power plant or sludge incinerator ash has been used successfully to improve mechanical dewatering performance on full-scale vacuum filters and filter presses (30). The properties of ash that improve dewatering of sludge include the solubilization of its metallic constituents, its sorptive capabilities, and its irregular particle size (31). The advantages and disadvantages of adding ash for sludge dewatering are given in Table 8-11. Major advantages are lower chemical requirements and improved cake release. Major disadvantages are the addition of a sizable quantity of inerts to the sludge cake and additional material handling. For installations where landfilling of sludge follows mechanical dewatering by vacuum filters or filter presses, the use of ash to improve the total solids content of the cake should be evaluated. If incineration is to follow the dewatering step, other additives such as pulverized coal or waste pulp should receive preferential considerations (32-34). In the design of incineration facilities, one of the main objectives is to reduce or eliminate auxiliary fuel demand. This can be done by feeding the driest solids cake possible to the incinerator and/or by enhancing the fuel value of the sludge solids. The addition of ash to the sludge assists the dewatering device in producing a dry cake, but it does nothing for the fuel value of the cake. Ash has no heating value and, in fact, requires additional heat input to raise its temperature.

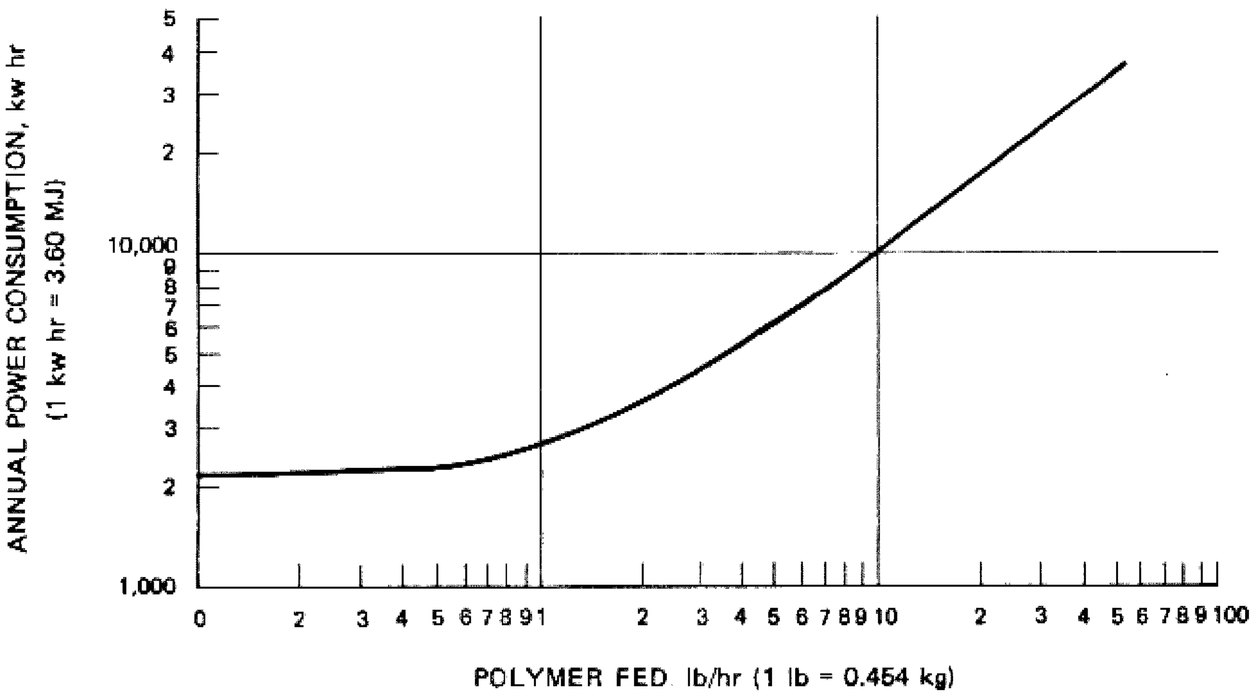


FIGURE 8-16

ELECTRICAL ENERGY REQUIREMENTS FOR A POLYMER FEED SYSTEM (22)

A pilot-scale vacuum filtration study has found pulverized coal to be an excellent sludge conditioner for improved dewatering (32). The coal contributed the same benefits as ash and increased the Btu content of the sludge solids. Economic analysis showed it to be cost-effective when compared to the addition of other supplemental fuels such as natural gas or #2 fuel oil. A full-scale solids handling study at St. Paul, Minnesota, demonstrated that an existing seven-hearth wastewater sludge cake incinerator could be fed coal or wood chips with the sludge cake to reduce consumption of natural gas or fuel oil (35). The process was found to be economically justifiable and practical only when a large quantity of natural gas or fuel oil is required for sludge cake incineration.

TABLE 8-11

ADVANTAGES AND DISADVANTAGES OF ASH ADDITION TO SLUDGE FOR CONDITIONING

Advantages	Disadvantages
Substantial increase in total cake solids	Ash handling generates considerable dust
Significant improvement in filtrate quality	Ash fines build-up
Excellent cake discharge	Possible equipment abrasion problems
Elimination or significant reduction in use of other conditioning agents	Increase in materials handling problems
	For those installations with incineration, the addition of ash lowers the percent volatile solids in the feed. Fuel usage can therefore increase.

The use of waste paper as a conditioner for sludge has also been studied in the laboratory and on a plant scale (33,34). Some paper-conditioned sludge was dewatered on full-scale vacuum filters (34). Results were excellent, indicating that the use of waste paper and polymer were significantly more economical than ferric chloride and lime.

8.7 Thermal Conditioning

This process involves heating of wastewater sludge to temperatures of 350° to 400°F (177° to 240°C) in a reaction vessel under pressures of 250 to 400 psig (1,723 to 2,758 kn/m^2) for periods of 15 to 40 minutes. One modification of the process involves the addition of a small amount of air. Figures 8-17 and 8-18 show a general thermal conditioning flow scheme for plants without and with the addition of air, respectively.

Thermal conditioning of sludge was first studied by William K. Porteous in England in the mid-1930s (36). Thermal conditioning in the United States was first studied in the mid-1960s, and the first facility having no air addition was installed at Colorado Springs, Colorado, in 1969 (37-39). The first plant with air addition was installed at Levittown, Pennsylvania, in 1967 (40). Since then, over one hundred thermal sludge conditioning installations have been built in the United States.

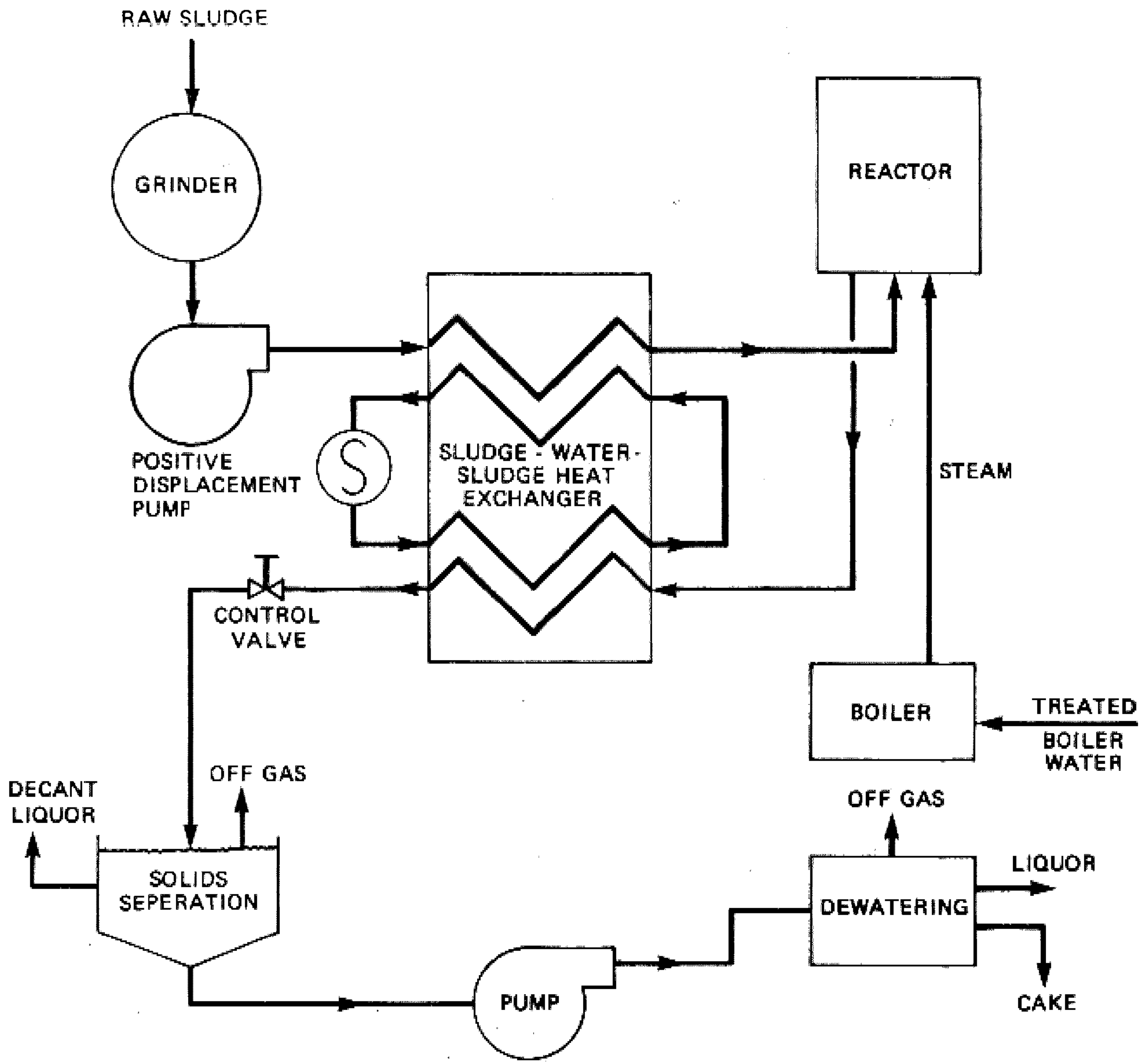


FIGURE 8-17

GENERAL THERMAL SLUDGE CONDITIONING FLOW SCHEME FOR A NON-OXIDATIVE SYSTEM

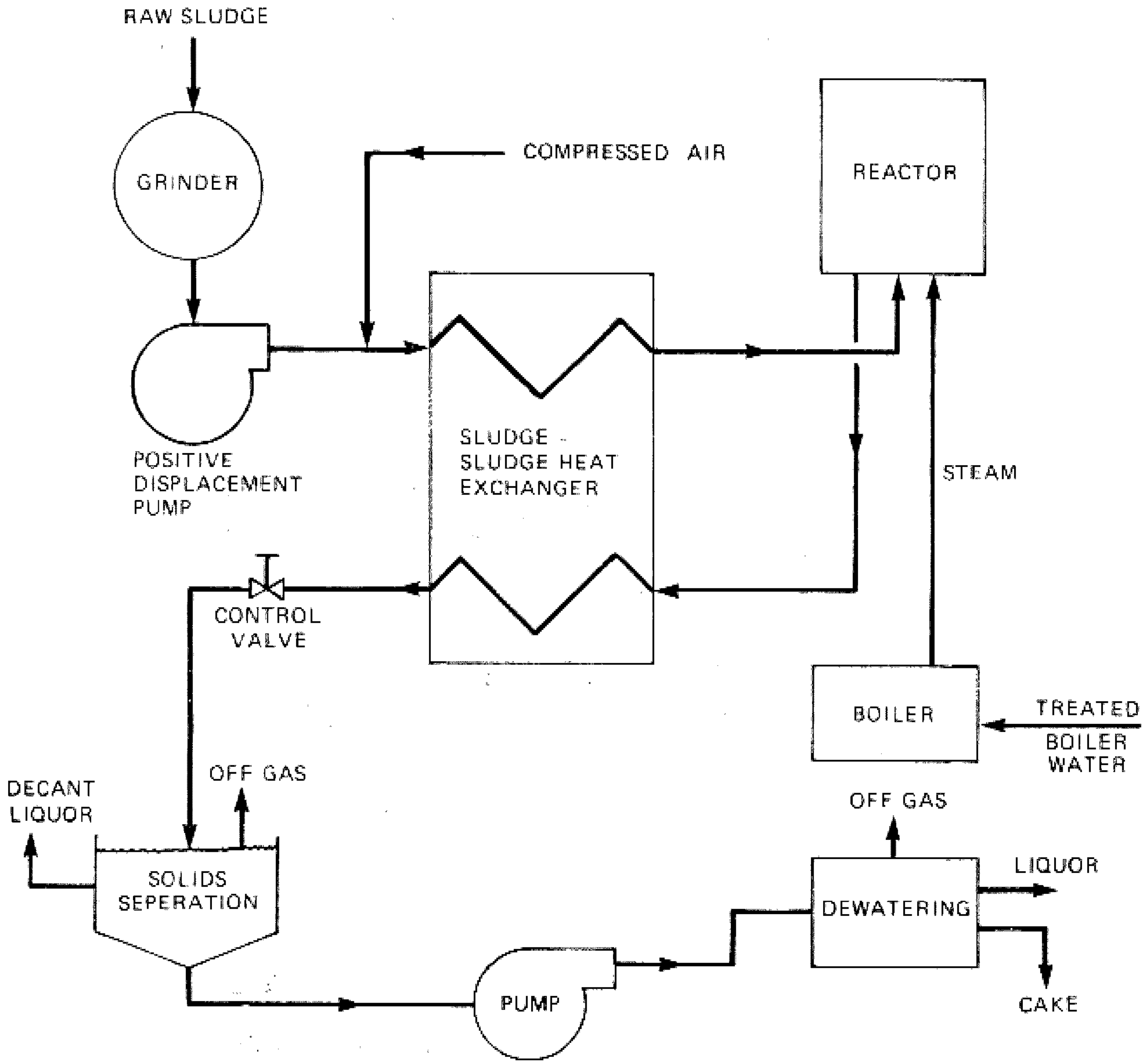


FIGURE 8-18

GENERAL THERMAL SLUDGE CONDITIONING FLOW SCHEME FOR AN OXIDATIVE SYSTEM

8.7.1 Advantages and Disadvantages

Thermal conditioning of wastewater sludges has the following advantages:

- Except for straight waste-activated sludge, the process will produce a sludge with excellent dewatering characteristics. Cake solids concentrations of 30 to 50 percent are obtained with mechanical dewatering equipment.

- Processed sludge does not normally require chemical conditioning to dewater well on mechanical equipment.

- Process sterilizes the sludge, rendering it free of pathogenic organisms.

- If done prior to incineration, the process will provide a sludge with a heat value of 12,000 to 13,000 Btu per pound of volatile solids (28 to 30 kJ/g).

- Process is suitable for many types of sludges that cannot be stabilized biologically because the presence of toxic materials.

- Process is insensitive to changes in sludge composition.

- No length or elaborate start-up procedures are required.

The disadvantages of thermal conditioning include:

- The process has high capital cost due to the use of corrosion-resistant materials such as stainless steel in the heat exchangers. Other support equipment is required for odor collection and control and high pressure fluid transport.

- Process requires supervision, skilled operators, and a strong preventative maintenance program.

- Process produces an odorous gas stream that must be collected and treated before release.

- Process produces sidestreams with high concentrations of organics, ammonia nitrogen, and color.

- Scale formation in heat exchangers, pipes, and reactor requires acid washing.

8.7.2 Process Sidestreams

Thermal sludge conditioning produces both gaseous and liquid sidestreams that must be considered in design.

8.7.2.1 Gaseous Sidestreams

A thermal sludge conditioning process produces odorous materials in:

- Vapors from treated sludge in the decant or thickener tanks.

- Vacuum filter pump exhaust and vacuum filter hood exhaust.

- Air exhausted from the operations and hopper areas of any enclosed mechanical dewatering system.

These odors must be treated by processing all exhaust air in some type of odor control system. Methods of odor control include combustion, adsorption, scrubbing, masking, dilution, and surface evaporation (41).

8.7.2.2 Liquid Sidestreams

Thermal sludge conditioning sidestreams originate from the conditioned sludge when it is decented, thickened or lagooned, or when it is mechanically dewatered. The composition of thermally conditioned sludge liquor is difficult to assess. In one study of thermal conditioning with no air addition, several types of sludges were treated and it was noted that in general (42):

- The concentration of the individual components in a heat-treatment sidestream increased in proportion to the feed-solids concentration.

- The COD of heat-treatment liquor was proportional to the dissolved solids for all sludges under all process conditions.

- The organic N content of heat-treatment liquor was proportional to the dissolved solids, there being one relationship for activated sludge and others for trickling filter, primary plus activated, and digested sludges.

- The breakdown of organic N to ammonia in activated sludge heat treatment liquor was a time-temperature phenomenon.

In general, therefore, the composition of the liquor is a function of the type of sludge, feed volatile solids content, reaction time, and temperature. Without a pilot scale investigation of process feasibility, it is difficult to specify design data. Table 8-12 gives ranges for various constituents that have been reported for both the process with air addition and the process without air addition that conditioned sludges having 3 to 6 percent feed solids concentrations (41-50).

Table 8-13 summarizes data from the literature on filtrate or centrate composition. Except for suspended solids, the parameters of filtrate are similar if not equal to the decant tank supernatant.

TABLE 8-12

GENERAL CHARACTERISTICS OF SEPARATED LIQUOR FROM THERMAL CONDITIONED SLUDGE[a]

Parameter	Oxidative	Non-oxidative
Suspended solids, mg/l	100-20,000	300-12,000
Dissolved solids, mg/l		1,700-12,000
COD, mg/l	10,000-30,000	2,500-22,000
BOD_5, mg/l	5,000-15,000	1,600-12,000
Phosphorus[c], mg/l	150-200	70-100
Total N, mg/l	650-1,000	700-1,700
Organic N, mg/l		100-1,000
Ammonia N, mg/l	400-1,700	30-700
pH	5.0-6.5	5.0-6.4
Color	1,000-6,000 units	2,000-8,000
Metals	-[d]	-[e]

[a]Mixture of 50 percent primary and 50 percent waste-activated at a feed solids concentration between 3 to 6 percent.

[b]Less than 20 percent of the COD is non-biodegradable.

[c]Depends on P of influent sludge.

[d]See Reference 43.

[e]See Reference 44.

Many methods have been used to treat the liquid sidestreams, and they are discussed in Chapter 16.

8.7.3 Operations and Cost

Analysis of the cost of installing and operating a thermal conditioning process should be comprehensive, as it impacts other parts of the liquid and sludge handling system. The discussion in this section is general; for those interested in more detail, two recent reports are available (41,53).

8.7.3.1 General Considerations

Thermal sludge conditioning has been operating in the United States for about ten years. During that time, over a hundred facilities have been built and much has been learned from past mistakes. Following are current design guidelines that must be considered in the cost determinations for a basic thermal sludge-conditioning system:

- If there is a chance of high chloride content (greater than 400 mg/l) in the sewage or sludge metal with corrosion-resistant properties greater than stainless steel must be used in the hot heat exchanger (nearest reactor).

- All potential sources of odor (decant tank, dewatering area, vacuum filter exhaust must be enclosed. In addition, an air collection and treatment system must be provided.

- Strength of the recycle streams depends on many variables. The worst possible conditions should be used as the design basis for the recycle liquor system.

- Good grit removal from the sludge is essential to prevent abrasion of metal piping. The provision of grit removal at the plant influent does not imply that grit will be absent in the sludge stream. Large quantities of material can blow into clarifiers and aeration tanks; therefore, separate grit removal before the thermal-conditioning system should be considered.

- Only the most rugged types of sludge handling pumps should be used.

- Present-day energy economics dictate careful review of heat recovery systems.

8.7.3.2 USEPA Survey Results

In May and June of 1979, USEPA Technology Transfer, Cincinnati, Ohio, conducted a survey of operation and maintenance problems at 76 thermal conditioning process facilities. Table 8-14 lists suppliers, number of plants involved in survey, and sum of operating experience.

Nearly all the plants contacted indicated high costs of operation and maintenance. The high operating costs resulted mainly from the cost of fuel for steam generation, the addition of chemicals for boiler water treatment, and in some cases (Lexington, Kentucky; Haverhill, Massachusetts; Poughkeepsie, New York), the addition of chemicals to improve dewatering. Plants that utilize waste heat from sludge cake incineration are able to cut considerably both fuel usage and the volume of sludge (as ash) that must be hauled.

Maintenance costs involve replacing various parts on a somewhat regular basis, washing the heat exchanger and reactor with acid to remove scaling, and the costs of the manpower needed to perform these tasks. Plants that have operating experience express requirements for highly trained personnel, regular preventive maintenance, and a good surveillance program. These practices can substantially reduce maintenance costs due to excessive shutdown time or replacement of major components that do not normally wear out.

TABLE 8-13

FILTRATE AND/OR CENTRATE CHARACTERISTICS FROM DEWATERING THERMAL CONDITIONED SLUDGE

Sludge type	Dewatering process	Characteristics	Reference
Raw primary plus trickling filter sludge (heavy industrial load)	Recessed plate pressure filter	Feed solids, percent[a] = 9.0 Filtrate[a] Total solids, mg/l = 8,000 SS, mg/l =150 BOD_5, mg/l = 6,500 COD, mg/l = 12,000 Total N, mg/l = 1,075 pH, units = 6.4	49
Anaerobically digested (primary plus waste-activated) plus raw primary	Rotary vacuum filter cloth media	Feed solids, percent = 10 - 15 Filtrate SS[a], mg/l = 5,000 BOD_5[a], mg/l = 10,000	_[b]
Raw primary plus waste-activated	Rotary vacuum filter cloth media	Feed solids, percent = 6 - 10 Filtrate SS, mg/l 1,000	_[c]
Raw primary plus waste-activated (high tannery load)	Rotary vacuum filter cloth media	Feed solids, percent = 8 - 13 Filtrate SS, mg/l 2,000 BOD_5, mg/l = 7,900 - 9,600	_[d]
Anaerobically digested (primary plus waste-activated) plus raw sludge	Sand dry beds	Soluble BOD_5 of drainage does not exceed 6,000 mg/l	51
Anaerobically digested primary plus oxygen waste-activated	Recessed diaphragm plate and frame pressure filter	Feed solids, percent 14 Filtrate SS, mg/l 1,400	_[e]
Raw primary plus trickling filter sludge	Rotary vacuum filter cloth media	Feed solids[a], percent = 18 Filtrate SS, mg/l 9,000 BOD_5, mg/l 6,800	52
Raw primary plus waste-activated	Centrifuge	Feed solids, percent = 6 - 7 Filtrate SS = 3,000 mg/l	_[f]
Raw primary plus waste-activated	Centrifuge	Feed solids, percent = 6 - 7 Filtrate SS = 6,000-9,000 mg/l Soluble BOD_5, mg/l = 4,200	_[g]
Raw primary plus waste-activated	Rotary vacuum filter cloth media	BOD_5, mg/l = 7,300 - 9,100	_[h]
Raw primary plus waste-activated	Rotary vacuum filter cloth media	Feed solids, percent 10 - 20 Filtrate, percent = 2 - 2.5 Soluble BOD_5, mg/l = 6,000 - 7,000	_[i]
Raw primary plus waste-	Coil vacuum filters	Feed solids, percent 13 Filtrate, percent solids = 6 - 7	_[j]

[a]Average values.

The buildup of scale in the heat exchanger, reactor, or pipes occurs in most plants that have hard water or industrial wastes in the influent. Regular washing with acid is practiced in all plants with this problem. The length of operating time between washes varies from as much as 1,500 hours to as little as 200 hours. Many plants acid-wash on a regular basis, about every month, not only to remove scale, but to prevent its initial buildup.

Many operators of the non-air thermal conditioned systems indicated that an important factor in a good maintenance program is the upkeep of a parts inventory. This eliminates the chance of the system being shut down over an extended period while parts are ordered.

TABLE 8-14

USEPA JULY 1979 SURVEY OF EXISTING MUNICIPAL WASTEWATER THERMAL CONDITIONING

	Zimpro	Envirotech[a]	Nichols[b]	Zurn
Total installations	83	30	6	1
Number of installations contacted in survey	57	19	0	0
Operating more than 120 hr/week	27	7		
Operating less than 120 hr/week	20	6		
Not operating	10	6		
Period of operation				
Less than 1 year	11	1		
Between 1 to 2 years	15	6		
Between 3 to 5 years	11	9		
Over 5 years	20	3		

[a]Formally called the Porteous process. Porteous process was licensed by Envirotech in the mid-1960's.

[b]Formally known as the Dorr Oliver Farrer System. Purchased by Nichols in the early 1970's.

The concensus of the operators is that after the "bugs" are worked out of the system, after the personnel have been familiarized and trained, and after a routine maintenance program is established, the process performs satisfactorily.

8.8 Elutriation

Elutriation is the term commonly used to refer to the washing of anaerobically digested sludge before vacuum filtration. Washing causes a dilution of the bicarbonate alkalinity in the sludge and therefore reduces the demand for acidic metal salt by as much as 50 percent (54).

The process itself was patented by Genter in 1941 (55). Although it typically employs one or two tanks, any number of tanks can be used. Two to six volumes of washwater, typically plant effluent, flow countercurrent to one volume of anaerobically digested sludge. Elutriation tanks are designed to act as gravity thickeners, with a mass solids loading of 8 to 10 pounds per square foot per day (39 to 48.8 kg/m^2/day).

At this time the process is not used as extensively as it had been because, in addition to reducing alkalinity, it also washed out 10 to 45 percent of the solids from the incoming sludge stream (56-60). Elutriate was recycled back to the main plant and eventually degraded the plant effluent (57,58,60).

Full-scale research (60-62) has shown that the solids problem can be solved, and 90 to 92 percent capture achieved, with the use of polymers. Recommended current elutriation design considerations are listed below:

- Tanks should be loaded at hydraulic loadings (total of both sludge and washwater flow) of 200 to 300 gallons per day per square foot (69 to 104 $l/day/m^2$) and solids loading of 8 to 15 pounds per day per square foot (39 to

- Tanks should have the best possible inlet structure to minimize inlet momentum.

- Baffling should be used to prevent tank currents.

- Tanks should be provided with scum collection.

- Polymer addition should be provided.

8.9 Freeze-Thaw

In 1929, Babbit and Schlenz demonstrated the benefit of freezing wastewater sludge (63). They noted that, after sludge was frozen on a sand drying bed during the winter and thawed in the spring, its drainage qualities were improved and it dried to a higher solids content.

Research has since been conducted in three areas of freeze conditioning: indirect and direct mechanical systems and natural freezing.

8.9.1 Indirect Mechanical Freezing

Until recently, all mechanical freeze-conditioning research has been oriented toward indirect freezing methods. Indirect freezing involves the separation of the refrigerant and the sludge by some type of partition. The studies (64-66) on wastewater sludges indicate that freezing:

- Causes cellular dehydration and thus allows better flocculation.

- Destroys the sliminess of biological sludges.

- Improves dewatering characteristics as measured by sandbed and vacuum filter dewatering rates.

- Must occur slowly to be effective.

Although freeze conditioning has been shown to be beneficial, it is expensive to implement. This is because the system cannot utilize the heat generated by the fusion of the frozen sludge to cool the refrigerant.

8.9.2 Direct Mechanical Freezing

To overcome the above-mentioned problem, pilot work has been conducted on direct freezing (67). In direct freezing, the liquefied refrigerant is vaporized and dispersed through the sludge slurry at a controlled rate. In Table 8-15, slurry freezing (direct mechanical method) is compared to solid freezing (indirect freezing) and several other treatment processes.

TABLE 8-15

COMPARISON OF SEWAGE SLUDGE HANDLING AND CONDITIONING PROCESSES (67)

Process	Reduction in sludge COD percent	Sludge solubilization	Supernatant and filtrate quality: pH	Supernatant and filtrate quality: Quality	Cost/ton dry solids
Slurry freezing	35	Low	7-8	Good	6-20
Solid freezing	50-70	High	7-7.5	Poor	5-35
Anaerobic digestion	60-70	High	6-7	Poor	15-20
Aerobic digestion	30-70	Low	4-7	Good	15-30
Chemical addition	20-40	Low	6-6.5	Moderate	10-25

1 ton = 0.907 t

8.9.3 Natural Freezing

In this method, the freezing is done by the environment. At least one facility (68) is operating in Canada, and extensive full-scale research is being conducted in facility design in order to improve this method of conditioning (69).

8.10 Mechanical Screening and Grinding

In some applications, screening or grinding can be considered part of the sludge conditioning process. A good example of screening for conditioning is in the application of a disc nozzle centrifuge. A stainless steel, self-cleaning screen is required to remove large solids and fibrous material that would clog the disc nozzle machine.

Grinding of primary sludge is an important step for some sludge handling processes. It has also been indicated that grinding of a thick (over 8 percent solids) sludge stream reduces viscosity, thus making the slurry easier to pump. One outstanding example of this is in the municipal system at Glen Cove, New York.

8.11 Miscellaneous Processes

In addition to the more commonly known conditioning methods previously discussed, research has also been conducted on more novel methods, such as bacteria, electricity, solvent extraction, and ultrasonic.

8.11.1 Bacteria

Autotrophic sulfur bacteria may provide conditioning if added to digested sludge prior to dewatering (54). Under aerobic conditions, sulfur-oxidizing bacteria stimulate the production of sulfuric acid, which, in turn, lowers the pH of the sludge and enhances the dewatering process as measured by the specific resistance test. In another study (70), it was shown that filtration rates of waste-activated sludge could be increased under anaerobic conditions with the use of the enzyme lysozyme.

8.11.2 Electricity

In extensive laboratory and pilot plant work studies, graphite anodes and iron cathodes have been used to conditon sludge (71-76).

These studies indicate that:

- At pH values lower than 4.0 electrical current can condition sludge for filtration without the use of chemicals.
- The quantity of water removed during dewatering (vacuum filtration) was proportional to the amount of electricity used. Thinner sludges required less current.
- Sludges electrically conditioned seemed to produce drier cakes than chemically conditioned sludges.

The disadvantages are that:

- Anodes had to be replaced frequently because a dried crust continually formed on them.
- The system uses a great deal of electricity; optimum current density was approximately 0.3 amp per sq ft (3.3 amp/m^2) of anode surface, with a potential drop of 4 volts between the electrodes.
- No full-scale facilities have ever been tested to evaluate operating problems.

8.11.3 Solvent Extraction

In 1957, research was conducted at Rockford, Illinois, with carbon tetrachlorethylene as the solvent, with distillation end products being dried oils, fats, and greases (77). It was not considered to be very economical at that time.

Although solvent extraction is becoming popular in industry (78), only recently has there been promotional activity in the municipal field (79). To date, no municipal installations are using the process.

8.11.4 Ultrasonic

Conditioning of sewage sludges by ultra- or supersonic vibration has been explored (54). Ultrasonic vibrations degasify sludge, which is beneficial, but the vibrations also tend to destroy sludge flocs, resulting in fine solids that are difficult to dewater.

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EPA 625/1-79-011

PROCESS DESIGN MANUAL FOR SLUDGE TREATMENT AND DISPOSAL

Chapter 9. Dewatering

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 9

DEWATERING

9.1 Introduction

Dewatering is the removal of water from wastewater treatment plant solids to achieve a volume reduction greater than that achieved by thickening. Dewatering is done primarily to decrease the capital and operating costs of the subsequent direct sludge disposal or conversion and disposal process. Dewatering sludge from a 5 to a 20 percent solids concentration reduces volume by three-fourths and results in a non-fluid material. Dewatering is only one component of the wastewater solids treatment process and must be integrated into the overall wastewater treatment system so that performance of both the liquid and solids treatment schemes is optimized and total costs are minimized (1-3).

9.1.1 Process Evaluation

Several pilot-scale studies have been published that compare the performance of various dewatering devices or techniques on different sludge types (4-9). Table 9-1 summarizes equipment and sludge types evaluated. One conclusion that can be drawn from these studies is that selecting sludge dewatering processes is still very much an art rather than a science. Bench or pilot scale testing is always recommended before final design. This, however, does not always guarantee successful operation of the full-scale system. As will be shown, there are many problems involved in the scale-up of dewatering equipment, and this, combined with the changing character of municipal wastewater sludges, can cause significant problems. Designers must be cognizant of these problems and allow for them in the design of full-scale installations.

The main variables in any dewatering process are:

- Solids concentration and volumetric flow rate of the feed stream.
- Chemical demand and cost.
- Suspended and dissolved solids concentrations and volumetric flow rate of the sidestream.

Solids concentration and volumetric flow rate of the dewatered sludge.

TABLE 9-1

PILOT-SCALE SLUDGE DEWATERING STUDIES

Reference	Sludge type	Type of equipment
4	Mesophilic, anaerobically digested primary sludge from a publicly owned treatment work (POTW)	Combination of a horizontal, solid bowl, decanter centrifuge and a imperforate basket centrifuge Rotary drum, cloth-belt, vacuum filter Rotary drum, coil-belt, vacuum filter Recessed plate pressure filters
5	Mesophilic and thermophilic anaerobically digested sludge (3/4 by weight primary plus 1/4 by weight waste-activated sludge) from a POTW	Horizontal, solid bowl, decanter centrifuge Imperforate basket centrifuge Rotary drum, cloth-belt, vacuum filter Recessed plate pressure filters Drying beds
6	Waste-activated sludge from a pulp and paper activated sludge plant	Horizontal, solid bowl decanter centrifuge Rotary drum, precoat vacuum filter Recessed plate pressure filters Belt filter press Capillary suction Ultrafiltration Dual cell gravity filter with multiple roll
7,8	Raw primary sludge (1/3 by weight) plus waste-activated sludge (2/3 by weight from a POTW)	Rotary drum, cloth-belt vacuum filter Recessed plate pressure filters Diaphragm recessed plate pressure filters Belt filter press
9	Mesophilic, anaerobically digested primary sludge (1/3 by weight) plus waste-activated sludge (2/3 by weight) from a POTW	Horizontal, solid bowl, decanter centrifuge Rotary drum, cloth-belt, vacuum filter Belt filter press

Specific design criteria for selection of a dewatering process can also be dependent upon subsequent processing steps. Both the sludge composting and the incineration process require sludge with a relatively low solids concentration.

Another important consideration is the operation and maintenance (O/M) cost and the variables affecting it. In the past, O/M costs have been given little attention. This should change as USEPA implements its new Operations Check List (10) in all phases of the Construction Grants Program.

Finally, dewatering device reliability is important for successful plant operation. A reliable dewatering system is needed to maintain relatively uninterrupted removal of wastewater solids from a continuously operated wastewater treatment process.

Sludges are generated constantly, and if they are allowed to accumulate for a long time, the performance of the entire wastewater treatment plant will be impaired.

9.1.2 Methods of Dewatering

While numerous techniques fulfill the basic functional definition of dewatering, they do so to widely varying degrees. It is important to note these circumstances when comparing different devices. For example, drying beds can be used not only to dewater a sludge, but also to dry it to a solids concentration of greater than 50 to 60 percent. Depending on the circumstances and particular device involved, dewatered sludge from a mechanical device may vary from a wet, almost flowable form, to a harder and more friable form.

9.2 Natural Sludge Dewatering Systems

When land is available, sludge dewatering by nature can be extremely attractive from both a capital and an operating cost viewpoint. Considering escalating electrical power costs, this method is even more attractive. Two types of systems can be categorized as natural: drying beds and drying lagoons.

9.2.1 Drying Beds

Drying beds are the most widely used method of municipal sludge dewatering in the United States (11). At the present time, two-thirds of all United States wastewater treatment plants utilize drying beds and one-half of all the United States municipal sludge is dewatered by this method. Although the use of drying beds might be expected in smaller plants and in the warmer sunny regions, they are also used in several large facilities in northern climates (12). Table 9-2 lists advantages and disadvantages of the drying bed method.

TABLE 9-2

ADVANTAGES AND DISADVANTAGES OF USING SLUDGE DRYING BEDS

Advantages	Disadvantages
When land is readily available, this is normally the lowest capital cost	Lack of a rational engineering design approach allowing sound engineering economic analysis
Small amount of operator attention and skill is required	Requires more land than fully mechanical methods
Low energy consumption	Requires a stabilized sludge
Less sensitive to sludge variability	Must be designed with careful concern for climatic effects
Low to no chemical consumption	May be more visible to the general public
Higher dry cake solids contents than fully mechanical methods	Removal usually labor intensive

Research into the dewatering of sludge by drying beds has been conducted since the early 1900s, when it was noted that digested sludge dewatered more rapidly than raw sludge (13). Design data, however, are still very empirical, and only recently has an effort been made to develop a rational engineering design approach (14-16). An excellent review of past work, detailed theoretical analysis, and current understanding of the sludge drying process is given by Adrian (14). Sludge dewatering on a drying bed is a multi-phase process and is shown pictorially on Figure 9-1.

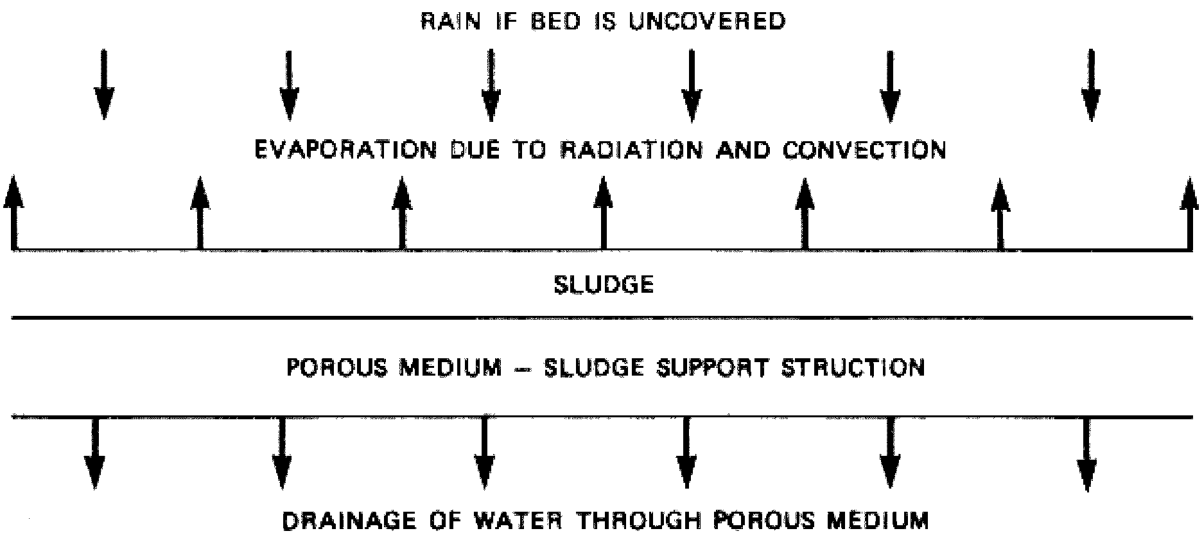

FIGURE 9-1

SCHEMATIC OF SLUDGE DEWATERING IN A DRYING BED SYSTEM

9.2.1.1 Basic Components and Operation

Drying beds generally consist of a one- to three-foot (0.3-1.0m) high retaining wall enclosing a porous drainage media. This drainage media may be made up of various sandwiched layers of sand and gravel, combinations of sand and gravel with cement strips, slotted metal media, or a permanent porous media. Appurtenant equipment includes: sludge feed pipelines and flow meters; possible chemical application tanks, pipelines, and metering pumps; filtrate drainage and recirculation lines; possible mechanical sludge removal equipment; and a possible cover or enclosure.

Operational procedures common to all types of drying beds involve:

- Pump 8 to 12 inches (20 to 30 cm) of stabilized liquid sludge onto the drying bed surface.

- Add chemical conditioners continuously, if conditioners are used, by injection into the sludge as it is pumped onto the bed.

- Permit, when the bed is filled to the desired level, the sludge to dry to the desired final solids concentration. This concentration can vary from between 18 to 60 percent, depending on the type of sludge, processing rate needed, degree of dryness required for lifting, etc.

- Remove the dewatered sludge either mechanically or manually.

- Repeat the cycle.

9.2.1.2 Types of Drying Beds

Drying beds may be classified as either conventional, paved, wedgewire, or vacuum-assisted.

Conventional Sand Drying Beds

Sand drying beds are the oldest, most commonly used type of drying bed. Many design variations are possible including the layout of drainage piping, thickness and type of gravel and sand layers, and construction materials.

Current United States practice (17-19) is to make drying beds rectangular with dimensions of 15 to 60 feet (4.5 to 18 m) wide by 50 to 150 feet (15 to 47 m) long with vertical side walls. Usually 4 to 9 inches (10 to 23 cm) of sand is placed over 8 to 18 inches (20-46 cm) of graded gravel or stone. The sand is usually 0.012 to 0.05 inches (0.3 to 1.2 mm) in effective diameter and has a uniformity coefficient less than 5.0. Gravel is normally graded from 1/8 to 1.0 inches (0.3 to 2.5 cm), in effective diameter. Underdrain piping has normally been of vitrified clay, but plastic pipe is also becoming acceptable. The pipes should be no less than 4 inches (10 cm), should be spaced 8 to 20 feet (2.4 to 6 m) apart, and have a minimum slope of one percent.

Figure 9-2 shows a typical sand drying bed construction. Sand drying beds can be built with or without provision for mechanical sludge removal, and with or without a roof.

Paved Drying Beds

Paved drying beds have had limited use since 1954 (20). The beds are normally rectangular in shape and are 20 to 50 feet (6 to 15 m) wide by 70 to 150 feet (21 to 46 m) long with vertical side walls. Current practice is to use either a concrete or asphalt lining. Normally, the lining rests on an 8- to 12-inch (20- to 30-cm) built-up sand or gravel base. The lining should have a minimum 1.5 percent slope to the drainage area. A minimum four-inch (10-cm) diameter pipe would convey drainage away. An unpaved area, 2 to 3 feet (0.6 to 1 m) wide is placed along either side or down the middle for drainage. Paved drying beds can be built with or without a roof.

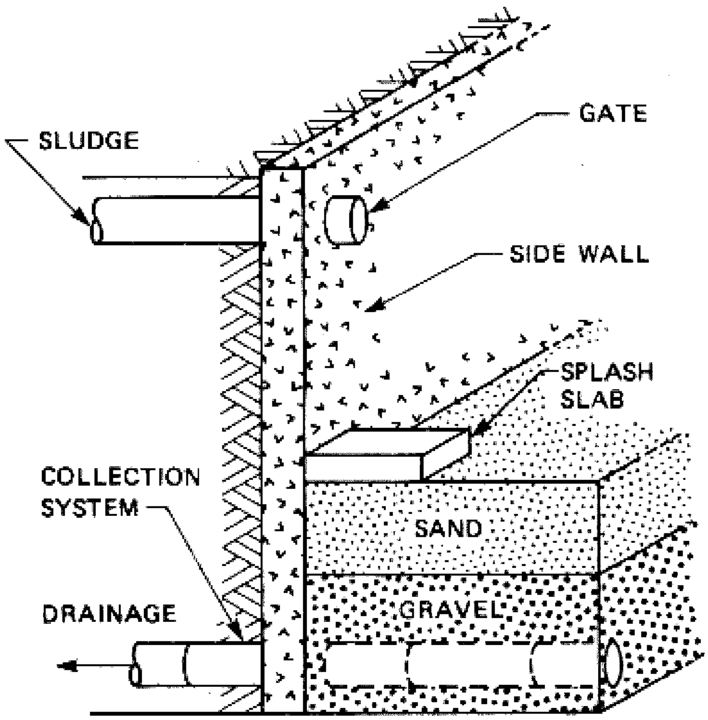

FIGURE 9-2

TYPICAL SAND DRYING BED CONSTRUCTION (18)

For a given amount of sludge, paved drying beds require more area than sand beds. Their main advantages are that front-end loaders can be used for sludge removal and reduced bed maintenance (21). Figure 9-3 shows typical paved drying bed construction.

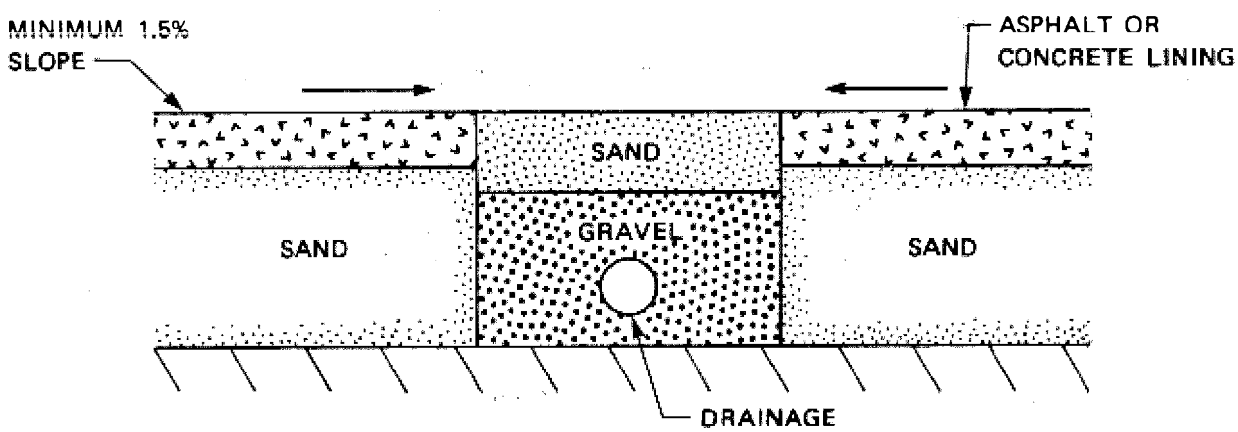

FIGURE 9-3

TYPICAL PAVED DRYING BED CONSTRUCTION

Wedge-Wire Drying Beds

Wedge-wire drying bed systems have been successfully used in England for over 20 years to dewater both municipal (22) and industrial (23,24) wastewater sludges. Used in the United States since the early 1970s, there are presently 18 wedge-wire installations. Ten of these installations are for municipal wastewater sludge.

In a wedge-wire drying bed, sludge slurry is introduced onto a horizontal, relatively open-drainage media in a way that yields a clean filtrate and provides a reasonable drainage rate (25). Table 9-3 lists reported advantages for this type of drying bed.

TABLE 9-3

ADVANTAGES OF A WEDGE-WIRE DRYING BED (26)

No clogging of the media	Easy bed maintenance
Constant and rapid drainage	Difficult-to-dewater sludges, for example, aerobically digested can be dried
Higher throughput rate than sand beds	Compared to sand beds dewatered sludge is easier to remove

Figure 9-4 shows a typical cross section of a wedge-wire bed. The bed consists of a shallow rectangular watertight basin fitted with a false floor of wedgewater panels. These panels have slotted openings of 0.01 inches (0.25 mm). This false floor is made watertight with caulking where the panels abut the walls. An outlet valve to control the rate of drainage is located underneath the false floor.

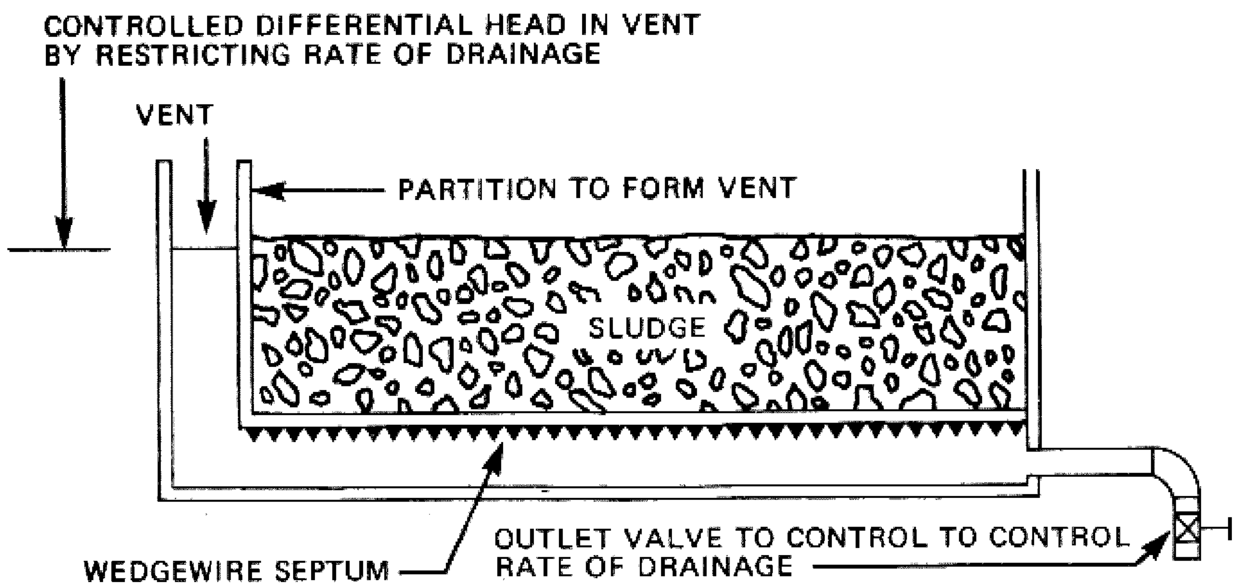

FIGURE 9-4

CROSS SECTION OF A WEDGE-WIRE DRYING BED

The procedure used for dewatering sludge begins with the movement of water or plant effluent into the wedgewater unit until a depth of approximately one inch (2.5 cm) over the wedge-wire septum is attained. This water serves as a cushion that permits the added sludge to float without causing upward or downward pressure across the wedge-wire surface. The water further prevents compression or other disturbance of the colloidal particles. After the bed is filled with sludge, the initially separate water layer and the drainage water are allowed to percolate away at a controlled rate, through the outlet valve. After the free water has been drained, the sludge further concentrates by drainage and evaporation until there is a requirement for sludge removal.

Vacuum-Assisted Drying Beds

The only operating vacuum-assisted drying beds at this time are two 20 feet (6 m) by 40 feet (12 m) units built in 1976 at Sunrise City, Florida. They dewater a two percent solids concentration, aerobically digested sludge from a contact stabilization wastewater treatment plant (27).

The principal components of the Sunrise facility are:

- A bottom ground slab consisting of reinforced concrete.
- A layer of stabilized aggregate several inches thick which provides support for the rigid multi-media filter top. This space is also the vacuum chamber and is connected to a vacuum pump.
- A rigid multi-media filter top is placed on the aggregate support. Sludge is then applied to the surface of this media.

The operating sequence is as follows:

- Sludge is introduced onto the filter surface by gravity flow at a rate of 150 gallons per minute (9.4 l/s) and to a depth of 12 to 18 inches (30 to 46 cm).
- Filtrate drains through the multi-media filter and into the space containing the aggregate and then to a sump, from which it is pumped back to the plant by a self-actuated submersible pump.
- As soon as the entire surface of the multi-media filter is covered with sludge, the vacuum system is started and vacuum is maintained at 1 to 10 inches mercury (3 to 34 kN/m^2).

Under favorable weather conditions, this system dewaters the dilute aerobically digested sludge to a 12 percent solids concentration in 24 hours without polymer addition, and to the same level in eight hours if polymer is added. This particular sludge of 12 percent solids concentration is capable of being lifted from the bed by a fork or mechanical equipment. The sludge will further dewater to about 20 percent solids concentration in 48 hours.

9.2.1.3 Process Design Criteria

Covered Beds

Whenever there is the possibility of long periods of rain, snow, or cold weather; potential odor or insect problems; or a problem with esthetics; consideration should be given to employing covers for the drying beds. When properly ventilated, so that air can flow over the surface of the bed, covered sand beds can be employed and require 25 to 33 percent less area than open sand beds (17,26). Although covers can be provided for paved, wedge-wire, and vacuum beds, no documentation could be found on how covers affect or improve bed loading rates.

Sludge Conditioning

Sludge conditioning can dramatically improve drying bed throughput (28) and should be considered as part of the design. See Chapter 8 for further discussion on conditioning.

Sludge Removal

The majority of United States facilities employ manual labor to remove dried sludge from drying beds. With this type of removal, a 30 to 40 percent solids concentration is required. With mechanical sludge removal systems (21,29,30), solids concentration between 20 and 30 percent can be handled (31). Depending on the bed size, a tiltable unit similar to the lift and dump mechanism of a dump truck is available for the wedge-wire drying bed.

Sidestreams

The only sidestream from a drying bed operation is under drainage liquor. While little is known about the characteristics of this sidestream, Table 9-4 shows the results from one pilot study. This flow is not normally treated separately, but is typically returned to the plant headworks.

TABLE 9-4

CHARACTERIZATION OF SAND BED DRAINAGE (32)

Sludge type	- Anaerobically digested mixture of primary and trickling filter sludge
Bed media	- 6 inches of sand
Color	- clear, dark amber
COD	- 300-400 mg/l
BOD_5	- 6-66 mg/l
BOD_{20}	- 1,900-2,360 mg/l (over 90 percent nitrogenous)

1 inch = 2.54 cm

TABLE 9-5A

SUMMARY OF RECOGNIZED PUBLISHED SAND BED SIZING CRITERIA FOR ANAEROBICALLY DIGESTED, NON-CONDITIONED SLUDGE

Initial sludge source	Uncovered beds, Area, sq ft/capita	Uncovered beds, Loading, lb solids/sq ft/yr	Covered beds area, sq ft/capita[a]
Primary			
Reference 33	1.0	27.5	
Reference 34	1.0 - 1.5		0.75 - 1.0
Reference 36			
N45° N latitude	1.25		0.93
Between 40-45° N	1.0		0.75
S40° N latitude	0.75		0.56
Primary plus chemicals			
Reference 33	2.0	22	
Reference 34	2.0 - 2.25		1.0 - 1.25
Reference 36			
N45° N latitude	2.5		1.87
Between 40-45° N	2.0		1.50
S40° N latitude	1.5		1.12
Primary plus low rate trickling filter			
Reference 33	1.6	22	
Reference 34	1.25 - 1.75		1.0 - 1.25
Reference 36			
N45° N latitude	1.87		1.56
Between 40-45°N	1.50		1.25
S40° N latitude	1.12		0.93
Primary plus waste-activated sludge			
Reference 33	3.0	15	
Reference 34	1.75 - 2.5		1.25 - 1.5
Reference 36			
N45° N latitude	2.18		1.68
Between 40-45°N	1.75		1.35
S40° N latitude	1.31		1.01

[a]Only area loading rates available for covered beds.

1 lb/sq ft/yr = 4.9 $kg/m^2/yr$
1 sq ft = 0.093 m^2

Bed Sizing Criteria

Despite the number of drying beds in use today, the lack of published bed sizing criteria have limited applicability. The majority of published and professionally utilized design data (33-36) are based on operations during the 1940s and 1950s. Tables 9-5A and 9-5B summarize the data for sand drying beds. At that time, sludges applied to sand beds were anaerobically digested. They originated predominantly in primary, primary plus low rate trickling filter, or primary plus conventional waste-activated sludge wastewater treatment processes. Many of the sludges presently generated do not readily fall within these categories.

TABLE 9-5B

SUMMARY OF RECOGNIZED PUBLISHED STATE BED SIZING CRITERIA FOR SAND BEDS BY USEPA REGIONS[a] SQUARE FEET/CAPITA

EPA Region	I		II		III[b]		IV		V[b]		VI		VII		VIII		IX		X[c]	
	U[a]	C[d]	U	C	U	C	U	C	U	C	U	C	U	C	U	C	U	C	U	C
Anaerobically digested																				
Primary only	1.5	1.0	1.5	0.75			0.5-1.0				1.0		1.0						1.5	1.0
Primary + low rate trickling filter	1.75	1.25	1.5	0.75			0.75-1.2				0.5-1.0	0.25	1.5		1.0	1.0	1.0		1.5-2.0	1.0-1.25
Primary + sand filter							1.0				1.0						0.5			
Primary + high rate trickling filter							1.0				1.0				1.25	1.25	1.0		2.0	1.25
Primary + waste activated sludge	2.5	1.5	2.0	1.0			1.5-2.5				1.0-1.5	1.0			1.35	1.35	1.0		1.5-2.5	1.0-1.5
Primary + chemical			2.0	1.0			1.0-1.33				1.0				1.5	1.3			3.0	2.0
Imhoff			1.5	0.75			0.66-1.0				1.0									
Imhoff + low rate trickling filter							1.0-1.2				1.0									

[a] Taken from individual State design criteria that do not use 10 State Standards.

[b] The states encompassed in USEPA Regions III and V do not have published requirements at this time.

[c] State of Idaho: Values shown are for rainfall of 30-45 inches (76-114 cm); for rainfall between 10-30 inches (25-76 cm), reduce these values by 25 percent; for rainfall of less than 10 inches (25 cm), reduce these values by 50 percent.

[d] U = uncovered sand beds
C = covered sand beds

1 sq ft/capita = 0.093 m^2/capita

Also, most data are given in square feet of bed surface area required for dewatering on a per capita basis. This criterion is only valid for the characteristics of a particular wastewater and has no rational design basis. A better criterion for sizing sand drying beds is the pounds of solids per square foot of bed surface area per year. The best criteria would take into consideration climatic conditions (such as temperature, wind velocity and precipitation), sludge characteristics, (grit, grease, fiber, and biological content), and solids concentration.

No generalized bed sizing criteria could be found for paved beds. Also very little information is available from full-scale facilities on bed sizing criteria for wedge-wire units. In one United States wedge-wire facility, 150 gallons per day (568 l/d) of excess biological sludge at a two percent solids concentration is conditioned with a polyelectrolyte and dewatered to a liftable eight percent solids concentration in two to three hours (27). Table 9-6 contains data on the performance of wedge-wire systems with several different sludges.

TABLE 9-6

WEDGE-WIRE SYSTEM PERFORMANCE DATA (25)

Sludge type[a]	Feed solids, percent	Sludge solids concentration, percent	Dewatering time	Solids capture, percent
Primary	8.5	25.0	14 days	99
Trickling filter humus	2.9	8.8	20 hours	85
Digested primary + waste activated sludge (WAS)	3.0	10.0	12 days	86
Fresh WAS	0.7	6.2	12 hours	94
Fresh WAS	1.1	9.9	8 days	87
Thickened WAS	2.5	8.1	41 hours	100

[a]All sludges were chemically conditioned.

9.2.1.4 Costs

Capital Costs

Several recent publications have developed capital cost curves for open sand beds (37-39). Probably the most accurate is the reference based on actual USEPA bid documents for the years 1973-1977 (38).

Although the data were scattered, a regression analysis indicated, that, on the basis of a USEPA Municipal Wastewater Treatment Plant Construction Cost Index for the 2nd quarter 1977 (38), the capital cost could be approximated by Equation 9-1.

$$C = 9.89 \times 10^4 Q^{1.35} \qquad (9\text{-}1)$$

where:

C = capital cost of process in dollars.

Q = plant design flow in million gallons of wastewater flow per day.

The associated costs include excavation, process piping, equipment, concrete, and steel. In addition, such costs as those for administrating and engineering are equal to 0.2264 times Equation 9-1 (38).

Operating and Maintenance Cost

Table 9-7 indicates open sand bed labor requirements for both operation and maintenance. The labor indicated includes: removal of dried sludge from the beds, sand maintenance, and weeding as necessary.

TABLE 9-7

SLUDGE DRYING BEDS, LABOR REQUIREMENTS (18)

Total bed area, sq ft[a]	Labor, hours per year		
	Operation	Maintenance	Total
1,000	300	100	400
5,000	400	180	580
10,000	500	220	720
50,000	1,500	710	2,210
100,000	2,900	1,500	4,400

[a]Assumes dry solids loading rate of 20 lb/sq ft/yr of bed area.

1 sq ft = 0.093 m^2
1 lb/sq ft/yr = 4.9 kg/m^2/yr

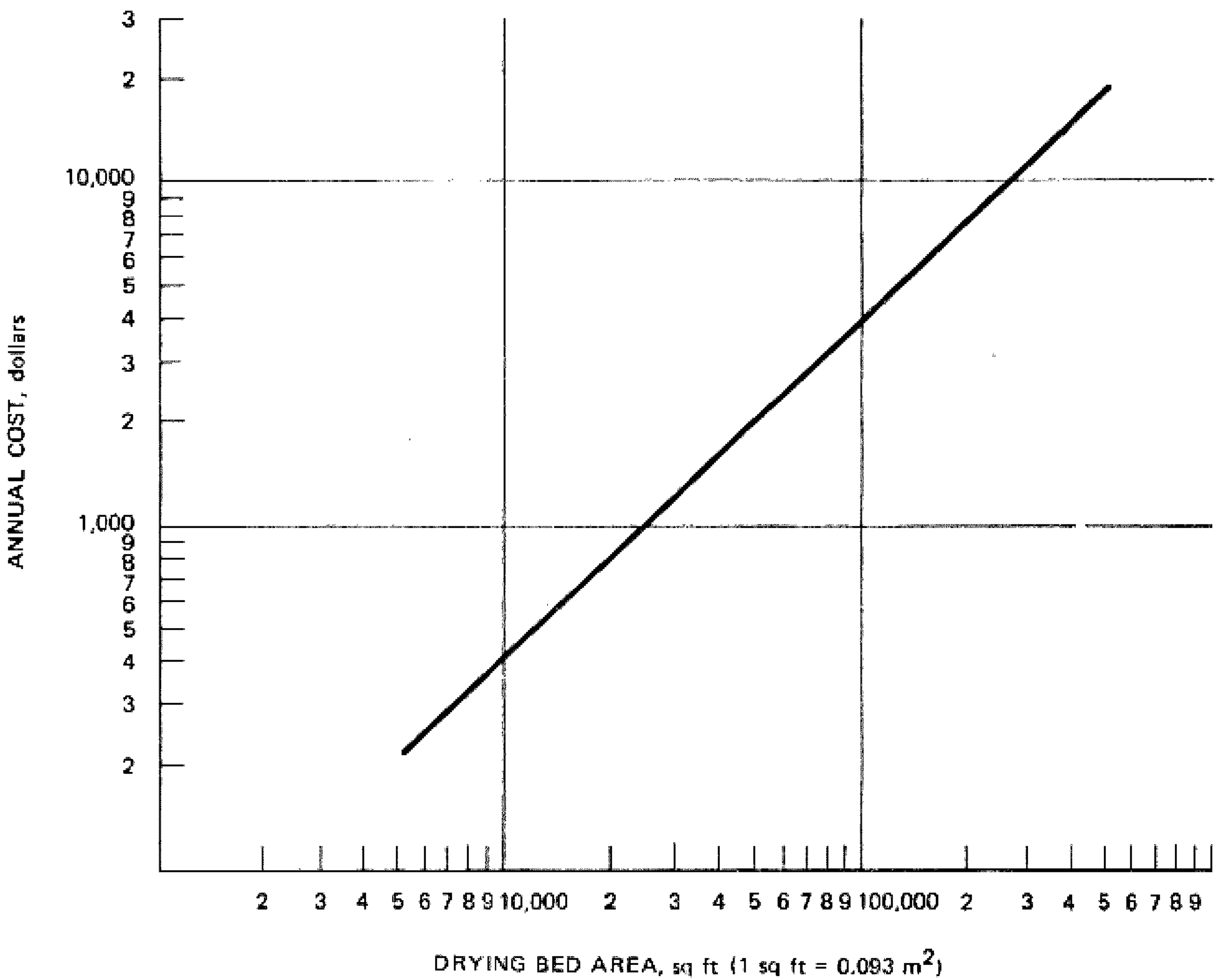

FIGURE 9-5

ESTIMATED JUNE 1975 MAINTENANCE MATERIAL COST FOR OPEN SAND DRYING BEDS (39)

Figure 9-5 shows a curve developed for estimating open sand bed maintenance material cost as a function of sand bed surface area. As an example, for a sand bed surface area of 10,000 square feet (930 m^2), a designer would estimate a yearly materials cost of $400. Since this number is based on a June 1975 cost, it must be adjusted to the current design period.

9.2.2 Drying Lagoons

Sludge drying lagoons are another method (12) of sludge dewatering when sufficient, economical land is available. Sludge drying lagoons are similar to drying beds. However, the sludge is placed at depths three to four times greater than it would be in a drying bed. Generally, sludge is allowed to dewater and dry to some predetermined solids concentration before removal and this might require one to three years. The cycle is then repeated. Sludge should be stabilized prior to addition to the lagoon to minimize odor problems. Large areas of lagoons can produce nuisance odors as they go through a series of wet and dry conditions. See Chapter 15 for further discussion. Table 9-8 lists present advantages and disadvantages for sludge drying lagoons.

TABLE 9-8

ADVANTAGES AND DISADVANTAGES OF USING SLUDGE DRYING LAGOONS

Advantages	Disadvantages
Lagoons are low energy consumers	Lagoons may be a source of periodic odor problems, and these odors may be difficult to control
Lagoons consume no chemicals	There is a potential for pollution of groundwater or nearby surface water
Lagoons are not sensitive to sludge variability	Lagoons can create vector problems (for example, flies and mosquitos)
The lagoons can serve as a buffer in the sludge handling flow stream. Shock loadings due to treatment plant upsets can be discharged to the lagoons with minimal impact	Lagoons are more visible to the general public
Organic matter is further stabilized	Lagoons are more land-intensive than fully mechanical methods
Of all the dewatering systems available, lagoons require the least amount of operation attention and skill	Rational engineering design data are lacking to allow sound engineering economic analysis
If land is available, lagoons have a very low capital cost	

Very little research has been conducted concerning sludge drying lagoons. Dewatering occurs in three ways: drainage, evaporation, and transpiration. Research seems to indicate that dewatering by drainage is independent of lagoon depth. Dewatering by drainage alone cannot produce a sludge sufficiently dry for easy removal (40,41). These studies further indicate that evaporation is the most important dewatering factor.

9.2.2.1 Basic Concept

Sludge drying lagoons consist of retaining walls which are normally earthen dikes 2 to 4 feet (0.7 to 1.4 m) high. The earthen dikes normally enclose a rectangular space with a permeable surface. Appurtenant equipment includes: sludge feed lines and metering pumps, supernatant decant lines, and some type of mechanical sludge removal equipment. The removal equipment can include a bulldozer, drag line or front-end loader. In areas where permeable soils are unavailable, underdrains and associated piping may be required.

Operating procedures common to all types of drying lagoons involve:

- Pumping liquid sludge, over a period of several months or more, into the lagoon. The pumped sludge is normally stabilized prior to application. The sludge is usually applied until a lagoon depth of 24 to 48 inches (0.7 to 1.4m) is achieved.
- Decanting supernatant, either continuously or intermittently, from the lagoon surface and returning it to the wastewater treatment plant.
- Filling the lagoon to a desired sludge depth and then permitting it to dewater. Depending on the climate and the depth of applied sludge, the time involved for dewatering to a final solids content of between 20 to 40 percent solids may be 3 to 12 months.
- Removing the dewatered sludge with some type of mechanical removal equipment.
- Resting (adding no new sludge) to the lagoon for three to six months.
- Repeating the cycle.

9.2.2.2 Design Criteria

Proper design of sludge drying lagoons requires a consideration of the following factors: climate, subsoil permeability, sludge characteristics, lagoon depth, and area management practices. A detailed discussion of these factors follows.

Climate

After dewatering by drainage and supernating, drying in a sludge lagoon depends primarily on evaporation. Proper size of a lagoon, therefore, requires climatic information concerning:

- Precipitation rate (annual and seasonal distribution).

- Evaporation rate (annual average, range, and seasonal fluctuations).

- Temperature extremes.

Subsoil Permeability

The subsoil should have a moderate permeability of 1.6×10^{-4} to 5.5×10^{-4} inches per second (4.2×10^{-4} to 1.4×10^{-3} cm/s), and the bottom of the lagoon should be a minimum of 18 inches (46 cm) above the maximum groundwater table, unless otherwise directed by local authorities.

Sludge Characteristics

The type of sludge to be placed in the lagoon can significantly affect the amount and type of odor and vector problems that can be produced. It is recommended that only those sludges which have been anaerobically digested be used in drying lagoons.

Lagoon Depth and Area

The actual depth and area requirements for sludge drying lagoons depend on several factors such as precipitation, evaporation, type of sludge, volume and solids concentration. Solids loading criteria have been given as 2.2 to 2.4 pounds of solids per year per cubic foot (36 to 39 kg/m^3) of capacity (46). A minimum of two separate lagoons are provided to ensure availability of storage space during cleaning, maintenance, or emergency conditions.

General Guidance

Lagoons may be of any shape, but a rectangular shape facilitates rapid sludge removal. Lagoon dikes should have a slope of 1:3, vertical to horizontal, and should be of a shape and size to facilitate maintenance, mowing, passage of maintenance vehicles atop the dike, and access for the entry of trucks and front-end loaders into the lagoon. Surrounding areas should be graded to prevent surface water from entering the lagoon. Return must exist for removing the surface liquid and piping to the treatment plant. Provisions must also be made for limiting public access to the sludge lagoons. Chapter 15 provides a description of a successful sludge drying lagoon operation for the Metropolitan Sanitary District of Greater Chicago.

9.2.2.3 Costs

Current published information on capital cost of constructing sludge lagoons is almost nonexistent. Some information is available from a recent USEPA publication (38), and from Chapter 15. Table 9-9 indicates labor requirements for sludge drying lagoons. The requirements include: application of sludge to the lagoon; periodic removal of supernatant; periodic removal of solids; and minor maintenance requirements, such as dike repair and weed control. No information could be found on maintenance material costs.

TABLE 9-9

SLUDGE DRYING LAGOONS, LABOR REQUIREMENTS (18)

Dry solids applied, tons/year	Labor, hours per year		
	Operation	Maintenance	Total
100	30	55	85
1,000	55	90	145
10,000	120	300	420
50,000	450	1,500	1,950

1 ton = 0.9 t

9.3 Centrifugal Dewatering Systems

9.3.1 Introduction

Centrifuges were first employed in the United States for dewatering municipal wastewater treatment plant sludges during the year 1920, in Milwaukee, Wisconsin, and during 1921 in Baltimore, Maryland (42). Early centrifuges were not designed to process extremely variable slurries such as those of municipal wastewater treatment plants. In addition, most wastewater treatment facilities provided little, if any, preventive maintenance. Consequently, early installations developed numerous operational and maintenance problems, and this led to an anti-centrifuge reaction among environmental engineers.

By the late 1960s, equipment manufacturers were designing and building new machines specifically for wastewater sludge applications, and the use of centrifuges for municipal sludge dewatering increased. In the past ten years, continuous improvements in design and materials have led to better machines. The machines now available (1979) require less power and attention and produce less noise.

Two categories of centrifuges are used for municipal wastewater sludge dewatering: imperforate basket and scroll-type decanter. A detailed discussion of each follows. The basic theory of thickening and process costs are presented in Chapter 5.

9.3.2 Imperforate Basket

Basket centrifuges for dewatering municipal wastewater treatment plant sludges were first used in the United States in 1920 (42). Since the mid 1960s approximately 300 machines were installed in 100 municipal treatment plant applications (43). About one-half of the installed machines are used for dewatering; the other half and used for thickening. The largest centrifuge facility in the world is located at the County Sanitation Districts of Los Angeles County Carson Plant in California, and uses 48 basket centrifuges (44). Table 9-10 lists the advantages and disadvantages of a basket centrifuge compared with other dewatering systems.

TABLE 9-10

ADVANTAGES AND DISADVANTAGES OF BASKET CENTRIFUGES

Advantages	Disadvantages
Same machine can be used for both dewatering and thickening	Requires special structural support
It may not require chemical conditioning	Except for vacuum filter, consumes more direct horsepower per unit of product processed
Centrifuges have clean appearance, little-to-no odor problems, and fast start-up and shut-down capabilities	Skimming stream could produce significant recycle load
Basket centrifuge is very flexible in meeting process requirements	Limited size capacity
It is not affected by grit	For easily dewatered sludges, has the highest capital cost versus capacity ratio
It is an excellent dewatering machine for hard-to-handle sludge	For most sludges, gives the lowest cake solids concentration
It has low total operation and maintenance costs.	
Does not require continuous operator attention	

9.3.2.1 Principles of Operation

The operation of an imperforate basket centrifuge is described in Chapter 5. There is, however, one additional operation to be added to that discussion.

After the centrifuge bowl is filled with solids, the unit starts to decelerate. In the thickening mode, deceleration was to a speed of 70 rpm or lower before commencement of plowing. In the dewatering mode, another step called "skimming" takes place before the initiation of plowing. Skimming is the removal of soft sludge from the inner wall of sludge within the basket centrifuge. The skimmer moves from its position in the center of the basket towards the bowl wall. The amount of horizontal travel is set at the time of installation, and start-up depends on sludge type and downstream processing requirements. The skimming volume is normally 5 to 15 percent of the bowl volume per cycle. After the skimmer retracts, the centrifuge further decelerates to the 70 rpm level for plowing. Skimming streams are typically 6 to 18 gallons (22 to 66 l) per cycle with a solids content of almost zero to eight percent. Treatment of this stream is typically by returning it either to the primary or secondary wastewater treatment system, or to some other pre-sludge handling step such as a thickener.

9.3.2.2 Application

A basket centrifuge is well suited for small plants that do not provide either primary clarification or grit removal (for example, wastewater plants that use extended aeration, aerated lagoons, and contact stabilization). These small plants require a piece of equipment that can, at different times, dewater or thicken conventional as well as biological sludges with a long sludge age. Also low overall operation and maintenance, and low operating costs, are associated with basket centrifuges.

9.3.2.3 Performance

Table 9-11 lists typical performance data for a basket centrifuge in a number of different applications. These data are expected values and are based on the performance of several different installations. Table 9-12 lists the average results from two specific operating facilities.

9.3.2.4 Case History

In 1973, a dewatering study was made in Burlington, Wisconsin, on the wastewater treatment facility located there (46). The plant treats a combination of domestic-industrial wastewater flow of 1.5 MGD (66 l/s) during dry weather and 2.0 MGD (88 l/s) during wet weather. The treatment plant has no primary clarification and uses the contact stabilization process with aerobic digestion. Approximately 150,000 gallons (568 m^3) per week of aerobically digested sludge with a 1.4 percent solids concentration requires disposal.

As the plant is located on a low flood plain, it was originally necessary to truck the dilute sludge to the lagoon. In 1972, the Wisconsin Department of Natural Resources ordered Burlington to discontinue use of the lagoons. Since the only options available were landfilling or cropland application, dewatering was required. In 1973, an engineering evaluation was performed to select the optimum dewatering unit. The equipment evaluated included: an imperforate basket centrifuge, a recessed plate filter, a horizontal belt filter press, and a rotary drum vacuum

TABLE 9-11

TYPICAL PERFORMANCE DATA FOR AN IMPERFORATE BASKET CENTRIFUGE

Sludge type	Feed solids concentration, percent solids	Average cake solids concentration, percent solids	Polymer required, pounds dry per ton dry feed solids	Recovery based on centrate,[a] percent
Raw primary	4-5	25-30	2-3	95-97
Raw trickling filter	2-3	9-10	0	90-95
(rock or plastic media)		10-12	1.5-3.0	95-97
Raw waste activated	0.5-1.5	8-10	0	85-90
		12-14	1.0-3.0	90-95
Raw primary plus rock	2-3	9-11	0	95-97
trickling filter (70-30)		7-9	1.5-3.0	94-97
Raw primary plus waste activated (50-50)	2-3	12-14	1-3	93-95
Raw primary plus rotating	2-3	20-24	0	85-90
biological contactor (60-40)		17-20	4-6	98+
Anaerobically digested	1-2	12-14	0	75-80
primary plus waste		10-12	1.5-3.0	85-90
activated (50-50)		8-10	4-6	93-95
Aerobically digested	1-3	8-11	0	80-95
		12-14	1-3	90-95
Combined sewer overflow treatment sludge	Extremely variable - see study by EPA (45)			
Centrate from decanter dewatering lime sludge	1-2	10-13	0	95-98

[a]Skimming losses, if any, have not been used in calculating recovery.

1 lb/ton = 0.50 kg/t

TABLE 9-12

SPECIFIC OPERATING RESULTS FOR IMPERFORATE BASKET

	County sanitation district of Los Angeles, CA (44)	Burlington, WI (46)	
Type of sludge	Centrate from solid bowl decanter dewatering anaerobically digested primary sludge	Aerobically digested, activated sludge from a plant without primary clarification	
Instantaneous flow rate, gpm	50	23	88
Feed solids concentration, mg/l	29,000	14,000	14,000
Polymer requirement	4[a]	0	30[b]
Cake solids content, percent	20	6-8	13-15
Centrate, mg/l	1,500	100	100
Skimmed volume, percent of total basket volume	Not given	50	14

[a]Dry polymer at 4 lb/ton (2.0 kg/t) of dry solids.

[b]Combination anionic-cationic system. Thirty dollars/ton ($33/t) of dry solids.

1 gpm = 0.063 l/s

filter. The recessed plate pressure filter option was ruled out as too expensive for Burlington's small plant. The horizontal belt filter press produced a low cake solids concentration and required high levels of polymer addition at a cost of $40 per ton ($44.44/t). The vacuum filter was not selected because of high capital cost. The imperforate basket was selected as the most cost-effective unit. Figure 9-6 shows a flow scheme of the Burlington wastewater treatment plant as it was operating in 1977.

The original design, as a result of the engineering evaluation, called for one basket centrifuge to operate 40 hours per week. This centrifuge was to dewater 96,000 gallons (370 m^3) per week of sludge at a 1.8 percent solids concentration to a nine to ten percent solids concentration without the use of polymers. This was all based on several days of pilot plant work conducted several months before equipment selection was made. At the time of centrifuge start-up, the actual sludge volume to be dewatered was 150,000 gallons (568 m^3) per week at 1.4 percent solids concentration. The column labeled "Without Polymer" in Table 9-13 shows performance results under this condition. Because of the 50 percent greater sludge volume and poorer operating results than had been indicated by pilot testing, the basket centrifuge had to operate 24 hours per day, seven days per week. This type of operation was prohibitive for a plant the size of the Burlington facility.

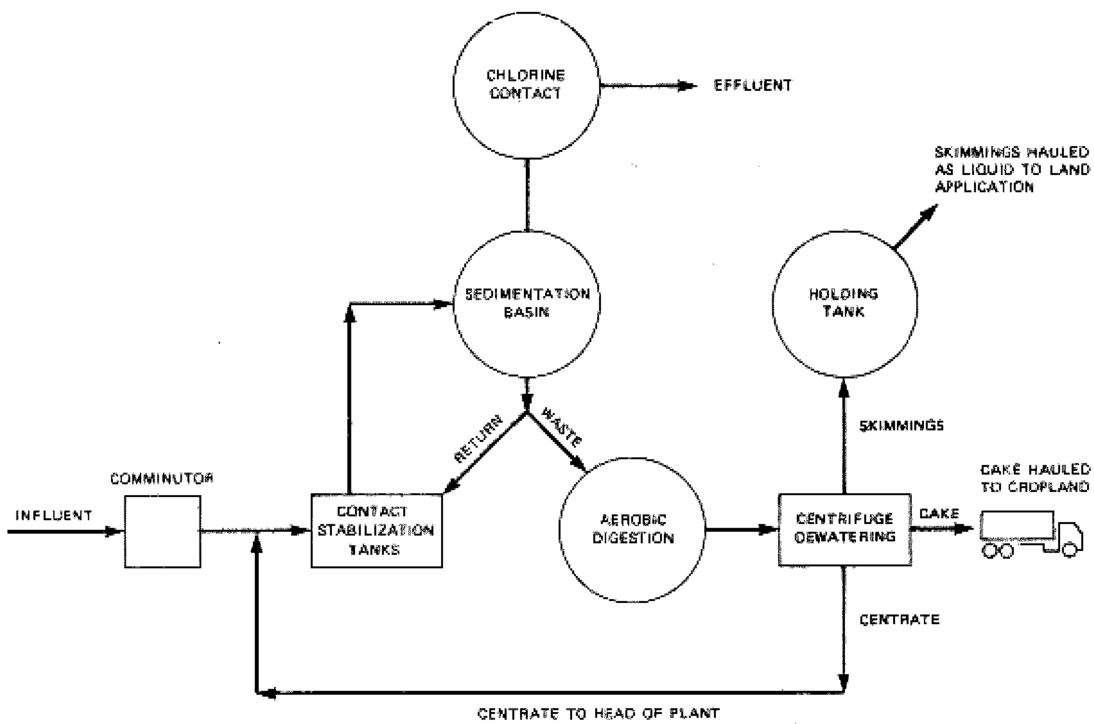

FIGURE 9-6

1977 FLOW DIAGRAM OF BURLINGTON, WISCONSIN WASTEWATER TREATMENT PLANT

TABLE 9-13

OPERATING RESULTS FOR BASKET CENTRIFUGE DEWATERING OF AEROBICALLY DIGESTED SLUDGE AT BURLINGTON, WISCONSIN

	Without polymer	With polymer
Gal/week of sludge to dewater	150,000	150,000
Lb/week of sludge to dewater	17,500	17,500
Instantaneous feed rate, gpm	23	88
Feed solids concentration, mg/l	14,000	14,000
Hr/week operation required	168	44
Labor and trucking cost (dollars)/week at 45 percent of the time	378	99
Electricity utilized/week, kWhr	4,888	1,584
Electricity cost at $0.03/kWhr	146.63	47.52
Chemical cost, dollars/ton	0	30
Cake solids, percent	6-8[a]	13-15[b]
Skimming volume of basket, percent of total	50	14
Cost/ton, dollars	59.96	46.74

[a]Material was untruckable.

[b]Material was truckable.

1 gpm = 3.78 l/min
1 gal = 3.78 l
1 lb = 0.454 kg
1 ton = 0.907 t
1 kWhr= 3.6 MJ

The plant superintendent instituted a polymer testing program and evaluated several hundred polyelectrolytes. The final selection resulted in the addition of an anionic polymer to the sludge feed line at a point several feet upstream of the sludge entry to the basket and then the addition of a cationic polymer at the bowl. The results of using polyelectrolytes are given in the column labeled "With Polymer" in Table 9-13. The results show that operating costs were $13.22 per ton ($14.69/t) cheaper with polymer addition than without. The savings occurred in reduced labor and power requirements.

9.3.3 Solid Bowl Decanters

Decanter centrifuges for dewatering municipal wastewater treatment plant sludges were first used in the United States in the mid 1930s. Since then, approximately 500 machines have been placed in 175 municipal installations (43). Most of these installations were for dewatering applications. Table 9-14 lists the advantages and disadvantages of a solid bowl decanter centrifuge compared with other dewatering processes.

TABLE 9-14

ADVANTAGES AND DISADVANTAGES OF SOLID BOWL DECANTER CENTRIFUGES

Advantages	Disadvantages
Centrifuges have clean appearance, little-to-no-odor problems, and fast start-up and shut-down capabilities	Scroll wear potentially a high maintenance item
It is easy to install	Requires grit removal or possibly a grinder in the feed stream
Provides high throughput in a small surface area	Requires skilled maintenance personnel
Gives for many sludges a cake as dry as any other mechanical dewatering process except for pressure filtration systems	
Has one of the lowest total capital cost versus capacity ratios	
Does not require continuous operator attention	

9.3.3.1 Application

Early applications of solid bowl centrifuges were for dewatering coarse easily dewaterable municipal wastewater treatment plant sludges. These included raw primary, anaerobically digested primary, and lime sludges, to name a few. The application of centrifuges to dewatering mixtures of sludges containing greater than 50 percent by weight of waste-activated sludges was limited because of very poor centrate quality. Advancements in design, especially in the entrance configuration, had reduced floc shear. The development of new polyelectrolytes has also contributed to greatly improving centrate quality. These developments have made the solid bowl decanter centrifuge applicable to a much wider range of sludge types. Further available capacities range from 6 gallons per minute (22 to 38 l/min) to over 400 gallons per minute (1,514 l/min). The decanter can successfully operate with a highly variable feed.

9.3.3.2 Performance

Table 9-15 lists operating results that can be expected when dewatering the sludges indicated with a solid bowl decanter. The data in this table can be used for conducting engineering evaluations when actual test results are not available.

TABLE 9-15

TYPICAL PERFORMANCE DATA FOR A SOLID BOWL DECANTER CENTRIFUGE

Sludge type	Feed solids concentration, percent solids	Average cake solids concentration, percent solids	Polymer required, pounds dry per ton dry feed solids	Recovery based on centrate, percent
Raw primary	5-8	25-36	1-5	90-95
		28-36	0	70-90
Anaerobically digested	2-5	28-35	6-10	98+
primary	9-12	30-35	0	65-80
		25-30	1-3	82-92
Anaerobically digested primary irradiated at 400 kilorads	2-5	28-35	6-10	95+
Waste-activated	0.5-3	8-12	10-15	85-90
Aerobically digested waste-activated	1-3	8-10	3-6	90-95
Thermally conditioned				
primary + waste-activated	9-14	35-40	0	75-85
	13-15	29-35	1-4	90-95
primary + trickling filter	7-10	35-40	0	60-70
		30-35	2-4	98+
High lime	10-12	30-50	0	90-95
Raw primary + waste-activated	4-5	18-25	3-7	90-95
Anaerobically digested	2-4	15-18	7-10	90-95
(primary + waste-activated)	4-7	17-21	4-8	90-95
Anaerobically digested	1.5-2.5	18-23	2-5	85-90
(primary + waste-activated) + trickling filter)		14-16	12-15	85-90
Combined sewer overflow treatment sludge	Extremely variable - see study by USEPA 45			

1 lb/ton = 0.50 kg/t

9.3.3.3 Other Considerations

Solid bowl decanter centrifuges are available in either countercurrent or concurrent flow design and either "high speed" or "low speed" design. In the countercurrent design, the sludge feed enters through the small diameter end of the bowl, and solids are conveyed towards the same end. In the concurrent flow design, the sludge feed enters through the large diameter end of the bowl and solids are conveyed towards the opposite end. Concurrent flow units have only been in use for about ten years. The reasons for conveying solids away from the sludge inlet are to reduce inlet turbulence conditions and therefore reduce floc shear and to provide a longer residence time for the solids. Though there are reports from Europe (47) indicating advantages of concurrent designs over countercurrent designs, United States experience is limited. One extensive comparative study (48) showed the countercurrent design to perform best on aerobically digested waste-activated sludge and the concurrent one to perform best on raw waste-activated sludge.

There is considerable controversy over the benefits associated with "high speed" or "low speed" solid bowl decanter centrifuges. One aspect of this controversy is the definition of "high speed" and "low speed." In a publication by one of the major suppliers of "low speed" machines (49), "low speed" was generally defined as a bowl speed of 1,400 rpm or less.

Manufacturers indicate that "low speed" decanter centrifuges consume less energy; require less polymer addition to the sludge; have a lower noise level; and require less maintenance than a comparable "high speed" machine to satisfy the same requirements. This combination should therefore give "low speed" machines a significant economical advantage on a total cost per unit weight of solids dewatered. European work seems to substantiate this (29), but this has not been the case in the United States. In very extensive side-by-side studies conducted at the Dallas-Fort Worth, Texas (50), Chicago-Calumet, Illinois, (9), Chicago-West-Southwest, Illinois (50), Milwaukee, Wisconsin (48), and Columbus, Ohio-Southerly wastewater treatment plants (50), "low speed" machines were not overall clearly advantageous compared to the high speed ones. In fact, in most cases, they were more expensive on a total cost basis than the "high speed" machines.

Additional information on solid bowl decanter centrifuges can be found in Chapter 5.

9.4 Filtration Dewatering Systems

9.4.1 Introduction

Filtration can be defined as the removal of solids from a liquid stream by passing the stream through a porous medium which retains the solids. Figure 9-7 shows a flow diagram of a filtration system.

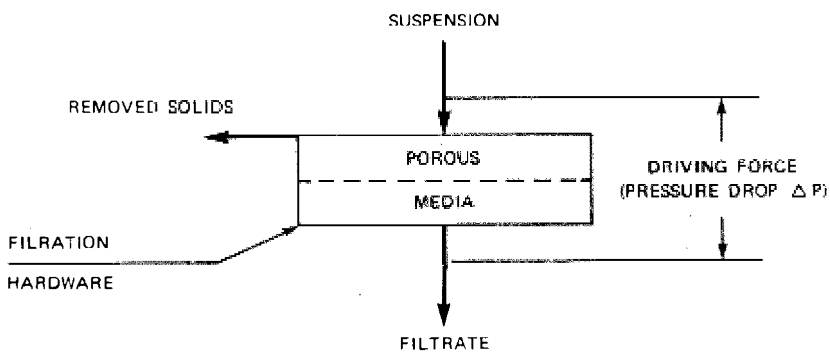

FIGURE 9-7

FLOW DIAGRAM OF A FILTRATION SYSTEM (51)

As indicated on Figure 9-7, a pressure drop is required in order for liquid to flow through the porous medium. This pressure drop can be achieved in four ways: by creating a vacuum on one side of the porous medium, by raising the pressure above atmoshperic pressure on one side of the medium, by creating a centrifugal force on an area of the porous medium, and by designing to make use of gravitational force on the medium.

Sludge filtration-dewatering processes use one or more of these driving forces and fall under the general filtration category of surface filters. "Surface filters are the general type of filtration in which solids are deposited in the form of a cake on the upstream side of a relatively thin filter medium" (54).

9.4.2 Basic Theory

All filtration theory stems from Darcy's original work in the mid-1850s (52). Darcy found that the flow rate Q of a filtrate of viscosity μ through a bed of thickness L and face area A was related to the driving pressure ΔP. This relationship is shown in Equation 9-2.

$$Q = \frac{KA\Delta p}{\mu L} \tag{9-2}$$

where K is a constant referred to as the permeability of the bed. Many times, Equation 9-2 is written:

$$Q = \frac{A\Delta p}{\mu R}$$

where R is called the medium resistance and is equal to L/K, the medium thickness divided by the bed permeability.

Extensive research has been, and continues to be, conducted in defining the factors involved and level of influence in dewatering both compressible or incompressible sludges. A comprehensive discussion on filtration has recently been published (51). This discussion, through examples, shows the effects of constant pressure filtration; constant rate filtration; constant rate-constant pressure filtration; and variable pressure and variable rate filtration on both compressible and non-compressible sludges.

9.4.3 Filter Aids

Filter aid is material such as diatomite, perlite, cellulose, or carbon (50) that serves to improve, or increase the filtration rate by physical means only. Filter aids are not added directly to the sludge body, as a conditioning agent is, but they are added in fixed amounts to the porous medium of the particular dewatering equipment. The amount of filter aid added is independent of sludge solids concentration. The filter aid literally becomes the "filtering surface" that achieves the liquid/solids separation, and the equipment functions as a filter holder. In order to perform its function satisfactorily, the filter aid's particles should be inert, insoluble, incompressible, and irregularly shaped, porous, and small (53).

Filter aids normally assist in dewatering difficult-to-handle industrial sludges by either vacuum filtration or pressure filtration (54). In the past ten years, research has been performed on the use of filter aids for improved dewatering of municipal wastewater treatment plant sludges (55). Table 9-16 lists results obtained from several test studies in which either a rotary drum vacuum filter or a recessed plate pressure filter were used.

TABLE 9-16

PRECOAT[a] PROCESS PERFORMANCE ON FINE PARTICULATE SLUDGES

Case	Sludge properties			Performance			
	Feed solids concentration, percent	Particle size, micron	Specific resistance x 10^7, sec^2/gm	Solids loading, lb/sq ft/hr	Cake solids, percent	Diatomite used, lb/ton dry solids	Solids capture, percent
1. Mixture alum and WAS[b] - RVPF[c]	0.5	4	354	0.28	26	820	99.9+
	5.0	2	-	1.00	23	280	99.9+
2. WAS - RVPF	2.2	10	3.2	2.20	25 - 30	160	99.9+
conditioned WAS-FP[d]	11.4[e]	-	-	0.30	40 - 45	-	98.5
3. WAS - RVPF	1.0 - 2.0	-	40 - 790	0.55 - 2.09	26 - 33	140	99.9+
conditioned WAS-FP	1.0 - 2.0	-	2 - 317	0.23 - 1.44	26 - 40	200	98.0
4. WAS - RVPF	1.5	-	53	0.88	29	280	99.9+
conditioned WAS-RVPF	1.5	-	16.8	2.51	25	120	99.9+
5. Alum RVPF	0.4 - 0.8	-	-	0.3	25 - 30	800	99.9+
6. Alum RVPF	8.0	15	118	1.37	25	120	99.9+

[a]Diatomite.
[b]Waste-activated sludge.
[c]Rotary vacuum precoat filter.
[d]Filter press.
[e]Fly ash conditioning and precoat.

1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 ton = 0.907 t
1 lb = 0.454 g
1 lb/ton = 0.5 kg/t

9.4.4 Vacuum Filters

In vacuum filtration, atmospheric pressure, due to a vacuum applied downstream of the media, is the driving force on the liquid phase that moves it through the porous media.

Vacuum filters were patented in England in 1872 by William and James Hart. The first United States application of a vacuum filter in dewatering municipal wastewater treatment plant sludge was in the mid-1920s (56). Until the 1960s, the drum or scraper-type rotary vacuum filter was predominant. Since then, the belt-type filter with natural or synthetic fiber cloth, woven stainless steel mesh, or coil springs media has become dominant. Recently, dewatering of municipal sludges by a top feed vacuum filter has been studied on a pilot scale (57). Results indicated that yields could be improved by 15 to 20 percent. The full scale operation is expected to begin in the summer of 1979. Table 9-17 lists the advantages and disadvantages of vacuum filtration when it is compared to other dewatering processes.

TABLE 9-17

ADVANTAGES AND DISADVANTAGES OF USING ROTARY DRUM VACUUM FILTERS

Advantages	Disadvantages
Does not require skilled personnel	Consumes the largest amount of energy per unit of sludge dewatered in most applications
Has low maintenance requirements for continuous operating equipment	Requires continuous operator attention
Provides a filtrate with a low suspended solids concentration	Auxiliary equipment (vacuum pumps) are very loud

9.4.4.1 Principles of Operation

Figure 9-8 shows the cutaway view of a drum or scraper-type, rotary vacuum filter. The unit consists mainly of a horizontal cylindrical drum that rotates, partially submerged, in a vat of conditioned sludge. The drum surface is divided into sections around its circumference. Each section is sealed from its adjacent section and the ends of the drum. A separate drain line connects each section to a rotary valve at the axis of the drum. The valve has "blocks" that divide it into zones corresponding to the parts of the filtering cycle. These zones are for cake forming, cake drying, and cake discharging. A vacuum is applied to certain zones of the valve and subsequently to each of the drum sections through the drainlines as they pass through the different zones in the valve.

Figure 9-9 illustrates the various operating zones encountered during a complete revolution of the drum.

About 10 to 40 percent of the drum surface is submerged in a vat containing the sludge slurry. This portion of the drum is referred to as the cake forming zone. Vacuum applied to a submerged drum section causes filtrate to pass through the media and cake to be formed on the media. As the drum rotates, each section is successively carried through the cake forming zone to the cake drying or dewatering zone. This zone is also under vacuum and begins where and when a drum section carries formed

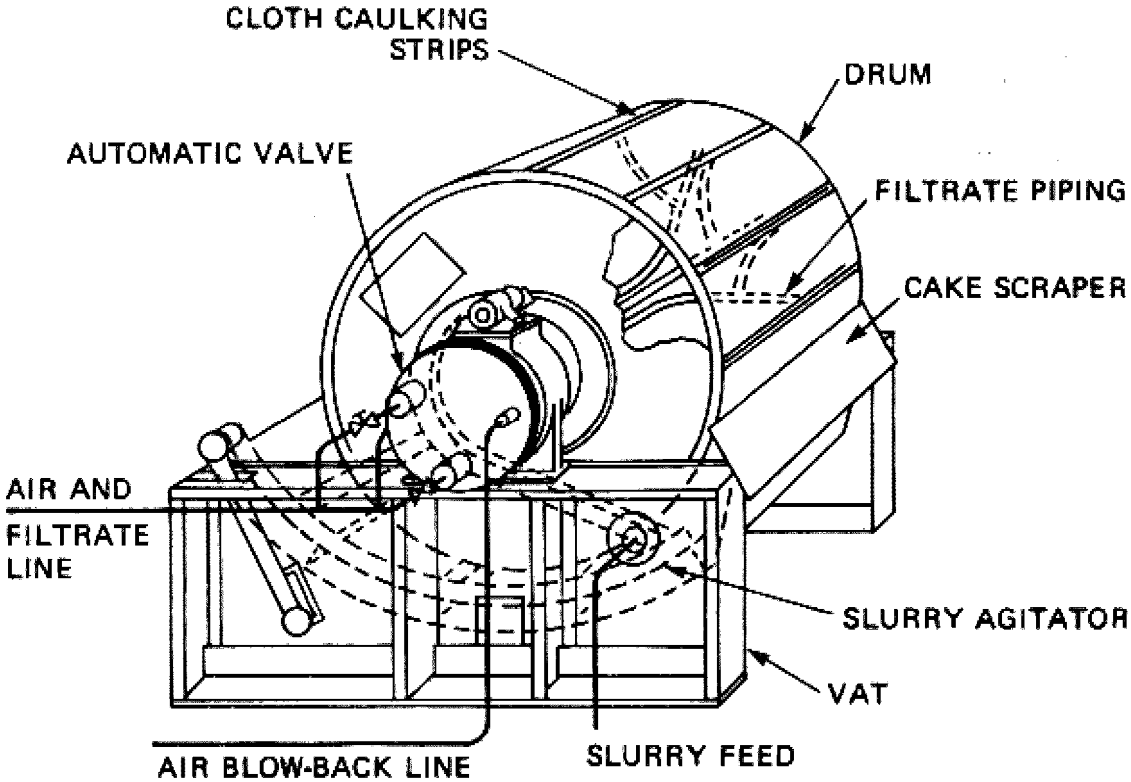

FIGURE 9-8

CUTAWAY VIEW OF A DRUM OR SCRAPER-TYPE ROTARY VACUUM FILTER

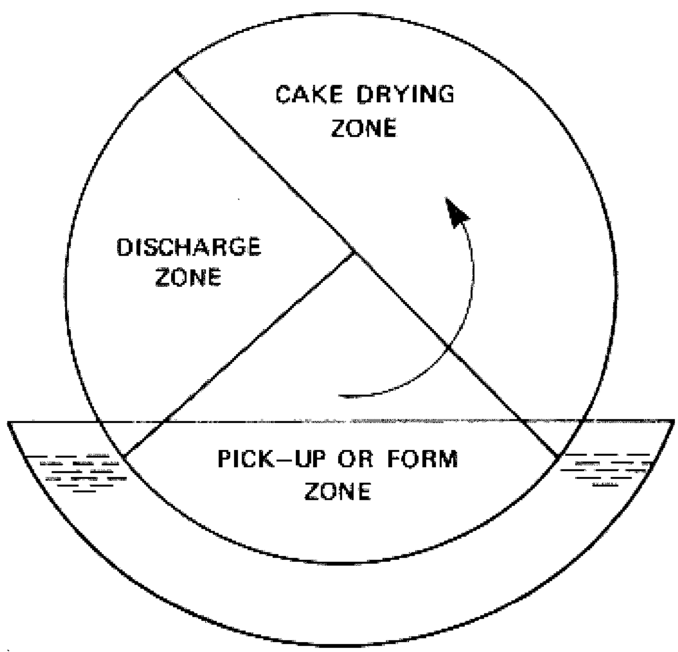

FIGURE 9-9

OPERATING ZONES OF A ROTARY VACUUM FILTER cake out of the sludge vat. The cake drying zone represents from 40 to 60 percent of the drum surface and terminates at the point where vacuum is shut off to each successive section. At this point, the sludge cake and drum section enter the cake discharge zone. In this final zone, cake is removed from the media. Belt-type rotary vacuum filters differ from the drum or scraper-type units, because the drum covering or media-belt leaves the drum. There are basically two coverings used with belt-type units: coil springs or fiber cloth.

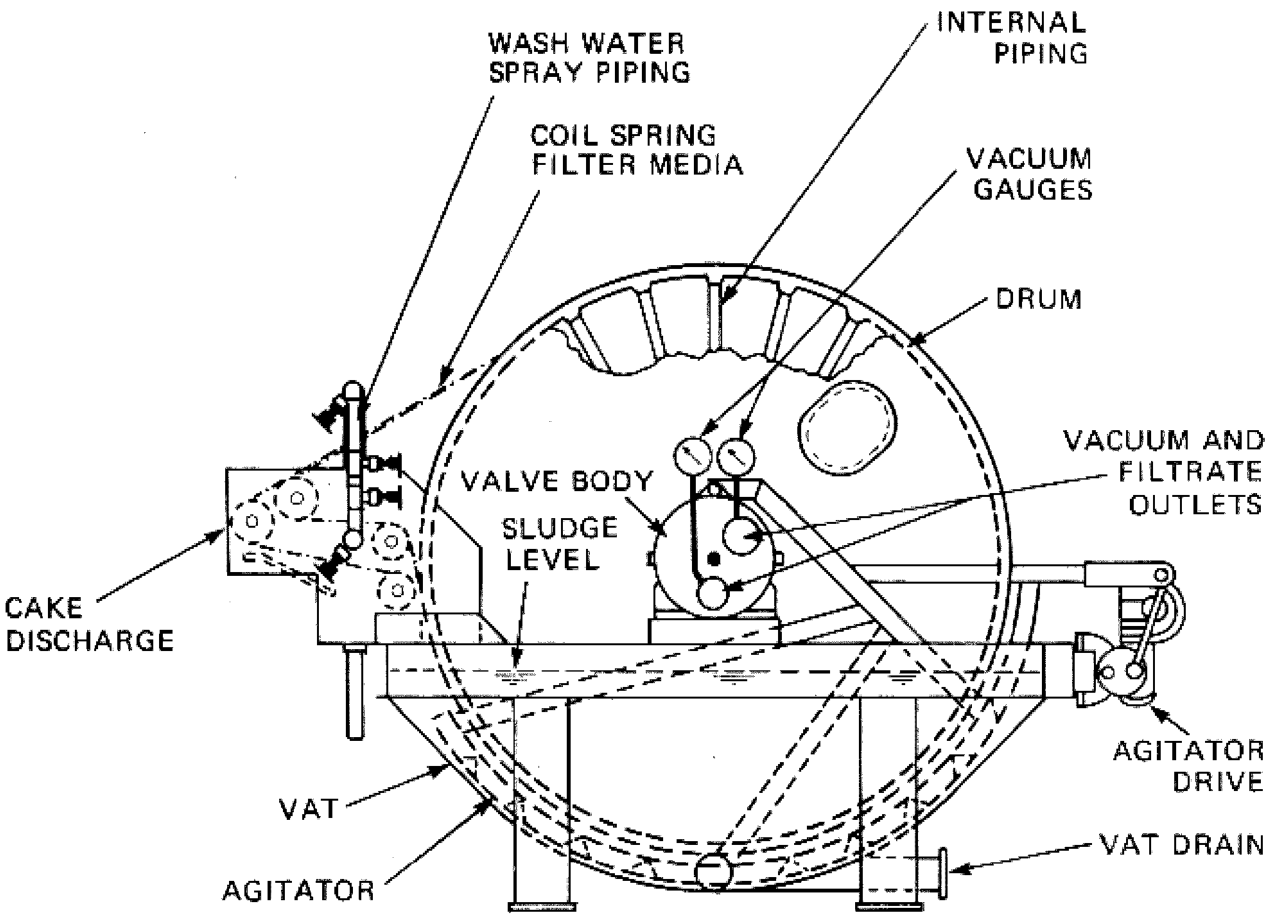

FIGURE 9-10

CROSS SECTIONAL VIEW OF A COIL SPRING - BELT TYPE - ROTARY VACUUM FILTER

Figure 9-10 shows a cross sectional view of a coil filter spring-belt type rotary vacuum. This filter uses two layers of stainless steel coils arranged around the drum. After the dewatering cycle, the two layers of springs leave the drum and are separated from each other. In this way, the cake is lifted off the lower layer of springs and can be discharged from the upper layer. Cake release is essentially never a problem. After cake discharge, the coils are washed and returned to the drum.

The coil filter has been and is widely used for all types of sludge. However, sludges with particles that are both extremely fine and resistant to flocculation dewater poorly on coil filters. Figure 9-11 shows a typical installation.

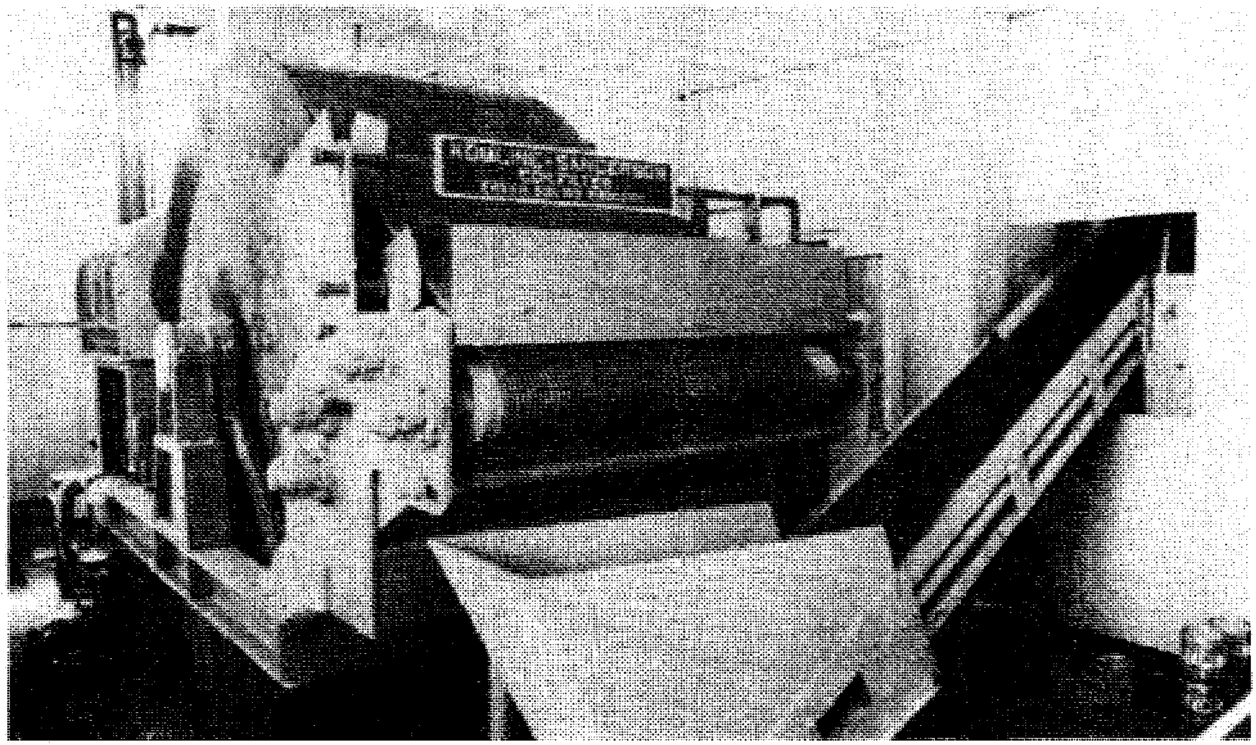

FIGURE 9-11

TYPICAL COIL SPRING - BELT TYPE - ROTARY VACUUM FILTER INSTALLATION

Figure 9-12 shows a schematic cross section of a fiber cloth-belt, rotary vacuum filter. Media on this type unit leaves the drum surface at the end of the drying zone and passes over a small-diameter discharge roll to facilitate cake discharge. Washing of the media occurs after discharge and before it returns to the drum for another cycle. This type of filter normally has a small-diameter curved bar between the point where the belt leaves the drum and the discharge roll. This bar aids in maintaining belt dimensional stability. In practice, it is frequently used to ensure adequate cake discharge. Remedial measures, such as addition of scraper blades, use of excess chemical conditioner, or addition of fly ash, are sometimes required to obtain cake release from the cloth media. This is particularly true at wastewater treatment plants which produce sludges that are greasy, sticky, and/or contain a large quantity of activated sludge. Figure 9-13 shows a typical installation.

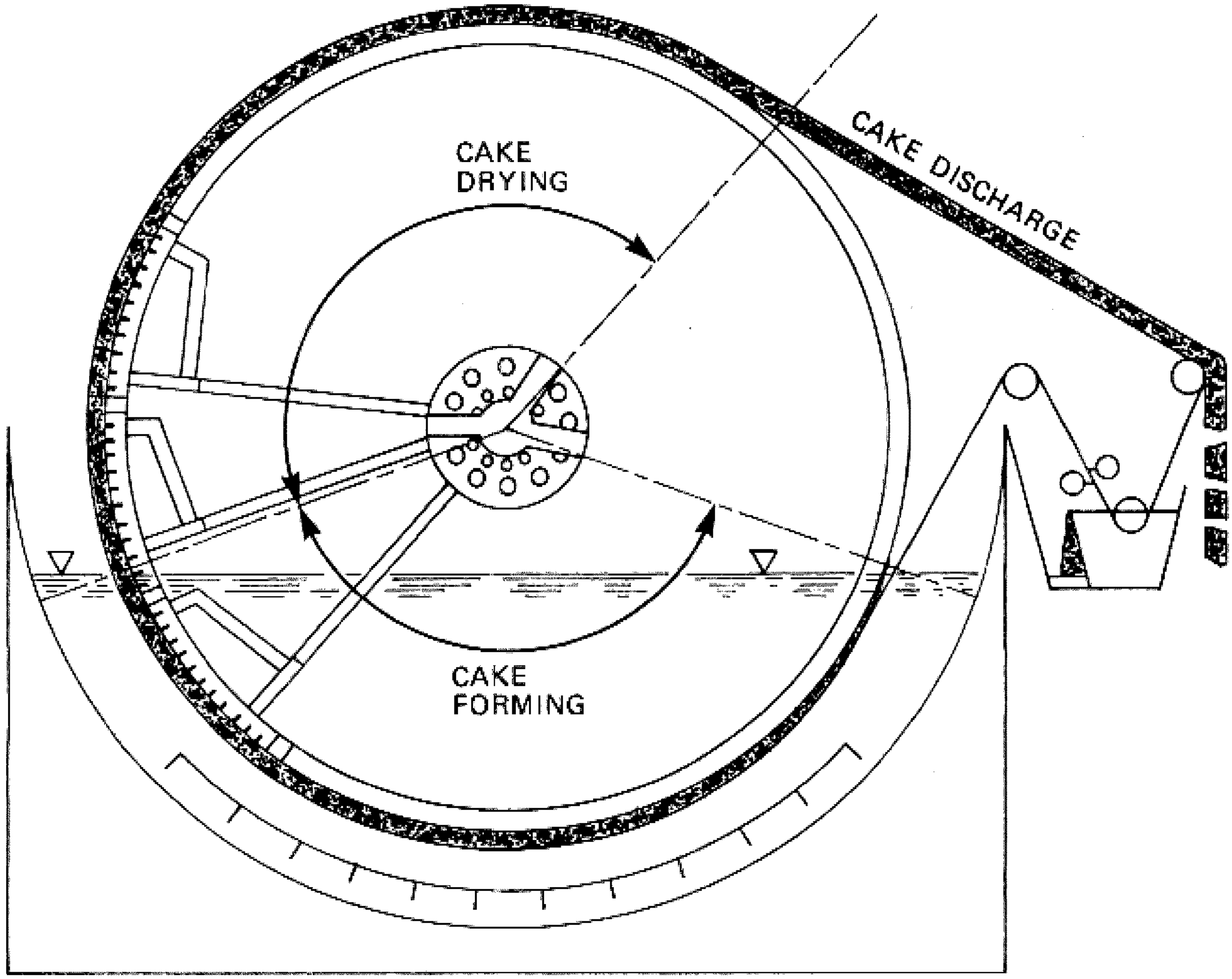

FIGURE 9-12

CROSS SECTIONAL VIEW OF A FIBER CLOTH - BELT TYPE - ROTARY VACUUM FILTER

9.4.4.2 Application

Vacuum filters have probably been used to dewater more types of municipal wastewater treatment plant sludges than any other mechanical dewatering equipment. Since the mid-1920s, more than 1,700 vacuum filters have been installed in over 800 United States municipalities (43). The era of vacuum filtration may be declining. Improvements in other dewatering devices, as well as the development of new dewatering devices, have permitted municipalities to dewater their sludge as well as they could with vacuum filters but at lower operation and maintenance costs.

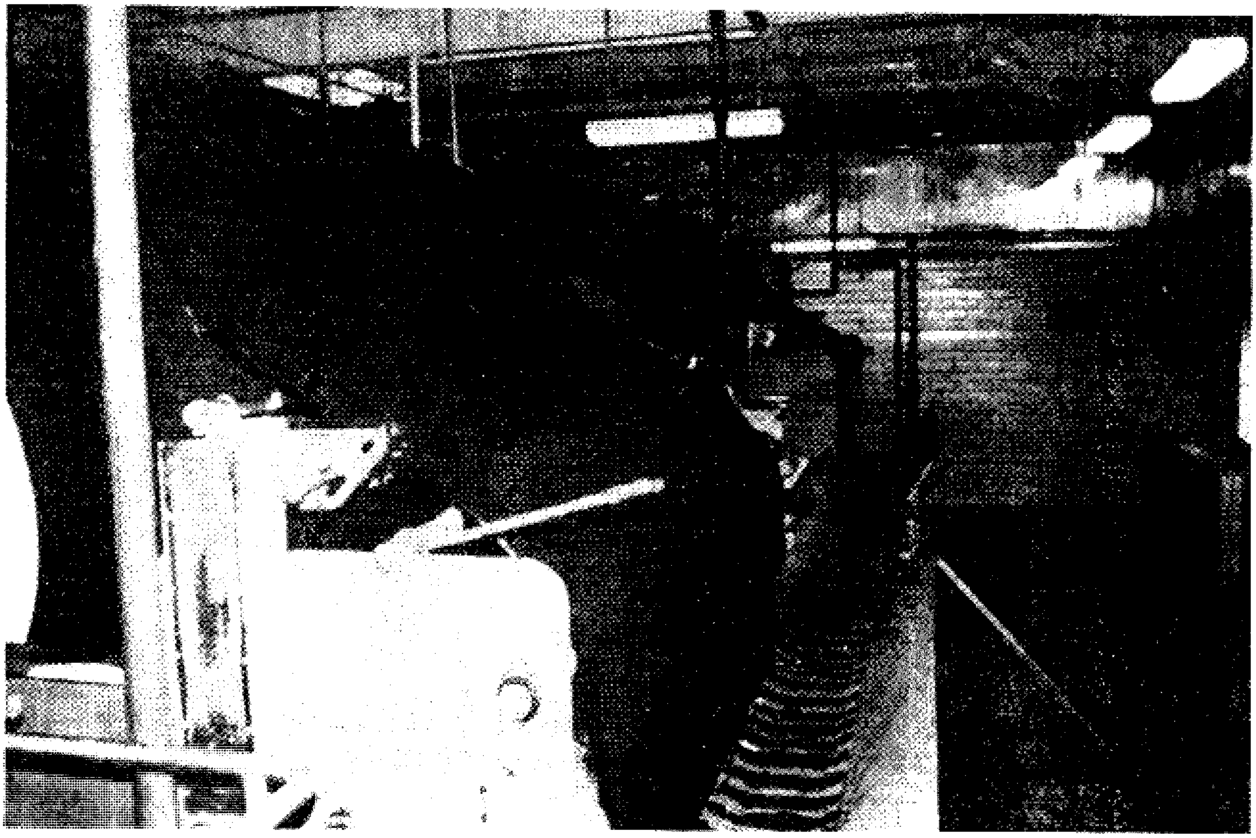

FIGURE 9-13

TYPICAL FIBER CLOTH - BELT TYPE - ROTARY VACUUM FILTER

9.4.4.3 Performance

As with all types of mechanical dewatering equipment, optimum performance is dependent upon the type of sludge and its solids concentration, type and quality of conditioning, and how the filter is operated. Selection of vacuum level, degree of drum submergence, type of media, and cycle time are all critical to optimum performance. Tables 9-18 and 9-19 contain expected performance data for cloth and coil media rotary vacuum filters for the sludge types indicated. Tables 9-20 and 9-21 contain specific operating data for several wastewater treatment plants using cloth media and coil media.

9.4.4.4 Other Considerations

Auxiliary Equipment

Rotary vacuum filters are normally supplied with auxiliary equipment including vacuum pump, filtrate receiver and pump, and sludge conditioning apparatus. Figure 9-14 shows a typical complete rotary vacuum filter process. Usually, one vacuum pump is provided for each vacuum filter, although some larger plants use less than one pump per filter and the pumps connect to a common header. Until the 1960s, reciprocating type dry vacuum pumps were generally specified, but since the early 1970s wet type vacuum pumps are universally used. The wet type pumps are more easily maintained and provide sufficient vacuum. Wet type pumps utilize seal water, and it is essential that a satisfactory water be used. If the water is hard and unstable, it may be necessary to prevent carbonate buildup on the seals through the use of a sequestering agent. The vacuum pump requirements are normally 1.5 to 2.0 adiabatic cubic feet per minute of air per square foot of drum surface area at 20 inches of mercury vacuum ($1.5\ m^3/min/m^2$ at $69\ kN/m^2$). This is true unless the expected yield is greater than 40 to 50 pounds per square foot per hour (20 to $25\ kg/m^2/hr$) and extensive sludge cake cracking is expected. In the latter case, an air flow 2.5 times higher should be used.

TABLE 9-18

TYPICAL DEWATERING PERFORMANCE DATA FOR ROTARY VACUUM FILTERS - CLOTH MEDIA

Type of sludge	Feed solids concentration, percent	Chemical dosage,[a] lb/ton dry solids		Yield,[b] lb dry solids/ sq ft/hr	Cake, percent solids
		$FeCl_3$	CaO		
Raw primary (P)	4.5 - 9.0	40-80	160-200	3.5 - 8.0	27-35
Waste-activated sludge (WAS)	2.5 - 4.5	120-200	240-360	1.0 - 3.0	13-20
P plus WAS	3 - 7	50-80	180-240	2.5 - 6.0	18-25
P plus trickling filter (TF)	4 - 8	40-80	180-240	3 - 7	23-30
Anaerobically digested					
P	4 - 8	60-100	200-260	3 - 7	25-32
P plus WAS	3 - 7	80-120	300-400	2 - 5	18-25
P plus TF	5 - 10	80-120	250-350	3.5 - 8	20-27
Aerobically digested no primary clarification	2.5 - 6	60-140	150-240	1.5 - 4.0	16-23
Elutriated anaerobic digested					
P	5 - 10	50-80	0-100	4 - 8	27-35
P plus WAS	4.5 - 8	60-120	0-150	3 - 6	18-25
Thermally conditioned P plus WAS	6 - 15	0	0	4 - 8	35-45

[a] All values shown are for pure $FeCl_3$ and CaO. They must be adjusted for anything else.

[b] Filter yields depend to some extent on feed solids concentrations. Increasing the concentration normally gives a higher yield.

1 lb/ton = 0.5 kg/t
1 lb/sq ft/hr = $4.9\ kg/m^2/hr$

TABLE 9-19

TYPICAL DEWATERING PERFORMANCE DATA FOR ROTARY VACUUM FILTERS - COIL MEDIA

Type of sludge	Feed solids concentration, percent	Chemical dosage,[a] lb/ton dry solids		Yield,[b] lb dry solids/ sq ft/hr	Cake, percent solids
		$FeCl_3$	CaO		
Raw primary (P)	8 - 10	40-80	160-240	6.5 - 8.0	28-32
Trickling filter (TF)	4 - 6	40-60	100-140	6 - 8	20-28
P plus waste-activated sludge (WAS)	3 - 5	20-60	180-220	2.5 - 4.0	23-27
Anaerobically digested					
P plus FT	5 - 8	50-80	240-320	4 - 6	27-33
P plus WAS	4 - 6	50-80	200-300	3.5 - 4.5	20-25
Elutriated anaerobically digested primary	8 - 10	20-50	30-120	4 - 8	28-32

[a]All values shown are for pure $FeCl_3$ and CaO. This must be adjusted for anything else.

[b]Filter yields depend to some extent on feed solids concentration. Increasing the solids concentration normally gives a higher yield.

1 lb/ton = 0.5 kg/t
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$

TABLE 9-20

SPECIFIC OPERATING RESULTS OF ROTARY VACUUM FILTERS - CLOTH MEDIA

Location	Sludge type[a]	Feed solids concentration, percent	Conditioner used, percent by weight[b]	Cake, percent solids	Yield, lb dry solids/ sq ft/hr	Filtrate, mg/l
Willoughby Eastlake, OH	P plus (WAS) plus septic	4 - 6	$FeCl_3$ - 3 Lime - 14	20	2.8 - 4.8	
Tamaqua, PA	Anaerobically digested (P plus WAS)	6	$FeCl_3$ - 3 Lime - 26	18	3	SS 20 - 30
Grand Rapids, MI	Thermally conditioned (P plus WAS)	10 - 15	None	50	6	SS 5,000 BOD 10,000
Fort Atkinson, WI	WAS	3 - 4	$FeCl_3$ - 6 Lime - 16	19	3.0 - 3.5	
Frankenmuth, MI	WAS	3.7	$FeCl_3$ - 8 Lime - 14	15	3.2	
Oconomowoc, WI	Anaerobically digested (P plus WAS)	2.3	$FeCl_3$ - 6 Lime - 20	18	2.5 - 3.0	SS 500 - 1,100 BOD_5 10
Genessee City, MI	P plus WAS	8	$FeCl_3$ Lime - 16	27	5.6	

[a]WAS = waste-activated sludge
P = primary sludge

[b]Numbers shown are based on pure $FeCl_3$ and pure CaO.

1 lb/sq ft/hr = 4.9 $kg/m^2/hr$

TABLE 9-21

SPECIFIC OPERATING RESULTS OF ROTARY VACUUM FILTERS - COIL MEDIA

Location	Sludge type[a]	Conditioner used, percent by weight[b]	Cake, percent solids	Yield, lb dry solids/ sq ft/hr
Blytheville, AR	TF	$FeCl_3$ - 36 CaO - 94	33.1	10.4
York, PA	Anaerobically digested (P plus WAS)	$FeCl_3$ - 80 CaO - 250	21.1	4.7
Wyomissing Valley, PA	Anaerobically digested TF	$FeCl_3$ - 62 CaO - 272	18.2	6.0
Bayonne, NJ	Anaerobically digested P	$FeCl_3$ - 28 CaO - 62	30.9	7.8
Woodbridge, NJ	P	$FeCl_3$ - 40 CaO - 240	29.7	8.0
Shadyside, OH	Anaerobically digested (P plus WAS)	$FeCl_3$ - 64 CaO - 310	29	4.2
Arlington, TX	TF	$FeCl_3$ - 64 CaO - 174	25.2	8.8

[a]WAS = waste-activated sludge; P = primary sludge. No data available for feed solids and filtrate concentrations.

[b]Numbers shown are based on pure $FeCl_3$ and pure CaO.

1 lb/sq ft/hr = 4.9 $kg/m^2/hr$

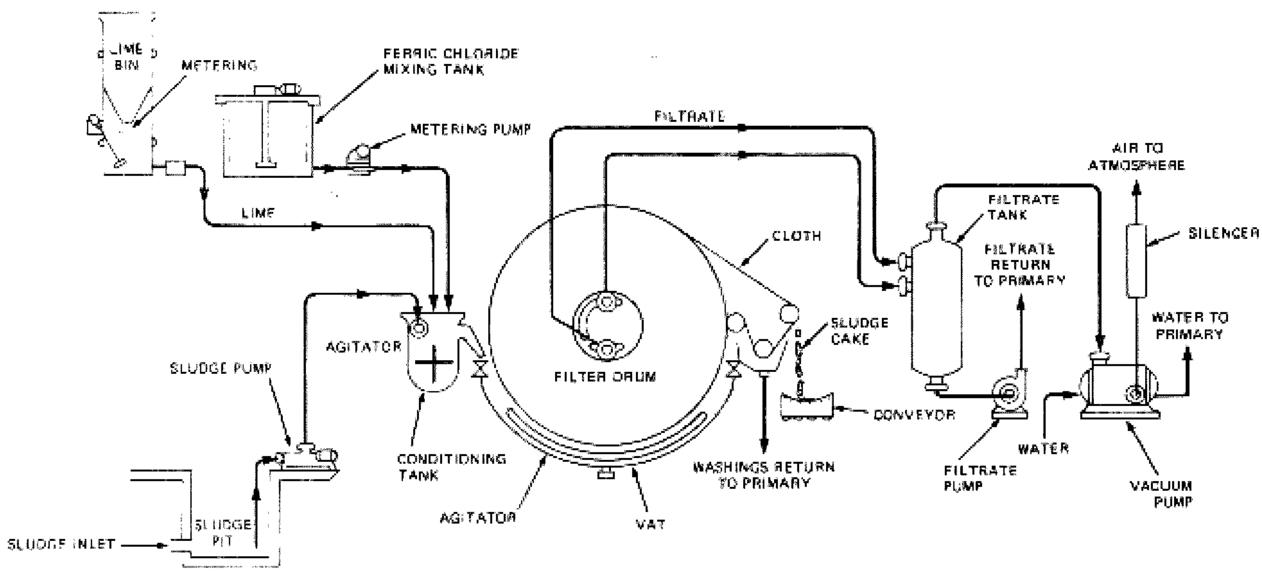

FIGURE 9-14

ROTARY VACUUM FILTER SYSTEM

Each vacuum filter must be supplied with a vacuum receiver located between the filter valve and the vacuum pump. The principal purpose of the receiver is to separate the air from the liquid. Each receiver can be equipped with a vacuum-limiting device to admit air flow if the design vacuum is exceeded (a condition that could cause the vacuum pump to overload). The receiver also functions as a reservoir for the filtrate pump suction. The filtrate pump must be sized to carry away the water separated in the vacuum receiver, and it is normally sized to provide a capacity two to four times the design sludge feed rate to the filter.

The filtrate pump should be able to pump against a minimum total dynamic head of between 40 and 50 feet (12 to 15 m), which includes a minimum suction head of 25-feet (7.5 m). Centrifugal-type pumps are commonly used but can become air bound unless they have a balance or equalizing line connecting the high point of the receiver to the pump. Typically, nonclogging centrifugal style pumps are used with coil filters because they permit a somewhat higher solids concentration in the filtrate. Self-priming centrifugal pumps are used most frequently, since they are relatively maintenance free. Check valves on the discharge side of the pumps are usually provided to minimize air leakage through the filtrate pump and receiver to the vacuum pump.

Sludge conditioning tanks are discussed in Chapter 8.

Filter Media

A major process variable is the filter media. The ideal media performs the desired liquid/solid separation and gives a filtrate of acceptable clarity (58). Further, the filter cake discharges readily from it, and it is mechanically strong enough to give a long life. The media must be chemically resistant to the materials being handled and provide minimal resistance to filtrate flow. A further characteristic to be minimized is "blinding" or clogging. All the characteristics mentioned above need to be evaluated during the selection procedure. One must, therefore, through experience, or bench or pilot-scale rotary vacuum filter testing, select the best media in terms of porosity, type of weave, material of construction, etc. for a particular sludge. This selection is normally made at the time of equipment start-up by the equipment supplier (15,59). The trend over the past few years is to select a monofilament fabric, as they seem the most resistant to blinding.

Solids Feed Content

The higher the feed suspended solids concentration of the sludge, the greater will be the production rate of the rotary vacuum filter (Figure 9-15) and the cake suspended solids concentration (Figure 9-16). Generally, municipal wastewater treatment plant sludges are not concentrated beyond about 10 percent solids, since above this concentration, the sludge becomes difficult to pump, mix with chemicals, and to distribute after conditioning to the filter. In addition, to increased production rates, higher sludge feed concentrations result in lower chemical dosage rates and lower cake moistures. Both of these consequences affect the cost of sludge dewatering and ultimate disposal.

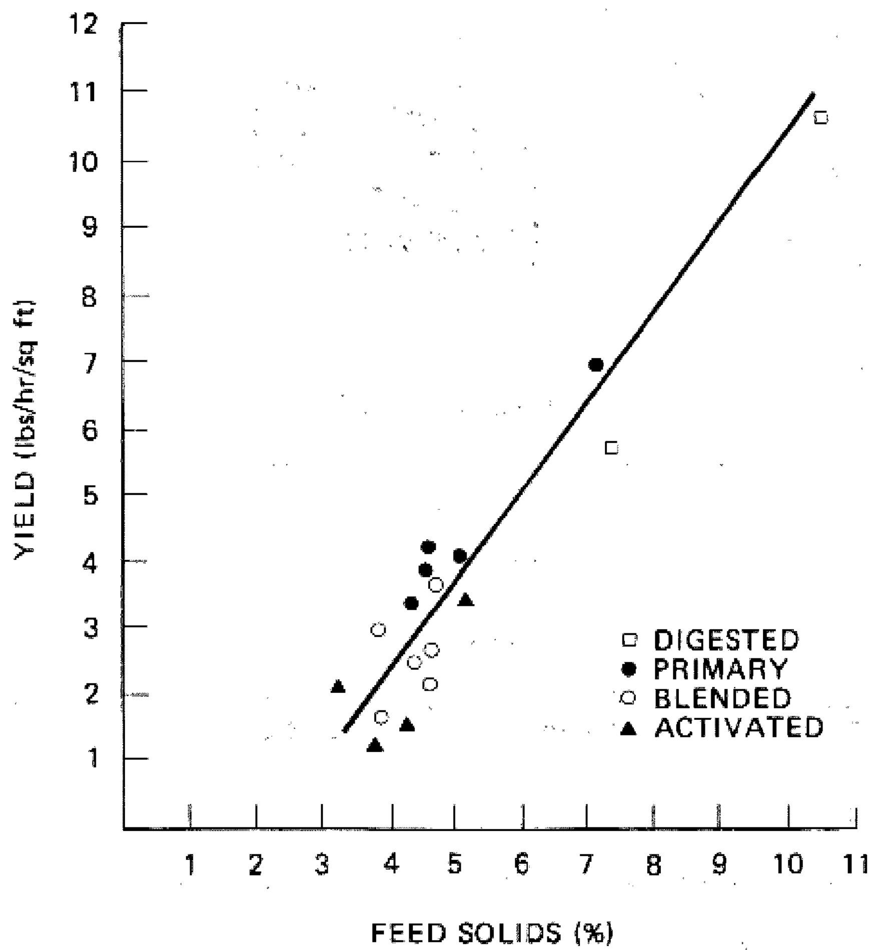

FIGURE 9-15

ROTARY VACUUM FILTER PRODUCTIVITY AS A FUNCTION OF FEED SLUDGE SUSPENDED SOLIDS CONCENTRATION (60)

The lowest feed sludge suspended solids concentration for successful vacuum filtration is generally considered to be 3.0 percent. Below this concentration it becomes difficult to produce sludge filter cakes thick enough or dry enough for adequate discharge. For this reason, it is extremely important that the design and operation of the preceding sludge processes take into consideration the need for an optimal solids concentration when dewatering on vacuum filters.

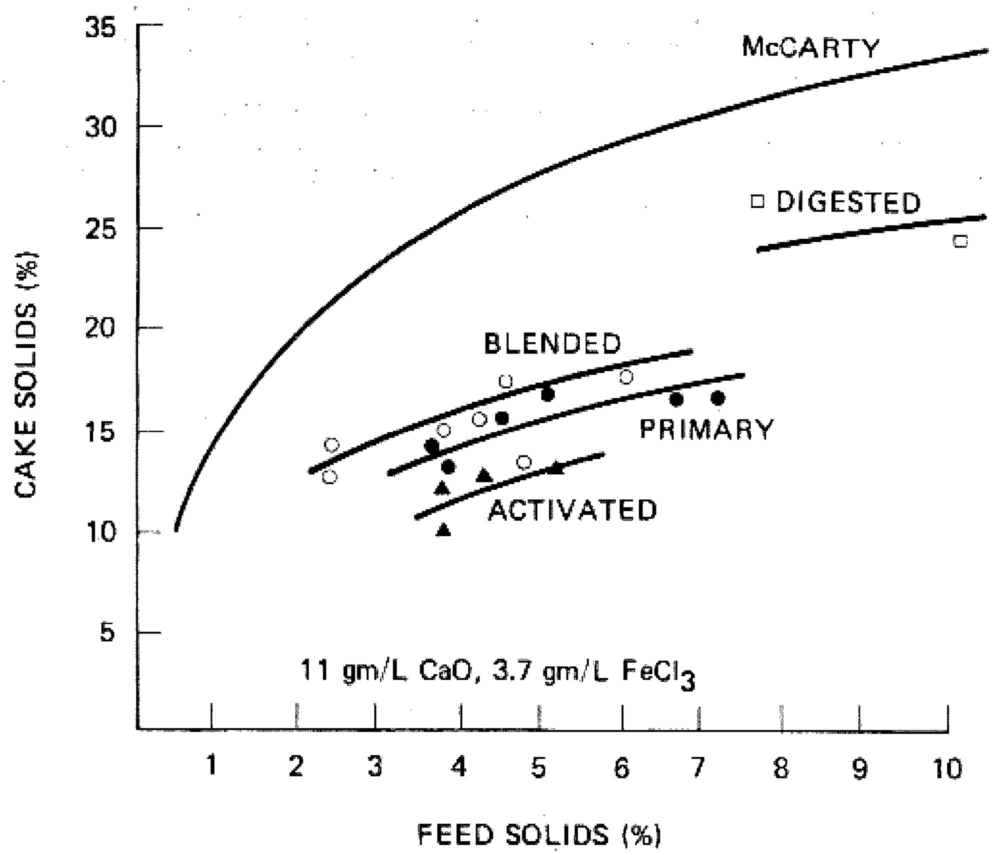

FIGURE 9-16

SLUDGE CAKE TOTAL SOLIDS CONCENTRATION AS A FUNCTION OF THE FEED SLUDGE SUSPENDED SOLIDS CONCENTRATION (60)

9.4.4.5 Case History

This study is summarized from a USEPA-sponsored investigation (61). Figure 9-17 shows the 1977 flow diagram for the 13-MGD (34 m^3/sec) Lakewood, Ohio, wastewater treatment plant. The sludge being handled at this plant has changed several times since the facility was built in 1938. At that time, the plant was designed for primary treatment, with sludge being anaerobically digested and dewatered on sand drying beds. Secondary treatment was added in 1966. Gravity thickeners, two new anaerobic digesters, two vacuum filters, and a flash dryer were installed to handle additional sludge. In 1974 and 1975, the plant was further upgraded. Alum (aluminum sulfate) was added to the aeration basin effluent channel for phosphorus removal, and the sludge handling system (filters and dryer) operating schedule was extended to two shifts. Finally, in 1977, the plant was returned to single shift sludge handling, and excess liquid sludge was hauled to land disposal.

The Lakewood plant has two polyethylene cloth belt rotary vacuum filters. Only one can be operated at a time because of the limited capacity of the flash dryer. Each filter has an effective area of 376 square feet (35 m^2) and operates best at a drum speed of one revolution per eight minutes and a drum submergence between 30 to 36 inches (0.76 to 0.91 m). A filter is operated five days per week in either one or two 6.5-hour shifts per day. Conditioning chemical dosages are approximately 275 pounds of dry lime (pebble lime - 72 percent CaO) per ton of dry feed solids (137 kg/t) and 30 pounds of $FeCl_3$ (liquid at 40 percent $FeCl_3$) per ton of dry feed solids (15 kg/t).

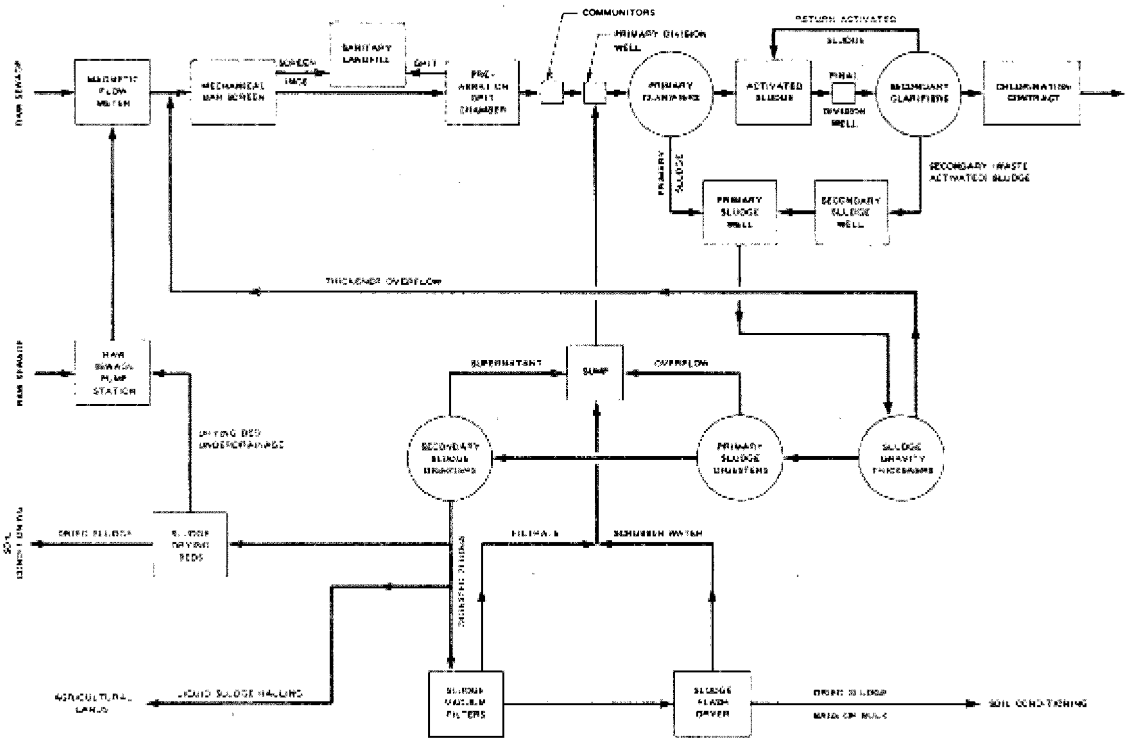

FIGURE 9-17

LAKEWOOD, OHIO WASTEWATER TREATMENT PLANT FLOW DIAGRAM

Prior to 1975, before alum was added for phosphorus removal (63 mg/l alum added), the average total solids concentration of the digested sludge (vacuum filter solids feed) was 4.45 percent. On the average, the sludge was dewatered to 23.8 percent solids. After alum addition, the feed sludge solids concentration increased to 6.5 percent, but the dewatered cake percent dropped to 21.4.

Table 9-22 indicates operational costs for 6.5-hour and 13-hour-per-day operations based on before and after alum addition for phosphorus removal. Because of the increase in the number of tons from 650 dry tons per year (590 t/yr) in 1974 to 1,820 dry tons per year (1,651 t/yr) in 1976, the treatment cost per ton of dry total solids was not much greater than it was in 1974.

TABLE 9-22

OPERATIONAL COST OF LAKEWOOD, OHIO VACUUM FILTER OPERATIONS

	Single shift operation - 1974 dollars per ton dry solids	Double shift operation - 1976 dollars per ton dry solids
Ferric chloride and lime	8.90	8.90
Electricity	1.98	1.29
Maintenance supplies	1.11	1.10
Maintenance and repair labor	3.65	3.60
Operational labor	3.46	6.25
Overhead	2.25	3.11
Total	21.35	24.25

1 ton = 0.907 t

9.4.4.6 Costs

Figure 9-18 gives the 1975 capital cost as a function of filter area for rotary vacuum filters. As an example, a 400-square-foot (37.2 m^2) area filter would cost 400,000 dollars. Since this number is based on a June 1975 cost, it must be adjusted to the current design period. Costs include those for filter, auxiliary equipment, piping, and building.

The labor requirements indicated in Figure 9-19 are given as a function of average area in use and include: start-up time and clean-up after the filter run, operation of filter, and operation of sludge pumping and conditioning facilities prior to treatment. As an example, a vacuum filter having 400 square feet (37.2 m^2) of filter area would require 550 man-hours of operation and maintenance per year and would be included in the cost analysis.

Figure 9-20 gives power consumption as a function of filter area. As an example, a vacuum filtration area of 400 square feet (37.2 m^2) would require 330,000 kilowatt-hours per year (1,200 GJ/yr) of electrical energy. If power costs are 0.05 dollars per kilowatt-hour (0.014 dollars/MJ), the cost would be 33,000 dollars annually. Operating parameters used were based on two adiabatic cubic feet of air per minute per square foot (10 $l/s/m^2$), 20 inches of vacuum (68 KN/m^2), and a total dynamic head of 50 ft (15 m) for the filtrate pump. Power required includes that for drum drive, discharge roller, and vat agitator, but does not include other accessory items, such as sludge feed pump or chemical feed system.

Figure 9-21 shows a curve developed for estimating rotary drum vacuum filter maintenance material cost as a function of filter area. As an example, for a filtration area of 400 square feet

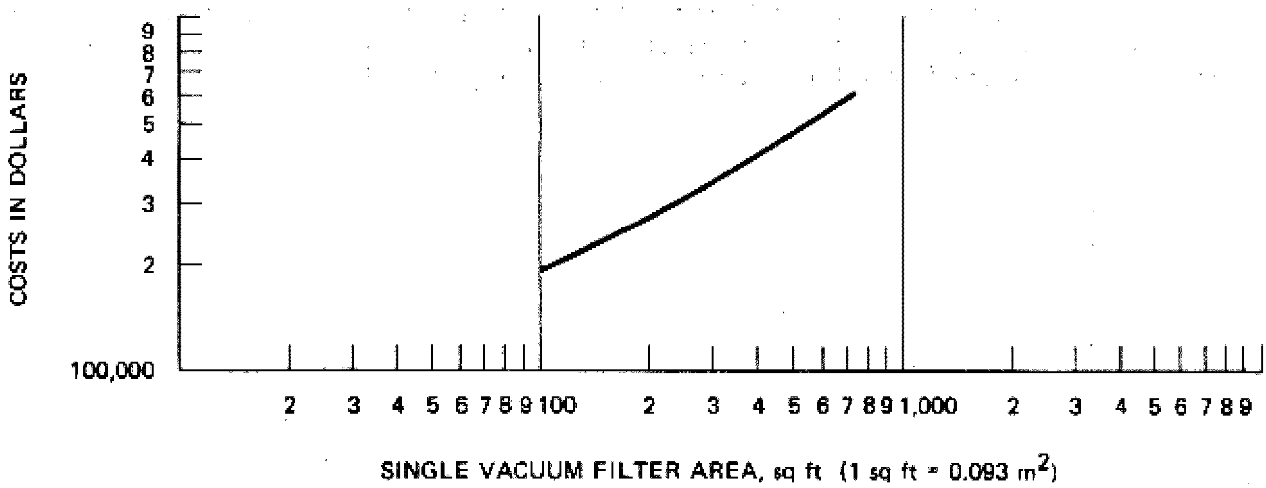

FIGURE 9-18

ESTIMATED JUNE 1975 CAPITAL COST FOR ROTARY DRUM VACUUM FILTERS (39)

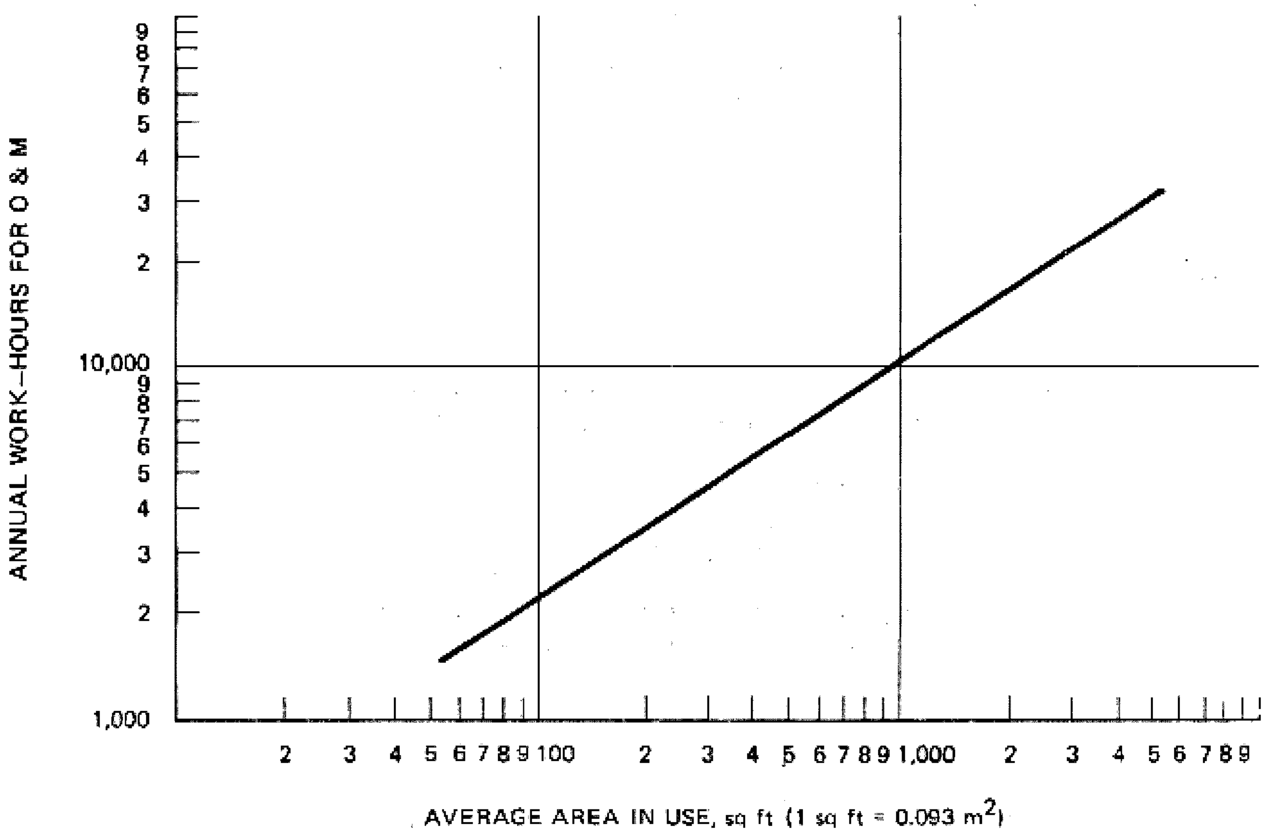

FIGURE 9-19

ANNUAL O&M MAN-HOUR REQUIREMENTS - ROTARY DRUM VACUUM FILTERS (39)

($37.2\ m^2$), a designer would estimate a yearly materials cost of 4,000 dollars. Since this number is based on a June 1975 cost, it must be adjusted to the current design period.

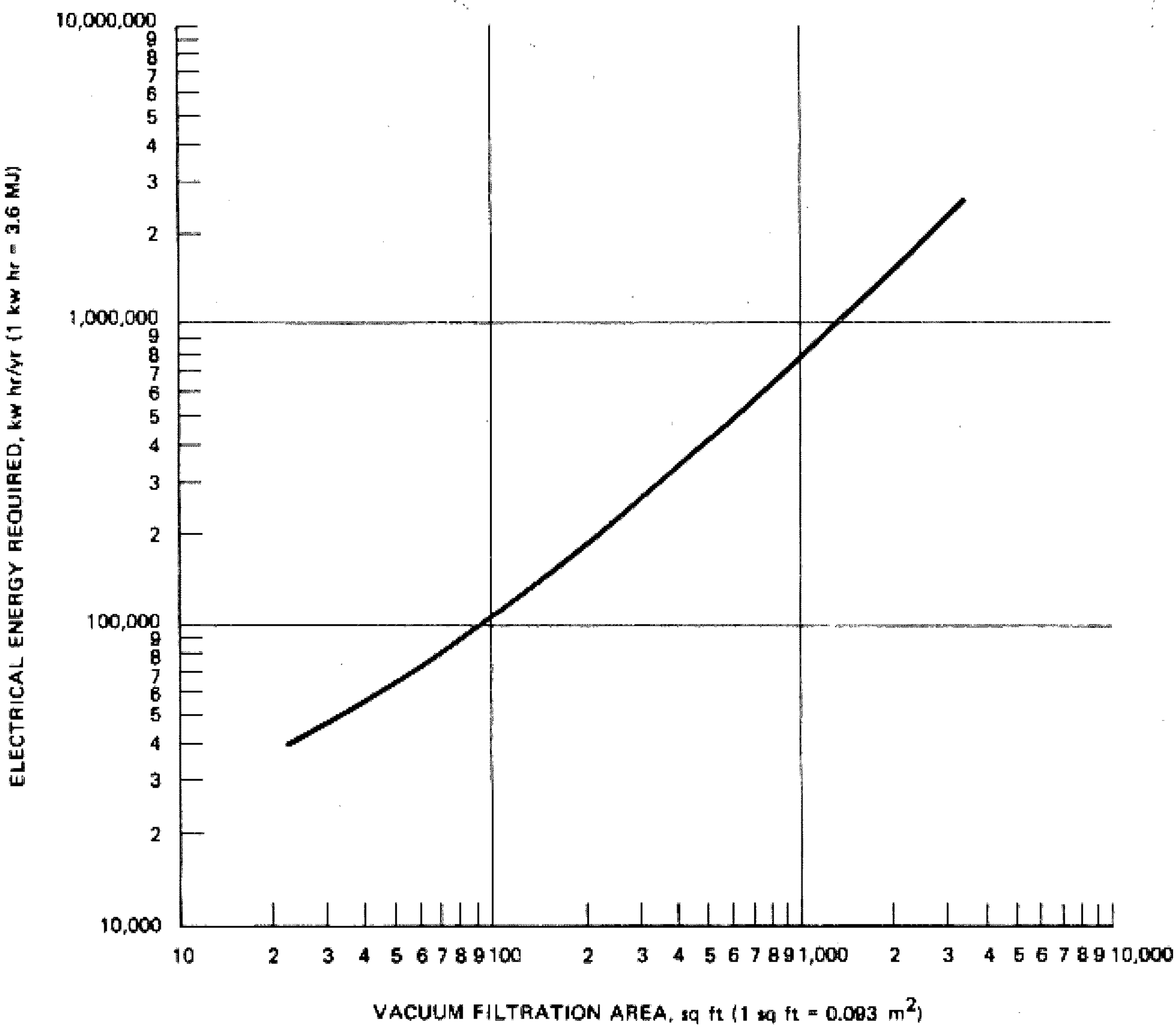

FIGURE 9-20

POWER CONSUMED BY ROTARY DRUM VACUUM FILTRATION PROCESS (39)

9.4.5 Belt Filter Press

Belt filter presses employ single or double moving belts to dewater sludges continuously.

The early belt presses used in the United States were those developed by Klein and by Smith and Loveless in the 1960s (62,63). Belt filter presses are currently very popular not only in the United States (64) but in other parts of the world as well (65). At least 20 equipment suppliers can furnish some type of belt press. This popularity has led to many units being sold, with very little operational experience to support the claimed advantages. One detailed report that evaluated belt press operating experience found that there were many operational and maintenance problems that still needed to be solved (66). As was pointed out by Austin (65), significant developmental work is still being conducted. Table 9-23 lists advantages and disadvantages of belt filter presses.

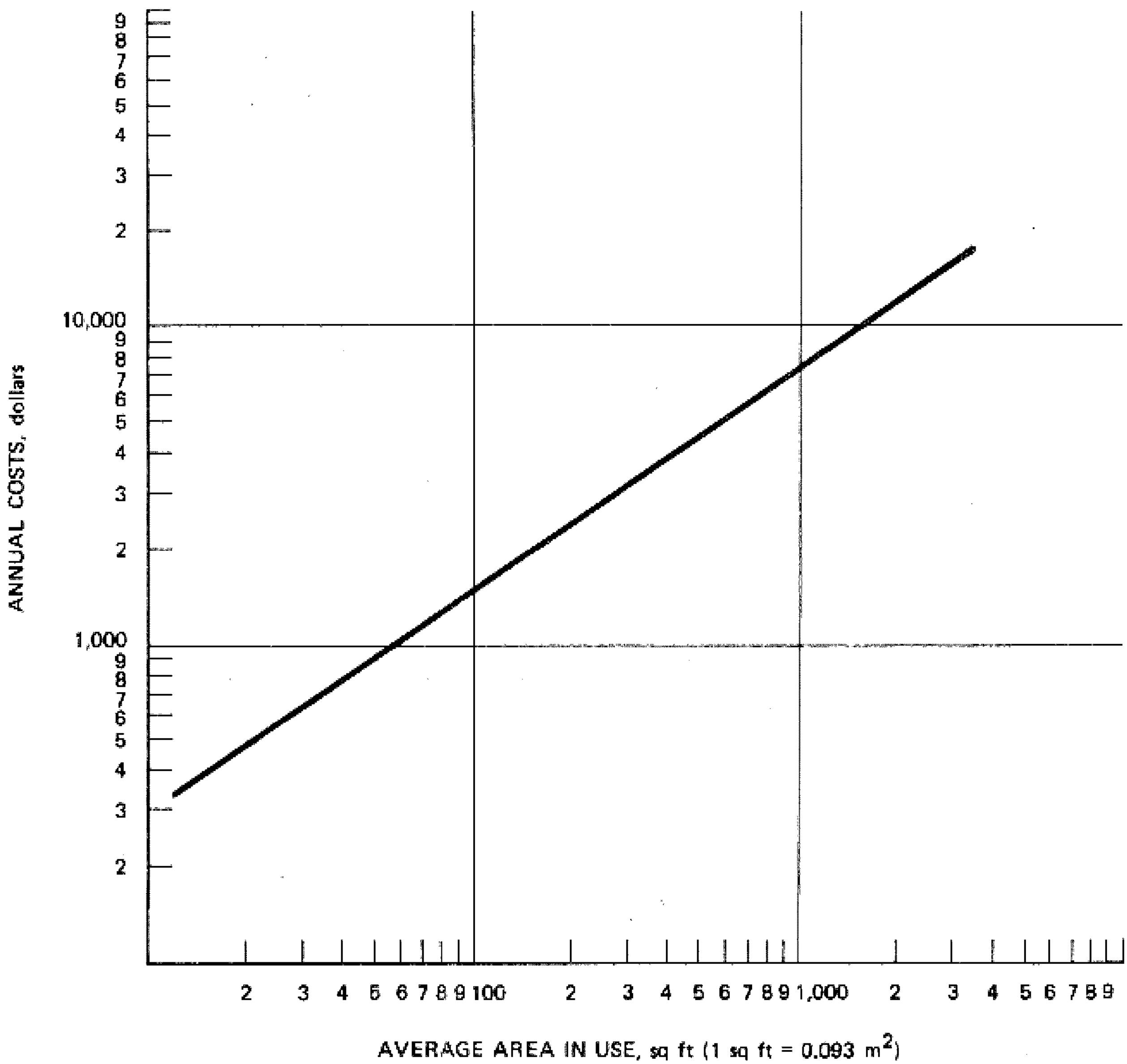

FIGURE 9-21

ESTIMATED JUNE 1975 ANNUAL MAINTENANCE MATERIAL COST - ROTARY DRUM VACUUM FILTER (39)

TABLE 9-23

ADVANTAGES AND DISADVANTAGES OF BELT FILTER PRESSES

Advantages	Disadvantages
High pressure machines are capable of producing very dry cake	Very sensitive to incoming feed characteristics
Low power requirements	Machines hydraulically limited in throughput
	Short media life as compared with other devices using cloth media

9.4.5.1 Principles of Operation

Any belt filtration process includes three basic operational stages: chemical conditioning of the feed slurry, gravity drainage to a nonfluid consistency, and compaction of the predewatered sludge (6).

Figure 9-22 depicts a simple belt press and shows the location of the three stages. Although present-day belt presses are more complex, they follow the same principles indicated in Figure 9-22.

Good chemical conditioning is the key to successful and consistent performance of the belt filter press, as it is for other dewatering processes. This is fully discussed in Chapter 8.

After conditioning, the readily drainable water is separated from the slurry by discharge of the conditioned material onto the moving belt in the gravity drainage section. Typically, one or two minutes are required for drainage. Following drainage, the sludge will have been reduced in volume by about 50 percent and will have a solids concentration of 6 to 10 percent. "The formulation of an even surface cake at this point is essential to the successful operation of subsequent stages of the dewatering cycle. The even surface prevents uneven belt tension and distortion while the relative rigidity of the mass of sludge allows further manipulation and gives maximum speed through the machine" (65).

The third stage of the belt press begins as soon as the sludge is subjected to an increase in pressure, due to either the compression of the sludge between the carrying belt and cover belt or the application of a vacuum on the carrying belt.

Pressure can be widely varied by design, as shown by the alternatives on Figure 9-23.

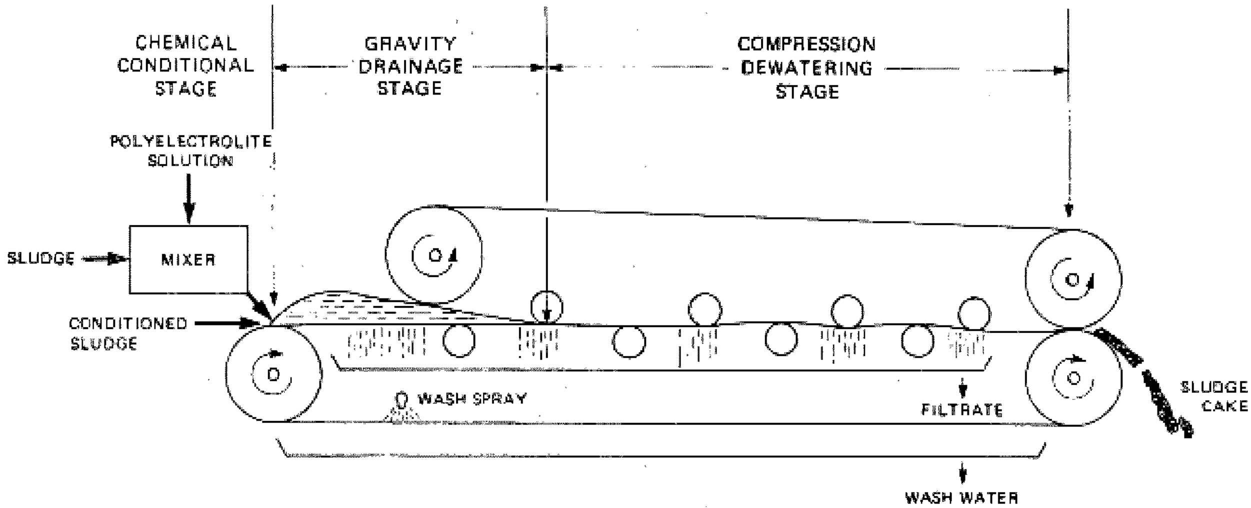

FIGURE 9-22

THE THREE BASIC STAGES OF A BELT PRESS

During pressure application, the sludge cake, squeezed between the two belts, is subjected to flexing in opposite directions as it passes over the various rollers. This action causes increased water release and allows greater compaction of the sludge.

Figure 9-24 shows a typical belt press installation.

9.4.5.2 Application

Belt filter presses are being installed in many United States municipalities to dewater many types of sludge. At this time, there is not enough operational data available to indicate any sludges to which a belt filter press could not be applied.

9.4.5.3 Performance

It is difficult to generalize about the operating performance of belt presses because results depend on many factors: method of conditioning, maximum pressure, number of rollers, etc. Table 9-24 was developed from minimum and maximum values given in all published data.

Published material on operating belt press installations is very limited. Medford, New Jersey (67) reported on a belt press dewatering aerobically digested sludge from a contact stabilization system. Feed sludge of a 3 to 4 percent solids concentration was dewatered to a cake of 17 to 19 percent solids (67). Polymer was added for conditioning at 7 to 10 pounds of dry polymer per ton of dry feed solids (3.5 to 5 kg/t). The solids concentration in the combination washwater and filtrate was 100 mg/l for an overall solids capture of 99 percent.

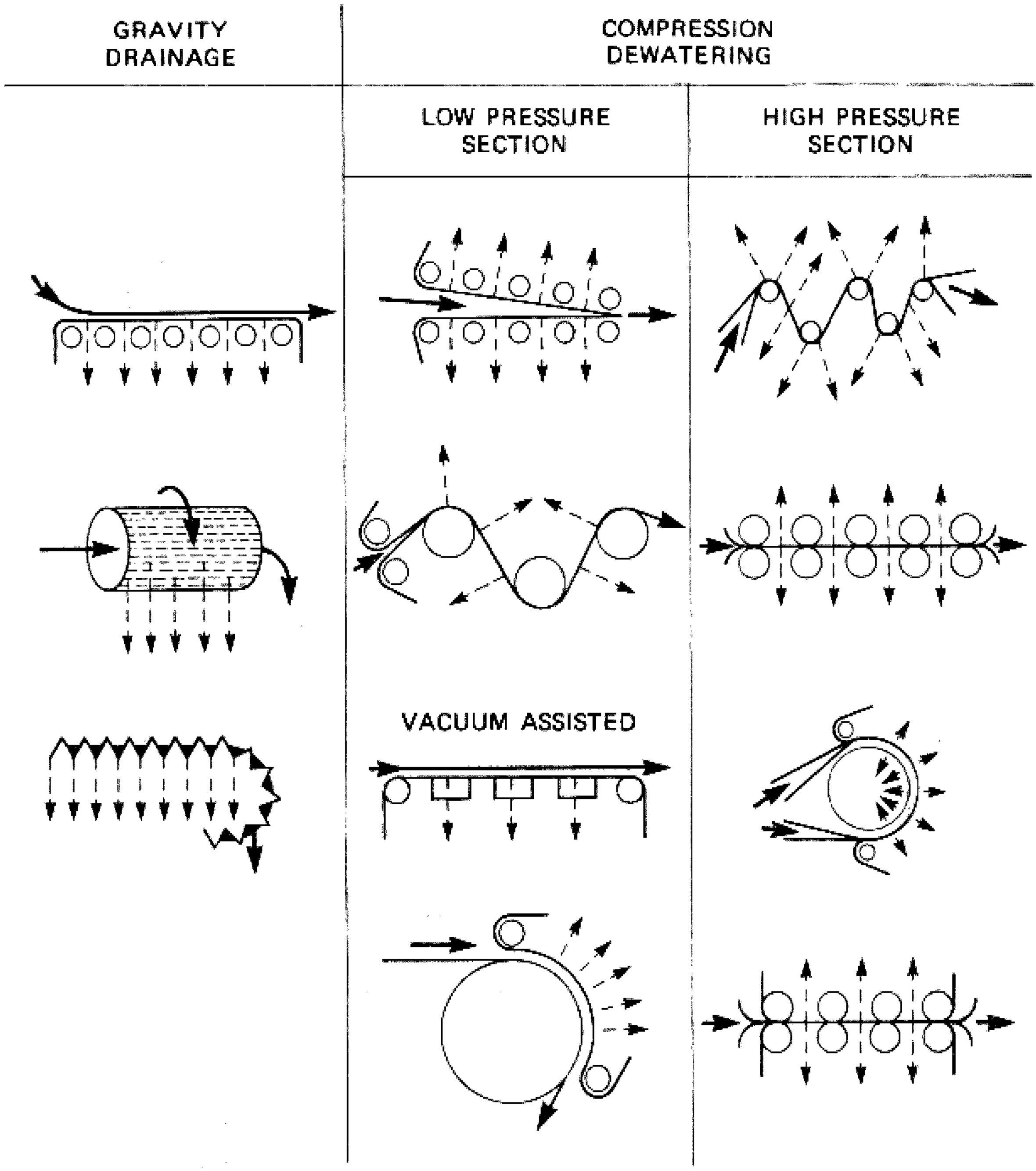

FIGURE 9-23

ALTERNATIVE DESIGNS FOR OBTAINING WATER RELEASES WITH BELT FILTER PRESSES (66)

9.4.5.4 Other Considerations

Failure of the chemical conditioning process to adjust to changing sludge characteristics can cause operational problems (66). If it is underconditioned, sludge does not

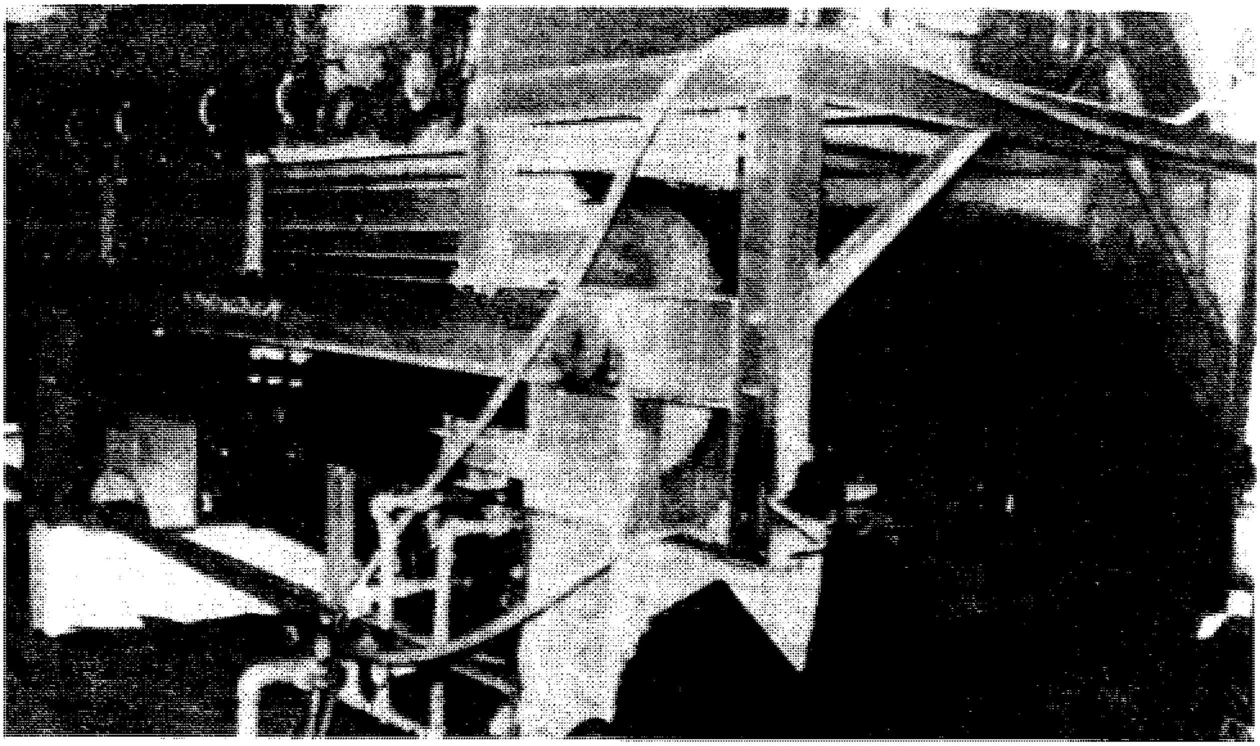

FIGURE 9-24

TYPICAL BELT FILTER PRESS INSTALLATION

TABLE 9-24

TYPICAL DEWATERING PERFORMANCE OF BELT FILTER PRESSES

Type of sludge	Feed solids, percent	Cake, percent solids	Polymer, pounds dry per ton dry solids
Raw primary (P)	3-10	28-44	2-9
Waste activated sludge (WAS)	1-3	16-32	2-4
	0.5-1.5	12-28	4-12
P + WAS	3-6	20-35	2-10
P + trickling filter (TF)	3-6	20-40	3-10
Anaerobically digested			
P	4-10	26-36	2-6
WAS	3-4	18-22	4-8
P + WAS	3-9	18-44	3-9
Aerobically digested			
P + WAS	1-3	12-18	4-8
	6-8	20-30	2-5
Thermal conditioned			
P + WAS	4-8	38-50	0

1 lb/ton = 0.5 kg/t

drain well in the gravity drainage section, and the result is either extrusion of inadequately drained solids from the compression section, or uncontrolled overflow of sludge from the drainage section. Both underconditioned and overconditioned sludges can blind the filter media. In addition, overconditioned sludge drains so rapidly that solids cannot distribute across the media. Inclusion of a sludge blending tank step before the belt press reduces this problem. See Chapter 15 for a discussion of blending tanks.

The combined filtrate and belt washwater flow is normally about one and one-half times the incoming flow. Some belt presses recirculate washwater from the filtrate collection system, but normally, secondary effluent or potable water is used. This total flow contains between 100 and 1,000 mg/l of suspended solids and is typically returned either to the primary or secondary treatment system.

Belt presses have numerous moving parts, and spare parts should be kept available to prevent prolonged unit down-time. Belts, bearings, and rollers deteriorate quickly, especially in municipal wastewater treatment plants where preventive maintenance is not normally practiced.

9.4.5.5 Design Example

The designer for an existing wastewater treatment plant has calculated that the plant needs to dewater 5,000 dry pounds of sludge (2,268 kg) per day, five days per week. The sludge to be dewatered is a mixture of one part primary and two parts waste-activated, stabilized by a two-stage, high-rate, anaerobic digestion process. Total feed solids concentration to the belt filter press was 2.8 percent. Pilot plant testing with a one-meter-wide belt filter press produced the following results.

- Total solids in the dewatered sludge ranged from 23 to 30 percent, averaging 25 percent.

- Optimum polymer dosage was 6 to 8 pounds of dry polymer per ton (3 to 4 kg/t) of dry feed solids, or 80 to 100 pounds of liquid polymer per ton (40 to 50 kg/t) of dry feed solids.

- At the optimum polymer dosage, the total solids in the filtrate plus washwater flow was 2,000 mg/l. The suspended solids averaged 900 mg/l.

- Optimum hydraulic feed rate at 2.8 percent solids for a one-meter-wide belt was 47 gallons per minute (3 l/s).

- Washwater requirements were 25 gallons per minute (1.6 l/s).

On the basis of pilot plant data, the engineer decided that one 1-meter-wide belt filter press could dewater the 5,000 pounds (2,268 kg) of sludge in 7.6 hours. Since it was important that the wastewater treatment plant always be able to dewater sludge, two 1-meter-wide belt filter presses would be purchased.

The current cost of dry polymer in 50 pound (22.7 kg) bags was $1.85 per pound ($0.84/kg); for liquid polymer in 55 gallon, 650 pound (208 1-295 kg) drums, the cost was $0.13 per pound. Daily cost for dry polymer at 8 pounds per ton (4 kg/t) would be:

$$\frac{5{,}000 \text{ lb solids}}{\text{day}} \times \frac{8 \text{ lb poly}}{2{,}000 \text{ lb solids}} \times \frac{\$1.85}{\text{lb poly}} = \$37.00 \text{ per day}$$

Daily cost for liquid polymer at 100 pounds per ton (50 kg/t) would be:

$$\frac{5{,}000 \text{ lb solids}}{\text{day}} \times \frac{100 \text{ lb poly}}{2{,}000 \text{ lb solids}} \times \frac{\$0.13}{\text{lb poly}} = \$32.50 \text{ per day}$$

Because sludge characteristics can change with time, a dual polymer system capable of utilizing either liquid or dry polymer will be installed. Since liquid polymer is currently less expensive, it will be used initially.

To allow subsequent computation of solids capture, the filtrate flow is calculated, using a suspended solids balance and a flow balance. The specific gravity of the feed, dewatered cake and filtrate are assumed to be 1.02, 1.07 and 1.01, respectively. The suspended solids balance is:

$$\frac{47 \text{ gal feed}}{\text{min}} \quad \frac{8.34 \times 1.02 \text{ lb feed}}{\text{gal feed}} \quad \frac{0.028 \text{ lb solids}}{\text{lb feed}}$$

$$= \frac{Q \text{ gal filtrate}}{\text{min}} \quad \frac{8.34 \times 1.01 \text{ lb filtrate}}{\text{gal filtrate}} \quad \frac{900 \text{ lb solids}}{10^6 \text{ lb filtrate}}$$

$$+ \frac{M \text{ gal cake}}{\text{min}} \quad \frac{8.34 \times 1.07 \text{ lb sludge}}{\text{gal cake}} \quad \frac{0.25 \text{ lb solids}}{\text{lb cake}}$$

The flow balance is:

$$\frac{47 \text{ gal feed}}{\text{min}} + \frac{25 \text{ gal washwater}}{\text{min}}$$

$$= \frac{Q \text{ gal filtrate}}{\text{min}} + \frac{M \text{ gal cake}}{\text{min}}$$

The suspended solids and flow balances are solved simultaneously. The flow of filtrate (Q) is 67.2 gallons per minute (254 l/m).

Solids capture

$$= \frac{\text{Solids in feed - solids in filtrate}}{\text{Solids in feed}} \times 100$$

$$= \frac{47\ (8.34 \times 1.02)\ (0.028) - 67.2\ (8.34 \times 1.01)\ \frac{900}{10^6}}{47\ (8.34 \times 1.02)\ (0.028)} \times 100$$

= 95 percent

All filtrate is returned to the secondary treatment process.

9.4.5.6 Costs

Current published information on capital cost of belt filter presses is almost nonexistent. Some information is available from a recent USEPA publication (68). According to this publication, construction costs for a belt filter press, sludge feed pump, polymer pump, and control panel to dewater 1,000 pounds (454 kg) of sludge per hour was $97,000. To dewater 2,500 pounds (1,134 kg) per hour, the cost would be $120,000.

Table 9-25 lists labor requirements for the operation and maintenance of belt filter presses. The labor indicated includes periodic operational adjustments and minor routine maintenance. No information is available on maintenance material cost.

TABLE 9-25

LABOR REQUIREMENTS FOR BELT FILTER PRESSES (19)

Number of units	Labor, hours per year		
	Operation	Maintenance	Total
1	265	100	365
2	530	200	730
3	795	300	1,095
4	1,060	400	1,460
5	1,325	500	1,825

9.4.6 Recessed Plate Pressure Filters

Pressure filtration for sludge dewatering evolved from the similar practice in sugar manufacturing of forcing juices through cloth. The first United States municipal sludge dewatering installations, which were also the first large-scale mechanical dewatering applications in this country, were located in Worcester, Massachusetts, and Providence, Rhode Island, in the early 1920s (56). Fixed- and variable-volume recessed plate pressure filters are discussed in this section.

Fluid pressure generated by pumping slurry into the unit provides the driving force for recessed plate pressure filters. Performance reliability is increased by modern design concepts, such as use of new construction materials to resist attack by acids and alkalis; mechanization of the operating sequence to reduce manpower requirements; and the use of membrane diaphragms for variable volume filtration (69). Table 9-26 lists the advantages and disadvantages of pressure filters compared with other dewatering methods.

TABLE 9-26

ADVANTAGES AND DISADVANTAGES OF RECESSED PLATE PRESSURE FILTERS

Advantages	Disadvantages
Highest cake solids concentration	Batch operation High labor cost High capital cost Special support structure requirements Large area requirement

9.4.6.1 Principles of Operation

Fixed-volume, recessed plate pressure filters, illustrated on Figure 9-25, are constructed from a series of recesssed plates. As shown on Figure 9-26, volume is provided by the depressions on the sides of the plates.

The surfaces of both sides of the filter plate are designed so that the filtrate drains from the filter cloth and from each plate.

A filter cloth is mounted over the two surfaces of each filter plate. Conditioned sludge is pumped into the pressure filter and passes through feed holes in the filter plates along the length of the filter and into the recessed chambers. As the sludge cake forms and builds up in the chamber, the pressure gradually increases to a point at which further sludge injection would

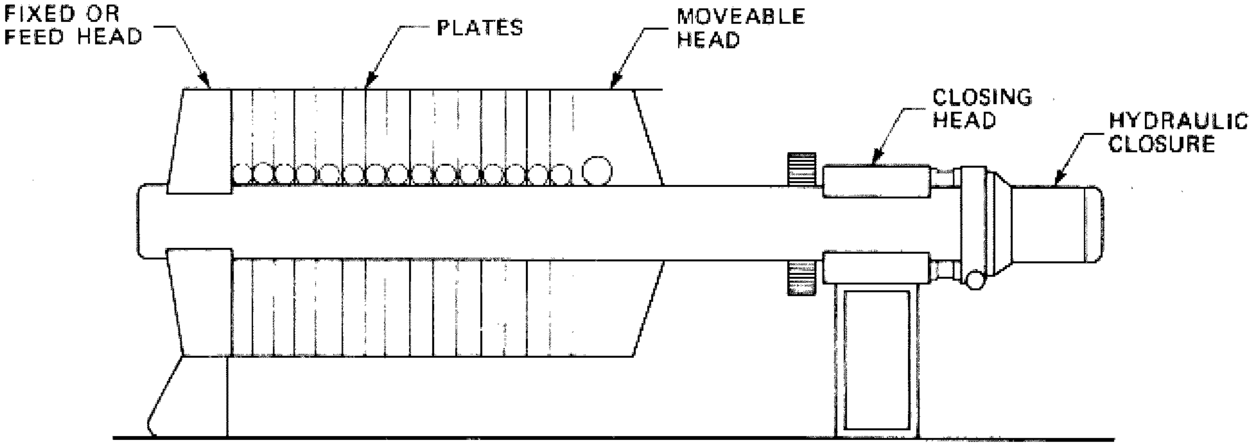

FIGURE 9-25

SCHEMATIC SIDE VIEW OF A RECESSED PLATE PRESSURE FILTER

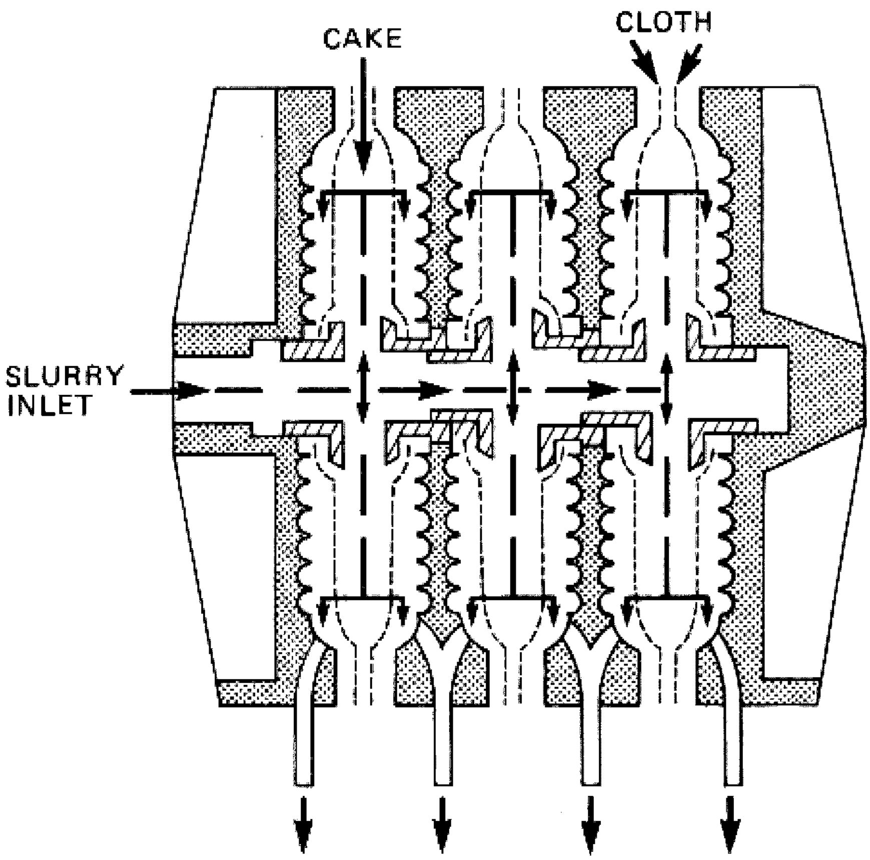

FIGURE 9-26

CROSS SECTION OF A FIXED-VOLUME
RECESSED PLATE FILTER ASSEMBLY

be counter-productive. Pressure filters operate at a pressure of 100 pounds per square inch (690 kN/m^2) or 225 to 250 pounds per square inch (1,550 to 1,730 kN/m^2).

A typical pressure filtration cycle begins with the closing of the press to the position shown on Figure 9-25. Sludge is fed for a 20- to 30-minute period until the press is effectively full of cake. The pressure at this point is generally the designed maximum and is maintained for a one- to four-hour period, during which more filtrate is removed and the desired cake solids content is achieved. The filter is then mechanically opened, and the dewatered cake dropped from the chambers onto a conveyor belt for removal. Cake breakers are usually required to break up the rigid cake into conveyable form. Figure 9-27 shows a typical pressure filter installation.

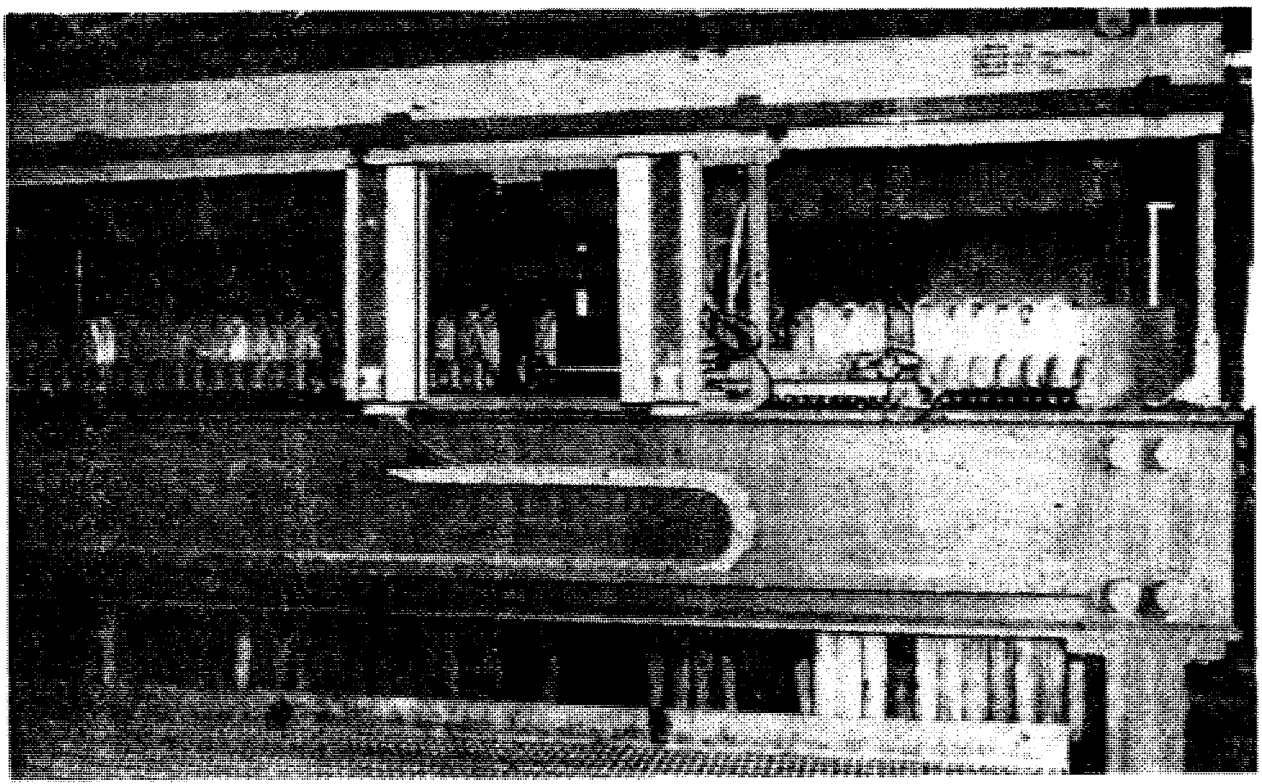

FIGURE 9-27

TYPICAL RECESSED PLATE PRESSURE FILTER INSTALLATION AT WASSAU, WISCONSIN

Construction of a variable-volume recessed plate pressure filter is similar to the fixed-volume filters, except that a diaphragm is placed behind the media as shown on Figure 9-28. A dewatering cycle begins as conditioned sludge is fed into each chamber from a slurry inlet pipe located in the top or bottom of each plate. Generally, about 10 to 20 minutes are required to fill the press and reach an end point determined by either instantaneous feed rate, filtrate rate, or time. When the end point is reached, the sludge feed pump is automatically turned off. Water or air, under high pressure, is then pumped into the space between the diaphragm and plate body squeezing the already formed and partially dewatered cake. Typically, 15 to 30 minutes of constant pressure are required to dewater the cake to the desired solids content. At the end of the cycle, the water is returned to a reservoir, plates are automatically opened, and sludge cake is discharged.

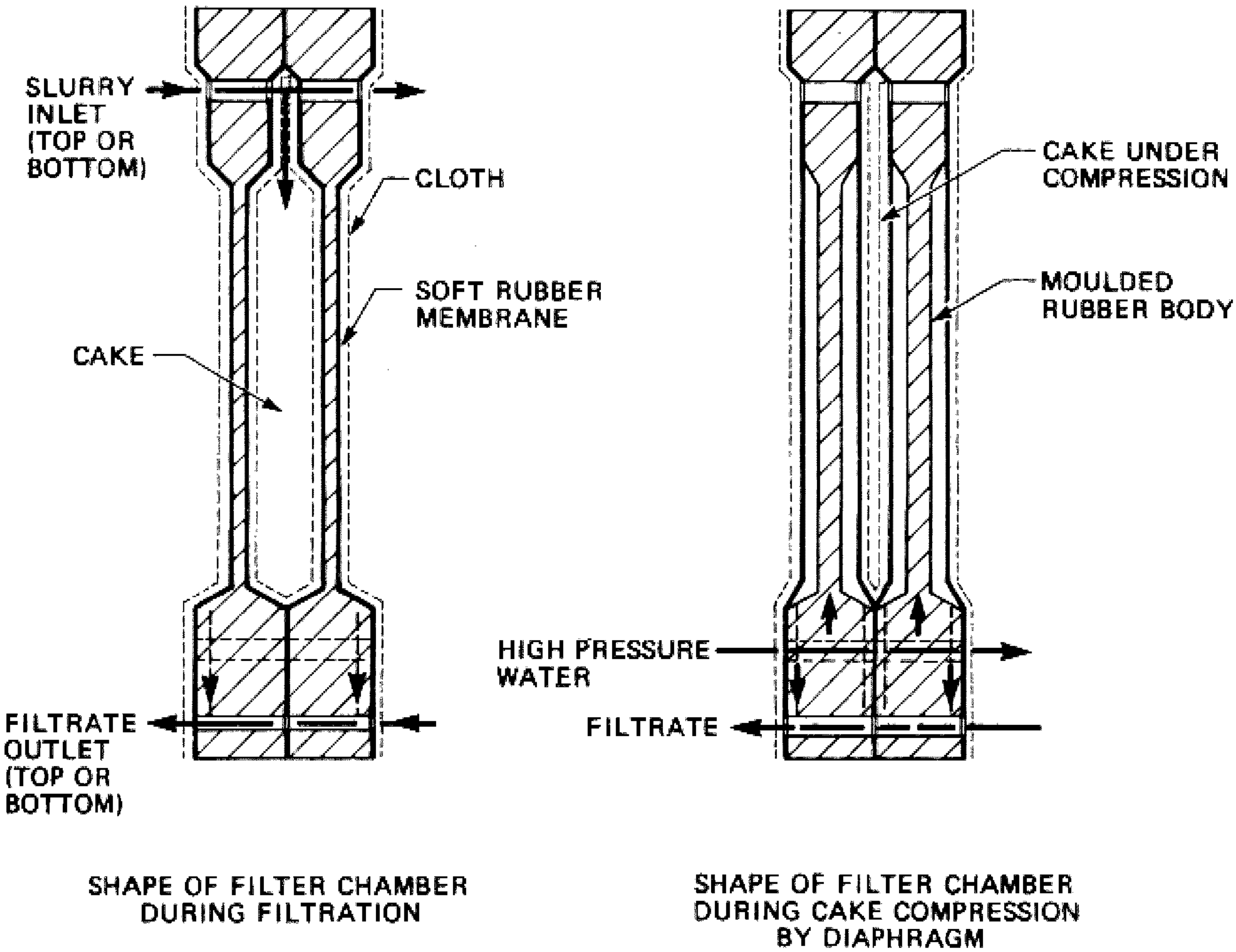

FIGURE 9-28

CROSS SECTION OF A VARIABLE VOLUME RECESSED PLATE FILTER ASSEMBLY

9.4.6.2 Application

Pressure filtration is an advantageous choice for sludges of poor dewaterability, such as waste-activated sludges, or for cases in which it is desirable to dewater a sludge to a solids content higher than 30 percent. If sludge characteristics are expected to change drastically over a normal operating period, or if less chemical conditioning is desired, the variable-volume units would probably be selected rather than the fixed-volume units.

TABLE 9-27

EXPECTED DEWATERING PERFORMANCE FOR A TYPICAL FIXED VOLUME RECESSED PLATE PRESSURE FILTER

Type of sludge	Feed solids, percent	Conditioning dosage, lbs/ton dry solids			Cake with conditioning material, percent solids	Cake without conditioning material, percent solids	Cycle time, hours
		$FeCl_3$[a]	CaO[a]	Ash			
Raw primary (P)	5-10	100	200		45	39	2.0
				2,000	50	25	1.5
Raw P with less than 50 percent waste activated sludge (WAS)	3-6	100	200		45	39	2.5
				3,000	50	20	2.0
Raw P with more than 50 percent WAS	1-4	120	240		45	38	2.5
				4,000	50	17	2.0
Anaerobically digested mixture of P and WAS							
Less than 50 percent WAS	6-10	100	200		45	39	2.0
				2,000	50	25	1.5
More than 50 percent WAS	2-6	150	300		45	37	2.5
				4,000	50	17	1.5
WAS	1-5	150	300		45	37	2.5
				5,000	50	14	2.0

[a]All values shown are for pure $FeCl_3$ and CaO. Must be adjusted for anything else.

1 lb/ton = 0.5 kg/t
1 lb/sq ft/hr = 4.9 kg/m^2/hr

9.4.6.3 Performance

As of 1979, very few fixed-volume recessed plate pressure filters are operating in the United States, and there are no variable-volume installations operating. Table 9-27 contains expected performance data for typical fixed-volume units, and Table 9-28 lists actual data from operating installations. Table 9-29 lists a performance from a large variable-volume pilot unit (62.4 square feet [5.8 m^2] of filtering area).

9.4.6.4 Other Considerations

Sludge Conditioning Process

Most systems are designed so that ferric chloride and lime are added in batches to sludge contained in an agitated tank, and the conditioned sludge is pumped from the tank into the pressure filter as required. However, experience indicates

TABLE 9-28

SPECIFIC OPERATING RESULTS OF FIXED VOLUME RECESSED PLATE PRESSURE FILTERS

Location	Sludge type[a]	Feed solids, percent	Conditioner, lb/ton dry solids[b]	Percent solids: Cake with conditioning material	Percent solids: Cake without conditioning material	Year and total cost, dollars/ton dry solids	Reference
Kenosha, WI	Anaerobically digested mixture (P plus WAS)	3.5 - 5	$FeCl_3$ - 54 Lime -340	41.5	35	1975 - 61	70
Wausau, WI	Water plant plus thermal conditioned mixture of anaerobically digested (P plus WAS)	2 - 8	0	34 - 45	35 - 45	Not given	71
Cedar Rapids, IA	Anaerobically digested mixture (P plus TF)	3.5 - 7	Fly ash at about 2,500	60	27	1972 - 30	72
Brookfield, WI	Aerobically digested WAS plus raw P	4	$FeCl_3$ - 143 Ash - 1,200 Lime - 346	43	25	Not given	61

[a]P = primary sludge; WAS = waste-activated sludge; TF = trickling filter sludge.

[b]All values shown for $FeCl_3$ and CaO are for pure chemicals. Must be adjusted for anything else.

1 lb/ton = 0.5 kg/t
1 ton = 0.907 t

TABLE 9-29

TYPICAL DEWATERING PERFORMANCE OF A VARIABLE VOLUME RECESSED PLATE PRESSURE FILTER

Site	Type of sludge	Feed solids, percent	Chemical dosage,[a] lb/ton dry solids: $FeCl_3$	Chemical dosage,[a] lb/ton dry solids: CaO	Yield, lb/sq ft/hr	Percent solids: Cake with chemicals	Percent solids: Cake without chemicals
	Anaerobically digested[b]						
1	60 P: 40 WAS	3.8	120	320	1.0	37	30
2	60 P: 40 WAS	3.2	180	580	0.7	36	25
3	40 P: 60 WAS	3.8	120	340	0.6	40	32
4	40 P: 60 WAS	2.5	180	500	0.6	42	30
5	50 P: 50 WAS	6.4	80	220	2.0	45	39
6	60 P: 40 WAS	3.6	160	320	0.8	50	40
7	Raw WAS	4.3	180	460	0.6	34	25
8	Raw (60 plus 40 WAS)	4.0	100	300	0.9	40	33
9	Thermal conditioned 50 P: 50 WAS	14.0	0	0	2.5	60	60

[a]All values shown are for pure $FeCl_3$ and CaO. Must be adjusted for anything else.

[b]P = primary sludge; WAS = waste-activated sludge.

1 lb/ton = 0.5 kg/t
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$

that the prolonged agitation and tank storage time associated with batch conditioning can result in a feed of varying and deteriorating dewaterability. For this reason, conditioning processes are now frequently designed to provide "in-line" conditioning. This can be accomplished by either the continuous pumping of sludge into a small tank and addition of chemicals, or directly injecting conditioning chemicals into the sludge on its way into the filter. In-line conditioning diminishes the deleterious effects of storage and prolonged agitation. Figure 9-29 shows a schematic for in-line conditioning.

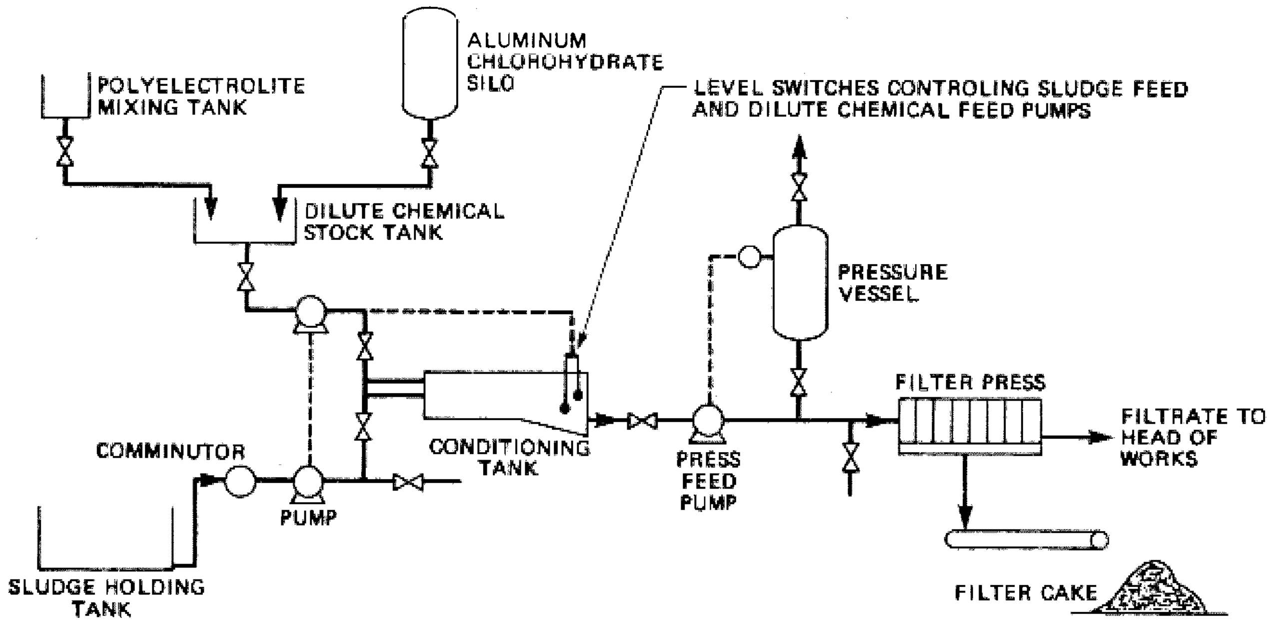

FIGURE 9-29

SCHEMATIC OF AN IN-LINE CONDITIONING SYSTEM FOR RECESSED PLATE PRESSURE FILTER (73)

Feed Pump System

One major problem with pressure filters has been the need to design a system that will pump from 30 to 2,000 gallons per minute (1.9 to 126 l/s) of a viscous, abrasive slurry at pressures of 40 to 225 pounds per square inch (276 to 1,551 kN/m^2).

Ideally, the feed system should inject conditioned sludge into the chamber as rapidly as possible but slowly enough to permit sufficiently prompt formation of a uniform and thick enough cake to prevent any incursion of sludge particles into the filter cloth. Imbalance of the sludge feed and cake formation rates can result in nonuniform, high resistance cake, or in cloth blinding and/or initial poor filtrate quality. If a nonuniform cake is formed or excessive fines migrate, then a long filter cycle or an inordinate amount of cloth plugging will result.

The filter feed method used for some pressure filters involves a combination of pumps and pressure vessels. These combinations are used to obtain a high initial feed rate of approximately 2,000 gallons per minute (126 l/s) via the pressure vessel, followed by the use of reciprocating ram high pressure pumps to pump at a pressure of 225 pounds per sqare inch (1,551 kN/m^2) at feed rates of 100 to 200 gallons per minute (6.3 to 12.6 l/s). In some cases, a combination of progressive cavity pumps and pressure vessels is used for the lower pressure, high-rate chamber filling phase.

Cloth Washing and Cleaning

Because recessed plate pressure filters operate at high pressures and because many units use lime for conditioning, the designer must assume that cloths will require routine washing with high pressure water, as well as periodic washing with acid. Practices vary according to the particular sludge and proprietary process. Designers should ask for recommendations from equipment suppliers on frequency of washing.

Dewatered Cake Breakers

Design of suitable breakers is a function of the structural properties of the dewatered cake. Pressure filter cake is usually friable enough that use of breaker wires, bars, or cables beneath the filter will be sufficient. If, however, polyelectrolyte conditioning is contemplated, consideration should be given to the resulting changes in cake structure.

9.4.6.5 Case History

This information is summarized from a recent sludge handling investigation by USEPA (61). The 1978 flow diagram for the 5-MGD (13-m^3/sec) Brookfield, Wisconsin, wastewater treatment plant is shown on Figure 9-30. In January 1974, Brookfield commenced treatment by the contact stabilization activated sludge process. Addition of ferrous sulfate from pickle liquor for phosphorus removal in the aeration tank was initiated in June 1976. The plant has one fixed-volume, recessed plate pressure filter with a design capacity of 530 pounds dry solids per hour (241 kg/hr).

Performance

The pressure filter is generally operated four days per week, 16 hours per day, 45 weeks per year. The other 7 weeks per year, the sludge is applied to land. Figure 9-31 summarizes operating performance before (letter B) and after (letter A) the addition of ferrous sulfate. Figure 9-31 also presents a mass flow diagram of an operating recessed plate pressure filter.

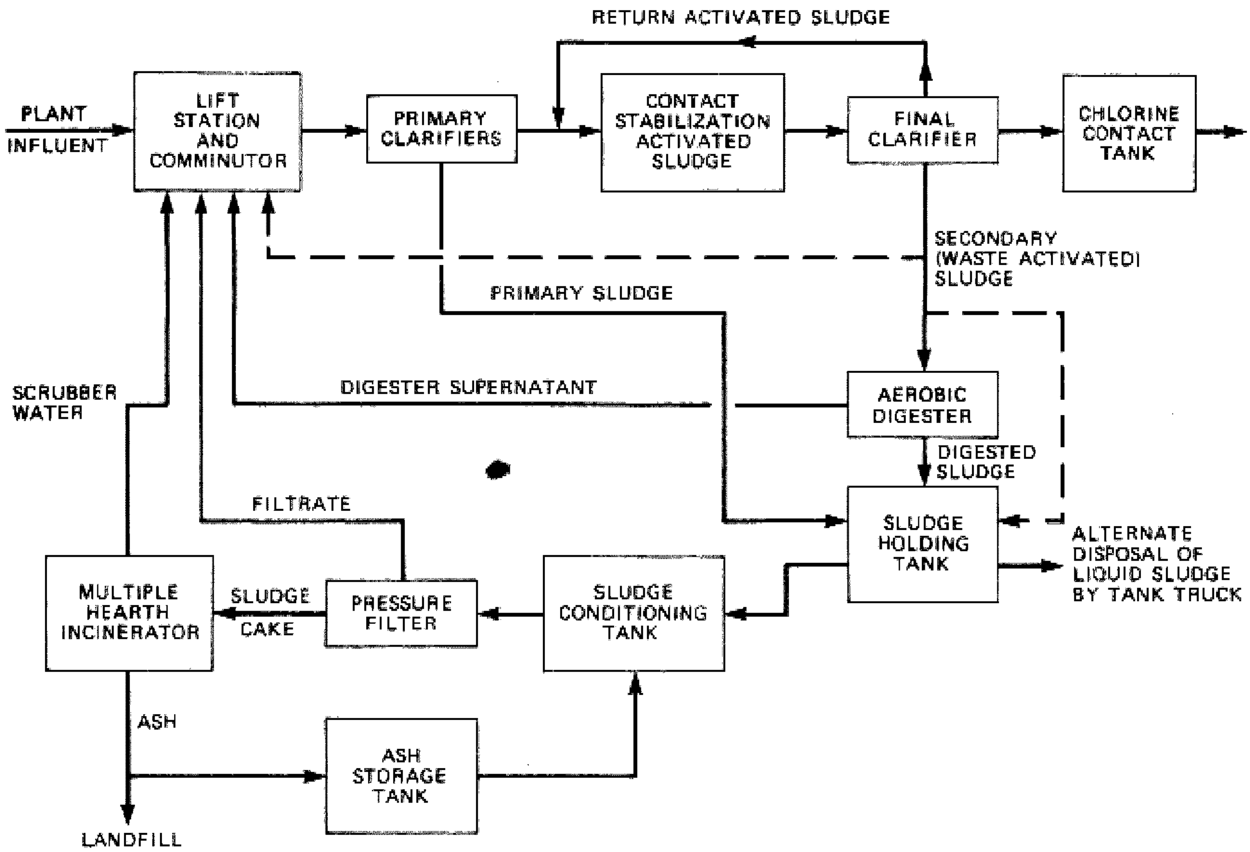

FIGURE 9-30

BROOKFIELD, WISCONSIN WASTEWATER TREATMENT PLANT FLOW DIAGRAM

The 1976 operating and maintenance costs for the pressure filter are combined with the incinerator operational cost in Table 9-30. With the initiation of chemical addition for phosphorus removal, the cost of treating and disposing of a ton of dry solids decreased by approximately $1.33, as shown in Table 9-30. This reduction was due to decreases in the amounts of chemical conditioners and electricity required by the plate pressure filter. These decreases were, however, partially offset by an increase in the amount of auxiliary fuel used by the incinerator. This was the result of decreased incinerator volatile solids feed rates.

9.4.6.6 Cost

Figure 9-32 gives fixed-volume, recessed plate pressure filter capital cost as a function of press volume. Costs include those for filter auxiliary equipment, piping, and building. As an example, a pressure filter having 100 cubic feet (2.8 m^3) capacity would cost about $700,000. Since this number is based on June 1975 cost, it must be adjusted to the current design year.

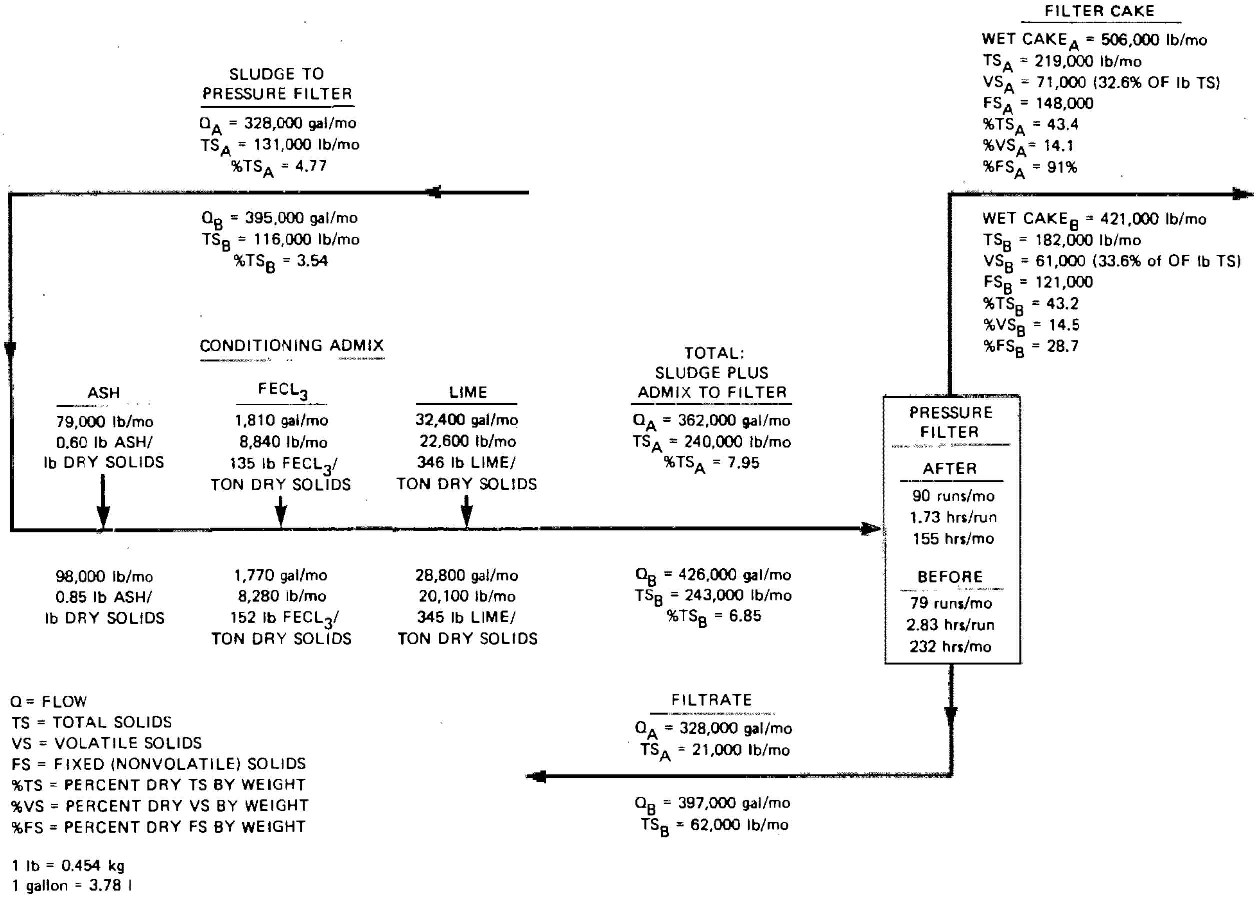

FIGURE 9-31

PERFORMANCE DATA FOR A PRESSURE FILTER BROOKFIELD, WISCONSIN

TABLE 9-30

PRESSURE FILTRATION AND INCINERATION OPERATIONAL COST

Item	Unit cost, 1976 dollars	1976 Dollar cost per ton dry solids: Before	After
$FeCl_3$		9.61	8.69
Lime	0.0305	10.52	10.55
Natural gas[a]	0.001786	11.73	12.29
Electricity	0.04	10.40	9.60
Labor	6.00	20.00	20.00
Total		$62.26	$61.13

[a]Includes incinerator warm-up.

1 ton = 0.907 t

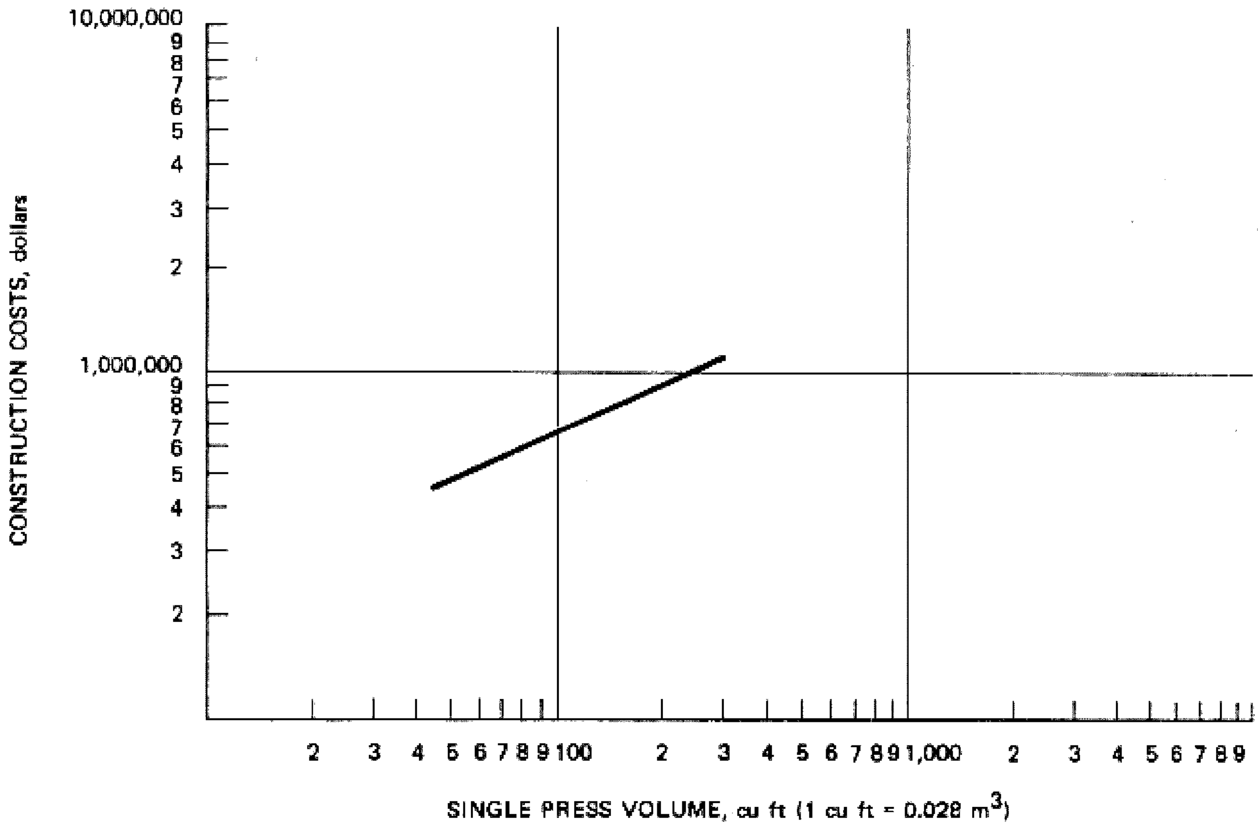

FIGURE 9-32

ESTIMATED JUNE 1975 COSTS FOR FIXED VOLUME RECESSED PLATE PRESSURE FILTERS (39)

Figure 9-33 indicates fixed-volume, recessed plate pressure filter labor requirements. Labor requirements are based on continuous, seven-day-per-week operation with two-hour cycles and include operation and maintenance for both press and related auxiliaries (chemical feed system and pumps). As an example, a pressure filter having 100 cubic feet (2.8 m^3) of capacity would require 8,000 man-hours of operation and maintenance per year and would be included in the cost analysis.

Figure 9-34 gives power consumption as a function of feed solids concentration and operating volume. The graph is based on a filter that operates continuously, seven days per week, and has a 2-hour cycle time. Power consumption includes that for the feed pump, open and close mechanisms, and moveable head mechanism.

Figure 9-35 presents a graph developed for estimating annual material and maintenance costs for a fixed-volume, recessed plate pressure filter. The graph is based on unit operation of seven days per week with a two-hour cycle time.

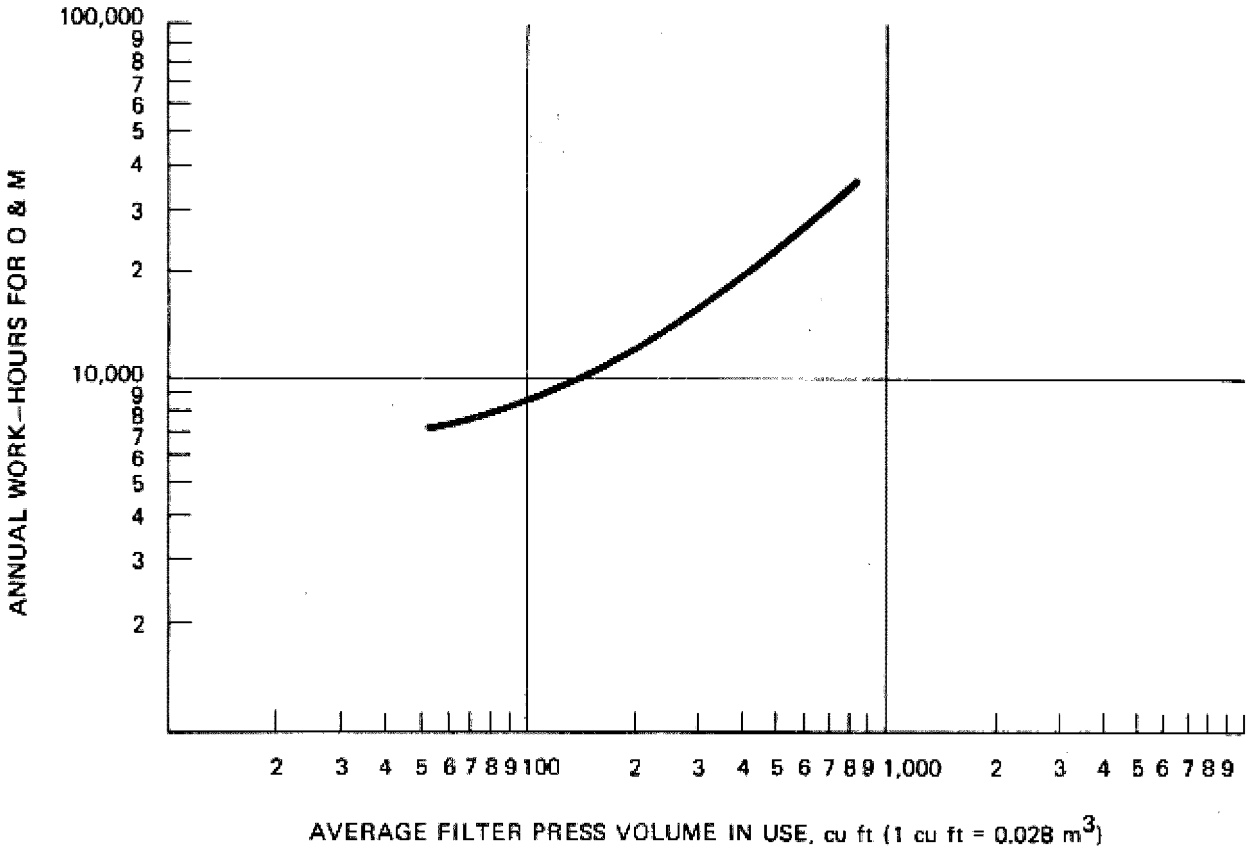

FIGURE 9-33

ANNUAL O&M MAN-HOUR REQUIREMENTS - FIXED VOLUME RECESSED PLATE PRESSURE FILTER (39)

9.4.7 Screw and Roll Press

9.4.7.1 Screw Press

This dewatering device employs a screw surrounded by a perforated steel (screen) cylinder. Sludge is pumped inside the screen and is deposited against the screen wall by the rotating screw. The cake that forms acts as a continuous filter. The screw moves the progressively dewatered sludge against a containment at the outlet and further dewaters the sludge by pressure of the screw action against the restriction. Figure 9-36 shows a typical layout from one screw press manufacturer. Although no full-scale municipal wastewater treatment plants are known to be in operation, large-scale studies have been conducted. Table 9-31 lists typical results.

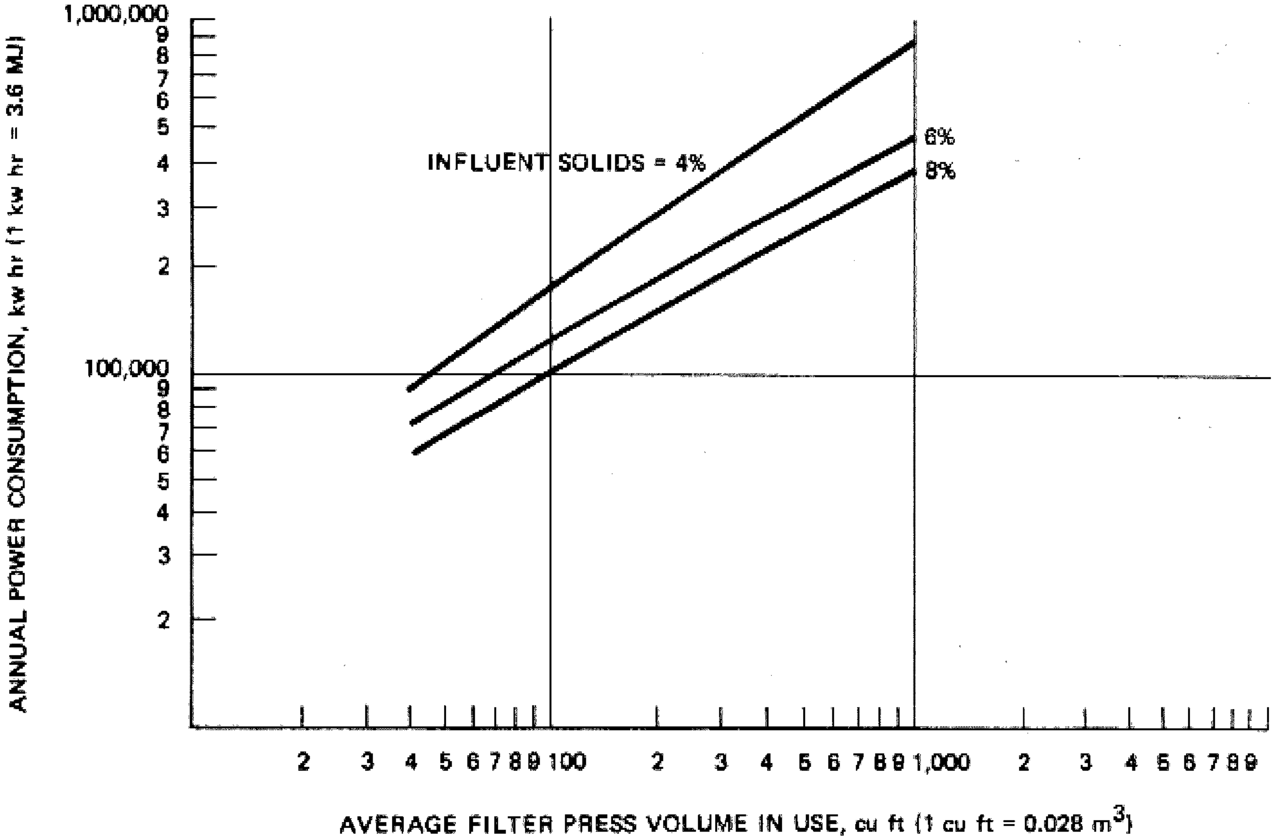

FIGURE 9-34

FIXED VOLUME RECESSED PLATE PRESSURE FILTER POWER CONSUMPTION (39)

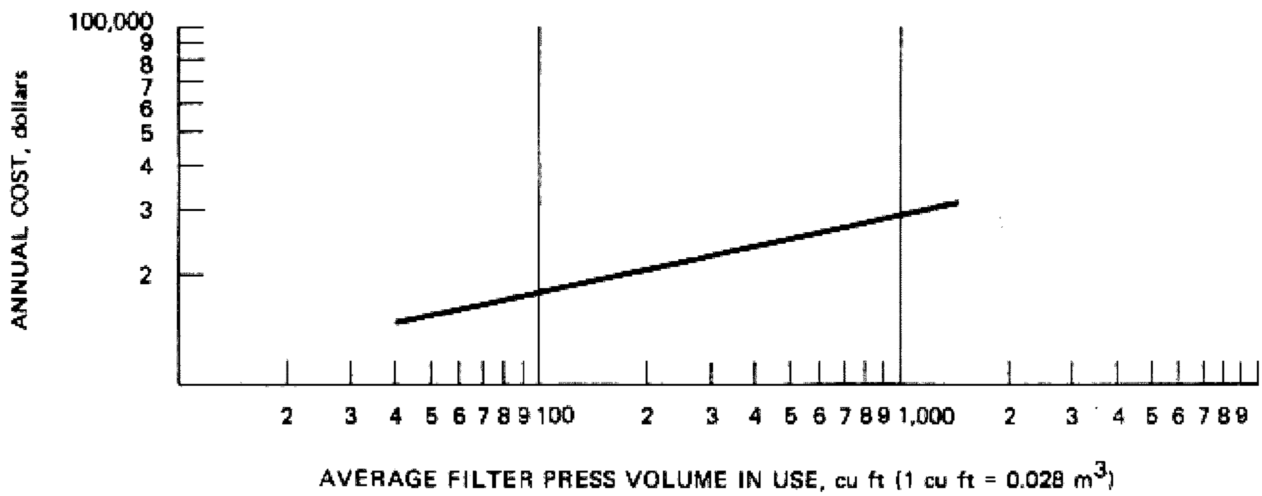

FIGURE 9-35

ESTIMATED JUNE 1975 ANNUAL MAINTENANCE MATERIAL COST-FIXED VOLUME, RECESSED PLATE PRESSURE FILTER (39)

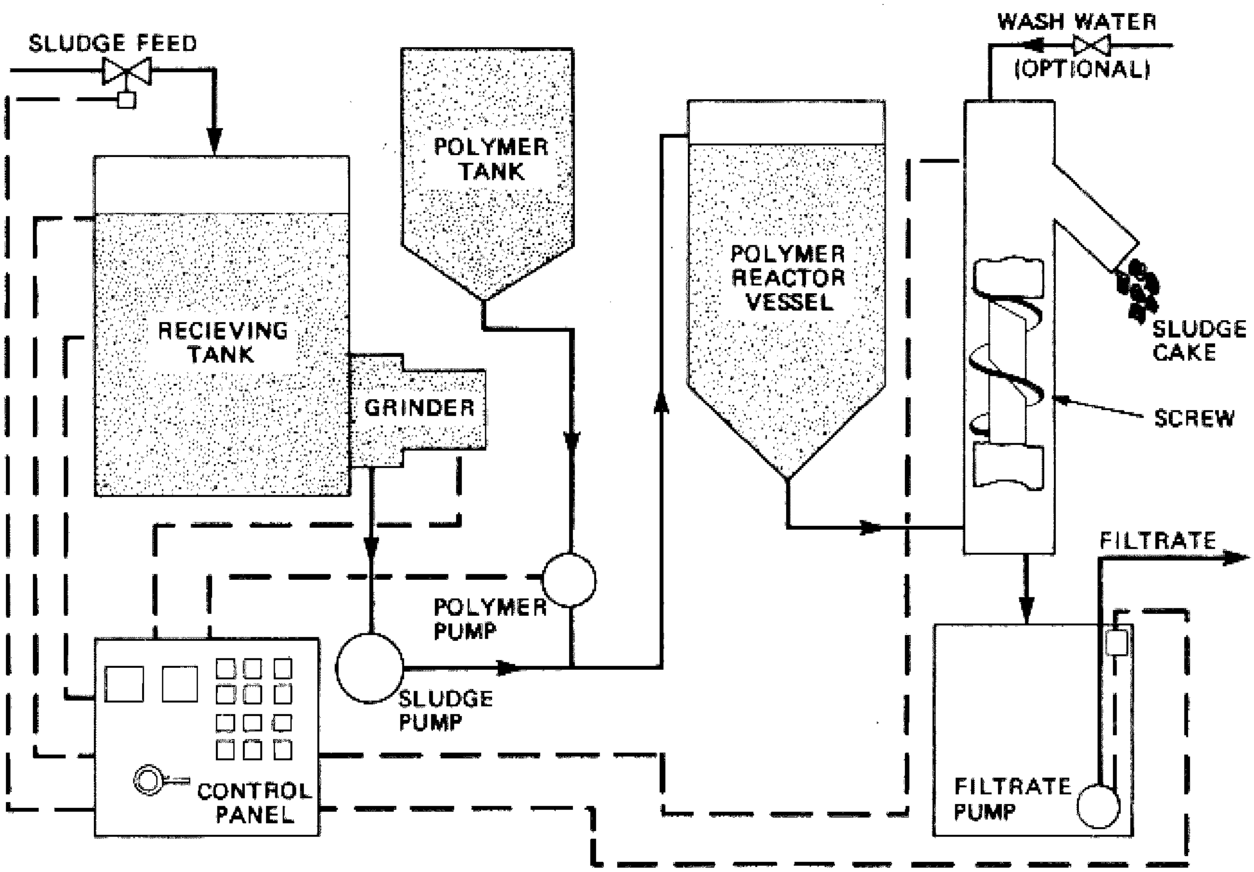

FIGURE 9-36

SYSTEM SCHEMATIC FOR ONE TYPE OF SCREW PRESS SYSTEM

TABLE 9-31

PERFORMANCE RESULTS FROM A SCREW PRESS

Location	Sludge type	Feed solids, percent	Polymer, lb dry/ton dry solids	Cake solids, percent	Filtrate, percent solids	Reference
Stratford, CT	Primary only	3-5	0	25-31	0.9-1.4	74
	Primary plus waste-activated					
	50:50 mixture	3-3.3	0	13-17	0.7-2.0	
	67:33 mixture	2.7-4.0	0	20-27	0.7-2.0	
Norwich, CT	Anaerobically digested mixture 60 percent primary plus 40 percent waste-activated	5.5-9.8	3.9-5.6	18.6-22.6	0.2-1.0	75

1 lb/ton = 0.5 kg/t

9.4.7.2 Twin-Roll Press

Figure 9-37 shows a cross section of a twin-roll, vari-nip press. Developed in 1970 by modifying a fixed nip twin-roll press, the vari-nip press was installed in 17 plants by 1976. One of these plants is municipal (76).

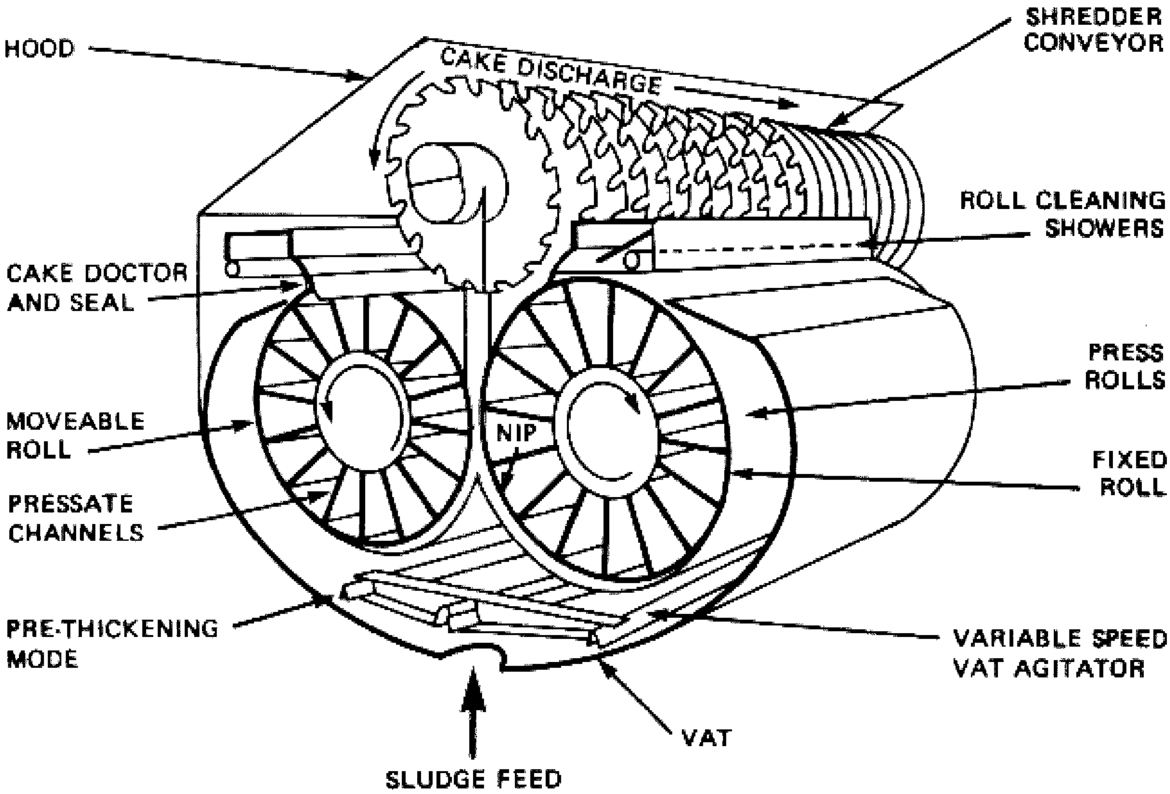

FIGURE 9-37

CROSS SECTION VIEW OF A TWIN-ROLL VARI-NIP PRESS

The unit consists of a pair of perforated rolls, one roll fixed and the other moveable, so that the nip (or space) between the rolls can be varied. The horizontal rolls are mounted in a sealed vat. Sludge is pumped into the vat under a slight pressure of two to four pounds per square inch (14 to 28 kN/m^2). This low vat pressure moves the sludge into the nip, where it is further dewatered by a nip pressure load of 200 to 400 pounds per lineal inch (36 to 72 kg/lineal cm) of roll length. Filtrate passes from the sludge through the perforated rolls and discharges by gravity. The compressed cake is then doctored off the rolls and discharged into a shredder and conveyor.

The "Pig's Eye Plant" at St. Paul, Minnesota has evaluated the dewatering of mixtures of primary and waste-activated sludge (76). Results showed that on raw primary sludge, a cake of 35 percent was obtainable after sludge conditioning with approximately seven pounds of dry polymer per ton (3.5 kg/t) of dry feed solids. When biological sludge was added, performance decreased and polymer requirements increased. At a mixture of 50:50, cake solids dropped to 28 percent, while polymer requirements increased to 17 pounds of dry polymer per ton (8.5 kg/t) of dry feed solids. The conclusion was that this was an excellent dewatering unit for primary sludge.

9.4.8 Dual Cell Gravity (DCG) Filter

The DCG unit consists of two independent cells formed by a nylon filter cloth. The cloth travels continuously over guide wheels and is rotated by a drive roll and sprocket assembly. A cross section of a typical DCG unit is shown in Figure 9-38. Dewatering occurs in the first cell, and cake formation, in the second cell.

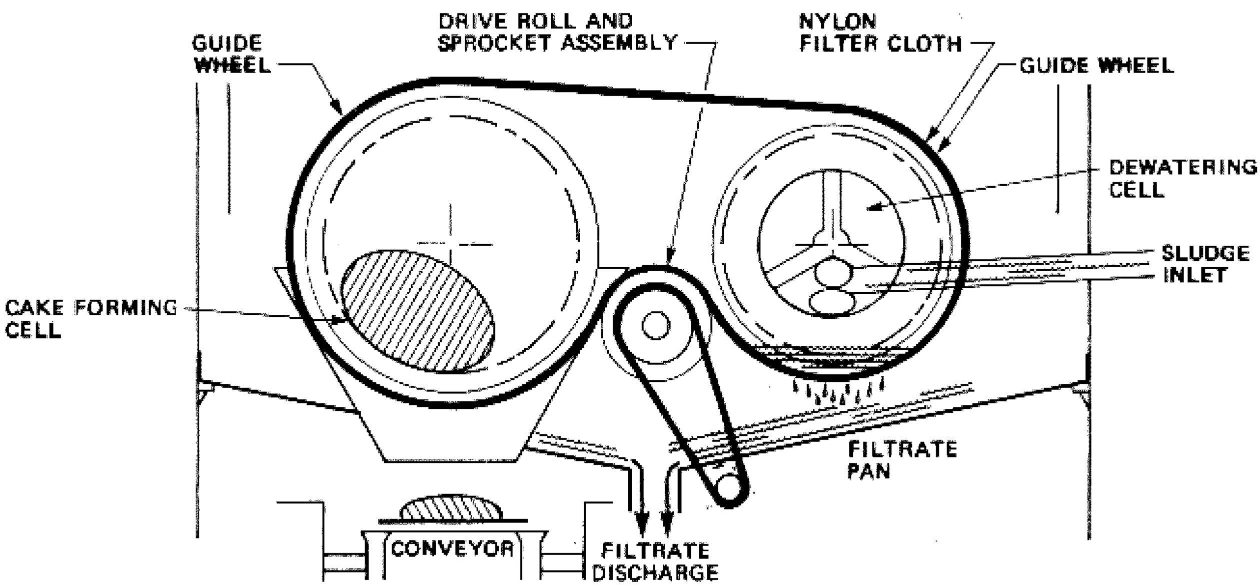

FIGURE 9-38

CROSS SECTION VIEW OF A DUAL CELL GRAVITY FILTER

Sludge is introduced in the dewatering cell, where initial liquid/solids separation takes place. The dewatering solids are then carried over the drive roll separator into the second cell. Here, they are continuously rolled and formed into a cake of relatively low moisture content. The weight of this sludge cake presses additional water from the partially dewatered sludge carried over from the dewatering cell. When the cake of dewatered solids grows to a certain size, excess quantities are discharged over the rim of the second cell to a conveyor belt that moves the material out of the machine.

Table 9-32 summarizes the operating results from Mentor, Ohio, which has three units to dewater an aerobically digested mixture of primary, waste-activated sludge and a mixture of primary, waste-activated, and alum sludge generated from phosphorus removal.

TABLE 9-32

SUMMARY OF PERFORMANCE RESULTS FOR A DUAL CELL GRAVITY FILTER - MENTOR, OHIO (61)

	Primary plus waste activated sludge	Primary plus waste activated plus alum sludge
Feed - percent total solids	2.1-2.7	2.5-3.1
Cake - percent total solids	8.8-9.2	8.2-9.1
Polymer usage		
Cationic - liquid lbs per ton solid	143	136
Anionic - dry lbs per ton solids	0.4	0.04
Filtrate characteristics	Not given	

1 lb/ton = 0.5 kg/t

9.4.9 Tube Filters

Tube filters can be either of the pressure type or of the gravity type.

9.4.9.1 Pressure Type

Commonly known as tube filter presses, pressure type tube filters have been used in industry (77). However, there are no municipal installations. Typically, this type of device consists of an outer cylinder, an internal rubber bladder, and an internal perforated cylinder which is covered with a filter media. The whole assembly is mounted vertically.

Slurry is pumped into the annular space between the bladder and media-covered wall. When this area is full, the bladder is filled with liquid, and the slurry is compressed against the filter media. Filtrate flows through the media and is discharged. When the desired cake solids concentration has been obtained, liquid pressure is released and the cake is discharged with a blast of air.

9.4.9.2 Gravity Type

In this application, sludge is mixed with polymer and then held in suspended porous bags. The weight of the sludge forces water out of the bag sides and bottom. Sludge is retained for a maximum of 24 hours, depending upon the desired dryness, and is then released through a bottom opening.

Following is a description of the 0.5-MGD (21.9 l/s) dewatering facility at Half Moon Bay, California.

This facility consists of four bags, each 3 feet (0.9 m) in diameter and 9 feet (2.7 m) long with a ring at the top to support the polyester media bag and a ring at the bottom, which is engaged circumferentially by a motor-driven chain. The chain twists the ring about 360 degrees, thereby closing off the bottom so that the bag can be filled. Suspended down the center of the bag is a polyester tube about 6 inches (15 cm) in diameter with the end extending about 12 inches (0.3 m) beyond the bottom of the closed ends. All four bags are mounted outdoors on a steel framework over a concrete pad containing the drainline and chemical conditioning system. The sludge fills the annular core, and the filtrate seeps through the outer polyester media surface and the inner core tube.

The batch operation practiced at Half Moon Bay is on a 24-hour cycle consisting of a four-hour fill period (waste-activated sludge from a complete mix aeration plant) and a 20-hour drain. With a 1.5 percent solids feed, a 16 percent solids cake has been obtained.

9.5 Other Dewatering Systems

Several other types of dewatering devices are available that do not readily fall into any of the previously discussed units. These include cyclones, screens, and electro-osmosis.

9.5.1 Cyclones

In the municipal wastewater field, cyclones or hydrocyclones (name given to cyclones specifically designed for liquids) have been used for cleaning and dewatering grit from grit chambers, primary clarifiers, and anaerobic digesters since the early 1950s. Since then, over 1,400 units have been installed (43).

When a liquid stream enters a cyclone, the particles are separated by centrifugal acceleration. Unlike centrifuges, cyclones have no moving parts. The liquid motion inside the unit causes the necessary acceleration. The theory of cyclones is thoroughly covered in a recent discussion by Svarovsky (78).

By itself, a cyclone does not dewater. The underflow from the cyclone discharges into a type of dewatering device. This device may be as simple as a steel bin with drainage holes, or as complex as a rotating screen screw or rake classifier. These dewatering devices will produce a grit with a moisture content ranging from 20 to 35 percent.

The degritted liquid stream (overflow) from a cyclone degritting raw sludge normally goes to a gravity thickener. When the cyclone is degritting the flow from grit chambers, the overflow is usually recycled to the grit chamber. Some designers have found it necessary to screen this overflow to keep debris from overwhelming the system. The drainage from the dewatering device is collected and typically returned to the head of the treatment plant.

9.5.2 Screens

"Screening is the process of separating grains, fragments or lumps of a variety of sizes into groups, each of which contains only particles in the size range between definite maximum and minimum size limits" (79). In addition to being used in dewatering (26), screens have also been used for primary treatment (80), thickening (81,82), and conditioning (see Chapter 8).

The primary use of screens in dewatering would be with bar screenings or the underflow from grit cyclones. In one extensive study (83), the following results were found:

- Ground bar screenings could be dewatered to six percent solids with a static type screen.
- Ground bar screening could be dewatered to sixteen percent solids with a revolving drum screen.
- Underflow from a grit cyclone could be dewatered to 25 percent solids with either the static or revolving screen.

The popularity of screens is slowly increasing in the United States because in certain applications they offer advantages in both capital cost and operating cost.

9.5.3 Electro-Osmosis

The use of electro-osmosis for dewatering municipal wastewater sludge has been studied on a pilot-plant scale (84). The system consists of a vertical-mounted, endless moving belt which is drawn over vertical plate-mounted, stainless steel cathodes, submerged in a tank of waste sludge. Results indicated that cakes of over 20 percent solids could be obtained from an anerobically digested sludge having 2.6 percent feed solids.

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 10. Heat-Drying

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

September 1979

CHAPTER 10

HEAT-DRYING

Heat-drying is the process of evaporating water from sludge by thermal means. Ambient air-drying of sludges is discussed in Chapter 9, and composting, in Chapter 12.

10.1 Introduction

In the United States, dry waste-activated sludges and those from Imhoff tanks have been heat dried to produce a soil conditioner and nutrient source since the early 1920s. Historically, the use of heat-drying has been justified based on the expectation that sales of the dried material would substantially offset process costs. However, demand for the product has generally been low in the fertilizer market. Milwaukee, Wisconsin; Houston, Texas; Chicago, Illinois; and Largo, Florida, are notable exceptions where marketing has been successful. Because revenues have generally been low and because heat-drying is expensive, net costs have often been high, and the process has not found wide application. The use of heat-drying must be evaluated in the context of overall sludge management at a given facility.

10.2 Heat-Drying Principles

Sludge is heat dried at temperatures too low to destroy organic matter. Water vapor is carried away by a moist gas (usually air). The designer establishes the actual conditions of drying--for example, temperature, humidity, detention time, velocity, and direction of flow of the gas stream across the drying surface.

10.2.1 Drying Periods

The following are the three well-defined stages in heat-drying:

1. Initial Drying. During this stage, the sludge temperature and the drying rates are increased to the steady state conditions of the second stage. Stage one is usually short; little drying occurs during this time.

2. Steady State Drying. The time that the sludge is in this stage is generally the longest of all the stages. The surfaces of the sludge particles are completely saturated with water. Surface water is replaced with water from

the interior of the solid as fast as it is evaporated. Drying proceeds as if the water were evaporated from a pool of liquid. The solid itself does not significantly influence the drying rate. For this drying period, the temperature at the sludge/gas interface is ordinarily kept at the wet-bulb temperature of the gas. As long as unbound surface moisture is present, the solid is heated only to the wet-bulb temperature of the gas; solids may therefore be dried with fairly hot gases and not themselves attain elevated temperatures. For example, the wet-bulb temperature is 133°F (56°C) for a gas stream that has an absolute humidity of 0.01 pounds water per pound dry air and a temperature of 600°F (316°C).

3. Final Drying. The final stage occurs when sufficient water has evaporated that the solid surface is only partially saturated. Surface water is evaporated more rapidly than it can be replaced by water from the interior of the solid. As a consequence, overall drying rates are markedly lower in stage 3 than in stage 2. During this period, the temperature of the solid/gas interface increases because latent heat cannot be transferred from the sludge to the gas phase as rapidly as sensible heat is received from the heating medium.

Sludge moisture content is normally expressed in percent moisture, percent solids, or pounds water per pound dry sludge. The minimum sludge moisture content practically attainable with heat drying depends upon the design and operation of the dryer, moisture content of the sludge feed, and the chemical composition of the sludge. For ordinary domestic wastewater sludges, sludge moisture contents as low as five percent may be achieved. Chemical bonding of water within the sludge, which can occur through chemical addition for sludge conditioning, or chemicals present in industrial sludges can increase the amount of water retained in the dried products beyond the five percent moisture level.

10.2.2 Humidity and Mass Transfer

Humidity is a measure of the moisture content of the gas phase at a given temperature and is important to consider when determining drying rates. Absolute humidity is a measure of the weight of water per unit weight of dry gas (for example, pounds water per pound dry air).

In heat-drying of sludge, water is transferred to the gas phase. The driving force for transfer is the difference between absolute humidity at the wetted solid/gas interface and the absolute humidity in the gas phase. The transfer rate--that is, the drying rate--can be described by the following equation:

$$W = K_y A\ (Y_s - Y_a) \qquad (10\text{-}1)$$

where:

- W = rate of drying, pounds water per hour (kg/hr);
- K_y = mass transfer coefficient of the gas phase, pounds water per hour per square foot per unit of humidity difference ($kg/hr/m^2$/unit of humidity difference);
- A = area of wetted surface exposed to drying medium, square feet (m^2);
- Y_s = humidity at the sludge/gas interface temperature, pounds water per pounds dry gas (kg/kg);
- Y_a = humidity of the gas phase, pounds water per pounds dry gas (kg/kg).

10.2.3 Temperature and Heat Transfer

In heat-drying, the temperature difference between the heating medium and the sludge/gas interface provides the driving force for heat transfer.

Dryers are commonly classified on the basis of the predominant method of transferring heat to the wet solids being dried (1). These methods include:

Convection (direct drying). Heat transfer is accomplished by direct contact between the wet sludge and hot gases. The sensible heat of the inlet gas provides the latent heat required for evaporating the water. The vaporized liquid is carried off by the hot gases. Direct dryers are the most common type used in heat-drying of sludge. Flash dryers, direct rotary dryers, and fluid bed dryers employ this method. Convective heat transfer is described by Equation 10-2.

$$q_{conv} = h_c A\ (t_g - t_s) \qquad (10\text{-}2)$$

where:

- q_{conv} = convective heat transfer, Btu per hour (kJ/hr);
- h_c = convective heat transfer coefficient, Btu per hour per square foot per °F ($kJ/hr/m^2/°C$);

A = area of wetted surface exposed to gas, square feet (m^2);

t_g = gas temperature, °F (°C);

t_s = temperature at sludge/gas interface, °F (°C).

Conduction (indirect drying). Heat transfer is accomplished by contact of the wet solids with hot surfaces (for example, a retaining wall separates the wet solid and the heating medium). The vaporized liquid is removed independently of the heating medium. The thin film dryer employs this principle. Conductive heat transfer is described by Equation 10-3.

$$q_{cond} = h_{cond} A \, (t_m - t_s) \qquad (10\text{-}3)$$

where:

q_{cond} = conductive heat transfer, Btu per hour (kJ/hr);

h_{cond} = conductive heat transfer coefficient, Btu per hour per°F (kJ/hr/°C);

A = area of heat transfer surface, square feet (m^2);

t_m = temperature of drying medium--for example, steam, °F (°C);

t_s = temperature of sludge at drying surface, °F (°C).

The conductive heat transfer coefficient (h_{cond}) is a composite term that includes the effects of the heat transfer surface and sludge-side and medium-side films. Descriptions of methods for computing h_{cond} are available in textbooks and from dryer manufacturers (1-4).

Radiation (infrared or radiant heat-drying). Heat transfer is accomplished by radiant energy supplied by electric resistance elements, by gas-heated incandescent refractories that also provide the advantage of convective heating, or by infrared lamps. The Shirco Company furnace and multiple-hearth furnaces are examples of drying equipment that use radiant heat. Radiation heat transfer is described by Equation 10-4.

$$q_{rad} = \varepsilon_s \, A \sigma \, (t^4{}_r - t^4{}_s) \qquad (10\text{-}4)$$

where:

q_{rad} = radiation heat transfer, Btu/per hour (kJ/hr);

ε_s = emissivity of the drying surface, dimensionless;

A = sludge surface area exposed to radiant source, square feet (m^2);

σ = Stefan - Boltzman constant, 1.73×10^{-9} Btu/per hour per square foot per ^oR (4.88×10^{-8} k cal/m^2/hr/°k);

t_r = absolute temperature of the radiant source, ^oR;

t_s = absolute temperature of the sludge drying surface, ^oR;

This discussion of heat drying is necessarily brief; the reader is referred elsewhere for more information (1-5). Equations for mass and heat transfer rates and for associated drying times for specific dryer types are discussed in detail in these references. It is often difficult to determine appropriate values of mass and heat transfer coefficients to be used in these equations. Thus, results predicted by the equations and results obtained in practice may be divergent, perhaps critically so. Most usable design information is obtained by testing with actual process feeds under conditions closely simulating prototype operations. Many dryer manufacturers provide such testing services.

10.3 Energy Impacts

Thermal evaporation of water from sludge requires considerable energy. The amount of fuel required to dry sludge depends upon the amount of water evaporated. It is imperative that a dewatering step precede heat-drying so that overall energy requirements can be minimized. Figure 10-1 shows a relationship between the solids content of the sludge and the energy required to produce a product containing ten percent moisture. The energy estimates for heat-drying of sludge must be considered rough approximations, since values can vary considerably depending upon the type of dryer, whether or not energy recovery is a part of the process, the flow sheet, and the characteristics of the sludge.

The heat required to evaporate water from the wet sludge is composed of:

- Heat to raise the sludge solids and associated residual water to the temperature of the sludge product as it leaves the dryer.

- Heat to raise the water temperature to the point where it can evaporate and then to vaporize the water (latent heat).

- Heat to raise the temperature of the exhaust gas, including water vapor, to the exhaust temperature.

- Heat to offset heat losses.

The above-mentioned heat must be supplied by the heating medium, for example, hot air or steam.

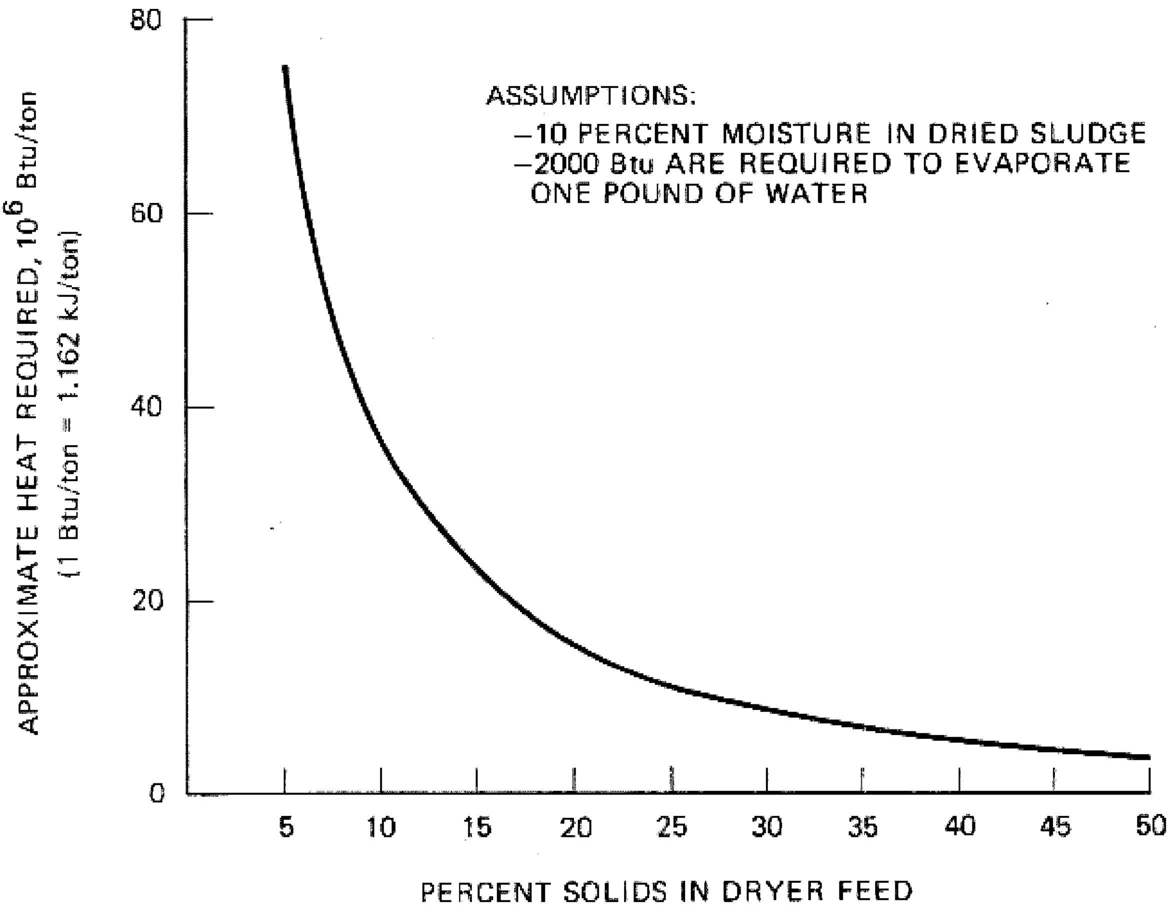

FIGURE 10-1

ESTIMATE OF ENERGY REQUIRED TO DRY WASTEWATER SLUDGE AS A FUNCTION OF DRYER FEED SOLIDS CONTENT

10.3.1 Design Example

Ten thousand pounds per hour (4,540 kg/hr) of a dewatered sludge containing 20 percent solids is to be dried by direct contact with hot air. The sludge temperature is 60°F (17°C). The temperature of the air prior to heating is 70°F (22°C) and its absolute humidity is 0.008 pounds water per pound of dry air. The temperature of the dried sludge is 140°F (60°C). The dried sludge is 91 percent solids and 9 percent water. The dryer exhaust gas temperature is 240°F (116°C), and it contains 0.12 pounds of water per pound of dry air. Radiant heat losses from the dryer structure are 1,000,000 Btu per hour (1,054,000 kJ/hr). A preheater is used to heat the air prior to its entering the dryer. Figure 10-2 is a schematic diagram for this example. The required air flow (G), the required air inlet temperature to the dryer (t_2), and the dryer evaporative efficiency must be calculated.

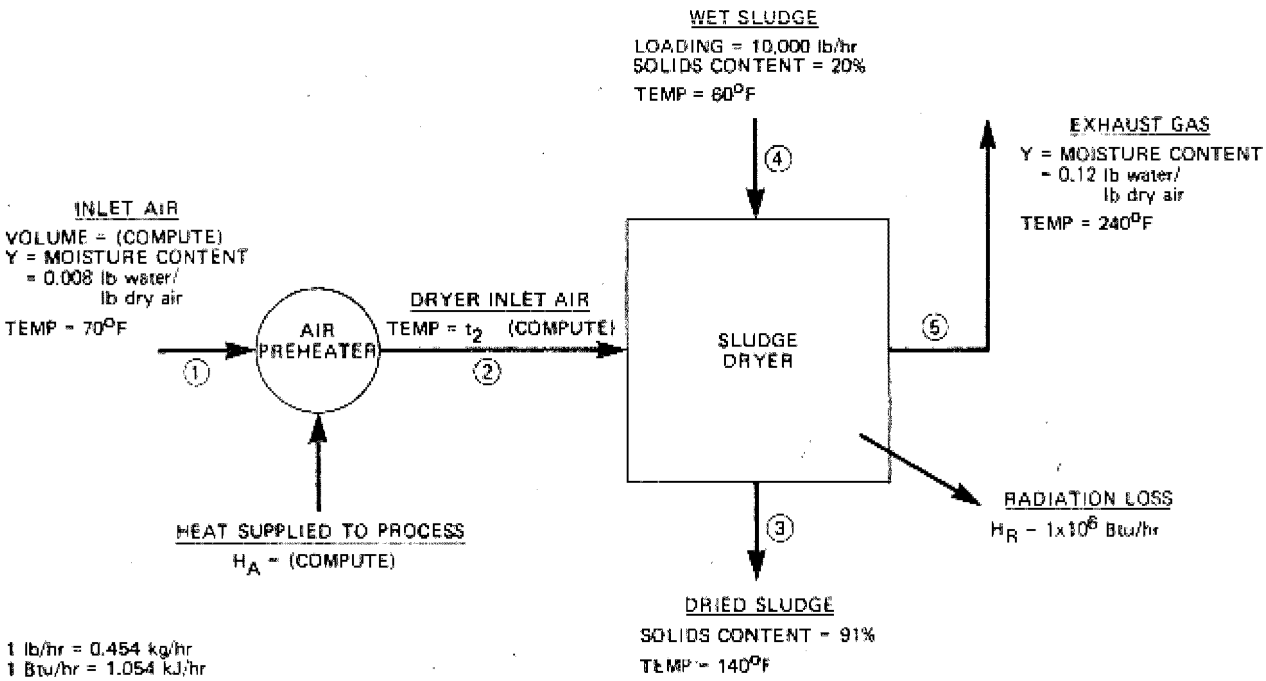

FIGURE 10-2

SCHEMATIC FOR SLUDGE DRYING EXAMPLE

The following heat capacity information is known or assumed:

Substance	Heat Capacity, Btu/lb/°F
Dry air	0.24
Dry solids	0.25
Water	1.0
Water vapor	0.45

Step 1 - Determine the required air flow, (G). Calculate a moisture balance of substances entering and leaving the dryer.

1. Moisture in:

   a. Moisture in sludge = $\left(10{,}000\ \frac{\text{lb sludge}}{\text{hr}}\right)\left(0.8\ \frac{\text{lb water}}{\text{lb sludge}}\right)$ = 8,000 lb per hour (3.6 t/hr).

b. Moisture in inlet air $= \left(G \ \frac{\text{lb dry air}}{\text{hr}}\right)\left(0.008 \ \frac{\text{lb water}}{\text{lb dry air}}\right) = 0.008$ G lb per hour.

2. Moisture out:

a. Moisture in sludge $= \left(10{,}000 \ \frac{\text{lb sludge}}{\text{hr}}\right)\left(0.2 \ \frac{\text{lb dry solids}}{\text{lb sludge}}\right)\left(\frac{9 \text{ lb water}}{91 \text{ lb dry solids}}\right) = 200$ lb per hour (91 kg/hr).

b. Moisture in air $= \left(G \ \frac{\text{lb dry air}}{\text{hr}}\right)\left(0.12 \ \frac{\text{lb water}}{\text{lb dry air}}\right)$

3. Equate moisture in and moisture out 8,000 + 0.008 G = 200 + 0.12 G.

4. Solve for inlet air flow (G):

G = 69,600 pounds per hour (31.6 t/hr).

Step 2 - Determine the required air inlet temperature (t_2). Calculate a heat balance for the dryer. A substance's heat content with respect to a given base temperature can be calculated by assuming the heat required to bring the substances from the base temperature to the temperature being considered. For this example, a base temperature of 32°F (0°C) is arbitrarily selected, and heat content (also known as enthalpy) is calculated with respect to it. At steady state, heat in must equal heat out. Consider the heat content of streams entering and leaving the dryer:

1. Heat into the dryer is the sum of

a. Heat content of sludge (H_4)

(1) Heat content of dry solids

$$= \left(10{,}000 \ \frac{\text{lb sludge}}{\text{hr}}\right)\left(0.20 \ \frac{\text{lb solids}}{\text{lb sludge}}\right)\left(0.25 \ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(60\text{–}32\text{°F}\right)$$

= 14,000 Btu per hour (14.8 GJ/hr).

(2) Heat content of water

$$= \left(10{,}000 \ \frac{\text{lb sludge}}{\text{hr}}\right)\left(0.80 \ \frac{\text{lb water}}{\text{lb sludge}}\right)\left(1.0 \ \frac{\text{Btu}}{\text{lb°/F}}\right)\left(60\text{–}32\text{°F}\right)$$

= 224,000 Btu per hour (233 GJ/hr).

(3) Summing,

H_4 = 14,000 + 224,000 = 238,000 Btu per hour (251 GJ/hr).

b. Heat content of air entering the dryer (H_2)

(1) Heat content of dry air

$$= \left(69{,}600\ \frac{\text{lb}}{\text{hr}}\right)\left(0.24\ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(t_2 - 32°\text{F}\right)$$

$$= 16{,}700\ (t_2 - 32)\ \text{Btu/hr.}$$

(2) Determine the heat content of the moisture associated with the air. This includes heat required to raise the moisture temperature from 32°F (0°C) to the dewpoint, vaporize the moisture, and finally increase the vapor temperature to t_2. From psychrometric charts (1), the dewpoint (the temperature at which the air in question is saturated) of air containing 0.008 pounds of water per pound of dry air is 50°F (10°C). From steam tables (6), the latent heat of vaporization at 50°F (10°C) is 1,065 Btu per pound (2.5 GJ/kg).

Heat content of moisture associated with air

$$= \left(69{,}600\ \frac{\text{lb dry air}}{\text{hr}}\right)\left(0.008\ \frac{\text{lb water}}{\text{lb dry air}}\right)\left[\left(1.0\ \frac{\text{Btu}}{\text{lb/°F}}\right)(50-32°\text{F}) + 1{,}065 + \left(0.45\ \frac{\text{Btu}}{\text{lb/°F}}\right)(t_2 - 50°\text{F})\right] = 603{,}000 + 250.7\ (t_2 - 50)$$

Btu per hour.

(3) Summing, $H_2 = 16{,}714\ (t_2 - 32) + 603{,}000 + 250.7\ (t_2 - 50)$

$$= 16{,}960\ t_2 + 55{,}600\ \text{Btu per hour.}$$

2. Heat out of the dryer is the sum of:

a. Heat content of the "dried" sludge (H_3)

(1) Heat content of the dry solids

$$= \left(10{,}000\ \frac{\text{lb sludge}}{\text{hr}}\right)\left(0.20\ \frac{\text{lb solids}}{\text{lb sludge}}\right)\left(0.25\ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(140-32°\text{F}\right)$$

$$= 54{,}000\ \text{Btu per hour (57 GJ/hr).}$$

(2) Heat content of residual water

$$= \left(10{,}000\ \frac{\text{lb sludge}}{\text{hr}}\right)\left(0.20\ \frac{\text{lb solids}}{\text{lb sludge}}\right)\left(\frac{9}{91}\ \frac{\text{lb water}}{\text{lb solids}}\right)\left(1.0\ \frac{\text{Btu}}{\text{lb/°F}}\right)$$

$$\times\ (140-32°\text{F}) = 21{,}400\ \text{Btu per hour (23 GJ/hr).}$$

(3) Summing,

$$H_3 = 54{,}000 + 21{,}400 = 75{,}400\ \text{Btu per hour (80 GJ/hr).}$$

b. Heat content of the exhausted air (H_5)

(1) Heat content of the dry air

$$= \left(69{,}600\ \frac{\text{lb dry air}}{\text{hr}}\right)\left(\frac{0.24\ \text{Btu}}{\text{lb/°F}}\right)\left(240-32\text{°F}\right) = 3{,}474{,}000\ \text{Btu}$$

per hour (3.7 TJ/hr).

(2) Determine the heat content of the moisture associated with the exhausted air. From psychrometric charts (1), the dewpoint of air containing 0.12 pounds water per pound of dry air is 135°F (58°C). The latent heat of vaporization at 135°F (58°C) is 1017 Btu per pound (2.4 GJ/kg).

Heat content of moisture associated with exhausted air

$$= \left(69{,}600\ \frac{\text{lb dry air}}{\text{hr}}\right)\left(0.12\ \frac{\text{lb water}}{\text{lb dry air}}\right)\left[\left(1.0\ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(135-32\text{°F}\right) + 1017 + \left(0.45\ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(240-135\text{°F}\right)\right] = 9{,}750{,}000\ \text{Btu per hour}$$

(10.3 TJ/hr).

(3) Summing,

H_5 = 3,474,000 + 9,750,000 = 13,224,000 Btu per hour

(13.9 TJ/hr).

c. Radiant heat loss, H_r = 1,000,000 Btu per hour (1.05 TJ/hr).

3. Calculate an overall heat balance around the dryer. At steady state, heat into the dryer equals heat out, that is $H_4 + H_2 = H_3 + H_5 + H_r$. Therefore, 238,000 + 16,960 t_2 + 55,600 = 75,400 + 13,224,000 + 1,000,000.

4. Solve for dryer inlet air temperature (t_2)

t_2 = 826°F (441°C).

<u>Step 3 - Determine the evaporative efficiency</u>. In this example, evaporative efficiency is defined as the heat supplied to evaporate one pound of water, in comparison to the theoretical heat of vaporization:

1. Determine heat supplied to the process (H_A). By an overall heat balance around the process (including the air preheater), $H_A = H_3 + H_5 + H_R - H_4 - H_1$.

a. From previous calculations, $H_3 + H_5 + H_R$ = "heat out" = 75,400 + 13,224,000 + 1,000,000 = 14,299,000 Btu per hour (15.0 TJ/hr).

b. From previous calculations, H_4 = 238,000 Btu per hour (251 GJ/hr).

c. Determine H_1, the heat content of the inlet air

(1) Heat content of dry air

$$= \left(69{,}600\ \frac{\text{lb}}{\text{hr}}\right)\left(0.24\ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(70\text{-}32\text{°F}\right) = 635{,}000 \text{ Btu}$$

per hour (669 GJ/hr).

(2) Heat content of moisture associated with dry inlet air

$$= \left(69{,}600\ \frac{\text{lb dry air}}{\text{hr}}\right)\left(0.008\ \frac{\text{lb water}}{\text{lb dry air}}\right)\left[\left(1.0\ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(50\text{-}32\text{°F}\right) + 1065 + \left(0.45\ \frac{\text{Btu}}{\text{lb/°F}}\right)\left(70\text{-}50\text{°F}\right)\right] = 608{,}401 \text{ Btu per hour}$$

(641 GJ/hr).

(3) Summing,

H_1 = 635,000 + 608,000 = 1,243,000 Btu per hour (1.3 TJ/hr).

d. H_A = 14,290,000-238,000 - 1,243,000 = 12,809,000 Btu per hour (13.5 TJ/hr).

2. Heat supplied to evaporate 1 pound of water.

$$= \frac{12{,}809{,}000 \text{ Btu}}{7{,}800 \text{ lb water}} = 1{,}642 \text{ Btu per pound of water}$$

(1.8 GJ/kg).

3. Heat of vaporization of water at the inlet sludge temperature = 1060 Btu per pound (2.5 GJ/kg):

$$\text{Evaporative efficiency} = \frac{1{,}060}{1{,}642}\ (100) = 64 \text{ percent.}$$

10.3.2 Energy Cost of Heat-Dried Sludges Used for Fertilizers

A simple analysis shows that heat-dried sludge is not competitive with commercial fertilizers when the two are compared on the basis of energy required per unit of nutrient produced. From

Figure 10-1, the energy required to flash-dry a well-dewatered sewage sludge (40 percent solids concentration) is approximately 5.6 x 10^6 Btu per ton (7.3 x 10^6 kJ/t) of dry solids. Assuming that the solids are four percent nitrogen by weight and that half of the nitrogen is in plant-available form, the energy required to produce 1.0 ton, (0.9 t) of plant-available nitrogen is

$$\frac{5.5 \times 10^6 \text{ Btu}}{\text{ton dry solids}} \times \frac{100 \text{ ton dry solids}}{4 \text{ ton N}} \times \frac{2 \text{ ton N}}{\text{ton available N}} = 280 \times 10^6 \text{ Btu}$$

(295 x 10^6 kJ).

The energy required to produce and distribute one ton of commercial nitrogen is estimated to be 49 x 10^6 Btu per ton of nitrogen (57 x 10^6 kJ/t) (7). Assuming all nitrogen in commercial fertilizers is plant-available and that 94 percent of the energy consumed is for production and six percent for distribution of raw materials and finished product, then approximately 46 x 10^6 (49 kJ) is required to produce one ton (0.9 t) of nitrogen on a commercial basis (7). This is approximately 16 percent of the energy required to produce one ton of available nitrogen from flash-dried sludge.

By similar calculations, it can be shown that one ton of phosphorus from flash-dried sludge requires about 15 to 20 times as much energy to produce as one ton of phosphorus from commercial fertilizers.

10.4 Environmental Impacts

Heat-drying of sludge produces a material that usually contains 10 percent or less moisture, a moist gas stream that is ejected to the atmosphere, and in some cases, a liquid sidestream. The impacts of all of these products must be considered in the design of the heat-drying facilities. Some data on pathogenic organism survival through heat-drying processes are presented in Chapter 7. Heat-dried sludge should not be allowed to become rewetted, since moisture creates an environment favorable for regrowth of organisms. Once sludge is rewetted, anaerobic decomposition can begin with the concomitant generation of noxious odors. This is particularly a problem for sludges that have not been previously stabilized.

Potential users of dried sludge prefer a granular or pelletized product. A product which is dusty, odorous, or contaminated with materials such as plastics, strings, or cigarette butts is difficult to sell or give away.

10.4.1 Air Pollution

The gas stream exhausted from the dryers may be the source of odors and visible emissions. These appear to be most significant in high-gas velocity processes where the product is subject to abrasion and dusting occurs. The most effective control measure for these problems is afterburning. However, afterburning requires supplementary fuel and may be prohibitively expensive for many installations. Cyclones, wet scrubbers, electrostatic precipitators, and baghouses have been used with varying degrees of success.

Wet-scrubbing, electrostatic precipitators, and baghouses were tested for the control of odors and visible emissions from a Toroidal dryer located at the Blue Plains plant in Washington, D.C. The electrostatic precipitator and wet scrubber were unable to reduce emissions sufficiently to satisfy Washington's stringent air pollution requirements. Baghouses were effective when operating, but they persistently caught fire as a result of ignited grease deposits and thus were not reliable.

10.4.2 Safety

Drying systems are exposed to heavy dusting and have had problems with fires. The combination of combustible particles, warm temperatures, sufficient oxygen, and high-gas velocities make these systems susceptible to fires.

10.4.3 Sidestream Production

Liquid sidestreams are produced by certain ancilliary equipment in heat-drying (for example, wet scrubbers). These sidestreams frequently can be recycled to the headworks of the treatment plant but may require separate treatment.

10.5 General Design Criteria

There are several common features of heat-drying processes for which general design criteria can be developed.

10.5.1 Drying Capacity

The number and size of the dryers depend on the type of drying operation contemplated. If the dryers are operated continuously, extra dryer capacity is needed so that all sludge produced can be dried while maintenance and repairs are being performed. In cases where non-continuous operation (for example, 40 hours per week) is envisioned or where only one dryer is installed, the dryer(s) must have sufficient evaporative capacity to handle all the sludge, including that generated when the dryers are not on line. In the latter case, wet sludge storage requirements may be significant.

10.5.2 Storage Requirements

The design engineer should consider storage requirements for both the wet sludge feed and the dried product. Sufficient wet sludge storage should be provided to allow orderly shutdown of continuously operated drying processes (approximately three day's production at a peak rate). Storage for the dried product depends on the final disposal arrangement. Sales of the product are likely to be seasonal, and considerable storage may be necessary unless bulk buyers provide off-site storage. If the dried product is burned as a fuel or undergoes further processing, storage requirements are indicated by subsequent steps in the sludge-processing system. Dust can become a problem if the dried product is stored in bulk and is not pelletized. In some cases, the material should be appropriately contained.

10.5.3 Heat Source

The large amounts of energy required for heat-drying dictate that close attention be given to the source used to heat the drying medium. Natural gas and fuel oil are most frequently used but are becoming more expensive, and shortages have occurred in the past few years. Energy recovery within the heat-drying system itself provides one way of reducing energy usage; for example, heat exchangers can be used to recover heat from the exhaust gases. Recovery of heat from a power source within the plant is another method; for example, Milwaukee recovers waste heat from gas turbine exhausts. The dried sludge itself has a fuel value and may be used as a heat source for the drying medium.

10.5.4 Air Flow

Air flow is an important consideration in the design of direct dryers. Air flow may be cocurrent, countercurrent, or crossflow. In direct drying, cocurrent flow offers the advantage of higher thermal efficiency due to rapid cooling of the heating medium near the feed end with concomitant reduced heat losses through the dryer structure. In addition, the dried sludge is not subjected to high-gas temperatures near the discharge end, as it would be in counterflow operation. This is advantageous because it minimizes distillation of odorous materials and increases thermal efficiency somewhat by reducing heat lost with the dried sludge.

The rates of air flow are a function of the dryer design. However, turbulent conditions must be maintained to ensure intimate contact between the warm air and wet sludge. Dusting problems may limit air flow rate.

10.5.5 Equipment Maintenance

A major maintenance problem in some dryers is erosion of conveying equipment and drying shells by the abrasive dried sludge. This is particularly a problem for dryers processing WAS from activated sludge plants which have only coarse screening for grit removal. The use of ferric chloride as a dewatering aid may also create corrosive conditions that exacerbate the problem. Worn conveying equipment can lead to dusting problems. Abrasive sludge may result in replacement of rotary dryer drum shells every few years.

10.5.6 Special Considerations

Special equipment may be needed when dried material is produced. For example, the value of dried sludge may be increased by nutrient supplements such as nitrogen, phosphorus, or potassium. Also, the dried product may require finishing before sales; for example, pelletizing or bagging operations may be needed.

In the United States, the Organiform process, developed by Orgonics, Inc., has been used to increase the nitrogen content of the dried sludge. This process, based on urea-formaldehyde technology, was used in an existing heat-drying operation at Winston-Salem, North Carolina, from 1973 to 1975, and the prototype system is still used at a leather tanning facility in Slatersville, Rhode Island (8). The heat-drying operation at Winston-Salem was abandoned, however, because railroad siding and terminal facilities for bulk storage and shipment could not be funded. The Basel County Thermal Sludge Drying Plant in Switzerland has provisions for adding nitrogen, phosphorus, and potassium to the dried sludge for improvement of its fertilizing properties.

10.6 Conventional Heat Dryers

Conventional heat-drying is usually preceded by mechanical dewatering and may be followed by air pollution control devices and systems which alter the form of the dried material.

Mechanical dewatering is discussed in detail in Chapter 9. It is an important pretreatment step since it reduces the volume of water that must be removed in the dryer. In the dryer, water that has not been mechanically separated is evaporated without decomposing the organic matter in the sludge solids. This means that the solids temperature must be kept between 140 and 200°F (60° and 93°C). A large portion of the dried sludge is often blended with the sludge feed to the dryer, making the drying operation more efficient by reducing agglomeration (large balls of sludge), thus exposing a greater solids surface area to the drying medium. Dried sludge and exhaust gases are separated in the dryer itself and/or in a cyclone. The gas stream can go to a pollution control system for removal of odors and particulates. The dried sludge is then sent to a finishing step such as pelletizing or bagging, or it is stored in bulk for marketing or use in the next portion of the sludge management scheme.

10.6.1 Flash-Drying

Flash-drying is the rapid removal of moisture by spraying or injecting the solids into a hot gas stream. This process was first applied in 1932 to the drying of wastewater sludge at the Chicago Sanitary District.

10.6.1.1 Process Description

The Combustion Engineering-Raymond Flash Drying and Incineration Process shown on Figure 10-3, is typical of flash-drying units used in the United States.

The flash-drying process is based on three distinct components that can be combined in different arrangements. In the first component, the wet sludge cake is blended with previously dried sludge in a mixer to improve pneumatic conveyance. The blended sludge and the hot gases from the furnace at 1,300°F (704°C) are mixed ahead of the cage mill, and flashing of the water vapor begins. Gas velocities on the order of 65 to 100 feet per second (20 to 30 m/sec) are used. The cage mill mechanically agitates the sludge-gas mixture, and drying is virtually complete by the time the sludge leaves the cage mill. The mean residence time is a matter of seconds. The sludge, at this stage, has a moisture content of only 8 to 10 percent and is considered dry. The dried sludge is then separated from the spent drying gases in a cyclone. Temperature of the dried sludge is about 160°F (71°C), and the exhaust gas temperature is about 220°F to 300°F (104° to 149°C). The dried sludge can be sent either to storage or to the furnace for incineration.

The second component is the incineration process. Gas, oil, coal, or partially dried sludge is burned in the furnace to provide heat needed to dry the sludge. Combustion air, provided by the combustion air fan, is preheated and injected into the furnace at high velocity to promote complete fuel combustion. Any ash that accumulates in the furnace bottom is periodically removed.

The third component is the effluent gas treatment facility or induced draft facility. This consists of the deodorizing preheater, the combustion air heater, the induced draft fan, and a gas scrubber. Odors are destroyed when the temperature of the gas from the cyclone is elevated in the deodorizing preheater. Part of the heat absorbed is recovered in the combustion air preheater. The gas then passes through a dust collector (generally a scrubber) and is discharged to the atmosphere.

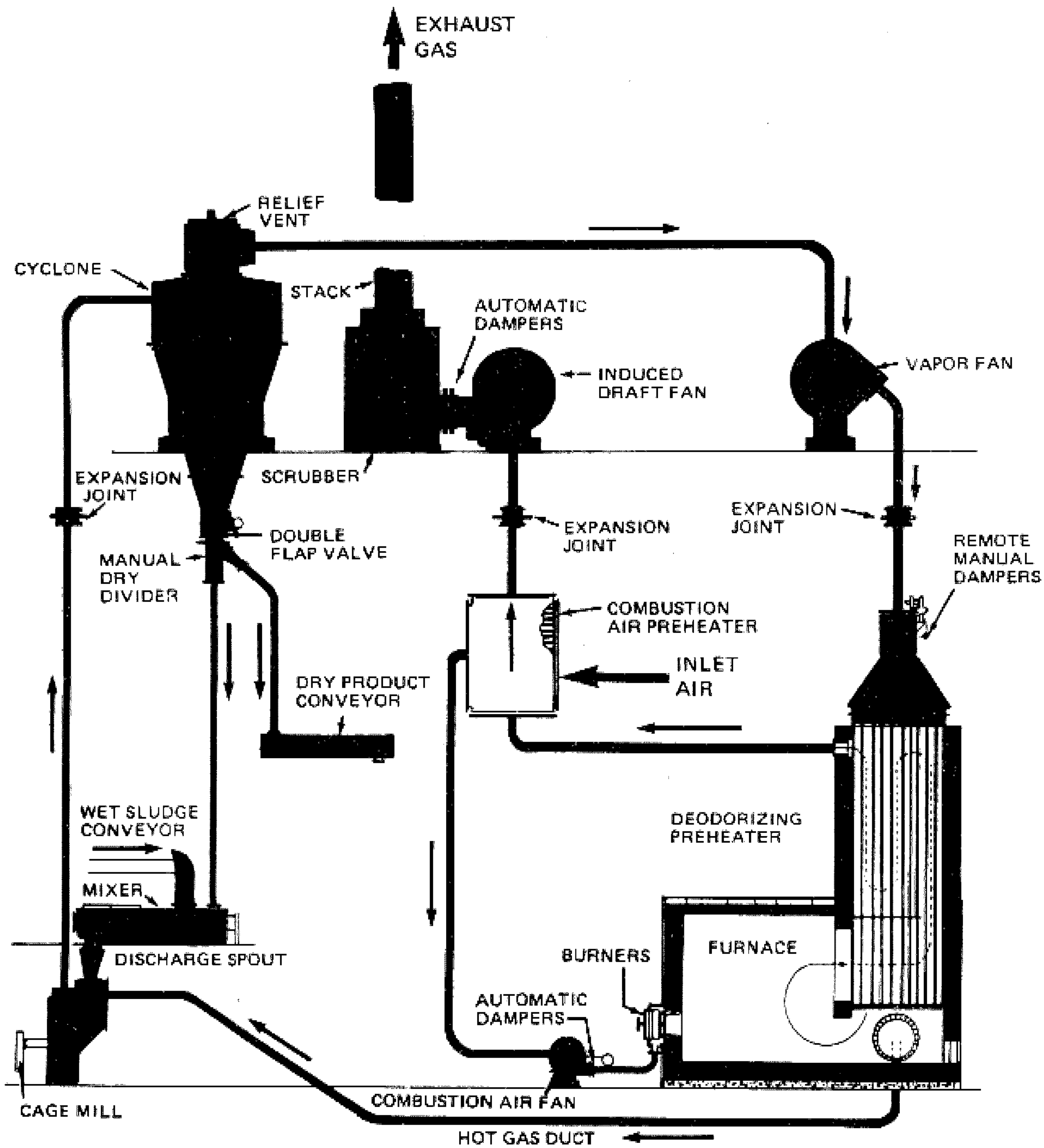

FIGURE 10-3

FLASH DRYER SYSTEM (COURTESY OF C.E. RAYMOND)

10.6.1.2 Case Study: Houston, Texas

The flash-drying operations at Houston, Texas, illustrate the operating experience and performance of the C-E Raymond Flash Drying process. There are four flash dryers at the 45-MGD (1.97-m^3/s) Sims Bayou plant and five flash dryers at the 75-MGD (3.29-m^3/s) Northside plant, with two additional units under construction. The liquid process stream consists of bar screening and activated sludge. Sludge treatment consists of degritting, vacuum filtration with ferric chloride addition, and flash-drying.

After gravity thickening, the sludge solids concentration is about two percent at the Sims Bayou plant and about three percent at the Northside plant. The cake from the vacuum filters is about 15 percent solids. The ferric chloride additions amount to about 75 pounds per ton (37 kg/t) of dry solids, or about 3.8 percent.

Dewatered sludge is transported to the dryers by belt conveyors. Each flash dryer, with cage mill and 14-foot (4.3 m) diameter cyclone, is rated at 12,000 pounds of water per hour (5,448 kg/hr) but is operated at 9,000 to 10,000 pounds of water per hour (4,086 to 4,540 kg/hr). Heat exchangers are provided for high temperature deodorization and for preheating the combustion air. The cage mill inlet temperature is 900°F to 1,150°F (482°C to 621°C), and the temperature at the cyclone is about 220°F (104°C). The deodorization temperature is controlled around 1,200°F (649°C), and the stack gas temperature is 500°F to 600°F (260°C to 316°C) after heat recovery. The fuel used is natural gas, and the heat input is about 22 million Btu per hour (23.2 million kJ/hr) or 2,200 to 2,400 Btu per pound (5,100 kJ/kg to 5,600 kJ/kg) water evaporated.

Moisture content of the dried product is about 5.5 percent. About nine times as much solids on a dry weight basis are recycled to the predryer double paddle mixer as are removed as product. The product is conveyed to a storage area or directly to railroad cars for shipment.

The process is automated and panel boards are provided that indicate and record variables such as air flow, temperatures at critical points, and amperage on fan motors. The controls are enclosed in air-conditioned cubicles. Horn alarms indicate unsuitable temperature conditions.

The controls for the ferric chloride feeding have proven to be inadequate and have led to operational problems.

Dust is also a major problem at the Sims Bayou plant. The dried sludge dust is extremely abrasive, causing wear on all mechanical equipment. Wet sludge has also overflowed the top of the conveyors at times, creating housecleaning problems.

No specific cost data are available for the Houston facilities. The dried product, Hou-actinite, is sold through a broker by yearly contract.

10.6.2 Rotary Dryers

Rotary dryers use a sloped rotating cylinder to move the material being dried from one end to the other by gravity. Direct, indirect, and direct-indirect rotary dryers have been used to dry sludge.

10.6.2.1 Direct Rotary Dryers

Direct rotary dryers have been used in the United States and in Europe for drying sludge. These include installations at Largo, Florida, and Stamford, Connecticut (in conjunction with a refuse incinerator) and in Basel, Switzerland. Manufacturers include the Heil Company, Combustion Engineering, Bartlett-Snow, and Euranica, Inc.

Process Description

The features of a typical direct rotary drying system are illustrated on Figure 10-4. Mechanically dewatered sludge is added to a mixer and blended with previously dried sludge to provide a low moisture dryer-feed. Hot gas at temperatures of 1,200°F (649°C) is added to the dryer, usually in a cocurrent flow pattern. After the sludge has been held in the dryer for 20 to 60 minutes, the dried sludge is discharged at a temperature of 180°F to 200°F (82 to 93°C). Exhaust gases are conveyed to a cyclone where entrained solids are separated from the gases. The spent gases exit at about 300°F (149°C). A portion of the dried product is recycled, and the balance goes to a finishing step, to further processing, or to disposal. Gaseous discharge from the cyclone goes to an air pollution control system for deodorization and particulate removal as necessary. Figure 10-4 shows several alternatives for handling the exhaust gas. A long residence time in the dryer may minimize deodorization requirements.

Design Considerations

The rotary drum usually consists of a cylindrical steel shell that revolves at 5 to 8 rpm. One end of the dryer is slightly higher than the other, and the wet sludge is fed into the higher end. Flights projecting from the inside wall of the shell continually raise the material and shower it through the dryer gas, moving the material toward the outlet.

Gas flow through the drum may be either cocurrent or countercurrent to the sludge flow. Gas velocities must be limited to 4 to 12 feet per second (1.2 m/sec to 3.7 m/sec) to prevent dust from being entrained with the exhaust gas.

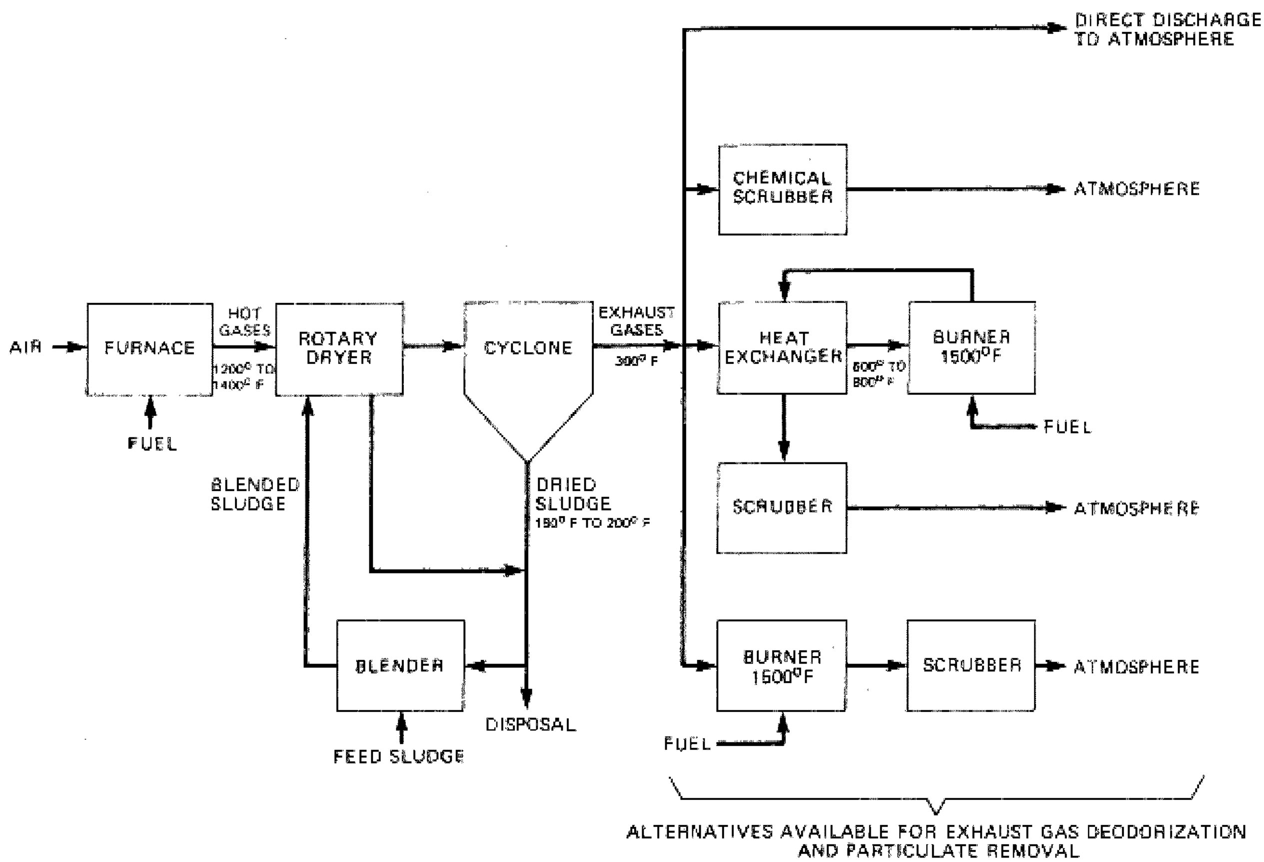

FIGURE 10-4

SCHEMATIC FOR A ROTARY DRYER

Case Study: Largo, Florida

The Largo, Florida, Wastewater Treatment Plant has a rated capacity of 9 MGD (0.39 m^3/s) with average summer flow of 6 MGD (0.26 m^3/s) and winter flows greater than 9 MGD (0.39 m^3/s). The liquid process stream consists of coarse screening, grit removal, contact stabilization activated sludge, chlorination, and dual media filtration. Waste-activated sludge is aerobically digested, batch gravity decanted, and thickened. Since 1976, the thickened sludge has been dewatered by belt filter presses and heat-dried in a rotary dryer. This system was supplied by Ecological Services Products, Inc. (ESP).

Approximately 1.6 dry tons (1.45 t) of digested sludge is produced daily and is processed at a rate of 2.2 tons (2.0 t) per day for a five-day week. Typical thickened aerobic sludge is 1 to 1.1 percent solids. The belt filter presses produce a sludge cake that is typically 10 to 12 percent solids. Polymer is used to condition the sludge prior to filtration.

The rotary dryer, manufactured by the Heil Company, has an evaporative capacity of approximately 5,400 pounds water per hour (2,450 kg/hr). The Heil dryer employs a 3-in-1 drum design. Sludge moves forward through the center cylinder, then back through the intermediate cylinder, and forward again through the outer cylinder toward a fan located at the discharge of the machine. The three cylinders are concentric and are mechanically interlocked so that they rotate at the same speed. Internal-external flights on each cylinder repeatedly raise the sludge to the top of the drum. This design is claimed to provide better heat utilization by minimizing radiation losses, but maintenance on the drums is more complex than with a single shell.

The facilities were designed assuming 1,000 pounds per hour (454 kg/hr) of dry solids throughput, based on feeding a sludge cake of about 20 percent solids. The dryer is water-limited because the cake produced by the belt presses is only 10 to 12 percent solids. Actual throughput is about 600 pounds per hour (272 kg/hr) of dry solids.

Heated air is provided by a natural gas burning furnace. Typical dryer inlet air temperature is about 800°F (427°C), and the outlet temperature is about 180°F (82°C). The average gas temperature in the dryer is estimated to be about 250°F (121°C). Off-gases from the cyclone separator are typically 120°F (49°C).

The dried product, Lar Grow, is a relatively fine pellet produced naturally by the rotating drum. Product bulk density is 45 to 55 pounds per cubic feet (720 to 880 kg/m^3). The bagged product moisture content is about five percent. The product is screened before bagging to remove cigarette filters and other nondegradable materials such as plastics. In 1978, a garden products wholesaler contracted to purchase the sludge produced for one year (approximately 570 dry tons [517 t]) at $54 per ton ($59/t). Because the wholesaler's markets are seasonal, the bagged product is stored on-site for a portion of the year.

The Ecological Services Products, Inc. (ESP) sludge drying plant was installed in 1975-76 at a contract price of $850,000 (cost of the building not included). The approximate capital cost for the facility can be broken down as follows: 41 percent for sludge and polymer pumping system, belt filter presses, and polymer preparation and feed system; 32 percent for the dryer, ductwork, fan, cyclones, and scrubber system; and 27 percent for mechanical conveyors, recycle bin, production storage bin and bagging facility. According to ESP personnel, the 1978 cost for a similar plant would be between $1.2 to $1.3 million, including installation and startup.

Typical operating and maintenance costs for dewatering, drying, and bagging during 1977 are shown in Table 10-1.

TABLE 10-1

ESTIMATED 1977 COSTS FOR DEWATERING, DRYING AND BAGGING AT LARGO, FLORIDA (7)

Item	Annual cost, dollars	Cost/ton, dollars
Polymer	13,000	23
Gas	26,000	45
Labor	21,000	36
Power	11,000	20
Total	77,000	134

These costs are based on unit costs at Largo of \$2.60 per pound (\$5.72/kg) of polymer, \$1.62 per 1,000 cubic feet (\$57.20/1000 m^3) of natural gas, 3.4 cents per kWhr of electricity, and \$0.24 per bag. Hence, approximately 9.9 pounds (4.5 kg) of polymer, 27,800 cubic feet (790 m^3) of natural gas, 590 kWhr of electricity, and 42 bags are used per dry ton of product.

Although a specific deodorization system has not been included, odor problems have been minimal. There are occasional odor problems when sludge that is too wet enters the dryer. There have been some problems with wear in the conveying facilities due to the dried sludge material being more abrasive than originally estimated. The pug mill blades and screw conveyor to the dryer have been replaced. Replacement parts have been specified to include heat treatment of the screw conveyor and the addition of cellite or carborundum plates on the wearing surfaces. The system supplier, ESP, has indicated that these changes will be considered for future equipment. There have been few other operating and maintenance problems.

10.6.2.2 Indirect Drying

Indirect rotary dryers have not been used in the United States for drying sludge. Vertical thin film dryers are used at the Dieppe, France, coincineration facility (9,10). The two LUWA Double-Wall Dryers installed at Dieppe operate on 140 psi (966 kN/m^2) steam at a temperature of about 355°F (180°C). The evaporaters are vertical, with top inlet and bottom outlet. Steam generated from refuse incineration is forced into the dryer and heats a "jacket" surrounding the incoming dewatered sludge. The sludge is spread over the inner cylindrical surface of the dryer by a rotor carrying self-adjusting vanes, at a top speed of about 25 feet per second (7.6 m/sec). The water vapor travels upward, counter to the sludge flow, and is blown into the incinerator, where it is deodorized. The dried sludge falls onto a conveyor belt and is incinerated with the refuse.

Another type of indirect sludge dryer is the jacketed and/or hollow-flight dryer and conveyor. A schematic of a jacketed hollow-flight dryer is presented on Figure 10-5. These units can perform the dual function of heat transfer and solids conveying in one piece of equipment--generally a horizontal, semi-circular trough with a jacket or coil to provide heat (10). This equipment has one or more agitation devices (for example, screw, flight, disc, paddle) rotating on the axis through the center of the trough. A significant degree of agitation is necessary to maintain reasonable heat transfer. Simple screw conveyors are notably poor in this regard, because increasing the speed reduces the residence time in the dryer by moving the sludge rapidly through the system. Heat transfer coefficients for this type of equipment range from 15 to 75 Btu per hour per square foot per °F (18.6 to 93 cal/sq cm/°C), depending on moisture content and degree of agitation.

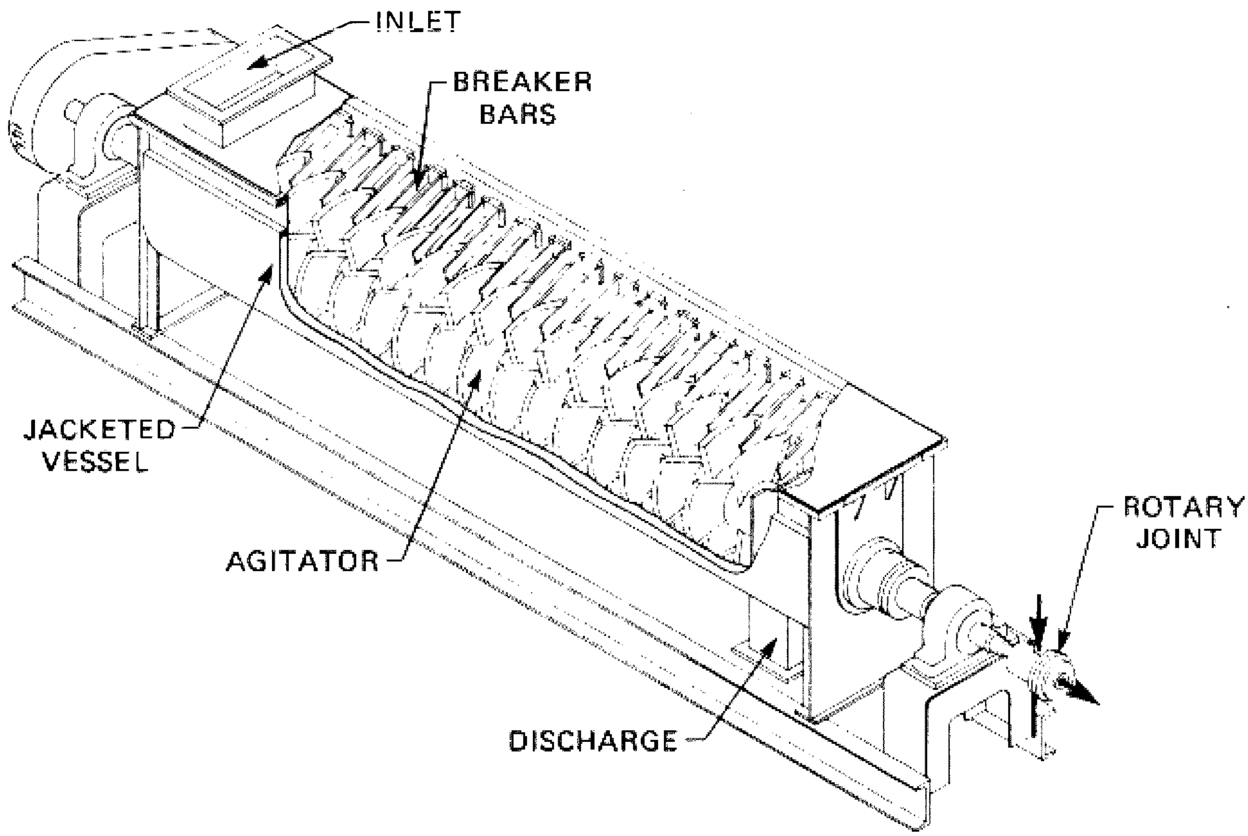

FIGURE 10-5

JACKETED HOLLOW-FLIGHT DRYER
(COURTESY BETHLEHEM CORPORATION)

The agitators, paddles, or flights should also be designed to minimize build-up on the walls of the dryer and on the agitator itself. Generally, baffles or ploughs should be provided between the flights to improve mixing and to break up any lumps that form. The rotating flights are often fitted with small paddles or similar projections to improve agitation and reduce fouling of the shell surface.

Significant increases in heat transfer can also be obtained if the rotor is hollow and fitted for steam heating. A hollow heated rotor often provides one to two times the heat transfer area available in the shell.

10.6.2.3 Direct-Indirect Rotary Dryers

The direct-indirect rotary dryer is similar to indirect dryers employing hot air or gases as the heating medium. In direct-indirect drying, however, the heating medium is recirculated to flow in direct contact with the drying sludge in addition to heating the metal drying surfaces.

Case Study: Milwaukee, Wisconsin

The drying operation at Milwaukee's 200-MGD (8.76-m^3/s) Jones Island Plant employs ten direct-indirect rotary, counterflow, kiln-type dryers for treating waste-activated sludge. The plant is designed for continuous operation. To achieve this, nine dryers must always be in operation. The drying system produced over 74,000 tons (67,300 t) of dried product in 1976. Thickened waste-activated sludge is conditioned with ferric chloride and filtered on vacuum filters. Wet filter cake (approximately 14 percent solids) is mixed with an approximate equal weight of previously dried material in a screw conveyor and fed to the direct-indirect dryers. The ten custom-built dryers are each 8 feet (2.4 m) in diameter and 57 feet (17.4 m) long. Each dryer can evaporate approximately 10,000 pounds (4,540 kg) water per hour (at 90 percent capacity) with an inlet air temperature of 1,200°F (649°C). The rotating drum, with lifting angles, picks up the wet mixture that is dropped subsequently to the bottom as a shower of particles. The sludge is continuously lifted and dropped through the hot gases, progressing as a moving curtain through the length of the dryer during the 45-minute drying cycle. The granular dried sludge (Milorganite) has been sold as a fertilizer since 1925. Rejected dust and fine particles are pelletized, and the pellets are reground to produce granular saleable material.

The dryer air inlet temperature is controlled at 1,200°F (649°C). The exhausted gas leaves the dryer at 250°F (121°C) and is passed through cyclone separators to remove fine particles. Each dryer has its own furnace. Originally, coal was used as a fuel, then coke oven gas (after furance modification), and then natural gas with standby fuel oil. In the mid-1970s, gas turbines were installed, and the gas from these turbines, at a temperature of approximately 900°F (482°C), is now fed to the modified furnaces and two waste heat recovery boilers. The gas burners are used to provide the additional heat necessary to maintain the dryer inlet temperature at 1,200°F (649°C). The recovered turbine exhaust heat supplies 70 percent of the heat required for the sludge drying operation.

The dried sludge product is abrasive, and the wet sludge is corrosive because of the ferric chloride used. Internals of the drum must be replaced about every three years. The present dryers are over 20 years old, and plans are being made to add three direct, cocurrent rotary dryers and to rehabilitate the existing dryers.

10.6.3 Incinerators

In sludge incineration, the temperature of the sludge is raised to 212°F (100°C), and the water is evaporated from the sludge before it is ignited; that is, the sludge is dried prior to ignition. Several options are available with incinerators. If heat inputs are reduced, the incinerator can be used as a dryer alone. Alternatively, a portion of the dried sludge can be removed at an intermediate point in the incinerator, with the remainder proceeding onward to be burned. Finally, all sludge may be incinerated.

Modifications may be required if these units are to be used for drying alone; for example, modifications to a multiple-hearth furnace would include fuel burners at the top and bottom hearths plus down-draft of the gases. If the sludge is to be disposed of, incineration provides greater volume reduction than drying alone.

Incineration is discussed in Chapter 11. Processes include multiple-hearth, fluid-bed, and electric furnaces.

10.6.4 Toroidal Dryer

The Toroidal (doughnut-shaped) dryer is a relatively new dryer that is employed in the UOP, Inc. ORGANO-SYSTEM^{R} for sludge processing. The dryer works on a jet mill principle and contains no moving parts. Transport of solid material within the drying zone is accomplished entirely by high-velocity air movement.

10.6.4.1 Process Description

A simplified process flow diagram of the UOP ORGANO-SYSTEM^{R} is shown on Figure 10-6. The system is composed of wet sludge storage, mechanical dewatering, sludge drying, air pollution control, final product finishing, and storage.

The mechanical dewatering step is designed to deliver the dewatered sludge to the dryer at about 35 percent to 40 percent solids. The dewatered sludge is mixed with previously dried sludge to reduce the moisture concentration of the dryer feed.

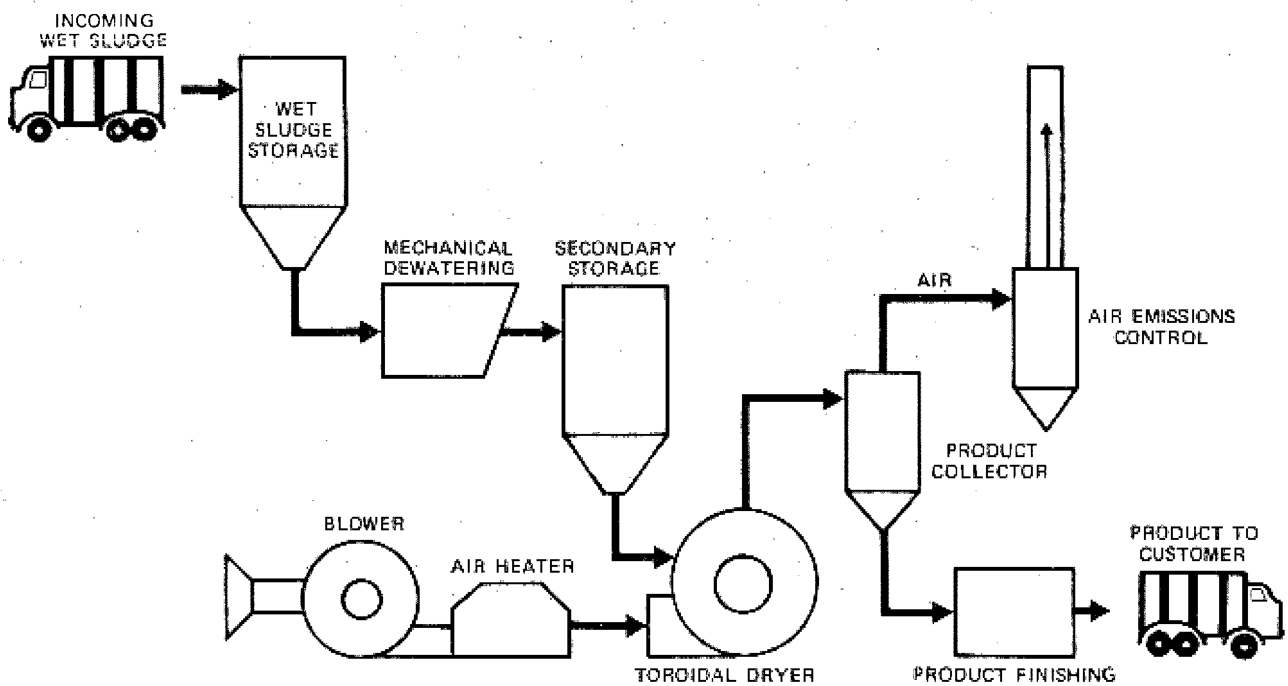

FIGURE 10-6

TOROIDAL DRYING SYSTEM

Heated process air is distributed through three manifold jets to the lower segment of the toroidal drying zone chamber. The air from one of the three jets is directed in such a way as to impinge upon the incoming wet feed material and propel this material into the drying zone, where particle size reduction and drying begins. Additional jets in the drying zone convey the material into the toroid for additional drying, grinding, and classifying.

Process air and solids within the toroid move at a velocity of approximately 100 feet per second (30 meters per second). The high-velocity gas stream reduces the size of lumps or agglomerated feed material by impingement against the interior walls of the drying chamber and by collision with other particles. Wetter and heavier particles travel a path along the internal periphery of the dryer, whereas drier and lighter particles are swept out with the gas stream and are removed from the drying zone. Heavy, wet particles stay in the dryer until they are broken up and dried.

The inlet termperature is usually controlled within the range of 500°F to 1,400°F (260°C to 760°C). There is a sharp drop in the gas temperature within the dryer when the hot inlet gas stream meets the incoming wet sludge. The dryer exhaust temperature is usually controlled at a specific setpoint within the range of 190°F to 300°F (90°C to 150°C). The product temperature normally does not exceed 150°F (66°C).

The dried sludge particles exiting the toroid are sent to a cyclone where they are separated from the gas stream. A portion of the dried sludge is back-mixed with the wet feed, and the remainder is transferred to the product finishing section. There, the dried product may be extruded (at a temperature of 140°F [60°C]), cut into pellets, and bagged, if desired. Otherwise, the product is routed to subsequent sludge processes including codisposal/energy recovery or land application. Gases from the cyclone are treated by processes that may include wet scrubbers, electrostatic precipitators, and baghouses. Deodorizing chemicals may be required.

10.6.4.2 Current Status

The toroidal dryer has been demonstrated on a full-scale basis. A 240-tons-water-per-day evaporative capacity ORGANO-SYSTEM[R] was operated by UOP Organic Recycling at the Blue Plains wastewater treatment plant in Washington, DC, for over three years. Raw sludge, digested primary sludge, and waste-activated sludge, as well as mixtures of these sludges, were processed. This system is no longer in operation. A 24-tons-water-per-day evaporative capacity unit is installed at UOP's West Chester, Pennsyvania, research and development facility.

10.6.5 Spray-Drying

Spray-drying systems are similar to flash-drying systems in that almost instantaneous drying occurs in both.

10.6.5.1 Process Description

Spray-drying involves three fundamental steps: liquid atomization, gas/droplet mixing, and drying from liquid droplets (1). Atomizers are usually high-pressure nozzles, or high-speed centrifugal dishes or bowls. The atomized droplets are usually sprayed downward into a vertical tower through which hot gases pass downward. Drying is complete within a few seconds; the product is removed from the bottom, and the gas stream is exhausted through a cyclonic dust separator.

Abrasive materials can cause problems with the atomizing devices. Centrifugal bowls or discs apparently require less maintenance because they are less likely to become plugged.

10.6.5.2 Current Status

A Nichols Spray Dryer was installed and operated at the wastewater treatment plant at Ansonia, Connecticut, to dry sludge. Dewatered sludge was sprayed into the top of a cone-like apparatus containing rotating "wheels." The heating medium was hot flue gases (1,300°F [705°C]) from the stack of a municipal refuse incinerator. Operation of the incinerator has been limited to about five hours per day because of state air pollution control requirements; the drying time was likewise limited. A burnable, dried product with greater than 90 percent solids has been produced with this system. The dried sludge has been given away as a soil conditioner rather than burned in the refuse incinerator.

10.7 Other Heat-Drying Systems

Two are currently available that differ somewhat from conventional heat-drying systems. They are the Basic Extractive Sludge Treatment (BEST) process, which employs solvent extraction, and the Carver-Greenfield process, which uses multiple-effect evaporation. Both of these systems employ an externally supplied liquid to assist in the removal of water from wet sludge.

10.7.1 Solvent Extraction--BEST Process

The BEST process is based on the use of an organic solvent to reduce the amount of water that must be evaporated in a conventional drying step. The process was developed by and is available from Resource Conservation Company of Renton, Washington.

10.7.1.1 Process Description

The BEST process, shown schematically on Figure 10-7, uses an aliphatic amine solvent (triethylamine or TEA) to separate sludge solids and water. The key to this process is the temperature-sensitive miscibility properties of TEA. Below 65°F (18°C), TEA and water solutions of any concentration are completely miscible and form a single-phase, homogeneous solution. Above this temperature, the mixture separates into two distinct layers, the top layer being nearly all TEA and the bottom layer nearly all water.

As shown in the diagram, incoming sludge is mixed with chilled, recycled solvent. The cooled mixture is then fed into a conventional dewatering unit, such as a vacuum filter, press, or centrifuge. After dewatering, the wet cake is fed to a continuous dryer operated between 250°F and 290°F (120°C and 140°C). The liquid in the wet cake contains a high percentage of TEA. The latent heat of TEA is approximately 133 Btu per pound (309 kJ/kg) compared to approximately 1,000 Btu per pound (2320 kJ/kg) of water. Because of this, the drying process is faster and uses less direct energy for drying than if the liquid were only water. Vapors coming from the dryer are condensed (condenser not shown) and combined with the liquid left from the dewatering step. This solvent/water mixture is then heated and collected in a decanter, where the components separate into two distinct layers.

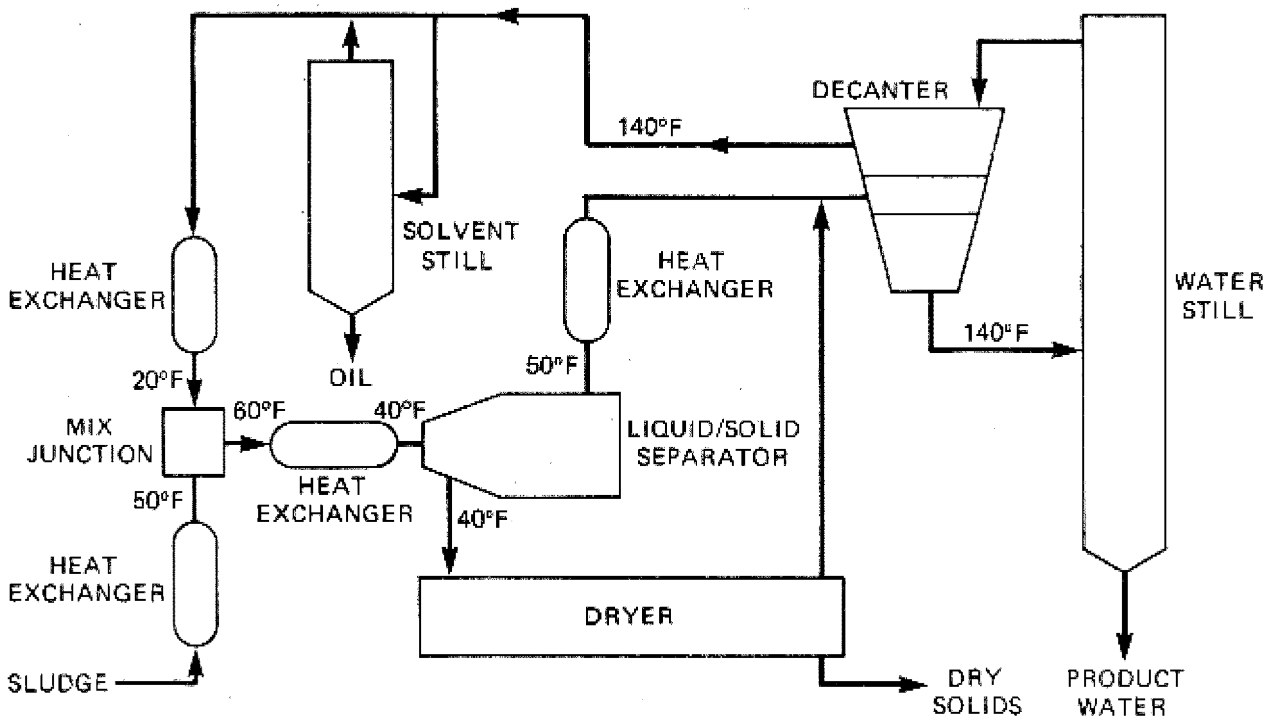

FIGURE 10-7

SCHEMATIC OF B.E.S.T. PROCESS

The solvent is drained off the top of the decanter and recycled (after chilling) to mix with new incoming sludge. Meanwhile, the water is decanted to a distillation column to be steam-stripped of residual solvent, which also is recycled. Oils and fats extracted from the sludge by the solvent are recovered in the solvent still. The product water is returned to the headworks of the treatment plant.

Resource Conservation Company claims that the system is entirely closed, except for a small gas vent, and creates no environmental problems. Air pollution and odor control equipment, if specified, would be required to handle only a relatively small volume of exhaust gas.

10.7.1.2 Current Status

A full-scale BEST system has yet to be operated. A 1-gallon-per-minute (4 l/m) demonstration test unit known as "mini-BEST" was evaluated by Metropolitan Engineers in 1975 as part of Municipality of Metropolitan Seattle's research program. Combinations of settled primary and thickened waste-activated sludges were treated in the pilot facility. The study team concluded that the BEST process was not cost-effective for

Seattle Metro (12). The process was also compared by the LA/OMA project with several other candidate sludge disposal systems and found to be one of the more expensive alternatives for the Los Angeles area (13).

10.7.1.3 Operating Experience

Operating experience is limited to laboratory and pilot plant tests. Dried solids (about 5 percent water) and product water are disinfected as a result of the high temperature (250°F [121°C]) in the dryer and the high pH of the solvent solution. Sodium hydroxide (NaOH) is added to maintain an alkaline condition, since TEA precipitates an acidic environment. NaOH also conditions the sludge to improve dewatering and the dryer performance. The dried product is easy to handle and transport; however, pelletizing may be necessary to prevent dusting and to enhance product marketability.

Primary sludge from Seattle Metro's West Point plant, containing 3.4 percent solids and pretreated with 2 to 5 g NaOH/l (100 to 300 pounds per ton dry solids), was blended with TEA and centrifuged. A cake of approximately 30 percent solids was produced. A solvent-to-sludge ratio of 6:1 was maintained. The liquid fraction contained 60 percent solvent and 40 percent water, which reduced the energy required to evaporate the liquid, compared to drying of 30 percent cake with a 100 percent water fraction. The dried product averaged 86 percent solids with 1.6 percent solvent by weight. Product water, following decanting and solvent extraction in the water still, averaged 280 mg/l suspended solids, contained less than 0.01 percent solvent, and had a pH of 10.6.

This high-technology process is quite complex and may require a competent chemical engineer to ensure efficient operation (12). There are a relatively large number of components in the system and, hence, maintenance costs may be high. Unpleasant odors (ammonia-like) existed in the exhaust gas during the Seattle study. A deodorization system may be required (12). Full-scale data on chemical and energy requirements, as well as operating reliability, are not currently available on the BEST system.

10.7.2 Multiple-Effect Evaporation--Carver Greenfield Process

Multiple-effect evaporation is another technique that can be used to remove water from sludge. The Carver-Greenfield process, offered jointly by Foster Wheeler Energy Corporation and Dehydro-Tech Corporation, uses this technology.

The basis of economy for multiple-effect evaporation is steam reuse. Steam generated in the first evaporator (by evaporation of water from sludge) is used as the heating fluid in the second evaporator. The method is feasible if the second evaporator is operated at a lower pressure than the first.

10.7.2.1 Process Description

The Carver-Greenfield process uses a multiple-effect evaporation process to extract water from sludge. The major steps in the process are oil mixing, multiple-effect evaporation, oil-solid separation, and condensate-oil separation.

The applied sludge is mixed with a petroleum hydrocarbon oil (Number 2 fuel oil and Isoparl, an Exxon product, have been used). The use of oil maintains fluidity in all evaporator effects and minimizes scale formation and corrosion of heat exchange surfaces. The sludge-oil slurry is pumped through a grinder to the multiple-effect evaporator. The grinder reduces the size of slurry solids to prevent obstructions in the evaporator tubes, to optimize evaporation, and to simplify control.

Falling-film evaporation is used; that is, the water to be evaporated is removed as the slurry rolls down the evaporator tubes in film flow. Steam and vapor flow is countercurrent to the slurry flow. Vapors flow from high temperature (high pressure) to low temperature (low pressure), while the slurry flows from low temperature (low pressure) to high temperature (high pressure). Steam is applied, at pressures as low as 50 psig (345 kN/m^2), to the shell side of the first effect (last stage) and its condensate returned to the boiler. The water vapors removed from the tube side in that stage provide the steam for the next (second) effect shell side. The water vapors condensed in the second effect are drained to the hot well. The steam energy, thus, is used many times. In each subsequent effect, the vapor temperature is lower. The vapor from the last effect (first stage) is condensed in a surface condenser and drained to the hot well.

Oil remaining after evaporation of water is separated from the solids by centrifuging. Oil is reused in the process, and the dried sludge product is subjected to further processing or disposal. The condensate from the evaporation system results in a sidestream containing ammonia and dissolved organics, but few inorganics. This sidestream may require subsequent treatment. Gaseous emissions from the system must be sent to a boiler or incinerator for odor destruction.

10.7.2.2 Current Status

According to the manufacturer, over 65 Carver-Greenfield installations are in operation worldwide. Many of these systems have operated at industrial facilities in the United States, including a four-effect system at the Adolph Coors Brewery in Golden, Colorado. This system's water evaporative capacity is 60,000 pounds per hour (27,240 kg/hr) which allows it to process approximately 180,000 gallons per day (682 m^3/day) of a 4 percent waste-activated sludge feed (8,10). Two systems are also operating at sewage treatment plants in Japan. The first, installed at Fukuchiyama, is a three-effect unit which processes combined primary and secondary sludge at rates up to 43,000 gallons per day (170 m^3/d) of 4.5 percent feed material. The second, installed at Hiroshima, is a four-effect unit, which can process up to 264,000 gallons per day (998 m^3/d) of a 2 percent feed solids. The product at both facilities is used as boiler fuel.

A 200-pound-per-hour (91 kg/hr) evaporative capacity single-effect pilot unit was evaluated at the Hyperion plant in Los Angeles by LA/OMA (14). LA/OMA engineers concluded that the Carver-Greenfield system appeared to be a viable sludge drying process that offered considerable energy efficiency when compared to conventional direct and indirect contact dryers. However, it was recommended that a large-scale facility should be built and operated to conclusively demonstrate process reliability and economics.

Energy requirements for a four-effect Carver-Greenfield system with hydroextraction were projected to be about 0.44 pounds of steam per pound of water evaporated. This value was based on data supplied by the manufacturer, data determined for the Coors facility, and supported by theoretical analysis of the system. The energy requirement, including steam production, was estimated at about 675 Btu per pound (1,568 kJ/kg) of water evaporated. This compares favorably with the 1,200 to 2,000 Btu per pound (2,790 to 4,650 kJ/kg) water required in most conventional heat dryers.

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 11. High Temperature Processes

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 11

HIGH TEMPERATURE PROCESSES

11.1 Introduction

High temperature processes have been used for combustion of municipal wastewater solids since the early 1900s. Popularity of these processes has fluctuated greatly since their adaptation from the industrial combustion field. In the past, combustion of wastewater solids was both practical and inexpensive. Solids were easily dewatered and the fuel required for combustion was cheap and plentiful. In addition, air emission standards were virtually non-existent.

In today's environment, wastewater solids are more complex and include sludges from secondary and advanced waste treatment (AWT) processes. These sludges are more difficult to dewater and thereby increase fuel requirements for combustion. Due to environmental concerns with air quality and the energy crisis, the use of high temperature processes for combustion of municipal solids is being scrutinized.

However, recent developments in more efficient solids dewatering processes and advances in combustion technology have renewed an interest in the use of high temperature processes for specific applications. High temperature processes should be considered where available land is scarce, stringent requirements for land disposal exist, destruction of toxic materials is required, or the potential exists for recovery of energy, either with wastewater solids alone or combined with municipal refuse.

High temperature processes have several potential advantages over other methods (1):

- <u>Maximum volume reduction</u>. Reduces volume and weight of wet sludge cake by approximately 95 percent, thereby reducing disposal requirements.

- <u>Detoxification</u>. Destroys or reduces toxics that may otherwise create adverse environmental impacts (2).

- <u>Energy recovery</u>. Potentially recovers energy through the combustion of waste products, thereby reducing the overall expenditure of energy.

Disadvantages of high temperature processes include (1):

- Cost. Both capital and operation and maintenance costs, including costs for supplemental fuel, are generally higher than for other disposal alternatives.

- Operating problems. High temperature operations create high maintenance requirements and can reduce equipment reliability.

- Staffings. Highly skilled and experienced operators are required for high temperature processes. Municipal salaries and operator status may have to be raised in many locations to attract the proper personnel.

- Environmental impacts. Discharges to atmosphere (particulates and other toxic or noxious emissions), surface waters (scrubbing water), and land (furnace residues) may require extensive treatment to assure protection of the environment (3).

This chapter describes both proven high temperature processes and those having high probability of success, as indicated by current research. Multiple-hearth and fluid bed furnaces, the most commonly used sludge combustion equipment in the United States, Europe, and Great Britain, are discussed, as well as newer furnace types such as the electric furnace, the single hearth cyclonic furnace, and modular combustion units. New thermal processes for wastewater solids reduction are also described. These processes include starved-air combustion and co-combustion of sludges and other residues. Also presented in the chapter are examples that illustrate the methodology used in selecting and designing processes and equipment.

11.2 Principles of High Temperature Operations

Combustion is the rapid exothermic oxidation of combustible elements in fuel. Incineration is complete combustion. Classical pyrolysis is the destructive distillation, reduction, or thermal cracking and condensation of organic matter under heat and/or pressure in the absence of oxygen. Partial pyrolysis, or starved-air combustion, is incomplete combustion and occurs when insufficient oxygen is provided to satisfy the combustion requirements. The basic elements of each process are shown on Figure 11-1. Combustion of wastewater solids, a two-step process, involves drying followed by burning.

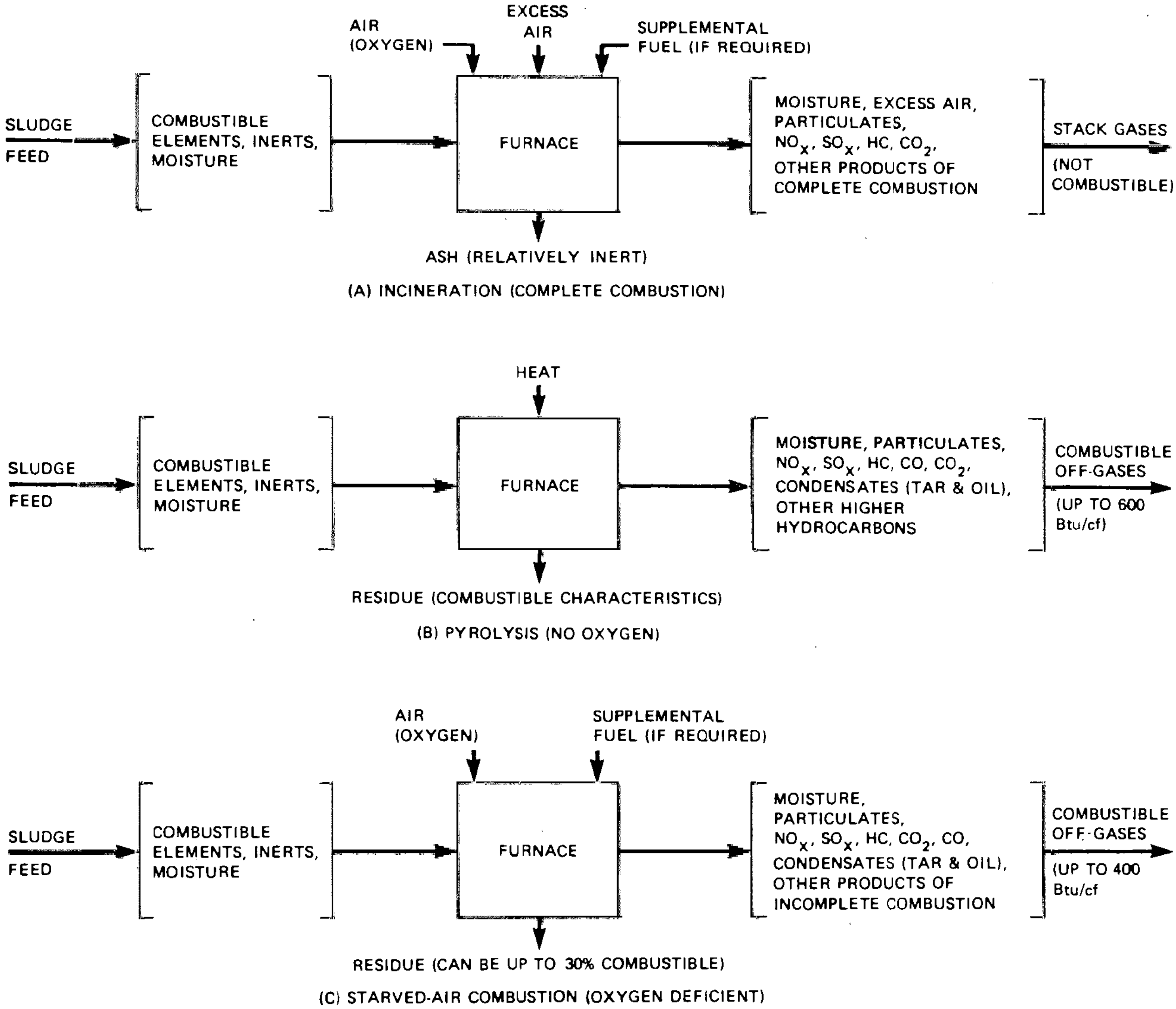

FIGURE 11-1

BASIC ELEMENTS OF HIGH TEMPERATURE PROCESSES

11.2.1 Combustion Factors

11.2.1.1 Sludge Fuel Values

A value commonly used in sludge incineration calculations is 10,000 Btu per pound of combustibles (see Table 11-1). It is important to clearly understand the meaning of combustibles. For combustion processes, solid fuels are analyzed for volatile solids and total combustibles. The difference between the two measurements is the fixed carbon. Volatile solids is determined by heating the fuel in the absence of air. Total combustibles is determined by ignition at 1,336°F (725°C). By definition, the difference in weight loss is the fixed carbon. In the volatile solids determination used in sanitary engineering (see Standard Methods, Reference 5), sludge is heated in the presence of air at 1,021°F (550°C). This measurement is higher than the volatile solids measurement for fuels and includes the fixed carbon. Numerically, it is nearly the same as the combustibles measurement. In the following, if volatile solids is used in the sense of the fuels engineer, it will be followed paranthetically by the designation "fuels usage." If the term "volatile solids" or "volatiles" is used without designation, it will indicate sanitary engineering usage and will be used synonymously with "combustibles."

TABLE 11-1

CHEMICAL REACTIONS OCCURRING DURING COMBUSTION

Reaction			High heat value of reaction[a,b]	Reference
$C + O_2$	⟶	CO_2	-14,100 Btu/lb of C	4
$C + 1/2\ O_2$	⟶	CO	-4,000 Btu/lb of C	4
$CO + 1/2\ O_2$	⟶	CO_2	-4,400 Btu/lb of CO	4
$H_2 + 1/2\ O_2$	⟶	H_2O	-61,100 Btu/lb of H_2	4
$CH_4 + 2O_2$	⟶	$CO_2 + 2H_2O$	-23,900 Btu/lb of CH_4	4
$2H_2S + 3O_2$	⟶	$2SO_2 + 2H_2O$	-7,100 Btu/lb of H_2S	4
$C + H_2O$ (gas)	⟶	$CO + H_2$	+4,700 Btu/lb of C	Calculated
Sludge combustibles	⟶	$CO_2 + H_2O$	-10,000 Btu/lb of combustibles	Estimated

[a]Negative sign convention indicates an exothermic reaction.

[b]High heat value assumes the latent heat of water generated is available for use: conversely, low heat values assumes the latent heat of water is not available hence no water is condensed.

1 Btu/lb = 2,324 J/kg

The amount of heat released from a given sludge is a function of the amounts and types of combustible elements present. The primary combustible elements in sludge and in most available supplemental fuels are fixed carbon, hydrogen, and sulfur. Because free sulfur is rarely present in sewage sludge to any significant extent and because sulfur is being limited in fuels, the contributions of sulfur to the combustion reaction can be neglected in calculations without compromising accuracy. Similarly, the oxidation of metals contributes little to the heat balance and can be ignored.

Solids with a high fraction of combustible material; for example, grease and scum, have high fuel values (see Table 11-2). Those which contain a large fraction of inert materials; for example, grit or chemical precipitates, have low fuel values. Chemical precipitates may also exert appreciable heat demands when undergoing high temperature decomposition. This further reduces their effective fuel value.

TABLE 11-2

REPRESENTATIVE HEATING VALUES OF SOME SLUDGES (6)

Material	Combustibles, percent	High heating value, Btu/lb of dry solids
Grease and scum	88	16,700
Raw wastewater solids	74	10,300
Fine screenings	86	9,000
Ground garbage	85	8,200
Digested sludge	60	5,300
Chemical precipitated solids	57	7,500
Grit	33	4,000

1 Btu/lb = 2,324 MJ/kg

The following are experimental methods from which sludge heating value may be estimated or computed:

- Ultimate analysis--an analysis to determine the amounts of basic feed constituents. These constituents are moisture, oxygen, carbon, hydrogen, sulfur, nitrogen, and ash. In addition, it is typical to determine chloride and other elements that may contribute to air emissions or ash disposal problems. Once the ultimate analysis has been completed, Dulong's formula (Equation 11-1) can be used to estimate the heating value of the sludge. Dulong's formula is:

$$\text{Btu/lb} = 14{,}544\ C + 62{,}208\ (H_2 - \frac{O_2}{8}) + 4{,}050\ S \qquad (11\text{-}1)$$

  where C, H_2, O_2, and S represent the weight fraction of each element determined by ultimate analysis. This formula does not take into account endothermic chemical reactions that occur with chemically conditioned or physical-chemical sludges.

  The ultimate analysis is used principally for developing the material balance, from which a heat balance can be made.

- Proximate analysis--a relatively low-cost analysis in in which moisture content, volatile combustible matter, fixed carbon, and ash are determined. The fuel value of the sludge is calculated as the weighted average of the fuel values of its individual components.

- Calorimetry--this is a direct method in which heating value is determined experimentally with a bomb calorimeter. Approximately 1 gram of material is burned in a sealed, submerged container. The heat of combustion is determined by noting the temperature rise of the water bath. Several samples must be taken and then composited to obtain a representative 1 gram sample. Several tests should be run, and the results must be interpreted by an experienced analyst. New bomb calorimeters can use samples up to 25 grams and this type of unit should be used where possible.

The above tests give approximate fuel values for sludges and allow the designer to proceed with calculations which simulate operations of an incinerator. If a unique sludge will be processed, or unusual operating conditions will be used, pilot testing is advised. Many manufacturers have test furnaces especially suited for pilot testing.

11.2.1.2 Oxygen Requirements for Complete Combustion

Air is the normal source of oxygen for combustion, although pure oxygen feed systems are sometimes used. Theoretical air and oxygen requirements for the combustion reactions are shown in Table 11-1. For rigorous analyses, the constants given in Table 11-3 should be used. For general applications in which fuel oil, methane, and/or sludge are used, a rule of thumb is that it requires 7.5 pounds (3.4 kg) of air to release 10,000 Btu (10.55 MJ) from sludge or supplemental fuel (7).

In practice, incinerator operations require air in excess of theoretical requirements for complete combustion. Excess air added to the combustion chamber increases the opportunity for contact between the fuel and oxygen. To ensure complete combustion, it is necessary to maintain 50 to 150 percent excess air over the stoichiometric amount required in the combustion zone. When the amount of excess air is inadequate, only partial combustion of carbon occurs, and carbon monoxide, soot, and odorous hydrocarbons are produced.

The excess air required for complete combustion adversely affects the cost of operation, because additional heat is needed to raise the excess air temperature to that of the exhaust gases. Supplemental fuel may be needed to furnish this additional heat. Thermal economy therefore demands that excess air be held to the minimum value required to effect complete combustion. The amount of excess air required varies with the type of incineration equipment, the nature of the sludges to be incinerated, and the disposition of the stack gases. The impact of excess air use on the cost of fuel in sludge incineration is shown on Figure 11-2.

TABLE 11-3

THEORETICAL AIR AND OXYGEN REQUIREMENTS FOR COMPLETE COMBUSTION (4)

	lb/lb of substance	
Substance	Air	Oxygen
Carbon	11.53	2.66
Carbon monoxide	2.47	0.57
Hydrogen	34.34	7.94
Sulfur	4.29	1.00
Hydrogen sulfide	6.10	1.41
Methane	17.27	3.99
Ethane	16.12	3.73
Ammonia	6.10	1.41

1 lb/lb = 1 kg/kg.

11.2.1.3 Factors Affecting the Heat Balance

The heat released by burning the wastewater solids must be sufficient to raise the temperatures of all entering substances from ambient levels to those of the exhaust and solid residue streams. Also, any radiant heat loss from the combustion structure must be included. If the heat is sufficient, the process is termed autogenous. If it is not sufficient, supplemental fuel must be burned to make up for the heat deficit.

A number of variables influence the amount of supplemental fuel required. As shown on Figure 11-2, the amount of excess air required to produce complete combustion has an important effect. Water associated with the sludge also exerts significant demands. For example, it takes almost 2,000 Btu per pound (4.64 MJ/kg) to vaporize water and raise the temperature of the water vapor to exhaust temperatures. When allowances are made for radiation losses and for heating of gas streams and sludge feed solids, it is found that approximately 3,500 Btu (3.69 MJ) are required for every pound (0.45 kg) of water evaporated in a multiple-hearth furnace (8).

The following example illustrates how the feed solids concentration required for autogenous combustion is determined.

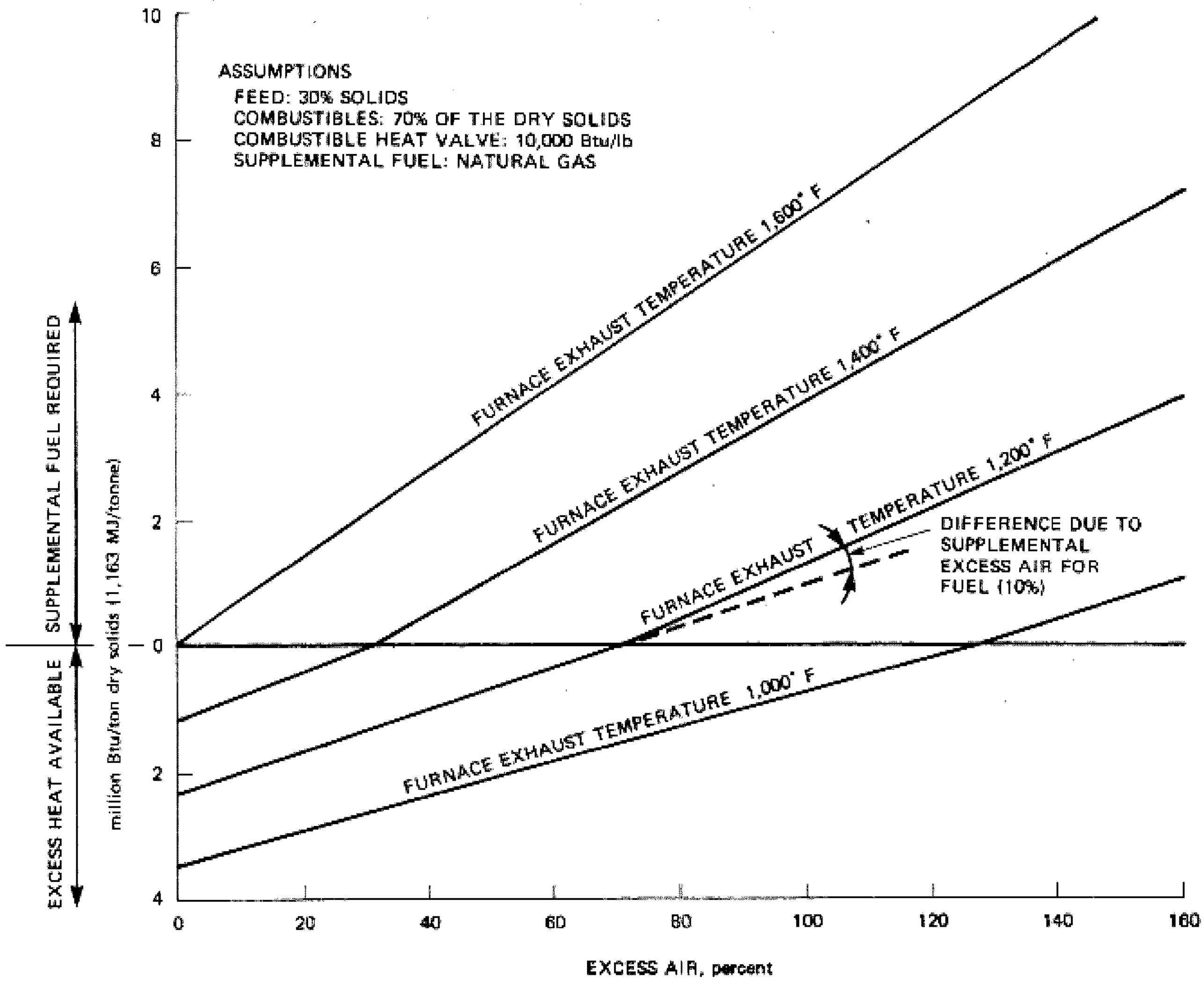

FIGURE 11-2

EFFECT OF EXCESS AIR AND EXCESS TEMPERATURE ON SUPPLEMENTAL FUEL REQUIREMENTS

Example

A designer uses a proximate analysis to derive the following values for a given sludge: volatile solids content(fuels usage--66 percent, fixed carbon content--11 percent, and inert content--23 percent. The sludge is to be dewatered and burned in a multiple-hearth incinerator. The solids concentration required for autogenous combustion in a multiple-hearth incinerator can be determined.

The sludge heating value can be estimated by multiplying the approximate fuel value of sludge--10,000 Btu per pound (23.2 MJ/kg) by the combustible fraction in the sludge. In this example, the combustible fraction is the sum of the volatile solids (fuels usage) and fixed carbon, or 77 percent. Therefore, sludge heating value is:

10,000 Btu/lb x 0.77 = 7,700 Btu per pound (17.89 MJ/kg)

The minimum percent sludge solids required to maintain autogenous combustion can be determined by equating the heat released by combustion to the heat required by the water. Therefore:

$$(P)(Q) = (100 - P)(W)$$

where:

P = Minimum percent dry solids in sludge required for autogenous combustion

Q = Fuel value of sludge, Btu per pound of dry solids

W = Heat required to evaporate one pound of water in a multiple-hearth furnace, Btu

The above equation is solved for P:

$$P = \frac{W}{Q+W}(100) \qquad (11\text{-}2)$$

For this example:

$$P = \frac{3,500}{7,700 + 3,500}(100) = 31.3 \text{ percent}$$

If the solids could be dewatered to 31.3 percent, they would be combusted autogenously. However, feed solids concentrations of this magnitude are seldom achieved without chemical conditioning. Allowances for the effect of chemical conditioning should therefore be made. Assume conditioning requirements are 25 percent lime and 3 percent ferric chloride by weight of dry solids fed. Therefore, for every 100 pounds (45.4 kg) of sludge dewatered, 28 pounds (12.7 kg) of chemicals are added. Assuming there is no heating value in the lime and ferric chloride, the combustible fraction of the feed solids is reduced to $\frac{100}{128}$ x 0.77 = 60 percent and the sludge heating value is 6,000 Btu per pound (13.9 MJ/kg). Using Equation 11-2, the dewatered sludge must be 36.8 percent solids to be autogenous.

Figure 11-3 shows a family of curves that can be used to calculate the minimum percent solids required at various dry solids heating values. This method of estimating takes into account the effect of moisture content, inerts, and combustibles on the combustion process and can be used for basic sizing prior to detailed analysis.

For example, in the above analysis, a sludge heating value of 6,000 Btu per pound of solids (13.9 MJ/kg) was calculated. From Figure 11-3, the 6,000 Btu per pound (13.9 MJ/kg) curve crosses the break-even point at approximately 36 percent dry solids. The importance of dewatering the sludge is illustrated on Figure 11-4. The amount of supplemental fuel required is plotted as a function of feed moisture content and combustible solids concentration.

The amount of supplemental fuel can be reduced if heat can be recovered from the process exhaust gases and reused. As an example, heat may be transferred from the furnace flue gas to incoming combustion air by means of heat exchangers (recuperators). Although energy recovery can significantly improve thermal efficiency, heat recovery equipment can be expensive and can only be recommended after complete economic evaluation.

11.2.2 Incineration Design Example

To evaluate combustion processes, a designer must determine if the sludge will burn autogenously. He must also assess the effects of different excess air rates, the effects of different types and quantities of supplemental fuel, and combustion air requirements.

Approximate and theoretical methods for calculating combustion requirements are presented in the following examples A summary is then provided that compares the results of each method. Either method provides the information necessary for preliminary evaluation and conceptual design of a sludge incinerator. When an ultimate analysis of the sludge is available or a good estimate of sludge constituents can be made, a theoretical analysis is preferred.

11.2.2.1 Problem Statement

The dewatered sludge production rate expected for a wastewater treatment plant is 14,000 pounds (6,350 kg) per hour at 20 percent solids. The dewatered material is a mixture of undigested primary and waste-activated sludges, with a volatile (combustible) content of 77 percent. The sludge temperature is 60°F (16°C). To limit hydrocarbon emissions, an afterburner is used to heat furnace exhaust gases to 1,400°F (760°C). The design is based on 100 percent excess air (two times the theoretical requirement). If supplemental fuel is required,

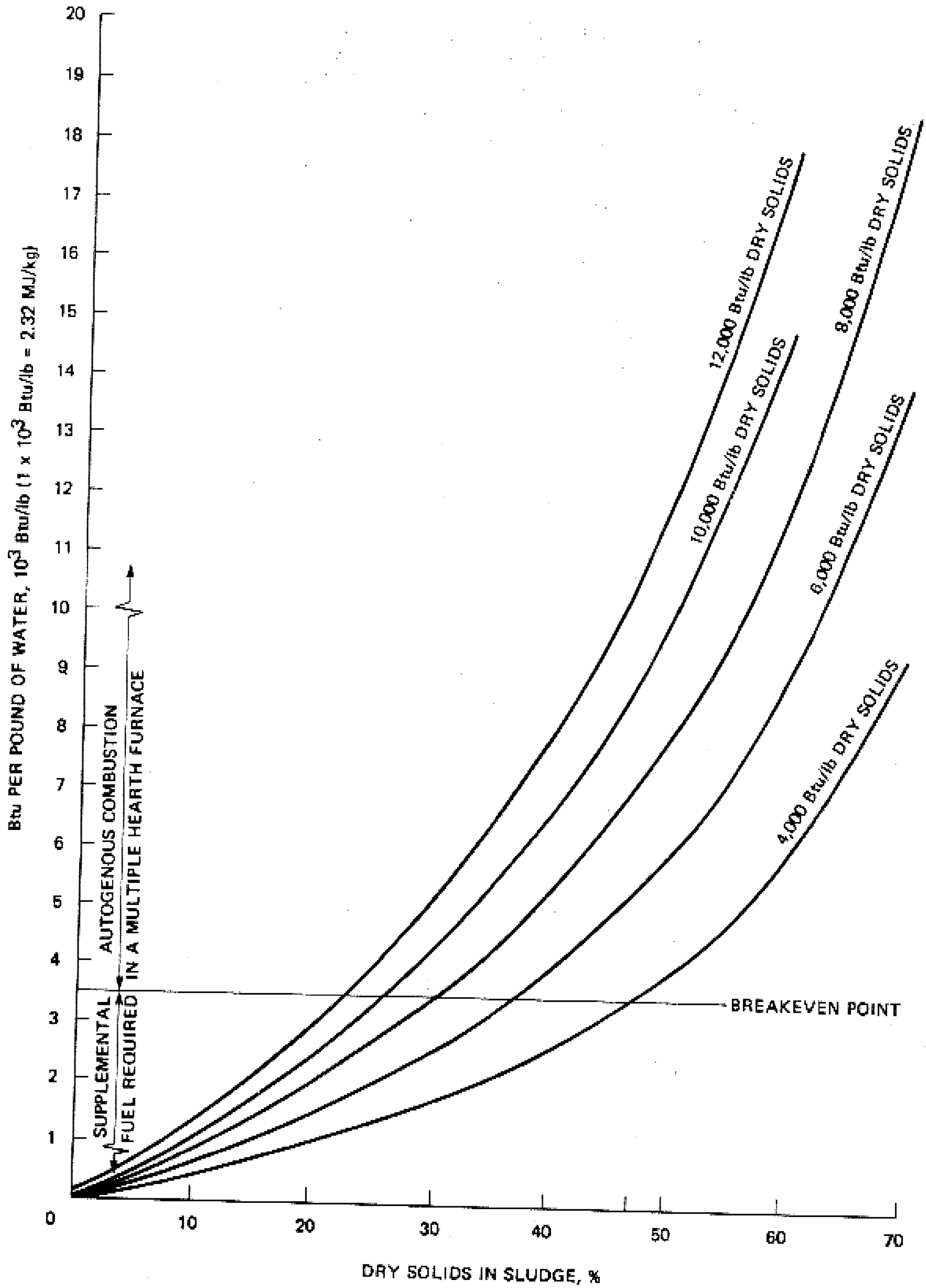

FIGURE 11-3

EFFECT OF DRY SOLIDS HEATING VALUE AND SLUDGE MOISTURE ON CAPABILITY FOR AUTOGENOUS COMBUSTION

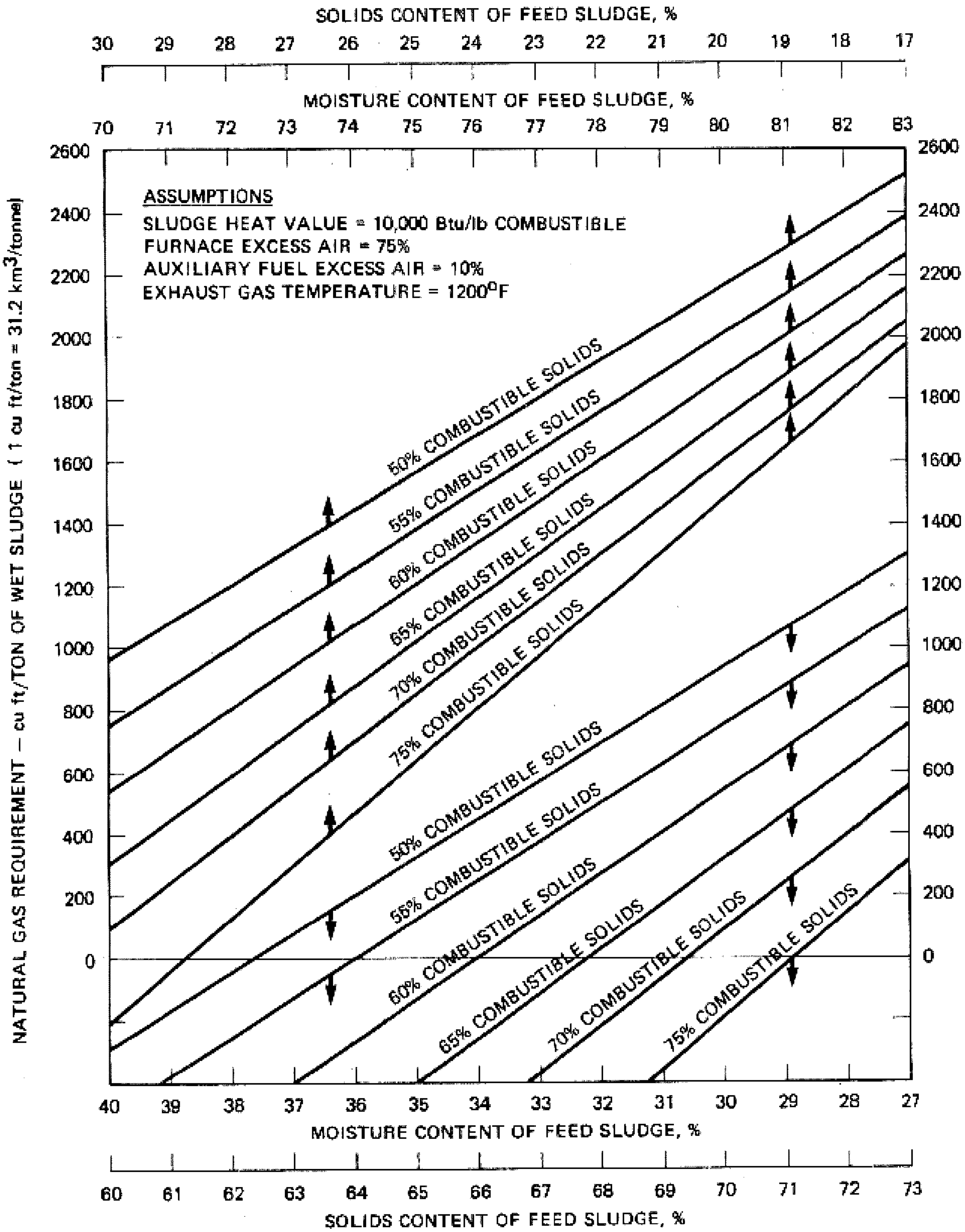

FIGURE 11-4

EFFECT OF SLUDGE MOISTURE CONTENT AND COMBUSTIBLE SOLIDS CONTENT ON SUPPLEMENTAL FUEL CONSUMPTION

No. 2 fuel oil will be used. Twenty-five percent excess air will be used for combustion of the fuel oil. The air temperature is 60°F (16°C); the absolute humidity of the air is 0.013 pounds of water per pound of dry air. Heat capacities of dry air, water vapor, dry sludge solids, and water are 0.256, 0.5, 0.25 and 1.0 Btu per pound per °F, respectively, (1.07, 2.1, 1.0, and 4.2 kJ/kg/°C. The latent heat of water is 970.3 Btu per pound (2,253 kJ/kg).

11.2.2.2 Approximate Calculation Method

Assuming 10,000 Btu per pound (23.2 MJ/kg) of sludge, the heat content of the sludge is:

$$10{,}000 \frac{\text{Btu}}{\text{lb}} \times 0.77 = 7{,}700 \text{ Btu per pound (17.9 MJ/kg)}$$

From Figure 11-3, a value of approximately 32 percent solids in the dewatered sludge is required for autogenous combustion. Therefore, supplemental fuel is required and its quantity must be determined. The demand for supplemental fuel equals the heat required minus the heat value of the sludge.

Step 1. Sludge Heating Value

The heating value of the sludge

$$= \frac{14{,}000 \text{ lb sludge}}{\text{hr}} \times \frac{0.2 \text{ lb solids}}{\text{lb sludge}} \times \frac{0.77 \text{ lb VS}}{\text{lb solids}} \times \frac{10{,}000 \text{ Btu}}{\text{lb VS}}$$

$= 21.56 \times 10^6$ Btu per hour (22.75 KJ/hr)

Step 2. Combustion Air Requirements

Therefore, combustion air requirements

$$= \frac{21.56 \times 10^6 \text{ Btu}}{\text{hr}} \times \frac{7.5 \text{ lb dry air}}{10{,}000 \text{ Btu}} \times 2 \text{(excess air factor)}$$

= 32,340 pounds dry air per hour (14.68 t/hr)

Step 3. Heat Required to Raise Ambient Air Temperature

The basic formula for determining the heat required is:

Q = Mass x heat capacity x temperature change (11-3)

Heat required to raise dry air from 60°F (15.6°C) to 1,400°F (760°C)

$$= \frac{32{,}340 \text{ lb dry air}}{\text{hr}} \times \frac{0.256 \text{ Btu}}{\text{lb-°F}} \times (1{,}400\text{°F} - 60\text{°F})$$

$= 11.09 \times 10^6$ Btu per hour (11.70 GJ/hr)

Heat required to raise the temperature of water vapor in air from 60°F (15.6°C) to 1,400°F (760°C)

$$= \frac{32{,}340 \text{ lb dry air}}{\text{hr}} \times \frac{0.013 \text{ lb water}}{\text{lb air}} \times \frac{0.5 \text{ Btu}}{\text{lb-°F}} \times (1{,}400\text{°F} - 60\text{°F})$$

$= 0.28 \times 10^6$ Btu per hour (0.30 GJ/hr)

Step 4. Heat Required to Raise Solids Temperature

Heat required to raise the temperature of the volatile (combustible) material from 60°F (15.6°C) to 1,400°F (760°C)

$$= \frac{14{,}000 \text{ lb sludge}}{\text{hr}} \times \frac{0.2 \text{ lb solids}}{\text{lb sludge}} \times \frac{0.77 \text{ lb VS}}{\text{lb solid}} \times \frac{0.25 \text{ Btu}}{\text{lb-°F}}$$

$\times (1{,}400\text{°F} - 60\text{°F}) = 0.72 \times 10^6$ Btu per hour (0.76 GJ/hr)

Heat required to raise the temperature of inerts (ash) from 60°F (15.6°C) to the ash discharge temperature of 200°F (93.3°C)

$$= \frac{14{,}000 \text{ lb sludge}}{\text{hr}} \times \frac{0.2 \text{ lb solids}}{\text{lb sludge}} \times \frac{(1-0.77) \text{ lb inerts)}}{\text{lb solids}} \times \frac{0.25 \text{ Btu}}{\text{lb-°F}}$$

$\times (200\text{°F} - 60\text{°F}) = 0.02 \times 10^6$ Btu per hour (0.02 GJ/hr)

Step 5. Heat Required to Raise Temperature of Water Associated with the Feed Sludge

This calculation does not include water formed during the combustion reaction.

Heat required to raise the water temperature from 60°F (15.6°C) to 212°F (100°C)

$$= \frac{14{,}000 \text{ lb sludge}}{\text{hr}} \times \frac{0.8 \text{ lb water}}{\text{lb sludge}} \times \frac{1.0 \text{ Btu}}{\text{lb-°F}} \times (212°\text{F} - 60°\text{F})$$

$= 1.70 \times 10^6$ Btu per hour (1.79 GJ/hr)

Heat required to evaporate water

$$= \frac{14{,}000 \text{ lb sludge}}{\text{hr}} \times \frac{0.8 \text{ lb water}}{\text{lb sludge}} \times \frac{970.3 \text{ Btu}}{\text{lb}}$$

$= 10.87 \times 10^6$ Btu per hr (11.46 GJ/hr)

Heat required to raise the temperature of water vapor to 1,400°F (760°C)

$$= \frac{14{,}000 \text{ lb sludge}}{\text{hr}} \times \frac{0.8 \text{ lb water}}{\text{lb sludge}} \times \frac{0.5 \text{ Btu}}{\text{lb-°F}} \times (1{,}400°\text{F} - 212°\text{F})$$

$= 6.65 \times 10^6$ Btu per hour (7.02 GJ/hr)

Step 6. Heat Required to Raise Temperature of Water Formed During the Combustion Reaction

Assume water formed during the combustion reaction to be 0.5 pound per 10,000 Btu (21.5 g/MJ) of sludge and supplemental fuel burned (9). The heat value of the sludge burned and supplemental fuel are equal to the heat demands. Therefore, water formed during combustion must be calculated on the basis of heat demands. Heat demands may be approximated by summing the calculations thus far:

Heat required for	Btu/hr x 10^6
Air	
Dry air	11.09
Water vapor in air	0.28
Sludge	
Volatile solids	0.72
Inerts	0.02

Heat required for	Btu/hr x 10^6
Sludge (continued)	
Free water	
Water	1.70
Evaporation	10.87
Water vapor	6.65
Total	31.33 (33.05 GJ/hr)

Water formed due to the combustion reaction

$$= \frac{0.5 \text{ lb}}{10{,}000 \text{ Btu}} \times \frac{31.33 \times 10^6 \text{ Btu}}{\text{hr}} = 1{,}567 \text{ pounds per hour (711 kg/hr)}$$

The heat of combustion given is the "high heat of combustion," which assumes all water formed is condensed. Heat must be provided to evaporate this water and bring it up to exhaust temperature.

Heat required to evaporate the water

$$= \frac{1{,}567 \text{ lb water}}{\text{hr}} \times \frac{970.3 \text{ Btu}}{\text{lb}} = 1.52 \times 10^6 \text{ Btu per hour (1.60 GJ/hr)}$$

Heat required to raise the temperature of water vapor to 1,400°F (760°C)

$$= \frac{1{,}567 \text{ lb water}}{\text{hr}} \times \frac{0.5 \text{ Btu}}{\text{lb-°F}} \times (1{,}400\text{°F} - 212\text{°F})$$

$$= 0.93 \times 10^6 \text{ Btu per hour (0.98 GJ/hr)}$$

Step 7. Heat Required to Compensate for Radiation Losses

Assume a radiation loss of 5 percent of the total heat demand. Total heat demand is

Heat required for	Btu/hr x 10^6
Total from Step 6	31.33
Water formed during combustion reaction	
Evaporation	1.52
Water Vapor	0.93
Total	33.78 (35.64 GJ/hr)

Heat to compensate for radiation losses

$$= \frac{33.78 \times 10^6 \text{ Btu}}{\text{hr}} \times 0.05 = 1.69 \times 10^6 \text{ Btu per hour (1.78 GJ/hr)}$$

Step 8. Determine Supplemental Fuel Required

Total heat requirements (from Step 7)

$= 33.78 \times 10^6$ Btu/hr + 1.69×10^6 Btu/hr

$= 35.47 \times 10^6$ Btu per hour (37.42 GJ/hr)

Total supplemental heat demand

= Heat demand minus heating value of sludge

$= (35.47 \times 10^6 - 21.56 \times 10^6)$ Btu/hr

$= 13.91 \times 10^6$ Btu per hour (14.68 GJ/hr)

Therefore, supplemental fuel (No. 2 fuel oil) must be supplied to provide 13.91×10^6 Btu per hour (14.68 GJ/hr) of heat.

Supplemental fuel also requires air for combustion, and this air exerts a heat demand. The air required for supplemental fuel is 1.25 times the theoretical value needed for supplemental fuel.

Air required for supplemental fuel

$$= \frac{13.91 \times 10^6 \text{ Btu}}{\text{hr}} \times \frac{7.5 \text{ lb dry air}}{10{,}000 \text{ Btu}} \times 1.25 \text{ (excess air factor)}$$

= 13,000 pounds dry air per hour (5,920 kg/hr)

The 13,041 pounds (5,920 kg/hr) dry air (plus any water formed by its reaction with the supplemental fuel) must also be raised to 1,400°F (760°C). By calculations similar to those presented in Steps 1 through 8, it can be shown that heat required to do this (and to account for additional radiation losses) is 20.24 x 10^6 Btu per hour (21.35 GJ/hr). Since only 13.91 x 10^6 Btu per hour (14.68 GJ/hr) was released by burning supplemental fuel, there is a heat deficit of 20.24 x 10^6 - 13.91 x 10^6 = 6.33 x 10^6 Btu per hour (6.67 GJ/hr). Thus, the effect of adding supplemental fuel was to reduce but not eliminate the initial deficit of 13.91 x 10^6 Btu per hour (14.68 GJ/hr).

To make up for this deficit, more supplemental fuel, equivalent to 6.33 x 10^6 Btu per hour (6.68 GJ/hr) is added. If 25 percent excess air is used for this fuel, 5,934 pounds per hour (2,694 kg/hr) of excess air will be required. The heat released is again insufficient to raise the air plus water vapor formed to 1,400°F (760°C) and to make up for additional radiation losses. The deficit for this iteration is 2.88 x 10^6 Btu per hour (3.04 GJ/hr).

The calculation can be carried forward for several more steps. Table 11-4 shows that progressively smaller additions of supplemental fuel and air are required for each iteration and that the amount of air and fuel needed for each iteration is a fixed fraction (0.45) of the fuel and air needed for the previous iteration. In general, if fuel required for each iteration is r percent of that required for the previous iteration, then total fuel required = (initial deficit)($1 + r + r^2 + r^3 + \ldots + r^n$). The term in the second bracket is an infinite geometric series equal to r^n. The series converges to $\frac{1}{1-r}$ if the absolute value of r is less than one (10).

TABLE 11-4

APPROXIMATE COMBUSTION CALCULATION - SUPPLEMENTAL FUEL REQUIREMENTS

Heat input		Heat demands					
Unit	Heat value, 10^6 Btu/hr	Unit	Heat value, 10^6 Btu/hr	Supplemental fuel requirements, 10^6 Btu/hr	Ratio[a]	Combustion air requirements, lb/hr	Ratio[b]
Sludge	21.56	Sludge and excess air	35.47	13.91		32,340	
Supplemental fuel	13.91	Supplemental fuel and excess air	20.24	6.33	.46	13,041	-[c]
Supplemental fuel	6.33	Supplemental fuel and excess air	9.21	2.88	.45	5,934	.46
Supplemental fuel	2.88	Supplemental fuel and excess air	4.19	1.31	.45	2,700	.46
Supplemental fuel	1.31	Supplemental fuel and excess air	1.91	0.60	.46	1,228	.45

[a] Ratio of supplemental fuel to that in the previous iteration.

[b] Ratio of air to air in the previous iteration.

[c] Ratio in this case is not applicable since sludge is included (100 percent excess air vs 25 percent excess air).

1 x 10^6 Btu/hr = 1,055 MJ/hr
1 lb/hr = 0.45 kg/hr

The total supplemental fuel requirements can be derived from Equation 11-4.

$$\text{Total supplemental fuel} = \text{Initial deficit} \times \frac{1}{1-r} \qquad (11\text{-}4)$$

Total supplemental fuel

$$= 13.91 \times 10^6 \frac{\text{Btu}}{\text{hr}} \times \frac{1}{1-0.45}$$

$= 25.32 \times 10^6$ Btu per hour (26.6 GJ/hr)

Step 9. Total Air Requirements

The air requirements for the supplemental fuel alone can be found from Equation 11-5, an analog to Equation 11-4.

Total supplemental air requirements

$$= \text{excess air for initial supplemental fuel addition} \times \frac{1}{1-r} \qquad (11\text{-}5)$$

Total supplemental air rquirements

$$= \frac{13{,}041 \text{ lb air}}{\text{hr}} \times \frac{1}{1-0.45}$$

= 23,735 pounds dry air per hour (10,766 kg dry air/hr)

Total dry air requirements

= air for sludge plus air for supplemental fuel

(32,340 + 23,735) lb dry air/hr

= 56,075 pounds dry air per hour (25,458 kg/hr)

Assuming an air density of 0.0749 pounds per cubic feet (1.2 kg/m^3):

Air flow rate

$$= \frac{56{,}075\ \text{lb/hr}}{0.0749} \times \frac{\text{hr}}{60\ \text{min}} = 12{,}478 \text{ cubic feet per minute } (5.9\ \text{m}^3/\text{sec})$$

Assume that No. 2 oil has heating value of 141,000 Btu per gallon

Supplemental fuel rate

$$= \frac{25.32 \times 10^6\ \text{Btu/hr}}{141{,}000\ \text{Btu/gallon}} \times \frac{\text{hr}}{60\ \text{min}}$$

= 3.0 gallons per minute (0.18 l/s)

11.2.2.3 Theoretical Calculation Method

The method presented herein is based on the actual combustion reactions and the method of approach used in steam generation calculations (9). Table 11-5 is to be used for steam generation calculations. A blank form is provided at the end of Chapter 11 for the reader's own use in making the calculations.

Step 1. (Line b). Determine the fuel analysis and include on the right hand side of the table (ultimate analysis).

Step 2. (Lines 1 through 12). Determine the pounds of component, moles of component, theoretical oxygen requirement and moles of material contributed to the flue gas by the fuel, based on 100 pounds of fuel feed. Assume complete combustion and no loss of combustibles to the ash.

Step 3. (Lines 13, 14, and 15). Assume the amount of excess O_2 to be used (100 percent) and calculate the moles of excess O_2 required.

Step 4. (Line 16). Calculate the amount of N_2 added from the air from the total O_2 (theoretical plus excess).

Step 5. (Lines 17, 18, 19, and 21). Calculate the amount of dry air, water in the air, the amount of wet air from the total dry air (O_2 + N_2).

Step 6. (Lines 20 and s). Calculate the moles of all components in the flue gas and the moles of wet and dry flue gas.

TABLE 11-5

COMBUSTION CALCULATION – MOLAL BASIS

Table 11-5 Combustion Calculations—Molal Basis

LINE	Fuel Constituent	Per Fuel Unit, lb	Mol. Wt Divisor	Moles Fuel Constituent	O_2 Multiplier	O_2 Moles Theo Reqd	CO_2 + SO_2	O_2	N_2	H_2O	CO
	Fuel, O_2, and Air per Unit of Fuel						*Flue Gas (F.G.) Composition Moles per Fuel Unit (AF)*				
1	C to CO_2	[illegible]	12	0.72	1	0.72	0.72				
2	C to CO	[illegible]	12	[illegible]	.5	[illegible]					[illegible]
3	CO to CO_2	[illegible]	28	[illegible]	.5	[illegible]	[illegible]				
4	C unburned, line k	[illegible]	12	[illegible]							
5	H_2	1.20	2	[illegible]	.5	0.32				[illegible]	
6	S	[illegible]	32	[illegible]	1	[illegible]	[illegible]				
7	O_2 (deduct)	4.77	32	0.15	1	−0.15					
8	N_2	0.77	28	0.03		0			0.03		
9	CO_2	[illegible]	44	[illegible]		0	[illegible]				
10	H_2O	[illegible]	18	4.44		0				4.44	
11	Ash	[illegible]		—		0					
12	Sum	100.0		[illegible]		[illegible]					
	O_2 and Air, Moles for Total Air = 200 % (see line d at right)										
13	O_2 (theo) reqd = O_2, line 12					[illegible]					
14	O_2 (excess) = $\frac{T.A. - 100}{100} \times O_2$, line 12					[illegible]		[illegible]			
15	O_2 (total) supplied = lines 13 + 14					[illegible]					
16	N_2 supplied = 3.76 × O_2, line 15					[illegible]			[illegible]		
17	Air (dry) supplied = O_2 + N_2					[illegible]					
18	H_2O in air = moles dry air × $\frac{A}{B-A}$ *					[illegible]				0.31	
19	Air (wet) supplied = lines 17 + 18					[illegible]					
20	Flue gas constituents = lines 1 to 18, total						[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
21	*Note – for air at 80 F and 100% relative humidity, $\frac{A}{B-A}$ = 0.037 is often used as standard.										

Conditions—Assigned or Observed and Miscellaneous

Date

Item	LINE
Fuel **SEWAGE SLUDGE** Source **MIDTOWN U.S.A.** Fuel Unit {100 lb, solid or liquid fuels / 100 moles, gaseous fuels	
Fuel Anal. as Fired (AF), % by Wt or Vol	a
C [illegible] *H_2* 1.20 *S* [illegible] *O_2* 4.77 *N_2* 0.77 *H_2O* [illegible] *Ash* [illegible] *100.0*	b
CO_2 — O_2 — CO — N_2 — %†	c
Total air (T.A.) assigned or by ORSAT 200 %	d
Lines f, g, h For Gaseous Fuels	e
Wt. fuel unit = Σ (moles each × mol. wt) lb	f
Mol. wt of fuel = line f ÷ 100	g
Density of fuel @ 80 F & 30 in. = $\frac{\text{line g}}{394}$ $\frac{\text{lb}}{\text{cu ft}}$	h
Fuel heat value, Btu/lb [illegible] as fed ††	i
Combustible in refuse, % "C" [illegible]	j
Carbon unburned, lb/100 lb fuel = % ash in fuel × $\frac{\%\ \text{"C"}}{100 - \%\ \text{"C"}}$	k
Exit temp of flue gas, t_2 1400 F	l
Dry-bulb (ambient) temp, t'_1 80 F	m
Wet-bulb temp F	n
Rel humid. (psychrometric chart) 100 %	o
B*, barometric pressure, in. Hg [illegible]	p
Sat. press. H_2O at amb temp, in. Hg	q
A*, press. H_2O in air, lines (o × q), in. Hg	r
Total Moles — Wet Flue Gas 13.71 — Dry Flue Gas [illegible]	s

Determination of Flue Gas and Combustible Losses in Btu per Fuel Unit (AF)

		CO_2+SO_2	O_2	N_2	H_2O	CO	Total
22	Flue gas constituents	CO_2+SO_2	O_2	N_2	H_2O	CO	Total
23	Mc_p, mean, t_2 to t'_1 (for t'_1 =	11.4 –	7.7	7.3	[illegible]	—	
24	In dry flue gas = moles each, line 20 × Mc_p × ($t_2 - t'_1$)	[illegible]	[illegible]	[illegible]		—	[illegible]
25	In H_2O in air = moles H_2O, line 18 × Mc_p × ($t_2 - t'_1$)				[illegible]		[illegible]
26	In sens heat, H_2O in fuel = moles, lines (5 + 10) × Mc_p × ($t_2 - t'_1$)				[illegible]		[illegible]
27	In latent heat, H_2O in fuel = moles, lines (5 + 10) × 1040 × 18				[illegible]		[illegible]
28	Total in wet flue gas						244,[illegible]
29	Due to carbon in refuse = line k × 14,100 [illegible]						–[illegible]–
30	Due to unburned CO in flue gas = moles C to CO × 12 × 9,755 [illegible]						–[illegible]–
31	Total flue gas losses + unburned combustible = lines 28 + 29 + 30 + radiation †††					Total	[illegible]
32	Heat value of fuel unit = 100 × line i for solid and liquid fuels; 394 × line i × 100, for gaseous fuels						[illegible]
33	Total excess heat per fuel unit = line 32 – line 31						– [illegible]

† Flue gas analysis by ORSAT. If CO is present in flue gases, a carbon balance is used to determine distribution of C, thus:
All C in fuel = C in flue gas constituents + C in refuse. Moles C in fuel = % C by analysis ÷ 12.
Moles C in refuse = line k ÷ 12. Moles C in CO_2 = (moles C in fuel – moles C in refuse) × % CO_2 by ORSAT ÷ % (CO_2 + CO) by ORSAT.
Moles in C in CO = moles C in fuel – moles C in refuse – moles C in CO_2.

†† By Dulong formula (11-1) or by calorimetry.

††† Radiation assumed to be a fixed percent of line 28, normally 2 to 3 percent.

GENERAL NOTES:

- See text for use of table.
- Refuse, as used in this table, is the residue (ash) from the process.

1 lb = 0.45 kg
1 in. = 2.54 cm
1 Btu/lb = 2,326 J/kg
1 lb/cu ft = 16 kg/m³

Step 7. (Lines 22 through 26). Determine the sensible heat content of the gas. A base temperature of 60°F (15°C) is used. The values for mean specific heat can be found in Reference 4.

Note: mean molar specific heat = mean specific heat x molecular weight.

Step 8. (Line 27). Determine the latent heat of water in the flue gas.

Step 9. (Line 28). Sum all heat in flue gas.

Step 10. (Lines 29, 30, and 31). Calculate heat losses due to carbon in refuse (residue), unburned CO in the flue gas, and radiation (assumed to be 5 percent). Sum all heat losses.

Step 11. (Line 32). Determine heat value of the sludge per 100 pounds, wet basis.

Step 12. (Line 33). Determine if the sludge is autogenous or requires supplemental fuel by subtracting line 32 from line 31. A zero or positive number indicates that the sludge is autogenous, supplemental fuel is not required, and the computation is complete. A negative number shows that supplemental fuel is necessary. The method used to determine the amount of fuel required is shown in steps 13 through 15.

Step 13. If Step 12 indicates that supplemental fuel is required, proceed through another theoretical calculation method table for the supplemental fuel in the same manner as Steps 1 through 12 (lines 1 through 33). This determines the amount of excess heat in the fuel after the combustion reaction. Table 11-6 illustrates the supplemental fuel calculation for this example.

Step 14. Determine the amount of supplemental fuel per 100 lb (45 kg) of wet sludge.

$$\frac{\text{lb supplemental fuel required}}{\text{100 lb of sludge, wet basis}}$$

$$= \frac{\text{heat required from fuel (line 33, Table 11-5)}}{\text{available heat from fuel (line 33, Table 11-6)}}$$

$$= \frac{\text{91,139 Btu/100 lb sludge}}{\text{1,165,443 Btu/100 lb fuel}}$$

$$= \text{7.82 lb fuel/100 lb sludge, wet basis}$$

TABLE 11-6

COMBUSTION CALCULATION – MOLAL BASIS

Table 11-6 Combustion Calculations—Molal Basis

LINE	Fuel Constituent	Per Fuel Unit, lb	Mol. Wt Divisor	Moles Fuel Constituent	O_2 Multiplier	O_2 Moles Theo Reqd	$CO_2 + SO_2$	O_2	N_2	H_2O	CO
	Fuel, O_2, and Air per Unit of Fuel						Flue Gas (F.G.) Composition Moles per Fuel Unit (AF)				
1	C to CO_2	[illegible]	12	[illegible]	1	[illegible]	[illegible]				
2	C to CO	[illegible]	12	[illegible]	.5	[illegible]					[illegible]
3	CO to CO_2	[illegible]	28	[illegible]	.5	[illegible]	[illegible]				
4	C unburned, line k	[illegible]	12	[illegible]							
5	H_2	12.7	2	[illegible]	.5	[illegible]				[illegible]	
6	S	[illegible]	32	[illegible]	1	[illegible]	[illegible]				
7	O_2 (deduct)	[illegible]	32	[illegible]	1	– [illegible]					
8	N_2	[illegible]	28	[illegible]		0			[illegible]		
9	CO_2	[illegible]	44	[illegible]		0	[illegible]				
10	H_2O	[illegible]	18	[illegible]		0				[illegible]	
11	Ash	[illegible]		[illegible]		0					
12	Sum	100.0		13.[illegible]		10.[illegible]					
	O_2 and Air, Moles for Total Air = 12[illegible] % (see line d at right)										
13	O_2 (theo) reqd = O_2, line 12					[illegible]					
14	O_2 (excess) = $\frac{T.A. - 100}{100} \times O_2$, line 12					[illegible]		[illegible]			
15	O_2 (total) supplied = lines 13 + 14					12.[illegible]					
16	N_2 supplied = 3.76 × O_2, line 15					[illegible]			[illegible]		
17	Air (dry) supplied = O_2 + N_2					[illegible]					
18	H_2O in air = moles dry air × $\frac{A}{B-A}$ *					[illegible]				[illegible]	
19	Air (wet) supplied = lines 17 + 18					[illegible],12					
20	Flue gas constituents = lines 1 to 18, total						7.22	[illegible]	[illegible]	[illegible]	[illegible]
21	*Note – for air at 80 F and 100% relative humidity $\frac{A}{B-A}$ = 0.037 is often used as standard.										

Conditions—Assigned or Observed and Miscellaneous

Date

Item	LINE
Fuel No 2 FUEL OIL Source MIDCITY REFINERY Fuel Unit {100 lb, solid or liquid fuels; 100 moles, gaseous fuels	
Fuel Anal. as Fired (AF), % by Wt or Vol	a
C [illegible] H_2 12.7 S [illegible] O_2 [illegible] N_2 [illegible] H_2O [illegible] Ash [illegible] 100.0	b
CO_2 __ O_2 __ CO __ N_2 __ %†	c
Total air (T.A.) assigned or by ORSAT 12[illegible] %	d
Lines f, g, h For Gaseous Fuels	e
Wt, fuel unit = Σ (moles each × mol. wt) lb	f
Mol. wt of fuel = line f ÷ 100	g
Density of fuel @ 80 F & 30 in. = $\frac{\text{line g}}{394}$ $\frac{\text{lb}}{\text{cu ft}}$	h
Fuel heat value, Btu/lb [illegible] ††	i
Combustible in refuse, % "C" [illegible]	j
Carbon unburned, lb/100 lb fuel = % ash in fuel × $\frac{\% \text{ "C"}}{100 - \% \text{ "C"}}$	k
Exit temp of flue gas, t_2 [illegible] F	l
Dry-bulb (ambient) temp, t'_1 [illegible] F	m
Wet-bulb temp F	n
Rel humid. (psychrometric chart) [illegible] %	o
B*, barometric pressure, in. Hg [illegible]	p
Sat. press. H_2O at amb temp, in. Hg	q
A*, press. H_2O in air, lines (o × q), in. Hg	r
Total Moles — Wet Flue Gas [illegible] — Dry Flue Gas [illegible]	s

Determination of Flue Gas and Combustible Losses in Btu per Fuel Unit (AF)

LINE	Item	CO_2+SO_2	O_2	N_2	H_2O	CO	Total
22	Flue gas constituents						
23	Mc_p, mean, t_2 to t'_1 (for t'_1 =	11.[illegible]–[illegible]	[illegible]	[illegible]	[illegible]	—	
24	In dry flue gas = moles each, line 20 × Mc_p × ($t_2 - t'_1$)	[illegible]	[illegible]	477,76[illegible]		—	[illegible]
25	In H_2O in air = moles H_2O, line 18 × Mc_p × ($t_2 - t'_1$)				27,311		27,311
26	In sens heat, H_2O in fuel = moles, lines (5 + 10) × Mc_p × ($t_2 - t'_1$)				[illegible]		[illegible]
27	In latent heat, H_2O in fuel = moles, lines (5 + 10) × 1040 × 18				[illegible]		[illegible]
28	Total in wet flue gas						[illegible]
29	Due to carbon in refuse = line k × 14,100						[illegible]
30	Due to unburned CO in flue gas = moles C to CO × 12 × 9,755						[illegible]
31	Total flue gas losses + unburned combustible = lines 28 + 29 + 30 + radiation †††					Total	[illegible]
32	Heat value of fuel unit = 100 × line i for solid and liquid fuels; 394 × line i × 100, for gaseous fuels						[illegible]
33	Total excess heat per fuel unit = line 32 – line 31						[illegible]

† Flue gas analysis by ORSAT. If CO is present in flue gases, a carbon balance is used to determine distribution of C, thus:
All C in fuel = C in flue gas constituents + C in refuse. Moles C in fuel = % C by analysis ÷ 12.
Moles C in refuse = line k ÷ 12. Moles C in CO_2 = (moles C in fuel – moles C in refuse) × % CO_2 by ORSAT ÷ % (CO_2 + CO) by ORSAT.
Moles in C in CO = moles C in fuel – moles C in refuse – moles C in CO_2.

†† By Dulong formula (11-1) or by calorimetry.

††† Radiation assumed to be a fixed percent of line 28, normally 2 to 5 percent.

GENERAL NOTES:

- See text for use of table.
- Refuse, as used in this table, is the residue (ash) from the process.

1 lb = 0.45 kg
1 in. = 2.54 cm
1 Btu/lb = 2,326 J/kg
1 lb/cu ft = 16 kg/m³

Step 15. Calculate the total fuel demand for 14,000 pounds per hour of wet sludge (6,356 kg/hr):

Total fuel

$$= \frac{7.82 \text{ lb fuel}}{100 \text{ lb sludge}} \times 14{,}000 \text{ lb sludge/hr}$$

= 1,095 pound fuel per hour (497 kg/hr)

From line i, Table 11-6, Btu value

= 1,095 lb fuel/hr x 20,440 Btu/lb

= 22.38×10^6 Btu per hour (23.61 GJ/hr)

Step 16. Calculate the total combustion air requirements:

From Table 11-5, line 17 combustion air required for sludge = 8.47 moles/100 lb sludge.

From Table 11-6, line 17 combustion air required for supplemental fuel = 61.83 moles/100 lb fuel.

Total dry air

$$= \left[\left(\frac{8.47 \text{ moles air}}{100 \text{ lb sludge}}\right)\left(14{,}000 \frac{\text{lb sludge}}{\text{hr}}\right) + \left(\frac{61.83 \text{ moles air}}{100 \text{ lb fuel}}\right)\left(1{,}095 \frac{\text{lb fuel}}{\text{hr}}\right)\right] \frac{29 \text{ lb air}}{\text{lb mole air}}$$

= 54,040 pounds per hour (24,534 kg/hr)

11.2.2.4 Comparison of Approximate and Theoretical Calculation Methods

Table 11-7 shows that the approximate method requires slightly more fuel and air than the theoretical method, but the values are close. This comparison shows that the approximate method is suitable for preliminary evaluations. More detailed information and combustion theory can be found in the literature (1,4,6,7,9, and 11-16).

TABLE 11-7

COMPARISON BETWEEN AN APPROXIMATE AND A THEORETICAL CALCULATION OF FURNACE COMBUSTION

	Approximate method (AM)		Theoretical method (TM)		
Item	Value	Calculation reference (AM)	Value	Calculation reference (TM)	Difference $\frac{AM-TM}{TM} \times 100$
Sludge heating value	$\frac{10,000 \text{ Btu}}{\text{lb VS}}$ [a]	Assumed	$\frac{1,661 \text{ Btu}}{\text{lb as fed}}$ [a]	Table 11-4 line i	-7.28
Furnace heat deficit	$13.91 \times 10^6 \frac{\text{Btu}}{\text{hr}}$	Step 8	$\frac{91,139 \text{ Btu}}{100 \text{ lb wet sludge}}$ [b]	Table 11-4 line 33	9.01
Supplemental fuel heating value	$\frac{141,000 \text{ Btu}}{\text{gal}}$ [c]	Step 8	$\frac{20,440 \text{ Btu}}{\text{lb}}$	Table 11-5 line i	-4.19
Supplemental fuel required	$25.32 \times 10^6 \frac{\text{Btu}}{\text{hr}}$	Step 8	$22.38 \times 10^6 \frac{\text{Btu}}{\text{hr}}$	Step 15	13.14
Total combustion air required	$56,075 \frac{\text{lb}}{\text{hr}}$	Step 9	$54,040 \frac{\text{lb}}{\text{hr}}$	Step 16	3.77

[a] 10,000 Btu/lb VS at 77 percent VS = 7,700 Btu/lb dry solids,
1,661 Btu/lb as fed ÷ 20 percent solids = 8,305 Btu/lb dry solids.

[b] 91,139 Btu/100 lb wet x 14,000 lb wet/hr = 12.76×10^6 Btu/hr.

[c] 141,000 Btu/gal ÷ 7.2 lb/gal = 19,583 Btu/lb.

1 Btu/lb = 2,324 J/kg
1 Btu/hr = 1,055 J/hr
1 Btu/gal = 279 kJ/m^3
1 lb/hr = 0.45/hr

11.2.3 Pyrolysis and Starved-Air Combustion Calculations

Pyrolysis and starved-air combustion have received considerable attention recently. The yield and composition of the gas and residue depend upon several variables. The actual interrelationships are so complex that final product characteristics must be determined empirically.

Currently, data are insufficient to provide information for designing pyrolysis equipment. Several large pyrolysis projects have been proposed, and some are in start-up or early operation. However, most work to 1979 has been at laboratory scale. At this writing, there are no full-scale pyrolysis projects proposed or under development that use sludge alone; all are for solid waste or specific industrial wastes.

Starved-air combustion, a partial pyrolysis process, has had a number of successful tests, such as those conducted at the Central Contra Costa Sanitary District (17,18), and the Interstate Sanitation Commission (19), and several modular combustion units have used municipal solid waste, sewage sludge, and/or agricultural wastes. Starved-air combustion has also had some failures such as at the Baltimore plant, which used only solid waste. The furnace at Baltimore is now being modified for further testing and use. Multiple-hearth furnaces have been tested for both sludge and co-disposal starved-air combustion. This work on starved-air combustion by multiple-hearth furnaces has been sufficient to allow development of empirical design criteria (17-20).

Some engineers and manufacturers use a hearth loading rate of 10 to 14 total pounds per square foot per hour (48.8 to 68.3 $kg/m^2/hr$) over the whole effective hearth area while assuming that up to 15 percent of the input energy remains in the ash as a char. Other engineers and manufacturers use the following design criteria which assumes a lower hearth loading rate and an additional hearth area to gasify the fixed carbon. This design results in a very low combustible content in the ash (20):

- 15 percent of the combustible matter becomes fixed carbon.
- Fixed carbon is gasified at a rate of 0.5 to 0.8 pounds per square foot per hour (2.4 to 3.9 $kg/m^2/hr$).
- Wet sludge feed rate (hearth loading rate) varies between 8 and 12 total pounds per square foot per hour (39.0 and 58.6 $kg/m^2/hr$).
- Assuming afterburning, 85 percent of the total feed energy remains in the afterburner gases.

Example

Estimate the required hearth area of a multiple-hearth furnace to burn the sludge generated from a 20 MGD (0.88 m^3/s) wastewater treatment plant by starved-air combustion and the heat content of the hot gas from the afterburner. Assume the furnace feed is 40,000 pounds per day dry solids (18,140 kg/day). Assume that the furnace feed is 40 percent solids and that the solids are 65 percent combustibles. Afterburning to 1400°F (760°C) is required.

Wet sludge feed rate

$$= \frac{40{,}000 \text{ lb dry solids}}{\text{day}} \times \frac{1 \text{ lb sludge}}{0.4 \text{ lb dry solids}} \times \frac{1 \text{ day}}{24 \text{ hr}}$$

= 4,167 pounds wet sludge per hour (1,890 kg/hr)

Fixed carbon rate

$$= \frac{40{,}000 \text{ lb dry solids}}{\text{day}} \times \frac{0.65 \text{ combustible solids}}{\text{lb dry solids}}$$

$$\times \frac{0.15 \text{ lb fixed carbon}}{\text{lb combustible solids}} \times \frac{1 \text{ day}}{24 \text{ hr}}$$

= 163 lb fixed carbon per hour (73.9 kg/hr)

Estimate hearth area and multiple-hearth furnace size. Hearth area is considered as the sum of the area required to convert the wet sludge to the fixed carbon stage and the area needed to burn out the fixed carbon.

Hearth area

$$= \frac{\text{wet sludge feed - fixed carbon feed}}{\text{allowable hearth loading rate}} + \frac{\text{fixed carbon feed}}{\text{gasification rate}}$$

$$= \frac{4{,}167 \text{ lb/hr} - 163 \text{ lb/hr}}{10 \text{ lb/sq ft/hr}} + \frac{163 \text{ lb/hr}}{0.5 \text{ lb/sq ft/hr}}$$

= 726 square feet (67.44 m^2)

After discussions with the furnace manufacturers, a 14-foot 3-inch (4.34 m) diameter, 8 hearth unit with an effective hearth area of 760 square feet (70.6 m^2) is selected.

Estimate the heat content of hot gases leaving the afterburner:

Heat content

$$= \frac{40{,}000 \text{ lb dry solids}}{\text{day}} \times \frac{0.65 \text{ lb combustible solids}}{\text{lb dry solids}}$$

$$\times \frac{10{,}000 \text{ Btu}}{\text{lb combustible solids}} \times \frac{1 \text{ day}}{24 \text{ hr}} \times 0.85$$

= 9.2×10^6 Btu per hour (9.72 GJ/hr)

Portions of this heat can be recovered and used benefically, for example, to generate steam or hot water (see Chapter 18).

BSP Division of Envirotech Corporation, and Nichols Engineering and Research (now part of Wheelabrator) have developed a large data base for evaluation of starved-air combustion operations.

Even with the amount of work that has been completed to date, however, calculations for starved-air combustion are still empirical. Because starved-air combustion is extremely complex and not completely understood, it is desirable to pilot any starved-air combustion process and, where possible, test at full-scale. There are several excellent texts and articles on combustion, but none deal to any great degree with oxygen-deficient combustion. Starved-air combustion is discussed in a number of publications (17-30).

11.2.4 Heat and Material Balances

Analysis of high temperature processes must include heat and material balances. Once provided, equipment can be sized and operating costs estimated. Throughout the remainder of this chapter, heat and material balances are displayed for several alternative combustion processes, all being fed the same hypothetical sludge. A flowsheet for a hypothetical wastewater treatment plant is depicted on Figure 11-5. Design data for 5, 15, and 50 MGD (0.22, 0.66, and 2.19 m^3/sec) wastewater treatment plants using this configuration are shown in Table 11-8. The "A" and "B" alternatives vary only in the percent solids feed (20 percent and 40 percent, respectively) and the addition of conditioning chemicals to obtain a dewatered cake of 40 percent solids. Use of conditioning chemicals reduces the percent combustibles of the "B" alternatives.

In Section 11.3, detailed heat and material balance tables are presented for each furnace type. The tables also display the amount of fuel and power each type of furnace requires, for each different treatment plant alternative. Balances given are for yearly average conditions. Operational costs can be estimated from the requirements for supplemental fuel and connected horsepower. General sizes and types of support facilities, such as ash handling equipment, water supply for the air pollution control equipment, and operating fuel requirements can also be estimated on the basis of the data shown in the heat and material balance tables.

In any steady-state balance, all inputs must equal all outputs. The following is a representative example of a heat and material balance for the Alternative IA in Section 11.3.1.

<u>Alternative IA--Heat Balance</u>

Inputs	10^6 Btu/hr
Combustibles in sludge	13.91
Supplemental fuel	2.64
Total	16.55 (17.46 GJ/hr)

Outputs	10^6 Btu/hr
Furnace exhaust	15.96
Ash	0.04
Radiation	0.32
Shaft cooling air (unrecovered portion)	0.22
Total	16.54 (17.45 GJ/hr)

Values are essentially equal; the balance checks. Note that shaft cooling air is an internal loop in the system. Since it is neither an input or output, only the unrecovered portion need be considered in the heat balance.

Alternative IA--Material Balance

Inputs	lb/hr
Dry solids in the sludge	1,806
Water in the sludge	7,224
Supplemental fuel	143
Combustion air	22,060
Total	31,233 (14,180 kg/hr)

Outputs	lb/hr
Ash	415
Furnace exhaust	30,817
Total	31,232 (14,179 kg/hr)

Again, values are essentially equal; the balance checks.

Reference 23 contains valuable information on heat and material balances.

11.3 Incineration

Incineration is a two-step oxidation process involving first drying and then combustion. Drying and combustion may be accomplished in separate units or successively in the same unit, depending upon temperature constraints and control parameters. The drying step should not be confused with preliminary dewatering, which is usually done mechanically prior to incineration. In all furnaces, the drying and combustion processes follow the same phases: raising the temperature of the feed sludge to 212°F (100°C), evaporating water from the sludge, increasing the temperature of the water vapor and air, and increasing the temperature of the dried sludge volatiles to the ignition point. Although presented in simplified form, incineration is a complex process involving thermal and chemical reactions which occur at varying times, temperatures, and locations in the furnace.

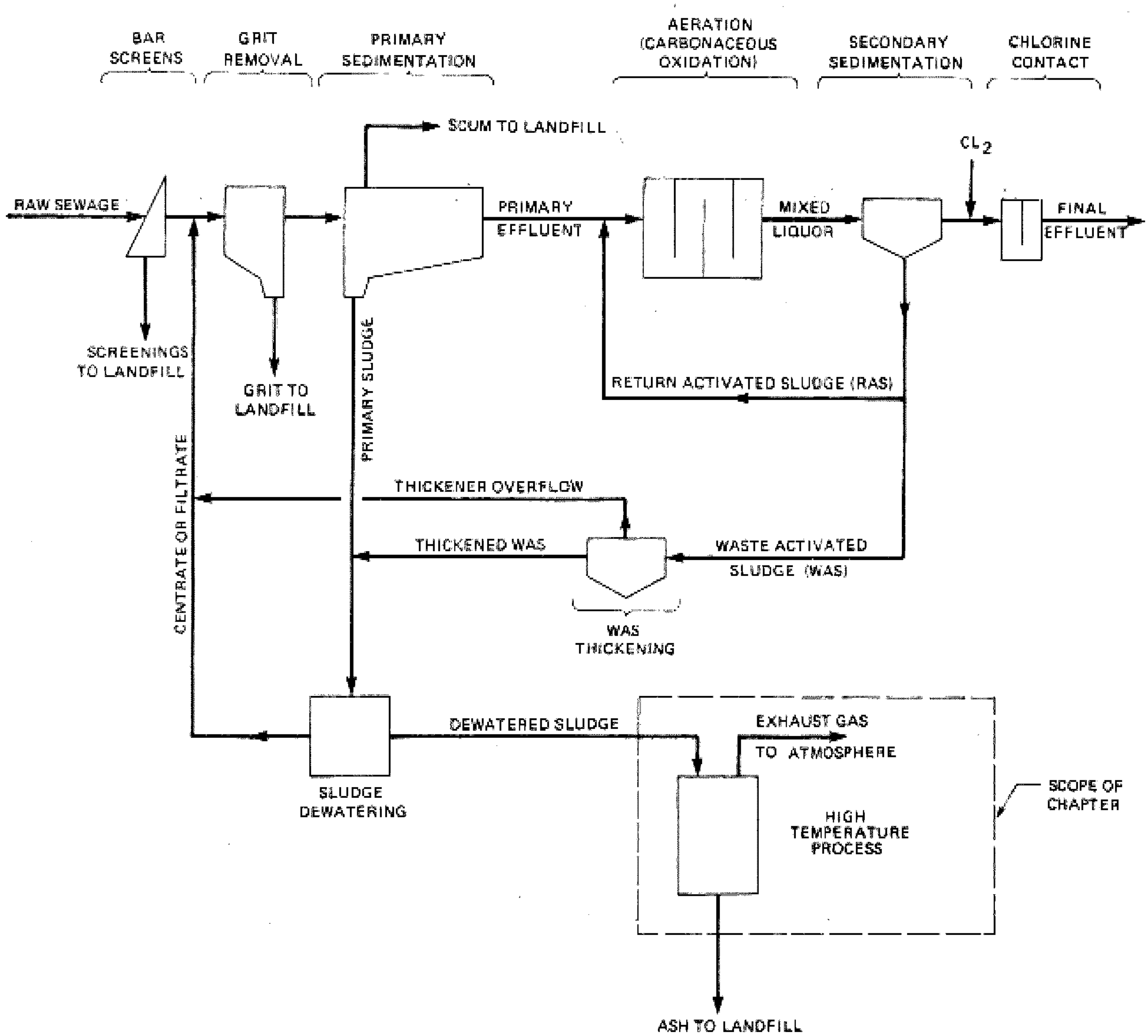

FIGURE 11-5

HYPOTHETICAL WASTEWATER TREATMENT PLANT FLOWSHEET

Manufacturers have developed a variety of equipment, each of which has advantages and disadvantages (19, 31-34). There are two major wastewater sludge incinerator equipment types used in the United States: the multiple-hearth and the fluid bed. The electric furnace, which is relatively new, has been used and, as of 1979, is planned for use in several wastewater treatment plants. A fourth type is the single hearth cyclonic furnace. This furnace has been used in Great Britain, but its only application in the United States has been in industrial service. These four systems are described in detail in this section. Heat and material balances are included for each type, assuming each is used in the hypothetical wastewater treatment plants described in Figure 11-5 and Table 11-8.

TABLE 11-8

HYPOTHETICAL WASTEWATER TREATMENT PLANT DESIGN DATA

	I (5-MGD flow)		II (15-MGD flow)		III (50-MGD flow)	
Alternative[a]	A	B	A	B	A	B
Sewage flow, MGD	5	5	15	15	50	50
Sludge solids, lb/day dry basis	10,320	10,320	31,000	31,000	103,000	103,000
Volatile solids, percent of dry solids	77	77	77	77	77	77
Furnace operation, hr/week	40	40	80	80	168	168
Sludge solids to furnace, lb/hr, dry basis	1,806	1,806	2,713	2,713	4,292	4,292
Conditioning chemicals, lb/hr, dry basis[b]	0	325	0	488	0	772
Total feed to furnace, lb/hr, dry basis	1,806	2,131	2,713	3,201	4,292	5,064
Solids content of furnace feed, percent by weight	20	40	20	40	20	40
Furnace loading rate, lb/hr, wet basis	9,030	5,327	13,565	8,003	21,460	12,660
Volatile content of furnace feed, percent of total solids	77	65	77	65	77	65

[a] The A alternatives have a 20 percent solid feed sludge while the B alternatives have a 40 percent solids feed sludge including conditioning chemicals.

[b] 15 percent lime (CaO) and 3 percent ferric chloride ($FeCl_3$), dry weight basis for the 40 percent cake only.

1 MGD = 0.04 m^3/s
1 lb/day = 0.45 kg/day
1 lb/hr = 0.45 kg/hr

11.3.1 Multiple-Hearth Furnace

The multiple-hearth furnace (MHF) is the most widely used sludge incinerator in the United States. As of 1977, approximately 340 units had been installed for wastewater sludge combustion (35). The MHF is durable, relatively simple to operate, and can handle wide fluctuations in feed quality and loading rates. The

MHF is designed for continuous operation. Start-up fuel requirements and the extended time needed to bring the hearths and internal equipment up to temperature from a completely cold condition normally preclude intermittent operations. The MHF is a vertically oriented, cylindrically shaped, refractory-lined steel shell containing a series of horizontal refractory hearths, one above the other. MHFs are available with diameters ranging from 4 feet-6 inches to 29 feet (1.4 to 8.8 m) and can have from 4 to 14 hearths. A cross section of a typical MHF is shown on Figure 11-6. A central shaft extends from the bottom of the furnace to the top and supports rabble arms above each hearth. There are either two or four rabble arms per hearth. Each arm contains several rabble teeth, or plows, which rake the sludge across the hearth in a spiral pattern. Sludge is fed at the periphery of the top hearth (see Figure 11-6) and is rabbled toward the center, where it drops to the hearth below. On the second hearth, the sludge is rabbled outward to holes at the periphery of the bed. Here the sludge drops to the next hearth. The alternating drop hole locations on each hearth and the counter-current flow of rising exhaust gases and descending sludge provide contact between the hot combustion gases and the sludge feed. Good contact ensures complete combustion. The drop holes on the "out" hearths distribute the sludge evenly around the periphery of the hearth beneath. The drop holes also regulate gas velocities.

Sludge is constantly turned and broken into smaller particles by the rotating rabble arms. Thus, a large sludge surface is exposed to the hot furnace gases. This procedure induces rapid and complete drying, as well as burning. The rabble arms also form spiral ridges of sludge on each hearth. The surface area of these ridges varies with the angle of repose of the sludge, and the angle varies with the moisture content of the material. Because of the ridges, the actual surface area of sludge exposed to the hot gases is considerably greater than the hearth area. An effective area of up to 130 percent of the hearth area is available. Two access doors are generally provided at each hearth. They have fitted cast-iron frames and machined faces to provide reasonably tight closure. An observation port is provided in each door.

Figure 11-7 shows an interior cut-away view of the MHF. The central shaft of the furnace is a hollow iron column cast in sections; shaft speeds are adjustable from about 1/2 to 1-1/2 revolutions per minute. The hollow rabble arms are connected to machined arm sockets in the shaft. The shaft and rabble arms are air-cooled and normally are insulated. A cold air tube runs up the center of the shaft. Air lances extend from the cold air tube out to the ends of each rabble arm. Ambient air of regulated pressure and volume is forced through the cold air tube and lances by means of a blower. The cold air exits from the tips of the lances, flowing backward through the space between the lances and the rabble arm walls to the annular space in the central shaft known as the hot air compartment. This flow

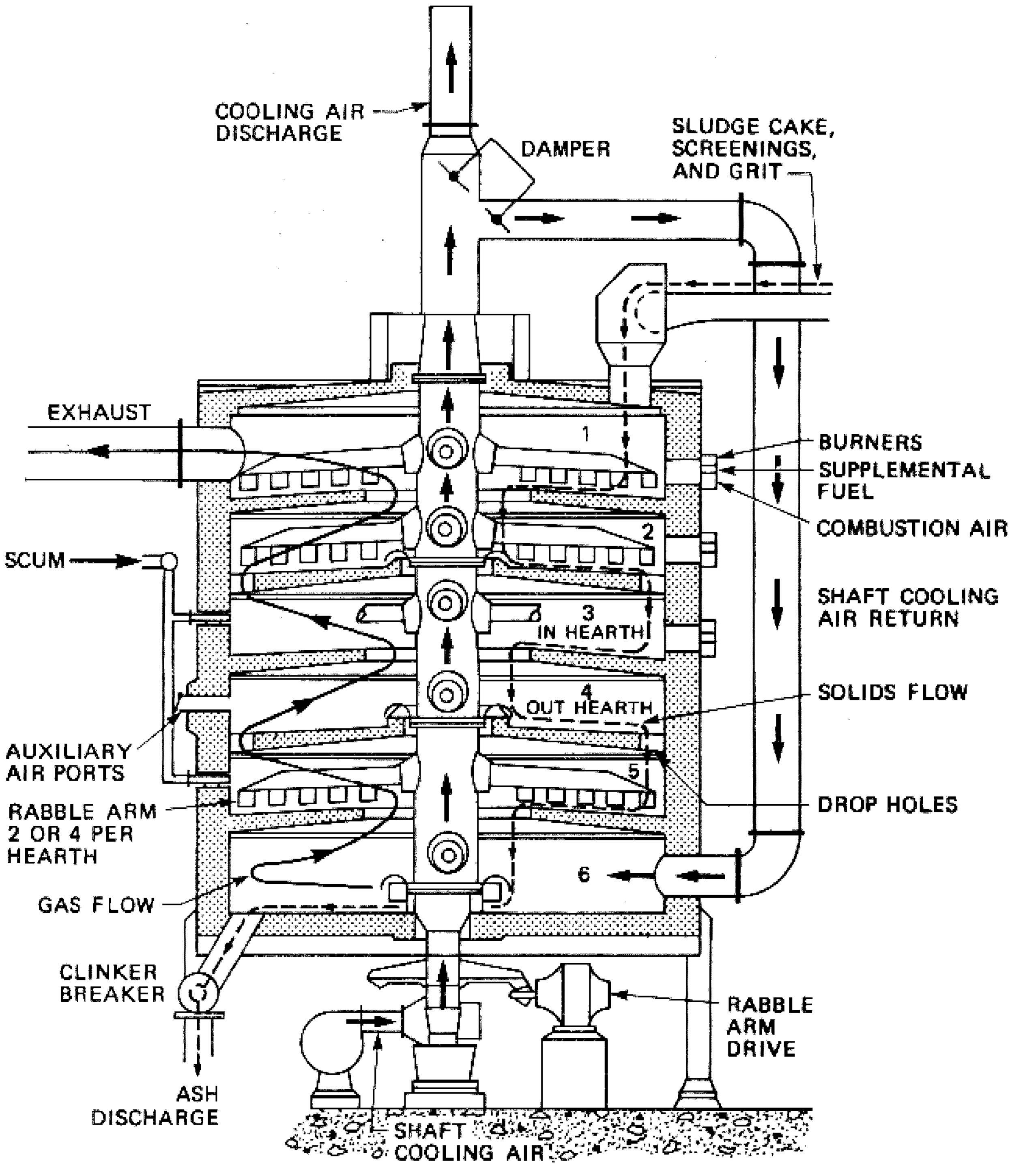

FIGURE 11-6

CROSS SECTION OF A MULTIPLE-HEARTH FURNACE

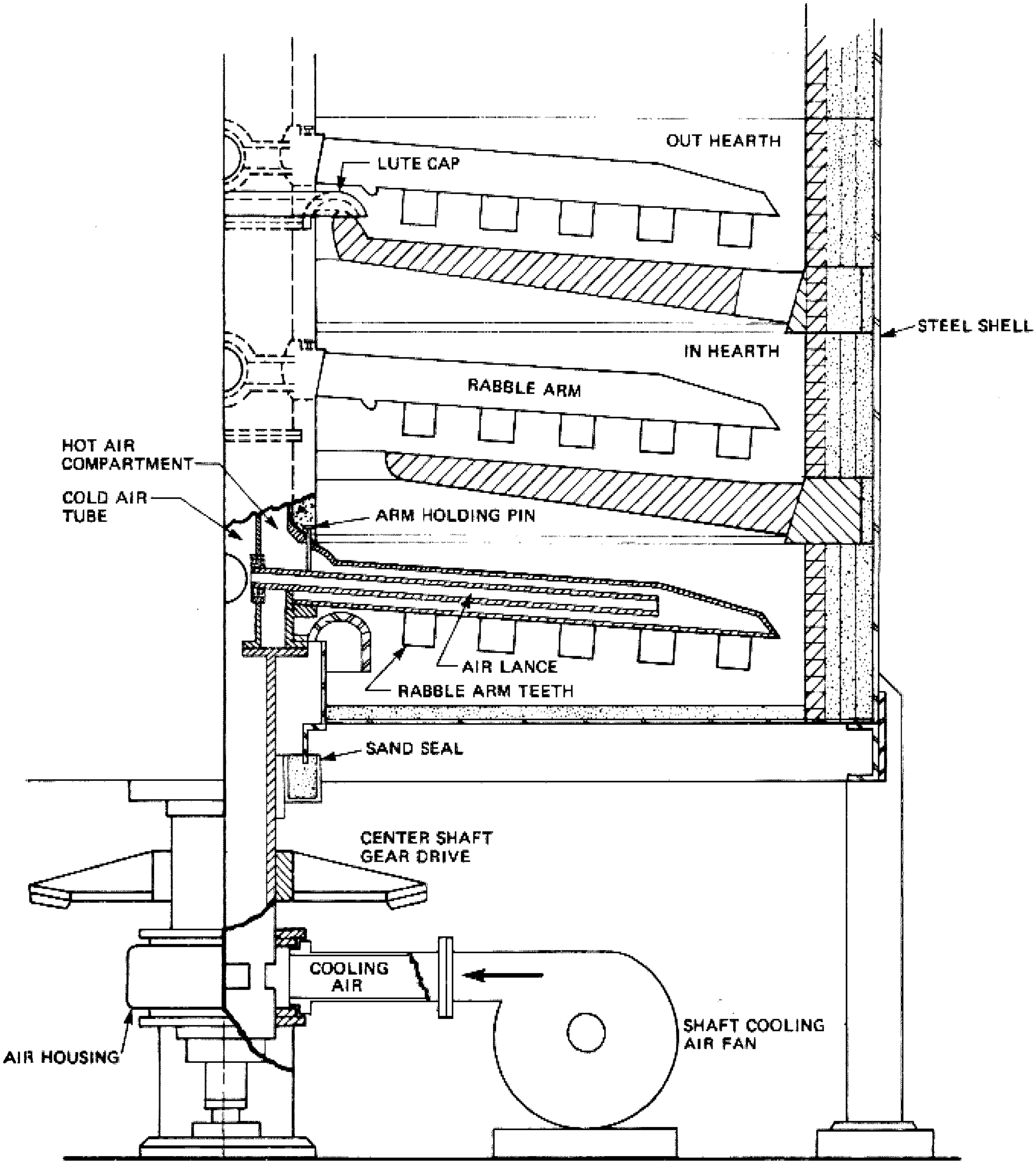

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FIGURE 11-7

SHAFT COOLING AIR ARRANGEMENT IN A MULTIPLE-HEARTH FURNACE

of air cools the arms. The air is conducted through the hot air compartment, cooling the shaft. The air is either discharged to the atmosphere via the exhaust gas stack or returned to the bottom hearth of the furnace as preheated air for combustion. Cooling air vented to the atmosphere represents a heat loss of roughly the same magnitude as the radiation loss from the furnace structure.

The MHF can be divided into four zones, as shown on Figure 11-8. The first zone, which consists of the upper hearths, is the drying zone. Most of the water is evaporated in the drying zone. The second zone, generally consisting of the central hearths, is the combustion zone. In this zone, the majority of combustibles are burned and temperatures reach 1,400°F to 1,700°F (760°C to 927°C). The third zone is the fixed carbon burning zone, where the remaining carbon is oxidized to carbon dioxide. The fourth zone includes the lowest hearths and is the cooling zone. In this zone, ash is cooled by the incoming combustion air. The sequence of these zones is always the same, but the number of hearths in each zone is dependent on the quality of the feed, the design of the furnace, and the operational conditions.

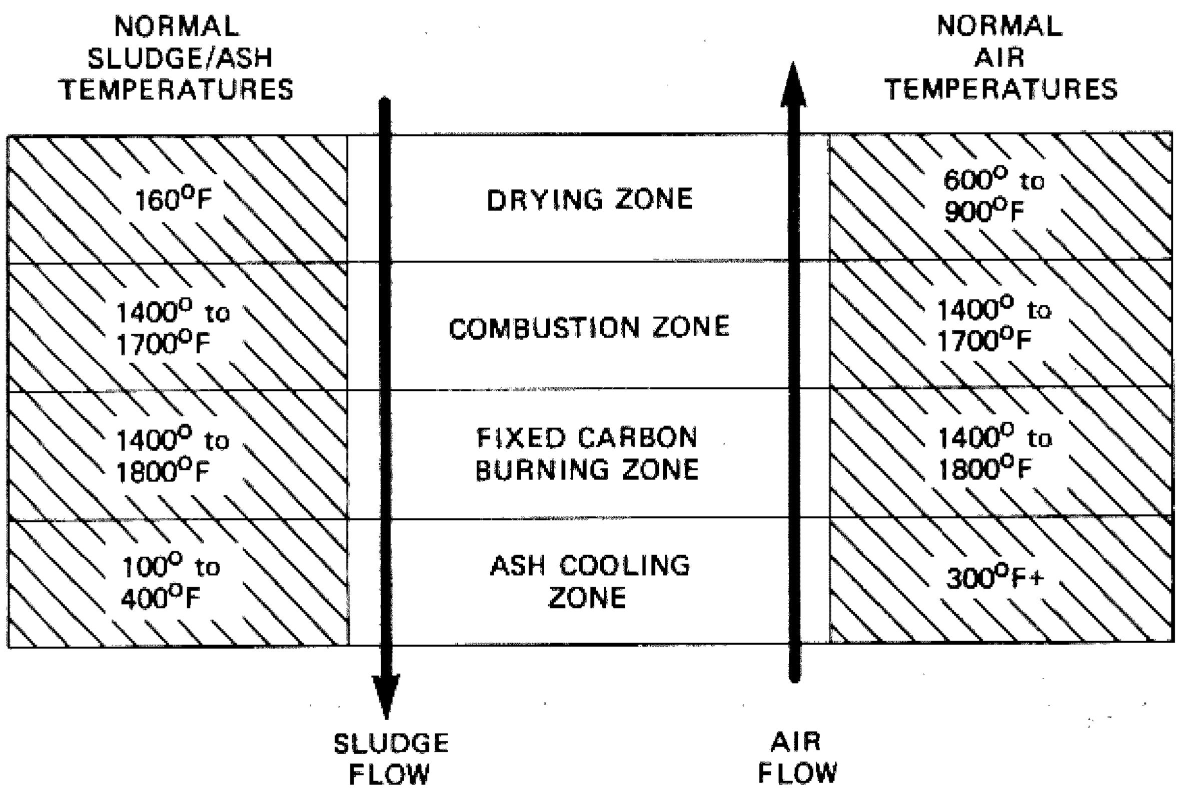


FIGURE 11-8

PROCESS ZONES IN A MULTIPLE-HEARTH FURNACE

When the heating value of the sludge is insufficient to sustain autogenous combustion, the additional heat required is supplied by adding supplemental fuel to burners located at various points in the furnace. Burners may operate either continuously or intermittently and on all or selected hearths.

A measure of the quantity of water evaporated from the sludge during burning is the drop in temperature of the hot gases as they pass between the combustion zone and the gas outlet. In a MHF, gas temperatures in the combustion zone may exceed 1,700°F (927°C). These gases sweep over the cold, wet sludge fed to the drying zone, giving up considerable portions of their heat in evaporating the water. While the temperature of the solids is only marginally increased in the drying zone, the gas temperature is drastically reduced, typically to the range of 600 to 900°F (316 to 482°C). Exhaust gas temperatures should be maintained at less than 900°F (482°C) by controlling air flow to prevent distillation of odorous greases and tars from the drying solids. If temperatures are so controlled, it may be possible to operate MHFs without devices such as afterburners, which are used to reduce odors and concentrations of unburned hydrocarbons.

However, afterburning MHF, exhaust gases will probably be needed in areas with very stringent carbonyl and unburned hydrocarbon emission limitations. In afterburning, furnace exhaust gases are conveyed to a chamber where their temperature is raised by direct contact with ignited supplemental fuel; the offending pollutants are oxidized to CO_2 and water. Afterburning, however, requires supplemental fuel, which raises operating costs significantly. In this respect, the MHF is at a disadvantage relative to FBF and single hearth cyclonic furnaces, which do not require afterburning. The reason may be seen when the air-sludge contact patterns in these furnaces are contrasted against the pattern in the MHF. In the MHF, warm air and unburned solids are contacted at the top of the furnace. Any compounds distilled from the solids are immediately vented from the furnace at temperatures too low to effect their destruction. In contrast, temperatures in FBF and single hearth cyclonic furnaces are high (1,200 to 1,600°F [649 to 760°C]) and nearly uniform throughout the furnace. Sludge and air are injected into the lower portion of the furnace, and any objectionable compounds distilled from the solids must traverse the entire length of the hot furnace before being vented. In the FBF and single hearth cyclonic furnaces, therefore, the volume of the furnace above the sludge injection zone is in effect an afterburner, supplying ample contact time and temperature for the destruction of pollutants. A flowsheet for the MHF process is shown on Figure 11-9.

The MHF can be provided with instrumentation to convey critical operating data to a central control panel. Temperature data can be monitored for each hearth and for other points in the exhaust gas system, such as the furnace exhaust, heat recovery device outlet, and scrubber exhaust. The temperature can be controlled on each hearth to within ± 40°F (22°C). Instrumentation such as CO_2 or O_2 meters can be used to control the flow of excess air, thereby conserving fuel and reducing the overall operating cost. Malfunctions such as burner shutdown, furnace over-temperature, draft loss, and feed shutdown can be monitored. In the event of power or fuel failure, the furnace should be shut down automatically and the shaft cooling air fan automatically transferred to a standby power source. This procedure will provide continued cooling and prevent serious deformations of the shaft and the rabble arms due to high temperature. Further details on instrumentation are provided in Chapter 17.

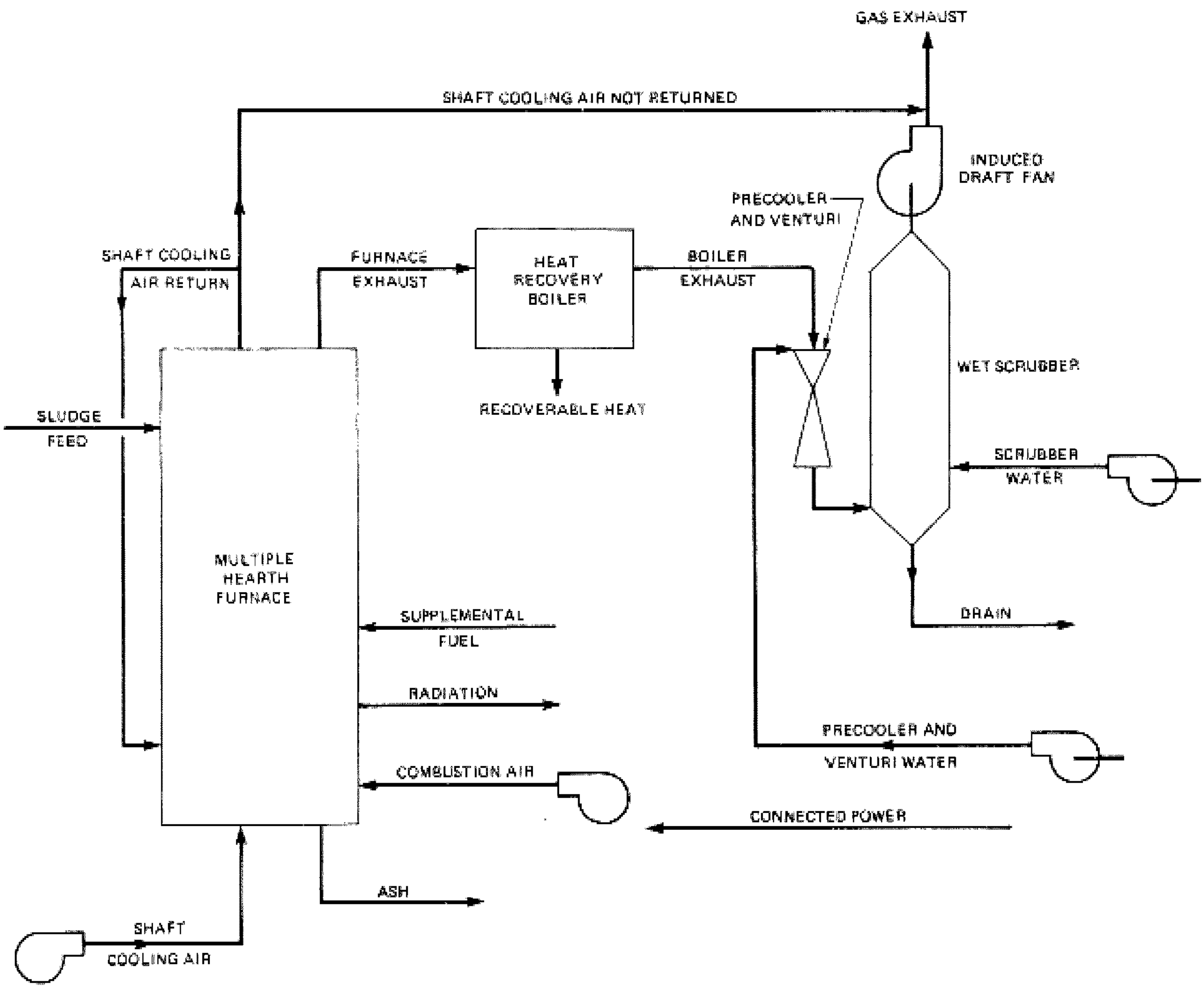


FIGURE 11-9

FLOWSHEET FOR SLUDGE INCINERATION IN A MULTIPLE-HEARTH FURNACE

Problems encountered with multiple-hearth furnaces have included (a) failure of rabble arms and teeth, (b) failure of hearths, and (c) failure of refractories. Improvements in materials used in constructing the rabble arms and teeth have reduced the first problem, increasing their ability to withstand high temperatures. Many refractory problems result because furnaces are not carefully heated and cooled during start-up and shutdown. Twenty-four hours or more are required to bring the furnace up to temperature or to cool it. This is an operational disadvantage since start-up fuel costs can be significant. However, there are several installations that do operate intermittently without significant refractory problems. The normal procedures at these installations is to fire supplemental fuel to maintain the temperature of the furnaces during the hours when they are not in use, thus reducing long reheat times. This procedure, known as "hot standby" is not generally economical. MHFs should not be operated at temperatures above 1,800°F (982°C) due to the metals exposed to the temperature. Thus with high energy fuels (for example, sewage scum), there may be problems with high temperatures in the combustion zones.

Heat and material balances for the hypothetical treatment plant alternatives listed in Table.11-8 are presented in Table 11-9 and should be used with the flowsheet presented in Figure 11-9. Figure 11-9 is the flowsheet for a typical multiple-hearth furnace. Figures 11-10 through 11-15 are generalized curves for capital and operating and maintenance costs for multiple-hearth furnaces. Table 11-10 gives typical hearth loading rates for multiple-hearth furnaces.

As expected, there are important differences between Alternatives "A" (20 percent solids feed) and "B" (40 percent solids feed) in terms of equipment size, capital costs, and operation and maintenance costs. This illustrates the value of preparing comparative cost tables for all options. Specific discussions of the MHF can be found in the literature (6,15,16,31, and 37-52).

The recycle concept is relatively new in MHF applications (53). This concept (54) is a modification of the multiple-hearth designed "....to control sludge combustion to burn where it is designed to burn, rather than to let it burn where it wants to go" (55). Recycle includes three control loops: an exit gas loop, a drying rate control loop, and a furnace combustion loop (see Figure 11-16). The exit gas loop allows hot gases to be exhausted from either or both the top-drying hearth and the combustion zone. For wet sludge, most or all of the air would be exhausted from the drying hearth, ensuring minimal fuel consumption (conventional MHF). For hot or dry sludges, most of the air would be drawn from the combustion zone so as to prevent uncontrolled burning on the upper hearths.

The drying rate control loop takes the air exhausted from the drying hearth and heats this air with exhaust gases from the combustion zone via an air heater (recuperator). The heated exhaust from the drying zone is returned as preheated combustion air to the furnace. This reduces the overall excess air requirements. The gas from the combustion zone exits from the first recuperator and enters a second, which serves as a preheater for makeup combustion air. Additional heat can be withdrawn from the combustion zone gas it passes through a scrubber and is vented by means of a heat recovery boiler.

TABLE 11-9

HEAT AND MATERIAL BALANCE FOR SLUDGE INCINERATION IN A MULTIPLE-HEARTH FURNACE[a]

Stream	Alternatives					
	IA 5 MGD 20 percent solids	IB 5 MGD 40 percent solids	IIA 15 MGD 20 percent solids	IIB 15 MGD 40 percent solids	IIIA 50 MGD 20 percent solids	IIIB 50 MGD 40 percent solids
Furnace design						
Diameter, ft-in.	18-9	14-3	22-3	16-9	22-3	18-9
Number of hearths	7	6	7	6	10	7
Hearth loading rate, lb wet solids/sq ft/hr	7.3	9.3	7.4	9.5	8.4	10.3
Sludge feed						
Lb dry solids/hr	1,806	2,131[b]	2,173	3,201[b]	4,292	5,064[b]
Heat value, 10^6 Btu/hr	13.91	13.91	20.89	20.89	33.06	33.06
Volatile content, percent dry solids	77	65	77	65	77	65
Supplemental fuel[c]						
No. 2 fuel oil, lb/hr	143	0	205	0	312	0
Heat value, 10^6 Btu/hr	2.64	0	3.79	0	5.77	0
Combustion air						
Mass at 60°F, lb/hr	22,060	27,531	32,959	41,544	51,945	66,740
Shaft cooling air						
Mass, lb/hr	19,273	9,178	24,321	13,766	34,416	19,273
Shaft cooling air return						
Mass at 325°F, lb/hr	16,560	0	20,880	0	29,520	0
Heat value, 10^6 Btu/hr	1.26	0	1.59	0	2.25	0
Shaft cooling air not recovered						
Heat loss, 10^6 Btu/hr	0.22	0.71	0.28	1.06	0.40	1.48
Ash						
Mass at 500°F, lb/hr	415	740	624	1,110	987	1,757
Heat value, 10^6 Btu/hr	0.04	0.07	0.06	0.10	0.09	0.15
Radiation						
Heat loss, 10^6 Btu/hr	0.32	0.21	0.41	0.26	0.53	0.33
Furnace exhaust						
Mass, lb/hr	30,817[d]	32,123[e]	46,102[d]	48,434[e]	72,735[d]	77,643[e]
Heat value, 10^6 Btu/hr	15.96	12.94	23.93	19.48	37.81	31.11
Boiler exhaust						
Heat value at 500°F, 10^6 Btu/hr	13.26	9.64	19.73	12.28	31.11	19.61
Recoverable heat						
70 percent efficiency, 10^6 Btu/hr	1.89	2.31	2.94	5.04	4.69	8.05
Precooler and Venturi water feed						
Flow at 70°F, gpm	90	86	135	130	215	209

TABLE 11-9

HEAT AND MATERIAL BALANCE FOR SLUDGE INCINERATION IN A MULTIPLE-HEARTH FURNACE[a] (CONTINUED)

Stream	IA 5 MGD 20 percent solids	IB 5 MGD 40 percent solids	IIA 15 MGD 20 percent solids	IIB 15 MGD 40 percent solids	IIIA 50 MGD 20 percent solids	IIIB 50 MGD 40 percent solids
	Alternatives					
Scrubber water feed						
Flow at 70°F, gpm	182	174	273	260	429	418
Scrubber drain						
Flow, gpm	296	264	428	398	676	638
Temperature, °F	98	98	98	98	98	98
Gas exhaust						
Mass, lb/hr	26,667	38,938	44,278	58,646	61,116	91,393
Temperature, °F	142	170	139	168	138	166
Heat value, 10^6 Btu/hr	9.44	6.00	14.01	6.80	22.09	10.82
Connected power						
Horsepower	238	93	305	178	305	238
Installed cost,[f] thousand dollars	2,000	1,600	2,200	2,000	2,400	2,000

Footnotes for Table 11-8.

[a]All data supplied by the manufacturer.

[b]Solids for B alternatives (40 percent solids feed), larger than A alternatives (20 percent solids feed), due to conditioning chemicals. See Table 11-7.

[c]Afterburner not included.

[d]At 800 °F.

[e]At 1,000 °F.

[f]Costs as of early 1978.

1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 ft = 0.31 m
1 in. = 0.02 m
1 MGD = 0.04 m^3/s

The furnace combustion control process allows the furnace to operate with sludges with a very high volatile content (for example, large amounts of scum) or those requiring supplemental fuel. This loop integrates the functions of the exit gas loop and the drying rate loop, providing for automatic control of the process without regard to feed quality.

The manufacturer of the furnace which uses the recycle concept claims that strict limits on gaseous emissions can be met without use of an afterburner. The air that is exhausted has not contacted wet sludge (the sludge in the drying zone) and thus has not distilled off odors or excess hydrocarbons from the sludge. Figure 11-16 is a flowsheet for a 50 MGD (2.2 m^3/s) plant.

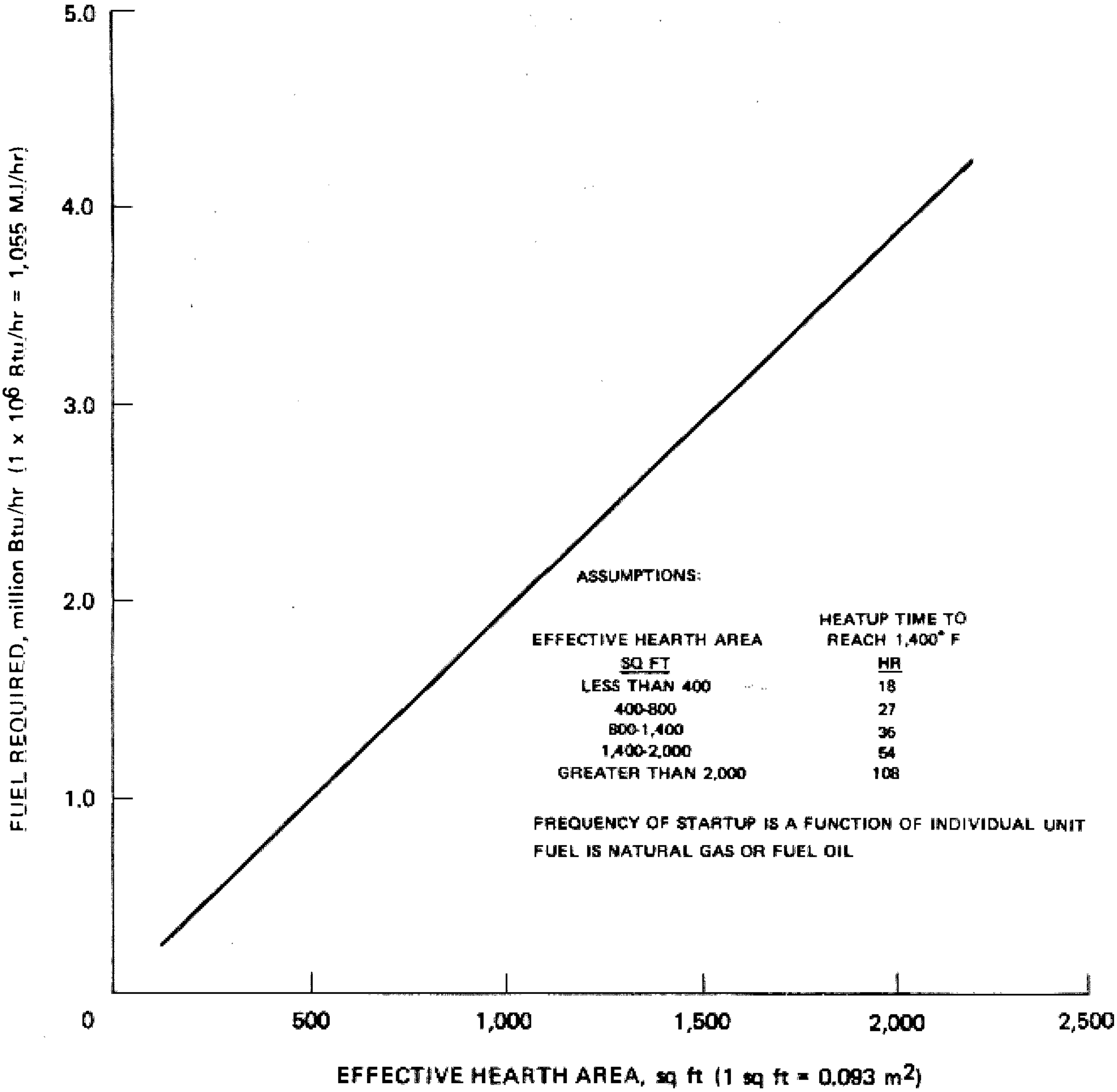


FIGURE 11-10

MULTIPLE-HEARTH FURNACE START-UP FUEL REQUIREMENTS (36)

Disadvantages of the recycle concept include those inherent in the MHF construction, as well as problems associated with ducting hot gases and with recuperators. Additional instruments and equipment add to operating and maintenance costs. These costs may be offset by a reduction in supplemental fuel demand. One municipal sludge installation similar to that depicted on Figure 11-16 is under construction in San Mateo, California. The recycle concept has been used in the MHFs for many years to produce bone char (a "hot" feed material) in the sugar industry.

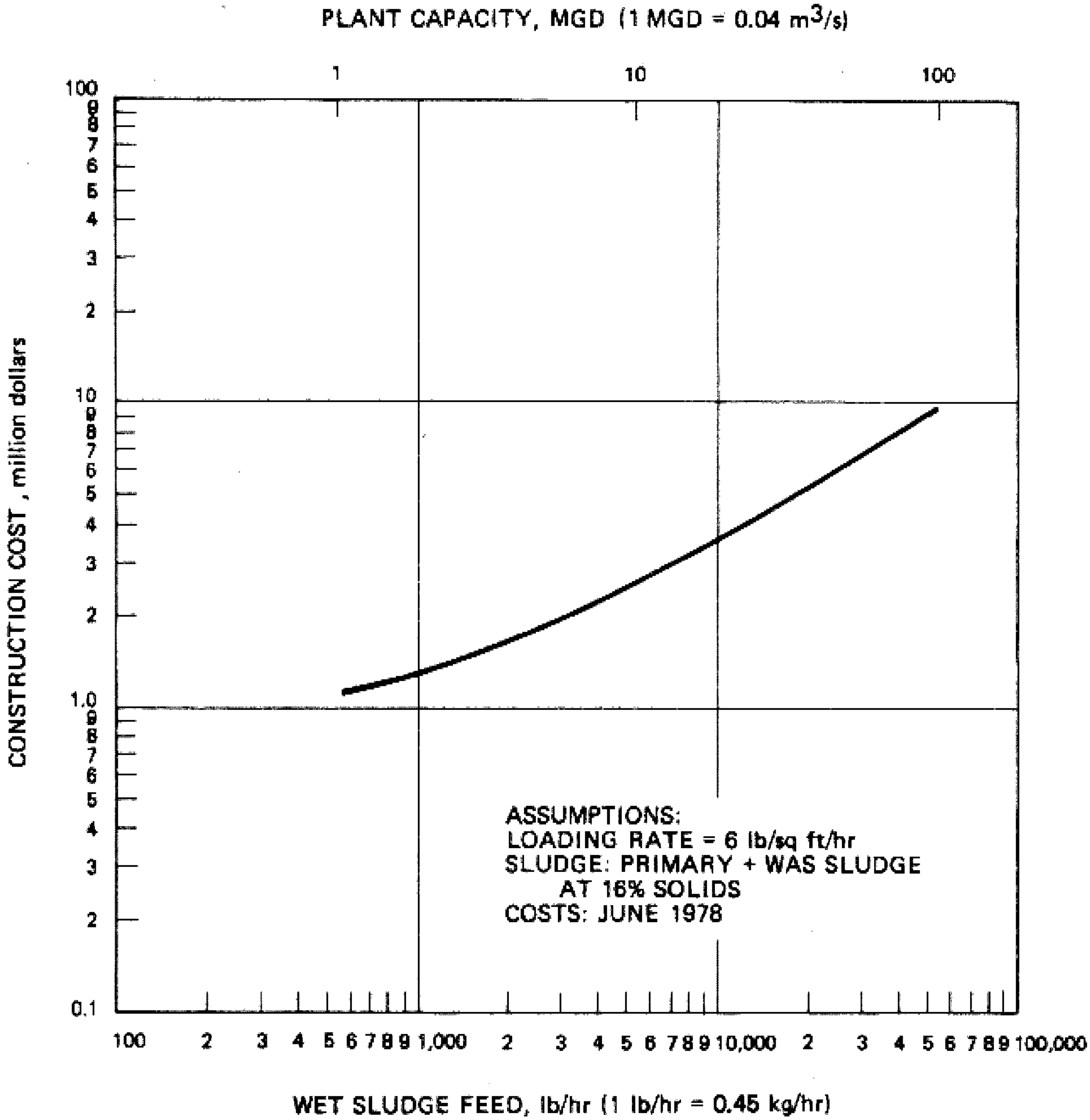


FIGURE 11-11

MULTIPLE-HEARTH FURNACE CONSTRUCTION COST (36)

11.3.2 Fluid Bed Furnace

The first fluid bed wastewater sludge furnace was installed in 1962. There are approximately 60 operating units in the United States (35) and many more in Europe. The fluid bed furnace (FBF) is a vertically oriented, cylindrically shaped, refractory-lined steel shell that contains a sand bed and fluidizing air diffusers. The FBF is normally available in sizes from 9 to 25 feet (2.7 to 7.6 m) in diameter. However, there is one industrial unit with a diameter of 53 feet (16.2 m). A cross section of the fluid bed furnace is shown on Figure 11-17. The sand bed is approximately 2.5 feet (0.8 m) thick and sits on a refractory-lined grid. This grid contains tuyeres through which air is injected into the furnace at a pressure of 3 to 5 psig (21 to 34 kN/m^2 gage) to fluidize the bed. The bed expands to approximately 100 percent of its at rest volume. Temperature of the bed is controlled between 1,400°F and 1,500°F (760°C and 816°C) by auxiliary burners located either above or below the sand bed. In some installations, a water spray or heat removal system above the bed controls the furnace temperature. In essence, the reactor is a single chamber unit in which both drying and combustion occur in either the dense or dilute phases in the sand bed. All of the combustion gases pass through the combustion zone with residence times of several seconds at 1,400°F to 1,500°F (760°C to 816°C). Ash is carried out the top of the furnace and is removed by air pollution control devices, usually venturi scrubbers. Sand carried out with the ash must be replaced. Sand losses are approximately 5 percent of the bed volume for every 300 hours of operation. Feed to the furnace is introduced either above or directly into the bed.

Air flow in the furnace is determined by several factors. Fluidizing and combustion air must be sufficient to expand the bed to a proper density yet low enough to prevent the sludge from rising to and floating on top of the bed. Too much air blows sand and products of incomplete combustion into the off-gases. This depletes stored heat energy and increases fuel consumption unnecessarily. Minimum oxygen requirements must be met to assure complete oxidation of all volatile solids in the sludge cake. Temperatures must be sufficiently high to assure complete deodorizing but low enough to protect the refractory, heat exchanger, and flue gas ducting. The quantities of excess air are maintained at 20 to 45 percent to minimize effects on fuel costs (see Figure 11-3). The fluid bed furnace operates at lower excess air rates than typically experienced in MHF operations. This accounts for the greater heat efficiency of the fluid bed system at similar exit temperatures . The intense and violent mixing of the solids and gases within the fluid bed results in uniform conditions of temperature, composition, and particle size distribution throughout the bed. Heat transfer between the gases and the solids is extremely rapid because of the large surface area available.

There are two basic process configurations for the FBF. In the first process, the fluidizing air passes through a heat exchanger, or recuperator, prior to injection into the combustion chamber. This arrangement is known as a hot windbox design. In the second process, the fluidizing air is injected directly into the furnace. This arrangement is known as a cold windbox design. The first arrangement increases the thermal efficiency of the process by using the higher temperature of the exhaust gases to preheat the incoming combustion air.

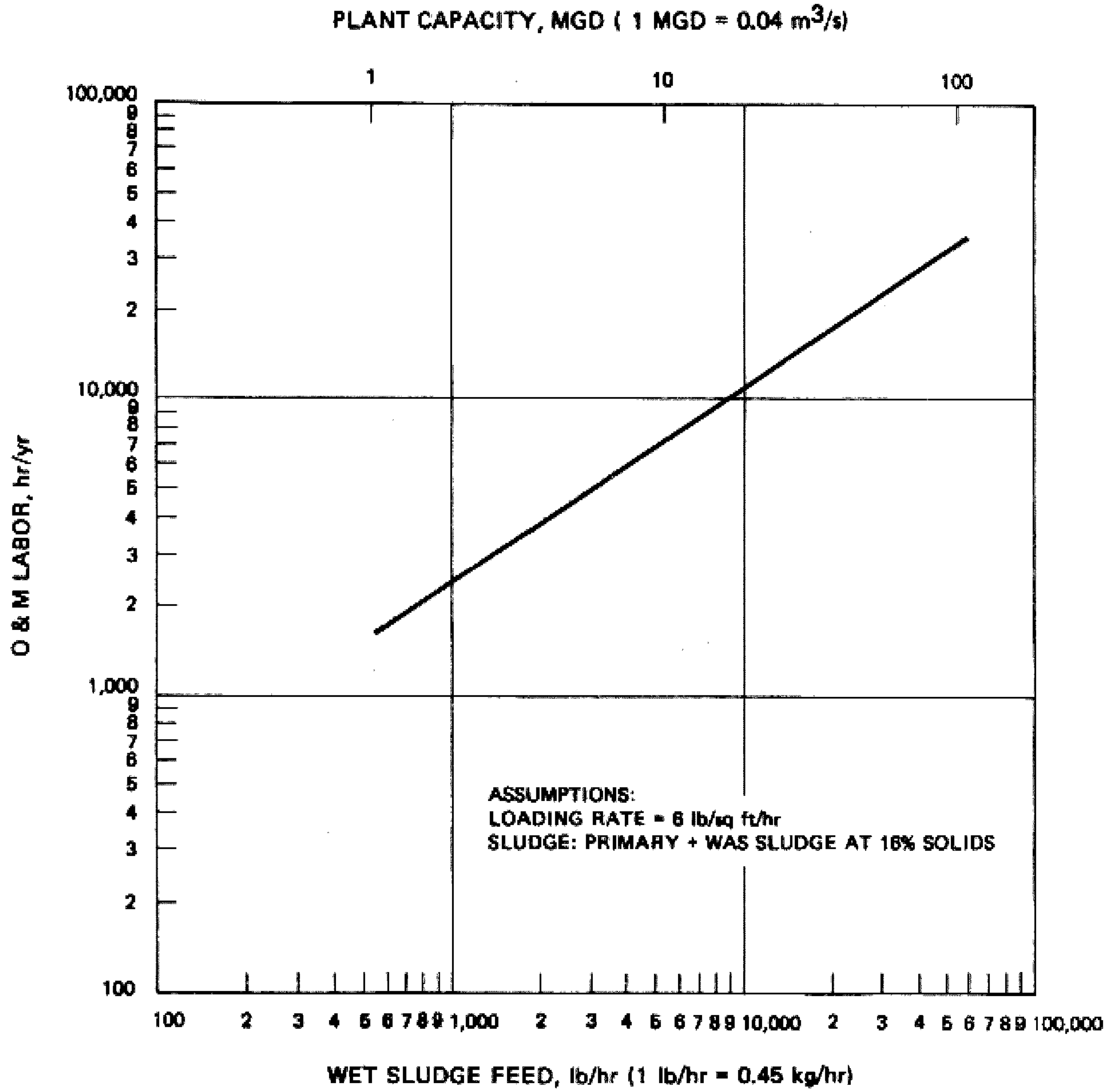


FIGURE 11-12

MULTIPLE-HEARTH FURNACE OPERATING AND MAINTENANCE LABOR REQUIREMENTS (36)

Preheating the incoming combustion air from 70°F to 1,000°F (21°C to 538°C) can yield a reduction in fuel costs of approximately 61 percent per unit wet sludge (39). Air preheating costs can represent 15 percent of the fluid bed furnace cost; therefore, a careful economic analysis is needed to determine cost-effectiveness for a given situation.

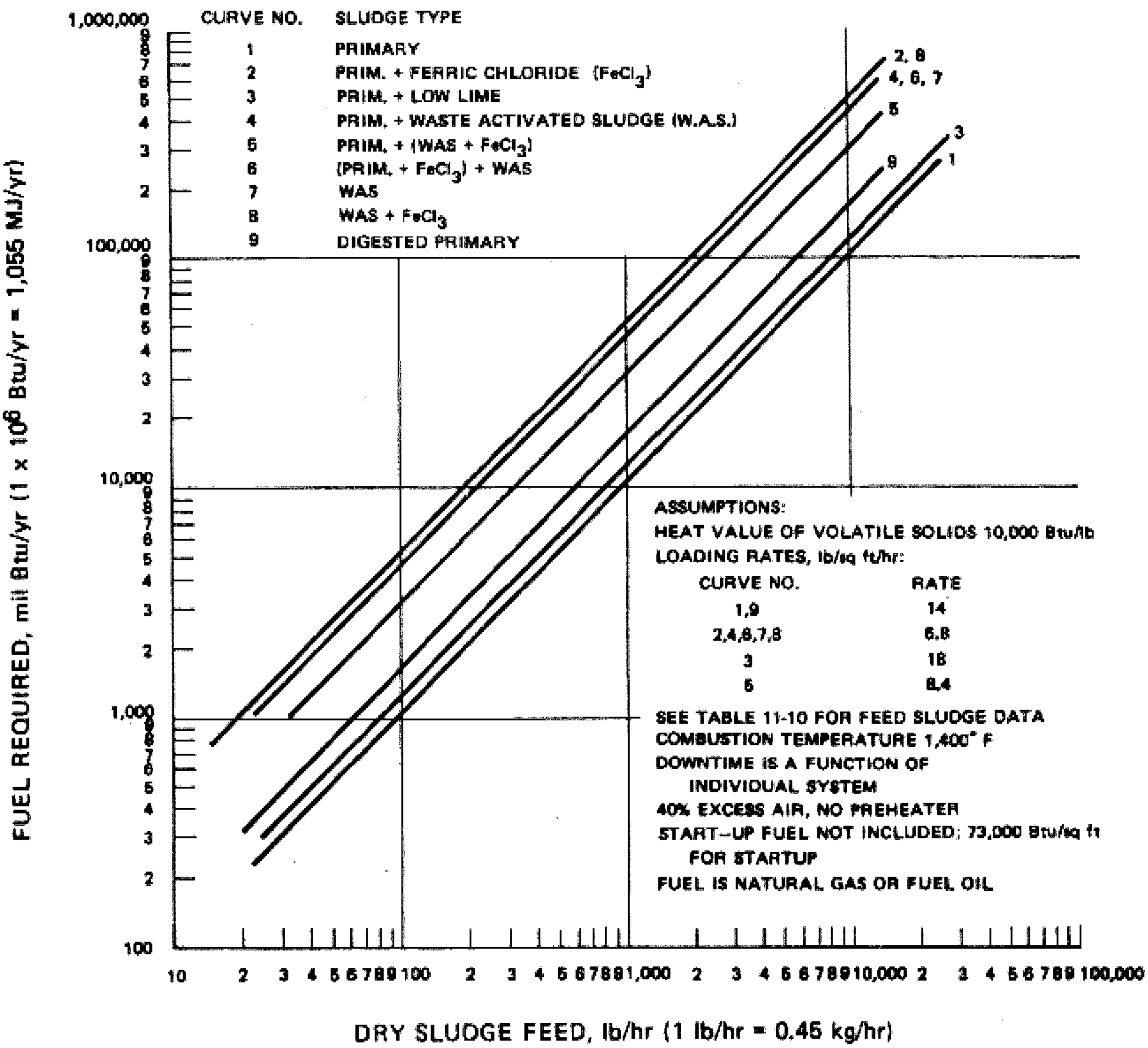


FIGURE 11-13

MULTIPLE-HEARTH FURNACE FUEL REQUIREMENTS (36)

Violent mixing in the fluidized bed assures rapid and uniform distribution of fuel and air, and consequently, good heat transfer and combustion. The bed itself provides substantial heat storage capacity. This helps to reduce short-term temperature fluctuations that may result from varying feed heating values. This heat storage capacity also enables quicker start-up, if the shutdown period has been short (for example, overnight). Organic particles remain in the sandbed until they are reduced to mineral ash. The violent motion of the bed comminutes the ash material, preventing the buildup of clinkers. The resulting fine ash is constantly stripped from the bed by the upflowing gases.

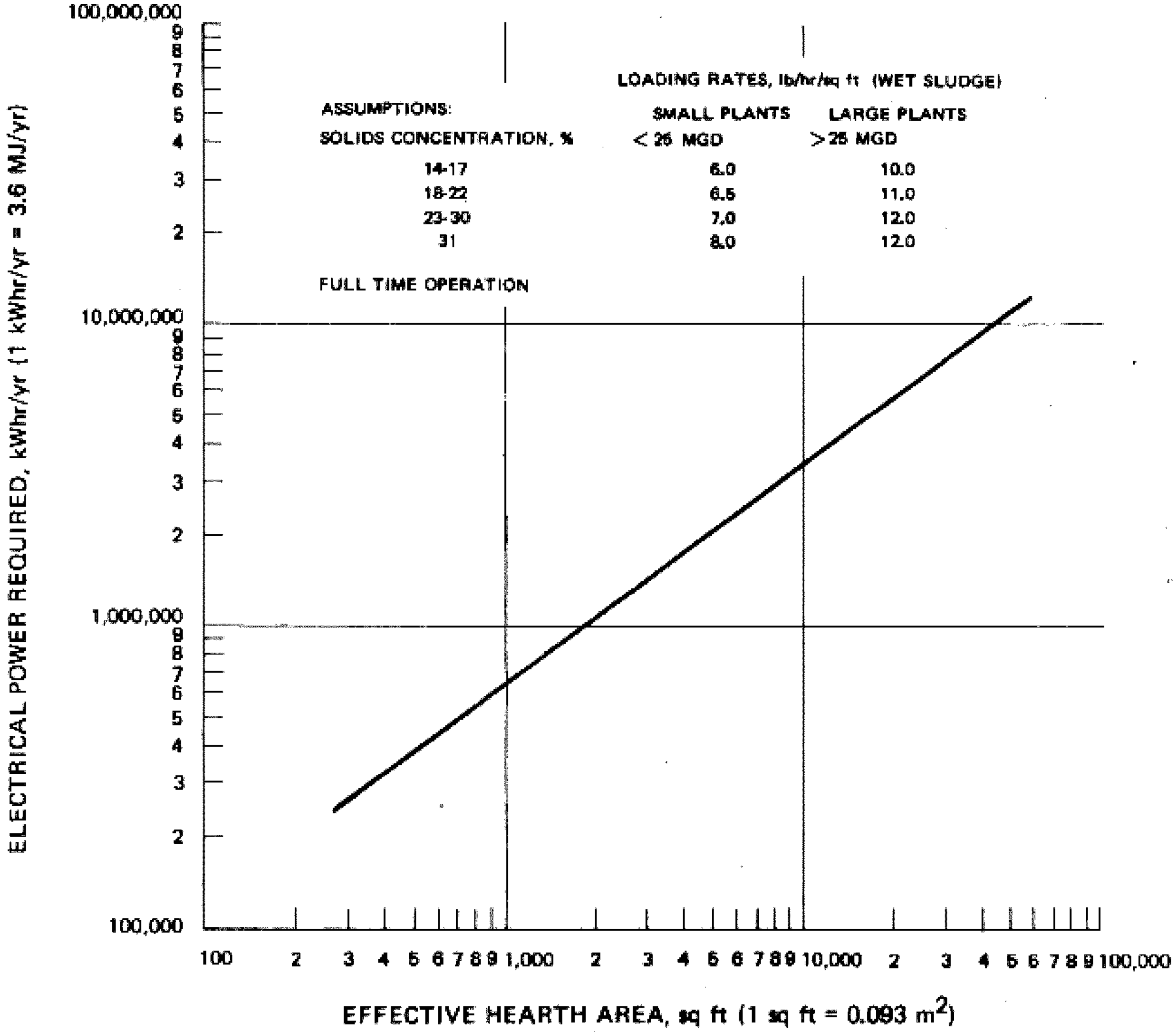


FIGURE 11-14

MULTIPLE-HEARTH FURNACE ELECTRICAL POWER REQUIREMENTS (36)

An oxygen analyzer in the stack controls air flow into the reactor. This type of control has limited application, since air flow ranges have upper and lower rates required for proper bed fluidization. The rate of use of auxiliary fuel is controlled by furnace exhaust gas temperature. Shutdown controls must be provided for emergency situations. Further details on instrumentation are provided in Chapter 17.

Heat and material balances for the hypothetical treatment plant alternatives (Table 11-8) are presented in Table 11-11. Figure 11-18 is the flowsheet for a typical FBF system. Figures 11-19 and 11-20 are generalized curves depicting fuel and power required for FBF systems.

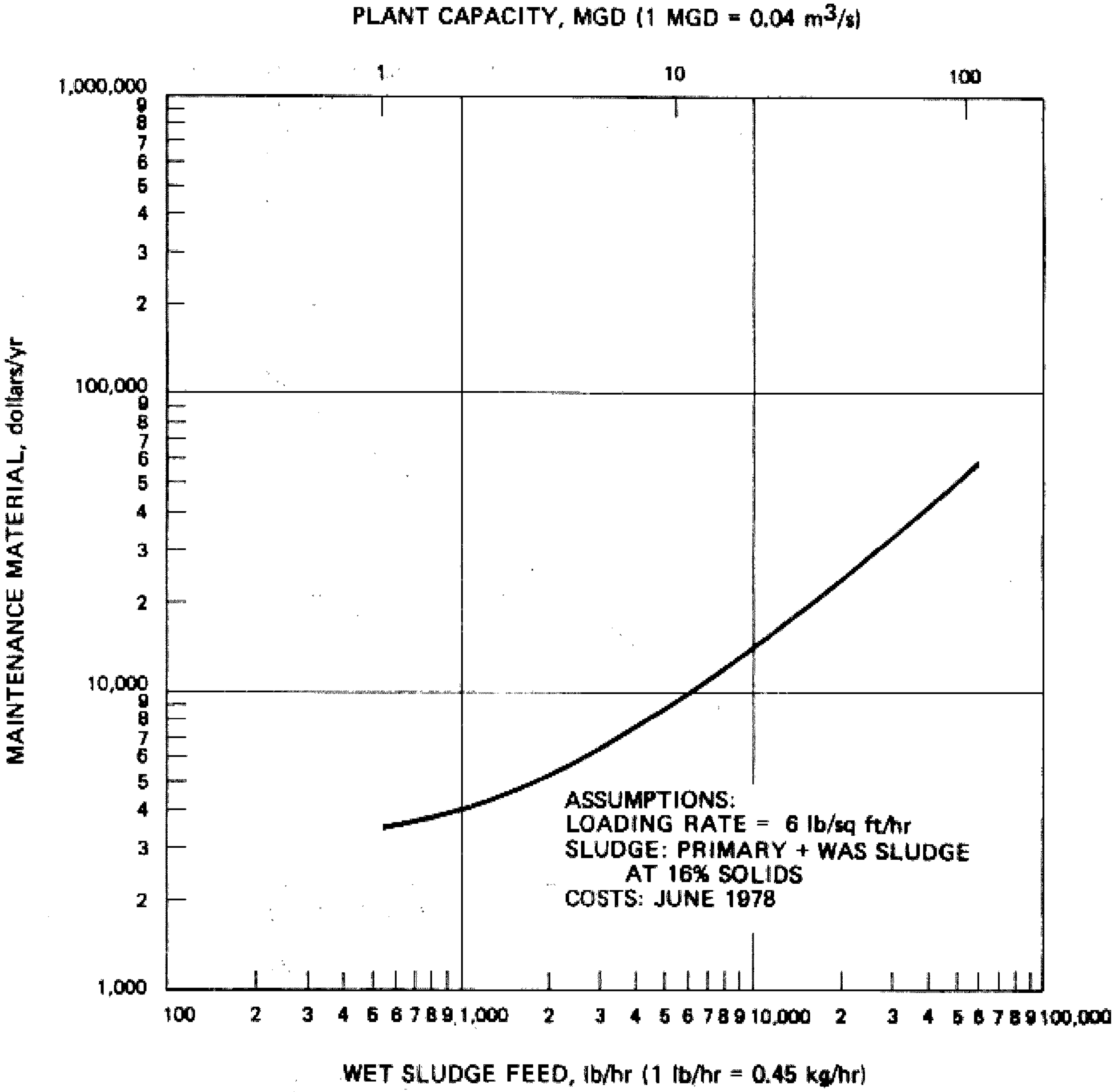


FIGURE 11-15

MULTIPLE-HEARTH FURNACE MAINTENANCE MATERIAL COSTS (36)

The FBF is relatively simple to operate, has a minimum of mechanical components, and typically has a slightly lower capital cost than the MHF. Normal operation of the FBF produces exhaust temperature in excess of 1,400°F (760°C). Because the exhaust gases are exposed to this temperature for several seconds, carbonyl and unburned hydrocarbon emissions are minimal, and strict hydrocarbon emission regulations are met without the use of an afterburner. However, it is important that operating conditions be optimum to assure this emission level at all times.

TABLE 11-10

TYPICAL HEARTH LOADING RATES FOR A MULTIPLE-HEARTH FURNACE[a]

Type of sludge	Percent solids	Percent combustibles	Chemical concentration,[b] mg/l	Typical wet sludge loading rate,[c] lb/sq ft/hr
Primary	30	60	N/A[d]	7.0 - 12.0
Primary plus ferric chloride ($FeCl_3$)	16	47	20	6.0 - 10.0
Primary plus low lime	35	45	298	8.0 - 12.0
Primary plus waste-activated sludge (WAS)	16	69	N/A	6.0 - 10.0
Primary plus (WAS plus $FeCl_3$)	20	54	20	6.5 - 11.0
(Primary plus $FeCl_3$) plus WAS	16	53	20	6.0 - 10.0
WAS	16	80	N/A	6.0 - 10.0
WAS plus $FeCl_3$	16	50	20	6.0 - 10.0
Anaerobically digested primary	30	43	N/A	7.0 - 12.0

[a]Data supplied by the manufacturer.

[b]Assumes no dewatering chemicals.

[c]Low number is applicable to small plants, high number is applicable to large plants.

[d]N/A - not applicable.

1 lb/sq ft/hr = 4.9 $kg/m^2/hr$

Problems with the FBF have occurred primarily with feed equipment and temperature controls. When sludge is injected directly into the bed, screw feeders may jam if the sludge has been overdried or if it solidifies at the point of injection. When spray nozzles have been used, thermocouples have occasionally burned out. These problems have generally been solved by the use of different construction materials. There have been some problems with preheaters and with sand scaling on the venturi scrubber. In some installations, there have been serious erosion problems in the scrubber due to the excessive carryover of bed material and the resulting sandblasting effect. The fluid bed furnace can be operated at 2,200°F (1,204°C) with appropriate design modifications and is suitable for high energy sludges. Combustion at temperatures over 2,000°F (1,093°C) can create many side effects such as ash fusion, high temperature corrosion, scaling, and clinker formation. Since a minimal amount of air is always required for bed fluidizing, energy savings from turndown (feed reduction) are minor. More detailed information can be found in the literature (39,40,41,43,48,49,50, and 56-63).

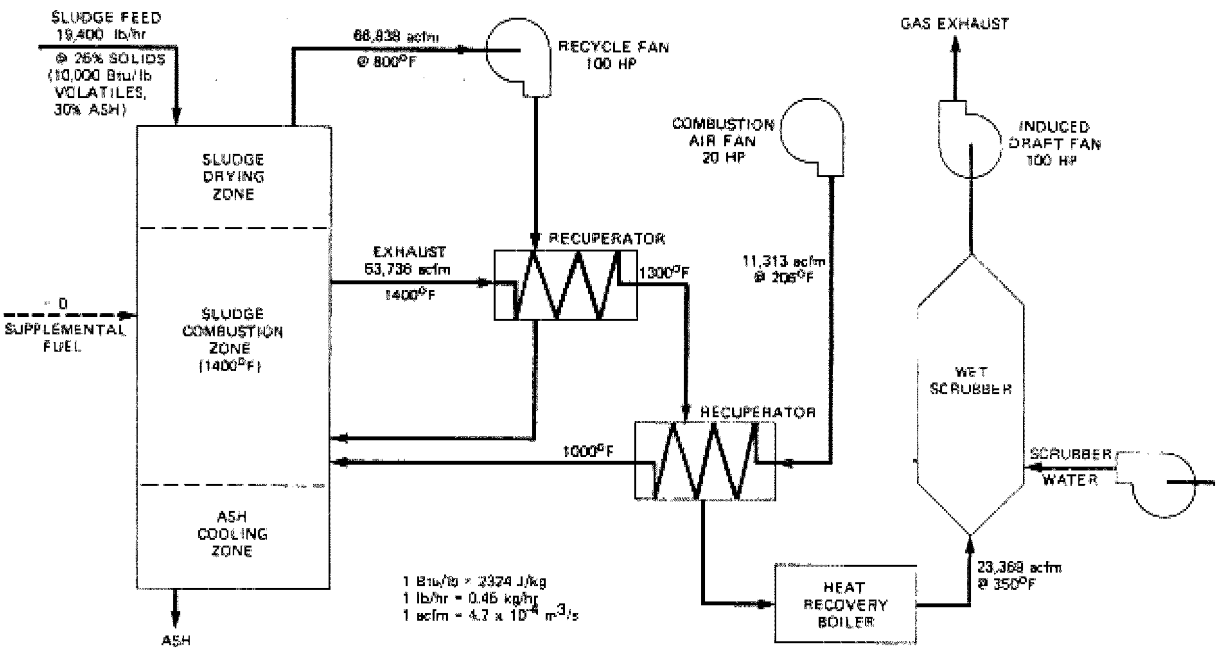


FIGURE 11-16

HEAT BALANCE FOR THE RECYCLE CONCEPT IN A MULTIPLE-HEARTH FURNACE (55)

11.3.3 Electric Furnace

The first electric furnace was installed in Richardson, Texas, in 1975. The electric, or infrared, furnace (EF) is a horizontally oriented, rectangular, steel shell containing a moving horizontal woven-wire belt. The unit is lined with ceramic-fiber blanket insulation. Electric furnaces are available in a range of sizes from 4 feet (1.2 m) wide by 20 feet (6.1 m) long to 9.5 feet (2.9 m) wide by 96 feet (29.3 m) long. Larger sizes are currently being developed. A typical cross section is shown on Figure 11-21.

Sludge is fed into the EF through a feed hopper that discharges onto the woven-wire belt. Shortly after the sludge is deposited on the belt, it is leveled by means of an internal roller to a layer approximately one inch thick (2.5 cm), across the width of the belt. A rabbling device is provided on several new installations to break up the surface of the sludge layer to afford better combustion. This layer of sludge moves under the infrared heating elements, which provide supplemental energy for the incineration process, if required. Ash is discharged from the end of the belt to the ash handling system. Combustion air flow is countercurrent to the sludge flow, with most of the combustion air being introduced into the ash discharge end of the unit. Excess air rates for the EF vary from 20 to 70 percent. The EF is divided into a feed zone, a drying and combustion zone, and an ash discharge zone. The feed and discharge zones are each 8 feet (2.4 m) long. The length of the drying and combustion zone varies with the design.

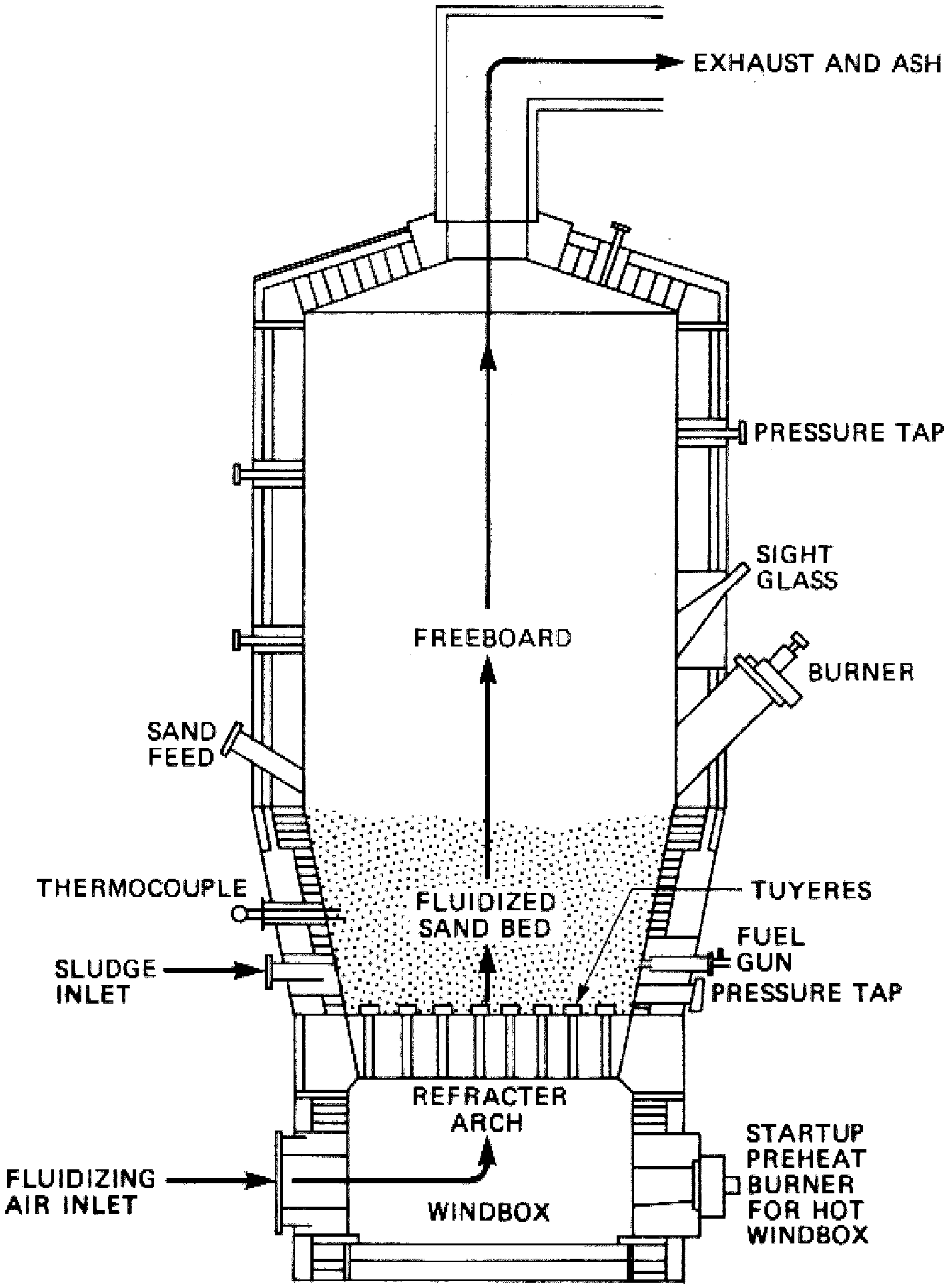


FIGURE 11-17

CROSS SECTION OF A FLUID BED FURNACE

TABLE 11-11

HEAT AND MATERIAL BALANCE FOR SLUDGE INCINERATION IN A FLUID BED FURNACE[a]

Stream	IA 5 MGD 20 percent solids	IB 5 MGD 40 percent solids	IIA 15 MGD 20 percent solids	IIB 15 MGD 40 percent solids	IIIA 50 MGD 20 percent solids	IIIB 50 MGD 40 percent solids
	Alternatives					
Furnace design						
Inside diameter, ft	14	12	18	14	22	18
Loading rate, lb wet solids/sq ft/hr	56.9	47.0	53.3	47.0	56.5	45.0
Sludge feed						
Lb dry solids/hr	1,806	2,131[b]	2,713	3.201[b]	4,293	5,064[b]
Heat value, 10^6 Btu/hr	13.91	13.91	20.89	20.89	33.06	33.06
Volatile solids, percent dry solids	77	65	77	65	77	65
Supplemental fuel[c]						
Mass, lb/hr	151	0	224	0	353	0
Heat value, 10^6 Btu/hr	2.80	0	4.14	0	6.52	0
Combustion air						
Mass, lb/hr	19,353	16,250	28,976	23,576	45,978	38,620
Heat value, 10^6 Btu/hr	4.4	0	6.7	0	10.6	0
Ash						
Mass, lb dry solids/hr	416	746	623	1,117	959	1,772
Heat value, 10^6 Btu/hr	0.12	0.14	0.18	0.26	0.29	0.42
Water flow, gpm	20	32	30	43	40	70
Radiation						
Heat loss, 10^6 Btu/hr	0.42	0.29	0.63	0.44	1.00	0.71
Recoverable heat						
70 percent efficiency, 10^6 Btu/hr	3.5[d]	6.2[e]	5.3[d]	9.4[e]	8.4[d]	12.7[e]
Recuperator	Yes	No	Yes	No	Yes	No
Venturi water						
Recycle water, gpm	83	68	124	102	197	161
Makeup water at 70°F, gpm	10	12	15	19	24	30
Scrubber water feed						
Flow at 70°F, gpm	365	345	548	565	868	824
Scrubber drain						
Flow at 130°F, gpm	391	359	582	600	924	900
Gas exhaust						
Volume, cfm	5,042	3,972	7,524	5,949	12,007	9,459
Temperature, °F	120	120	120	120	120	120
Connected power						
Horsepower	218	162	320	234	425	350
Installed cost,[f] thousand dollars	1,100	1,000	1,400	1,100	1,600	1,500

[a]All data provided by Dorr-Oliver, Inc.

[b]Solids for B alternatives (40 percent solids feed), larger than A alternatives (20 percent solids feed), due to conditioning chemicals. See Table 11-7.

[c]Afterburner not required.

[d]At 1,400°F.

[e]At 1,650°F.

[f]Costs as of early 1978.

1 ft = 0.31 m
1 lb/sq ft/hr = 4.9 kg/m^2/hr
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 cfm = 4.72 x 10^{-4} m^3/s
1 MGD = 0.04 m^3/s

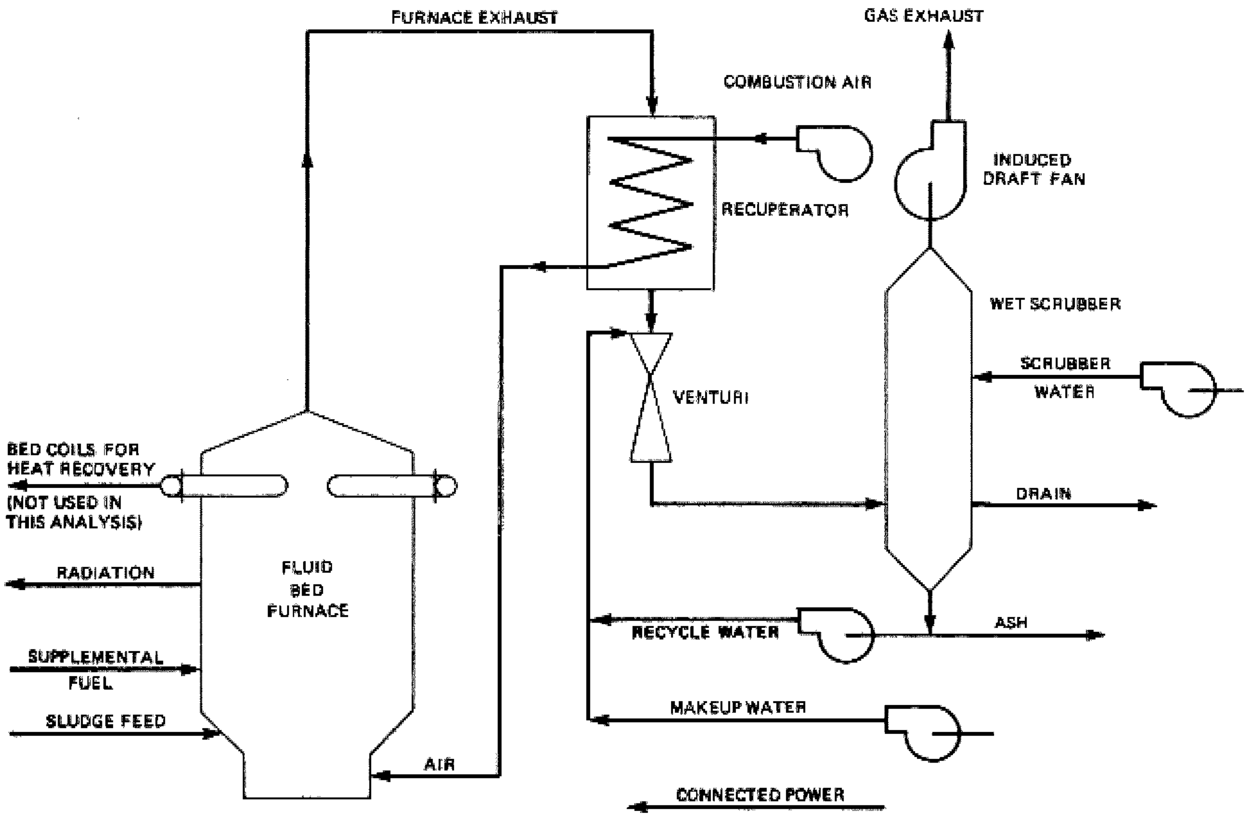


FIGURE 11-18

FLOWSHEET FOR SLUDGE INCINERATION IN A FLUID BED FURNACE

A flowsheet for the typical electric furnace is shown on Figure 11-22. Heat and material balances for the hypothetical treatment plant alternatives (Table 11-8) are presented in Table 11-12. In addition to the alternative cases I, II, and III, balances for a 1 MGD (0.04 m^3/s) treatment plant have been included. The EF is suited to small wastewater treatment plants.

The effective belt loading rate of a large EF is slightly greater than the hearth loading rate of a multiple-hearth furnace. The supplemental energy requirements of the EF are lower than the requirements of the MHF, FBF, or the cyclonic furnace. Because electricity is used to provide the supplemental energy, no fuel is burned, and consequently, no excess air for this purpose is required. However, when the generation efficiency of electricity is included, the supplemental energy requirements are similar for all furnaces. Electricity, rather than fossil fuel, is the energy source for the EF. Electricity is generally a more expensive energy source than the fossil fuel used by the other unit types. Depending upon the energy cost differential, the advantage of low excess air may be reduced. When autogenous sludge is available, the only difference between the EF and other processes with low excess air rates would be the motive power.

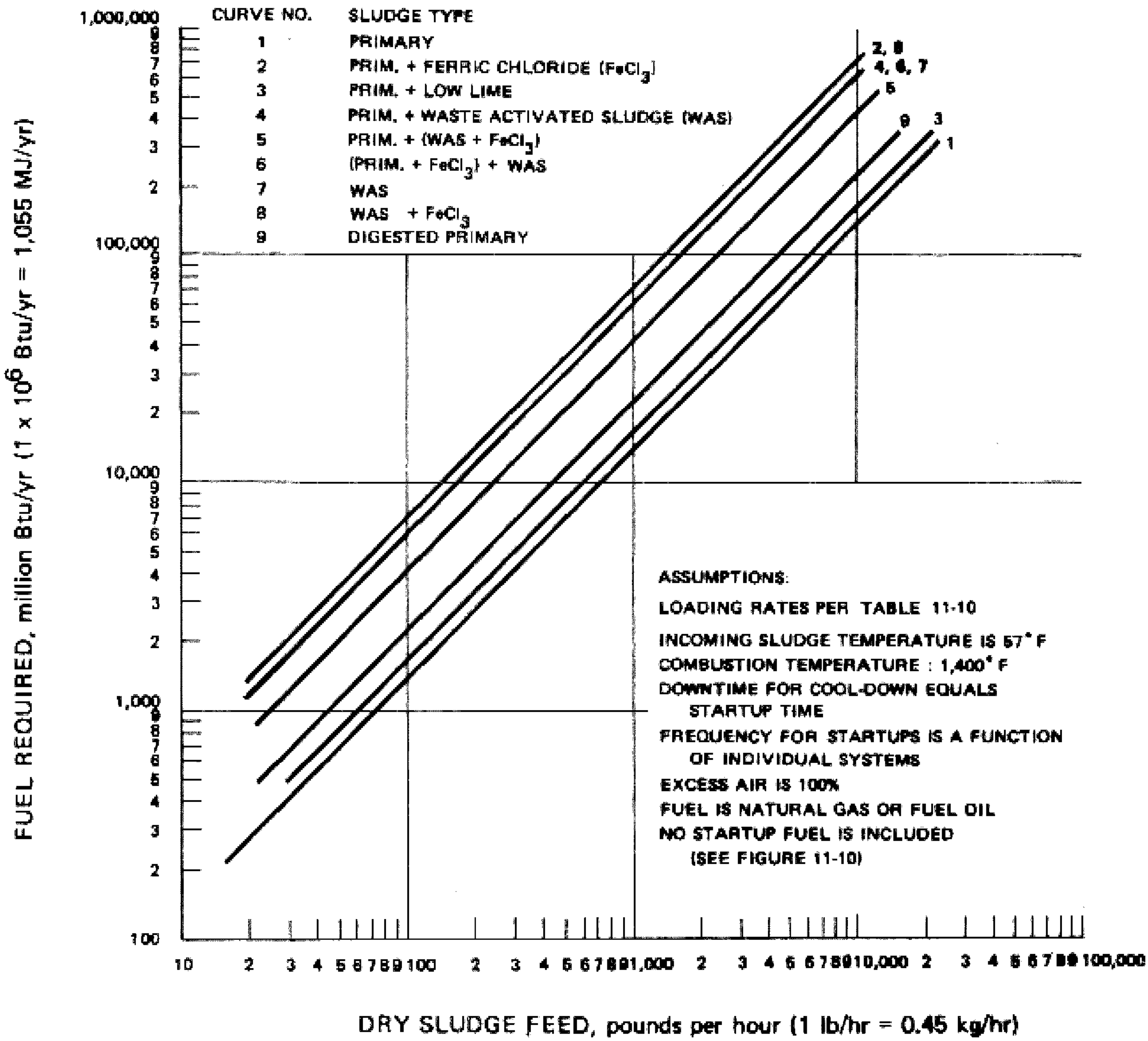


FIGURE 11-19

FLUID BED FURNACE FUEL REQUIREMENTS (36)

Low capital cost combined with modular construction makes the EF attractive, especially for small treatment systems. Because of the use of ceramic-fiber blanket insulation instead of solid refractories, the electric furnace may be shut down and heated up without the refractory problems that can occur in the other furnaces. This makes the EF suitable for intermittent operation. However, each restart requires supplemental energy (electricity), since there is no heat sink similar to the sandbed in the FBF. Currently, no EF units are installed with a capacity of over 1,200 pounds per hour.

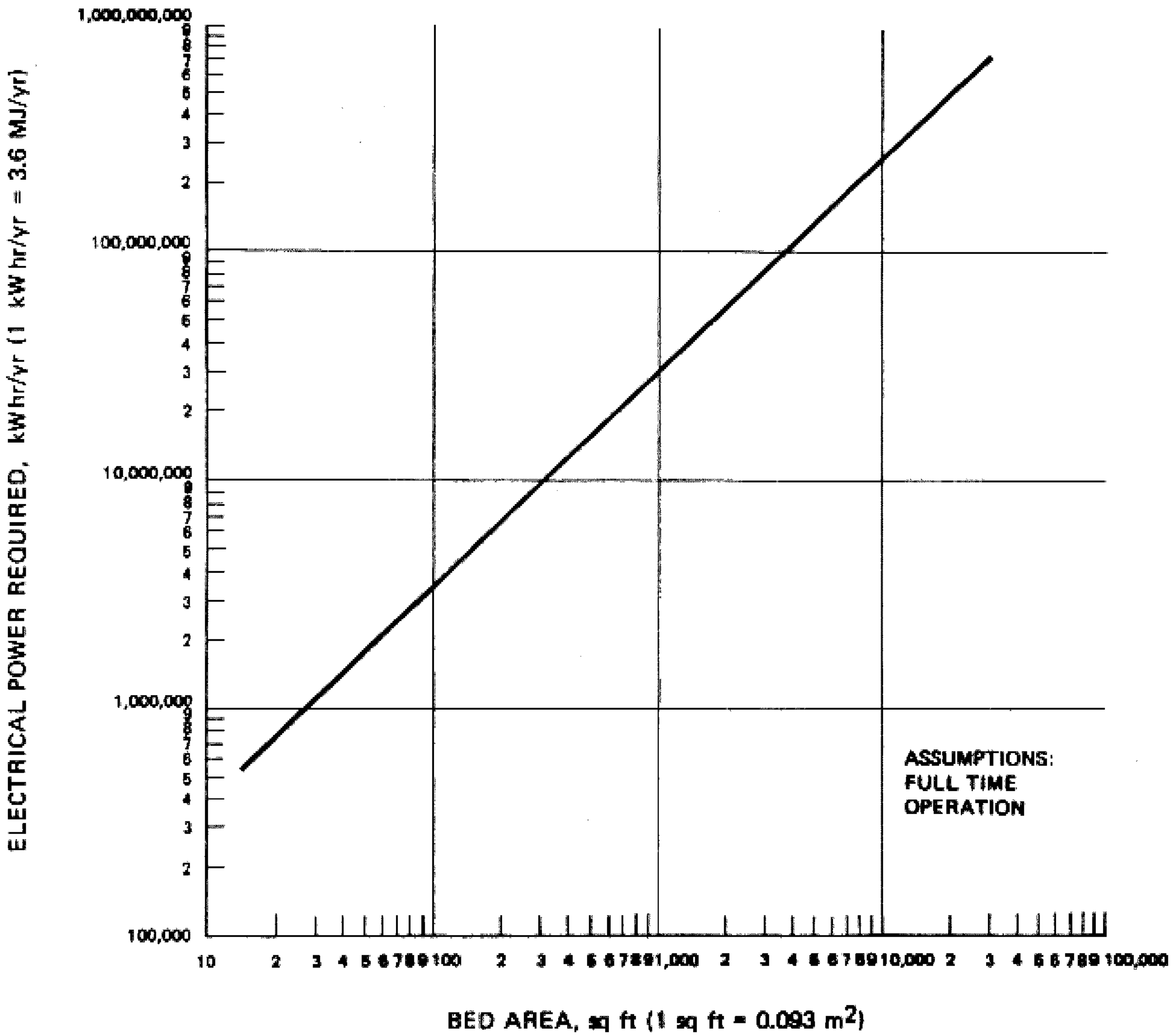


FIGURE 11-20

FLUID BED FURNACE ELECTRICAL POWER REQUIREMENTS (36)

The EF appears to be a feasible alternative for both small and large systems due to its inherent simplicity and low cost. However, the EF requires considerably more floor space than furnaces which are vertically oriented. Another concern is the replacement of various components such as the woven-wire belt (3 to 5-year life) and the infrared heaters (3-year life). These items represent a sizable portion of the capital cost. Replacement costs must be considered in any overall evaluation. Connected power, whether for heating or motive power, may create a large electric demand charge in some areas. This may be the case whether the energy is used or not. Also, time-of-day charges could be significant. One concern is the high voltage, 240 to 480 V, required for the furnace infrared heaters. This may create safety problems in small plants, where workers are unaccustomed to high voltage equipment.

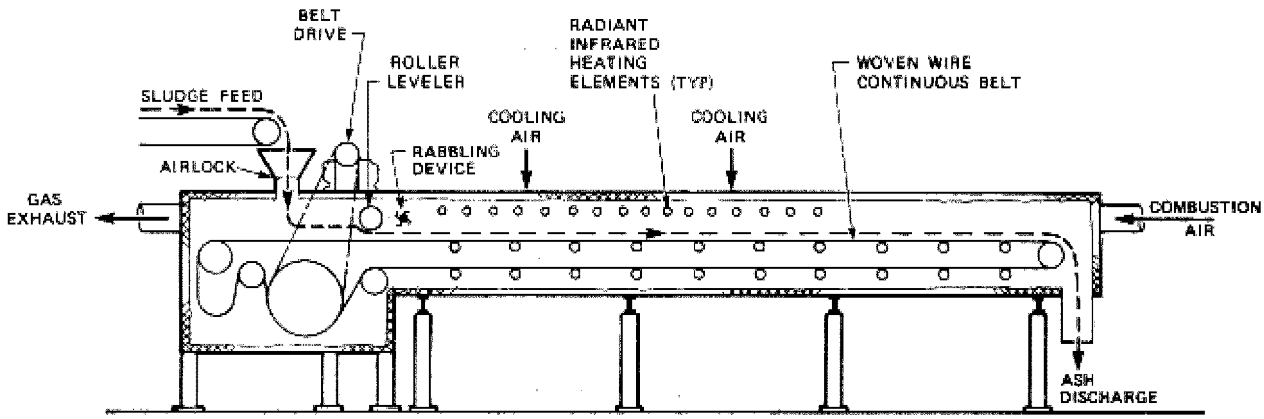


FIGURE 11-21

CROSS SECTION OF AN ELECTRIC INFRARED FURNACE

Because the gas flow in an EF runs countercurrent to the sludge flow, the furnace will probably require an afterburner to comply with strict carbonyl and hydrocarbon emission regulations. This would increase the supplemental energy requirement, the amount of equipment, and the capital and operating costs to levels greater than those shown in Table 11-12. Allowing for the low excess air requirements and the countercurrent flow pattern, air emission control equipment would generally be smaller than control equipment on MHF or FBF units of similar feed capacity.

11.3.4 Single Hearth Cyclonic Furnace

Cyclonic furnaces were developed by the British (64), and several units are operating in Great Britain. However, as of 1979, there are no units processing wastewater sludge in the United States. The cyclonic furnace is sometimes called a single-rotary hearth furnace. It is a vertical, cylindrical, refractory-lined, steel shell, normally provided with a domed cover. There is one rotating hearth and a fixed plow that moves the combustible material from the outer edge of the hearth to the center. The furnaces are currently available with hearths to 30 feet (9.1 m) in diameter, but larger sizes can be built. The sludge is fed by a screw feeder and deposited near the periphery of the rotating hearth. A sectional view of the furnace is given on Figure 11-23.

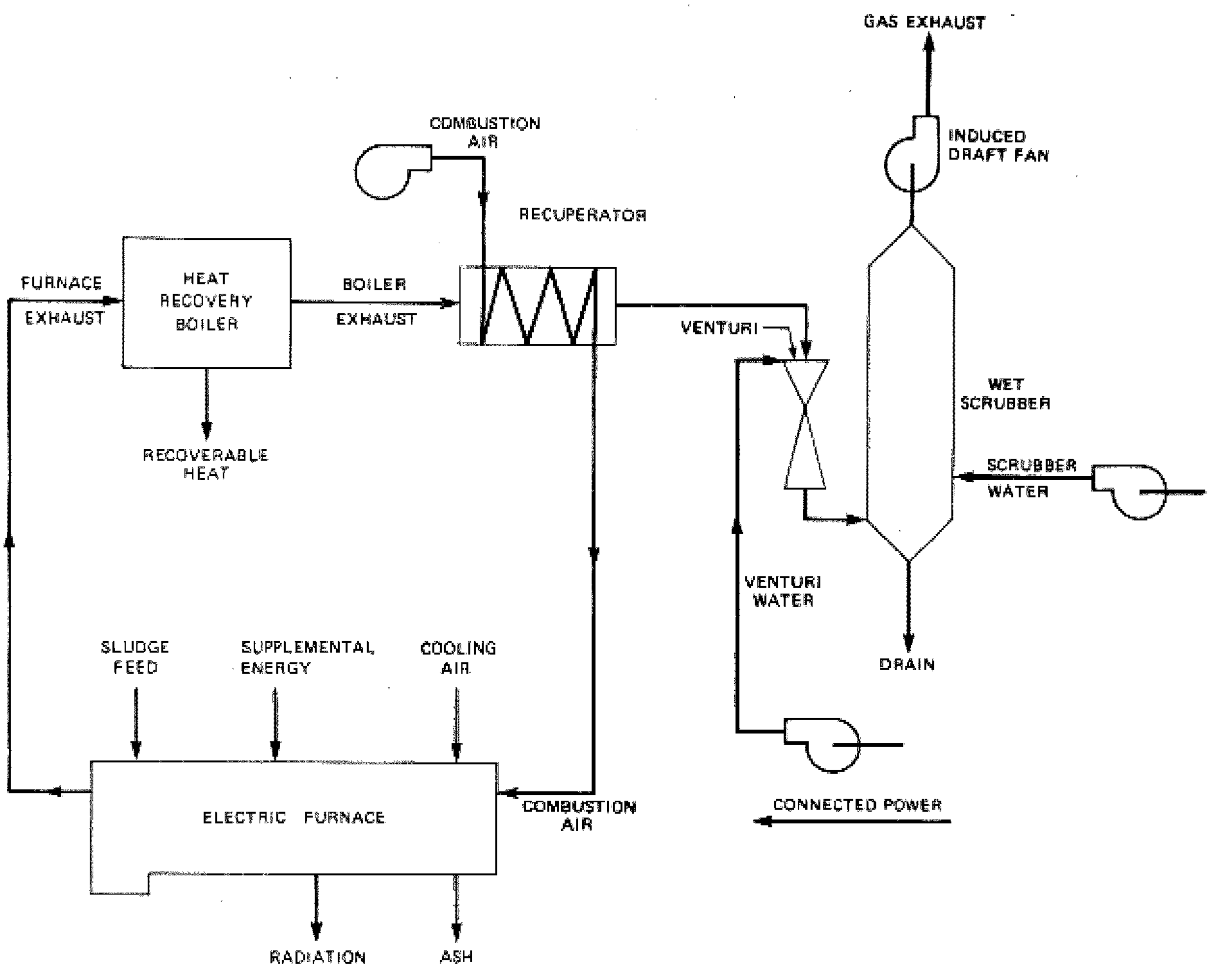


FIGURE 11-22

FLOWSHEET FOR SLUDGE INCINERATION IN AN ELECTRIC INFRARED FURNACE

The cyclonic furnace design differs from the multiple-hearth and fluid bed designs in that it does not allow the combustion air to pass upward through the feed material. Combustion air and supplemental fuel, if required, are injected tangentially into the combustion chamber above the rotating hearth. This creates a swirling (cyclonic) action that mixes the gases and allows adequate contact between the oxygen and the furnace feed. The gases from the combustion process spiral upward to the outlet. The furnace exhaust temperature is approximately 1,500°F (816°C). Heat could be recovered from the exhaust with a heat recovery boiler followed by a recuperator. The ash is moved to the middle of the hearth, where it drops through to a quench tank for final disposal. The rotating hearth is sealed at the edges by a water bath.

TABLE 11-12

HEAT AND MATERIAL BALANCE FOR SLUDGE INCINERATION IN AN ELECTRIC INFRARED FURNACE[a]

	Alternatives						
Stream	IA 5 MGD 20 percent solids	IB 5 MGD 40 percent solids	IIA 15 MGD 20 percent solids	IIB 15 MGD 40 percent solids	IIIA 50 MGD 20 percent solids	IIIB 50 MGD 40 percent solids	1 MGD 40 percent solids
Furnace design							
Number of units	2	1	2	1	3	2	1
Overall width, ft	8.5	8.5	9.5	9.5	9.5	8.5	6
Overall length, ft	72	72	88	88	96	88	32
Belt area/furnace, sq ft	382.6	382.6	560.5	560.5	616.8	479.5	94.5
Loading rate, lb wet solids/sq ft/hr[b]	11.8	13.9	12.1	14.3	11.6	13.2	11.3
Sludge feed							
Lb dry solids/hr	1,806	2,131[c]	2,713	3,201[c]	4,292	5,064[c]	427
Heat value, 10^6 Btu/hr	13.91	13.91	20.89	20.89	33.06	33.06	2.79
Volatile solids, percent dry solids	77	65	77	65	77	65	65
Water, lb/hr	7,224	3,200	10,582	4,800	17,172	7,596	641
Heat value, 10^6 Btu/hr	0.28	0.12	0.41	0.18	0.65	0.29	0.02
Supplemental power[d]							
Electric infrared, kW	280.8	0	402.5	0	643.8	0	0
Heat value, 10^6 Btu/hr	2.98[e]	0	4.27[e]	0	6.82[e]	0	0
Combustion air							
Mass at 60°F, lb/hr	17,736	24,786	26,676	37,184	42,161	58,844	4,962
Heat value, 10^6 Btu/hr	0.26	0.36	0.38	0.54	0.61	0.85	0.07
Ash							
Mass at 500°F, lb/hr	415	747	624	1,120	987	1,772	149
Heat value, 10^6 Btu/hr	0.10	0.18	0.16	0.28	0.24	0.44	0.04
Radiation							
Heat loss, 10^6 Btu/hr	.36	.18	.47	.24	.77	.43	.07
Furnace exhaust							
Mass, lb/hr	26,351[f]	29,372[g]	39,616[f]	44,064[g]	62,628[f]	69,732[g]	5,880[g]
Heat value, 10^6 Btu/hr	14.95	14.03	22.42	21.09	34.54	33.34	2.70
Boiler exhaust							
Heat value at 500°F, 10^6 Btu/hr	13.00	8.53	19.49	12.79	31.33	20.23	1.71
Recoverable heat							
70 percent efficiency, 10^6 Btu/hr	1.37	3.85	2.05	5.81	2.25	9.18	0.69
Scrubber water feed							
Flow, at 70°F, gpm	397	201	584	314	1,049	498	201
Scrubber drain							
Flow, gpm	390	196	606	306	1,081	485	196
Temperature, °F	120	120	120	120	120	120	150
Gas exhaust							
Mass, lb/hr	29,538	35,811	39,616	53,838	54,744	85,186	7,183
Temperature, °F	120	120	120	120	120	120	120
Heat value, 10^6 Btu/hr	1.98	2.77	2.96	4.18	4.71	6.57	0.55
Total connected power							
Horsepower[h]	22	25	30	40	50	60	7
Total installed cost,[j] thousand dollars	1,000	700	1,300	900	1,500	1,200	300

[a]All data supplied by Shirco, Inc.

[b]Useable (effective) area of belt.

[c]Solids for B alternatives (40 percent solids feed), larger than A alternatives (20 percent solids feed), due to conditioning chemicals. See Table 11-7.

[d]Afterburner not included.

[e]Autogenous with combustion air preheated to 500 °F. kW = 10,600 Btu/hr to allow for generation efficiency.

[f]At 750 °F.

[g]At 1,200 °F.

[h]Does not include supplemental power requirements for infrared heaters.

[j]Costs as of early 1978.

1 ft = 0.31 m
1 sq ft = 0.093 m^2
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 MGD = 0.04 m^3/s

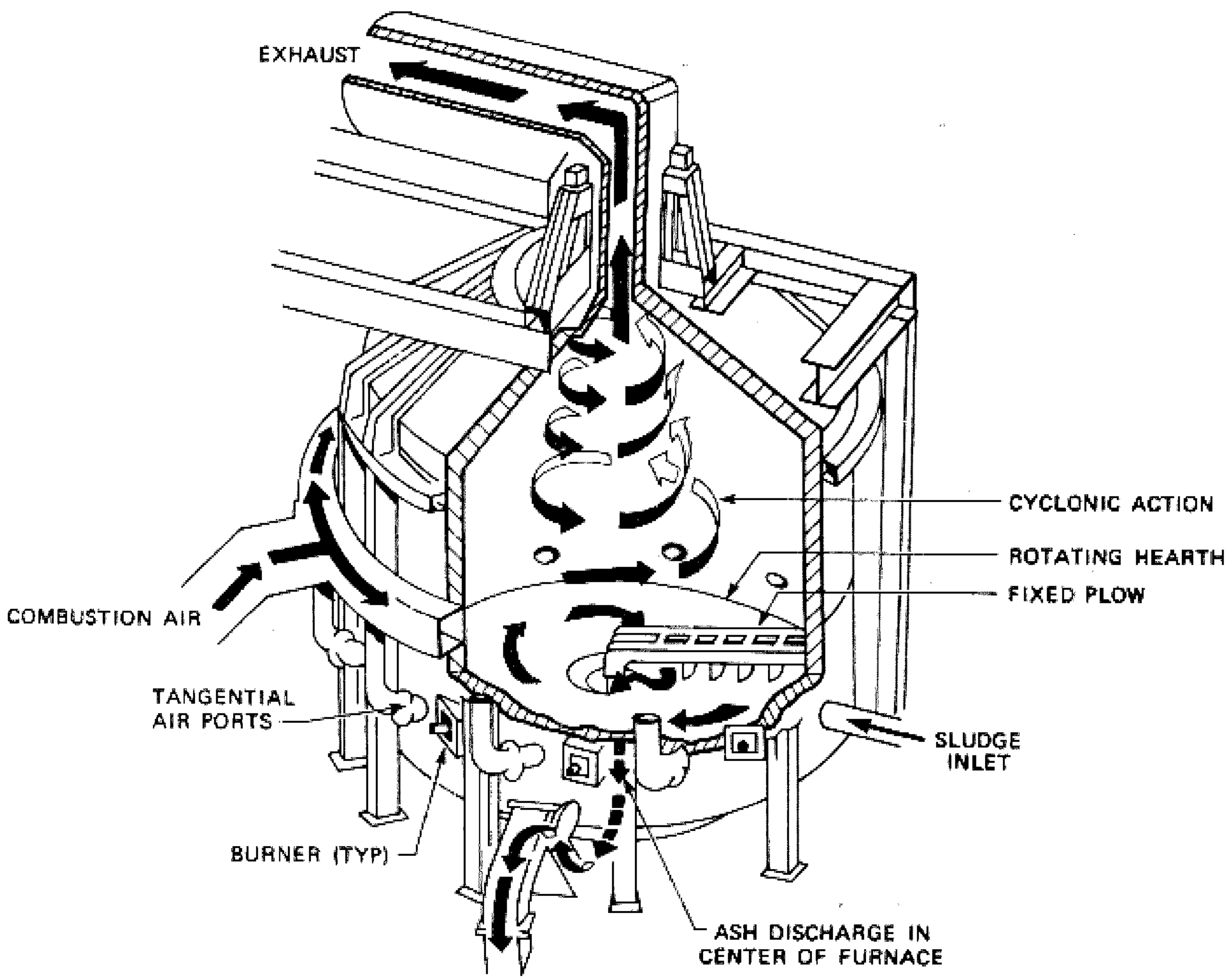


FIGURE 11-23

CROSS SECTION OF A CYCLONIC FURNACE

A general flowsheet for the furnace is given on Figure 11-24. Heat and material balances for the hypothetical treatment plant alternative (Table 11-8) are presented in Table 11-13.

The rotary hearth furnace has a relatively low capital cost and is mechanically simple, since it has only one rotating hearth. However, the feed mechanism is similar to that of the fluid bed furnace and has the same plugging problem. Because exhaust temperatures are high, afterburners or supplemental heaters are generally not required to achieve compliance with strict carbonyl or hydrocarbon air emission regulations. As with the FBF, good operating conditions must be maintained if low gaseous emission limitations are to be met. The rotary hearth furnace requ:res 30 to 80 percent excess air.

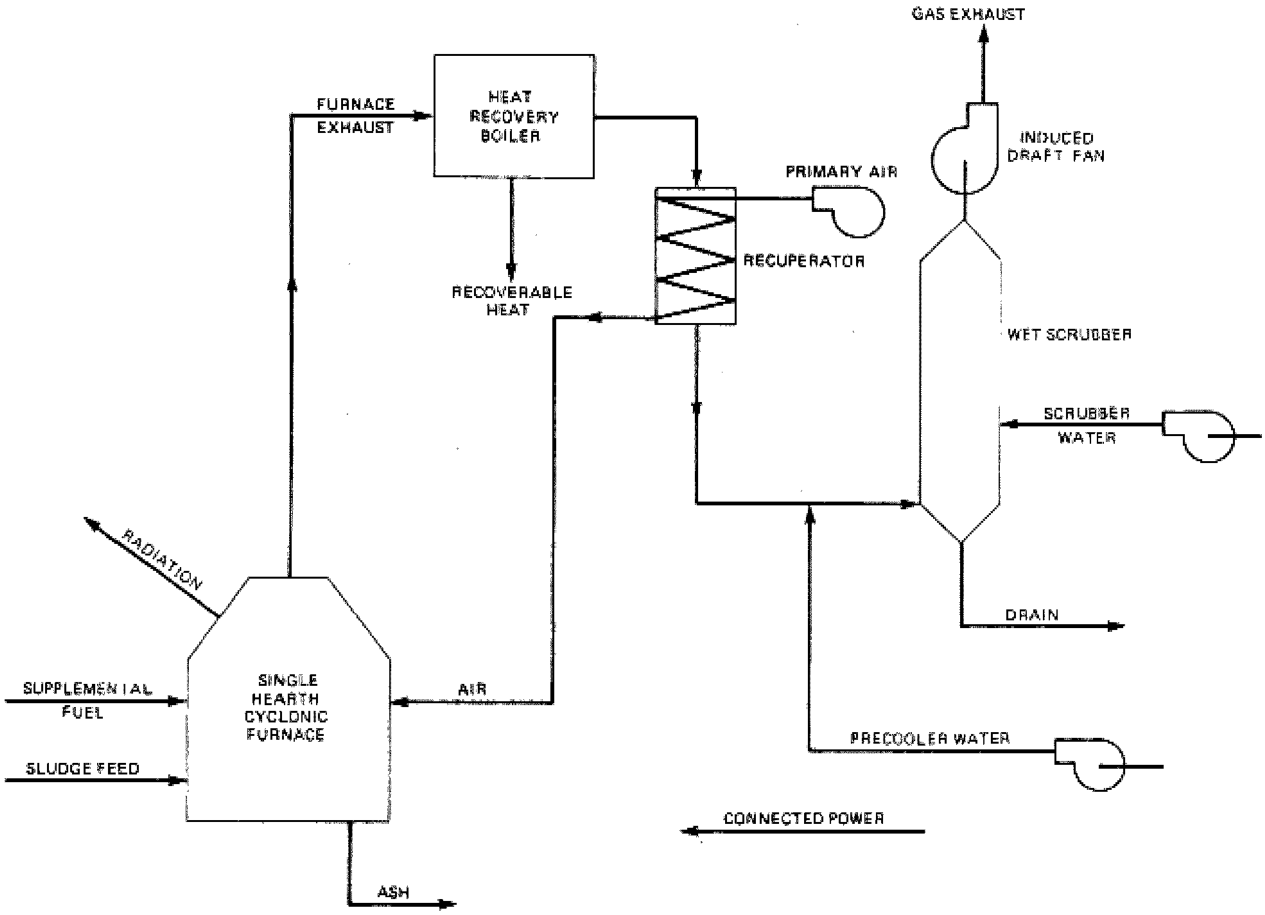


FIGURE 11-24

FLOWSHEET FOR SLUDGE INCINERATION IN A CYCLONIC FURNACE

11.3.5 Design Example: New Sludge Incineration Process

To minimize increasing disposal costs, a municipal wastewater treatment plant with an average daily flow of 5 MGD (0.22 m^3/s) must modify its present solids handling and disposal system. The plant uses a conventional activated sludge process with anaerobic digestion of combined primary sludge, waste-activated sludge, and scum. Table 11-14 shows the basic plant data. The digested sludge is vacuum filtered and is hauled to the local landfill. This landfill is scheduled to close. The new landfill site has somewhat limited capacity and is located several miles from the treatment plant. Projected disposal costs for the new site are very high. The treatment plant site has very little unoccupied space. The area surrounding the plant has been heavily developed by meat packing and rendering operations. These industries discharge large amounts of animal greases and oils to the treatment plant. Naturally, they are concerned about industrial sewer service charges resulting from any action by the plant.

TABLE 11-13

HEAT AND MATERIAL BALANCE FOR SLUDGE INCINERATION IN A CYCLONIC FURNACE[a]

	Alternatives					
Stream	IA 5 MGD 20 percent solids	IB 5 MGD 40 percent solids	IIA 15 MGD 20 percent solids	IIB 15 MGD 40 percent solids	IIIA 50 MGD 20 percent solids	IIIB 50 MGD 40 percent solids
Furnace design						
Diameter, ft	19.50	13.75	24.00	17.00	30.25	21.50
Hearth loading rate, lb wet solids/sq ft/hr	30.4	30.9	30.1	30.1	29.9	29.7
Sludge feed						
Lb dry solids/hr	1,806[b]	1,806[b]	2,713[b]	2,712[b]	4,292[b]	4,292[b]
Heat value, 10^6 Btu/hr	14.27[b]	14.27[b]	21.43[b]	21.43[b]	33.91[b]	33.91[b]
Volatile solids, percent dry solids	77	77[b]	77	77[b]	77	77[b]
Supplemental fuel[c]						
Mass, lb/hr	132	0	184	0	546	0
Heat value, 10^6 Btu/hr	2.48	0	3.46	0	10.28	0
Primary air						
Mass, lb/hr	19,665	19,665	29,519	29,519	46,694	46,694
Temperature, °F	1,100	60	1,100	60	1,100	60
Burner air						
Mass at 60°F, lb/hr	2,280	0	3,178	0	9,430	0
Ash						
Mass at 260°F, lb/hr	415	415	624	624	987	987
Heat value, 10^6 Btu/hr	0.19	0.19	0.29	0.29	0.46	0.46
Radiation						
Heat loss, 10^6 Btu/hr	0.90	0.60	1.17	0.80	2.00	1.00
Waste heat boiler	No	Yes	No	Yes	No	Yes
Recuperator	Yes	No	Yes	No	Yes	No
Furnace exhaust						
Mass, lb/hr	30,692	23,765	45,817	35,675	77,143	57,424
Temperature, °F	1,420	1,411	1,420	1,421	1,420	1,420
Heat value, 10^6 Btu/hr	19.90	13.48	29.75	20.34	50.10	32.38
Boiler/recuperator exhaust						
Temperature, °F	960	500	960	500	960	500
Heat value, 10^6 Btu/hr	15.66	6.87	23.43	10.32	39.45	16.51
Recoverable heat - boiler 70 percent efficiency, 10^6 Btu/hr	0	4.63	0	7.01	0	11.11
Precooler water feed						
Flow at 60°F, gpm	12	5	19	7	30	15
Scrubber water feed						
Flow at 60°F, gpm	292	197	437	296	699	507
Scrubber drain						
Flow, gpm	319	207	477	311	763	535
Temperature, °F	120	110	120	110	120	110
Gas exhaust						
Mass, lb/hr	23,468	21,209	34,969	31,838	62,225	49,002
Temperature, °F	120	110	120	110	120	110
Heat value, 10^6 Btu/hr	1.79	1.62	2.67	2.43	4.75	3.74
Connected power						
Horsepower	175	125	260	190	460	290
Installed cost[f], thousand dollars	1,300	1,000	1,600	1,100	N/A	1,500

[a]All data provided by AFB Engineers/Contractors sole U.S. distributors of the Lucas Cyclonic Furnace.

[b]Data used by manufacturer is slightly different from that developed in Table 11-7.

[c]Afterburners not required.

[d]Not available.

[e]Costs as of early 1978.

1 ft = 0.31 m
1 lb/sq ft/hr = 4.9 kg/m^2/hr
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 MGD = 0.04 m^3/s

Most of the industrial wastes discharged to the plant are removed in the primary tanks, and the result is a combined scum and sludge with an extremely high heating value.

TABLE 11-14

DESIGN EXAMPLE: WASTEWATER TREATMENT PLANT OPERATING DATA

Parameter	Value
Plant flow, MGD	5
Sludge to disposal, lb/day dry basis	10,320
Solids heat value, Btu/lb dry basis	11,000
Volatile solids to digester, percent of dry solids	77
Sludge solids content, percent solids by weight	20
Vacuum filter operation, hr/ week	40

1 MGD = 0.04 m^3/s
1 lb/day = 0.45 kg/day
1 Btu/lb = 2,324 MJ/kg

11.3.5.1 Approach

A consultant was hired to evaluate several disposal methods, including land disposal, composting, heat treatment, combustion, and continuation of landfill disposal. Combustion was identified as the most cost-effective solution. The high energy content of the sludge and the limited available land for sludge disposal influenced this decision. The digestion step was eliminated from the design so that the full heat value of the sludge could be used in combustion. It was expected that this would obviate the need for any supplemental fuel. The existing digesters would be converted to sludge thickening/storage units, and the existing vacuum filters would provide an incinerator feed solids content of approximately 20 percent.

At present, the vacuum filter operates 6 to 8 hours a day, 5 days per week. Because of the limited plant area, no space is available for filter cake holding facilities. Therefore, the furnace will be designed to operate in conjunction with the vacuum filters. A review of the various furnace systems indicated that because of the high heating value of the sludge, the intermittent operation requirements, and the space limitations, a fluid bed system would be the most cost- and energy-effective solution.

11.3.5.2 Preliminary Design

Fluid bed furnace manufacturers were provided the data in Table 11-15 for analysis and development of heat and material balances. Table 11-16 and Figure 11-25 show all sizing criteria, as well as the requirements for peripheral equipment. On the basis of this and additional data, a 15-foot (4.6 m) diameter fluid bed furnace was specified. A recuperator to recover the heat in the exhaust gas and return it to the furnace (hot wind box design) was included.

TABLE 11-15

DESIGN EXAMPLE: SLUDGE FURNACE DESIGN CRITERIA

Parameter	Value
Sludge feed	
Solids content, percent by weight	20
Volatile solids content, percent of dry solids	77
Heat value, Btu/lb of dry solids	11,000
Furnace operation, hr/week	40
Average solids loading rate, lb/hr, dry basis	1,810

1 Btu/lb = 2,324 MJ/kg
1 lb/hr = 0.45 kg/hr

Detailed design of the complete system actually begins with the data provided by the furnace manufacturer. More than one manufacturer should be consulted for design data. Air emissions must be estimated and these estimates submitted to local, state, and federal authorities in order to obtain a permit to construct. Because of the small orifices in the venturi scrubber, potable makeup water at 5 gpm (0.3 l/s) is required. The impingement scrubber water flow of 397 gpm (24 l/s), 0.6 MGD (0.03 m^3/s), will be secondary effluent. Note that the scrubber water flow is 12 percent of the average plant flow and approximately 25 percent of the plant's minimum flow. Because this return flow is expected to be of low BOD and of high SS, it will be returned to a point upstream of

TABLE 11-16

DESIGN EXAMPLE: HEAT AND MATERIAL BALANCE FOR A FLUID BED FURNACE[a]

Stream, unit	Value
Furnace design	
Inside diameter, ft	15.0
Loading rate, lb wet solids/ sq ft/hr	51.2
Sludge feed	
Lb dry solids/hr	1,810
Heat value, 10^6 Btu/hr	19.91
Volatile solids, percent of dry solids	77
Supplemental fuel	0
Combustion air	
Mass, lb/hr	22,950
Heat value, 10^6 Btu/hr	5.40
Ash	
Mass, lb dry solids/hr	416
Heat value, 10^6 Btu/hr	0.12
Water flow, gpm	20
Radiation	
Heat loss, 10^6 Btu/hr	1.27
Furnace exhaust	
Temperature, °F	1,400
Recoverable heat	
70 percent efficiency, 10^6 Btu/hr	4.2
Recuperator	Yes
Venturi water	
Recycle water, gpm	94
Makeup water at 70 °F, gpm	5
Scrubber water feed	
Flow at 70 °F, gpm	397
Scrubber water drain	
Flow at 130 °F, gpm	410
Gas exhaust	
Volume, cfm at 120°F	6,162
Connected power, hp	240
Startup fuel requirements	
Weekday operation, 16-hr shutdown, 10^6 Btu/hr	0
Monday morning operation, 64-hr shutdown, 10^6 Btu/hr	0.42[c]

[a]Data supplied by Dorr-Oliver, Inc.

[b]At 1,400 °F.

[c]Fuel required:
- 1 hr on Saturday.
- 1 hr on Sunday.
- 1/2 hr on Monday morning.

1 ft = 0.30 m
1 lb/sq ft/hr = 4.89 kg/m^2/hr
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 cfm = 4.7 x 10^{-4} m^3/s
1 gpm = 0.06 l/s

the aeration tank (see Chapter 16). The temperature of the sidestream, 130°F (54°C), was not considered to have an adverse effect on the secondary process.

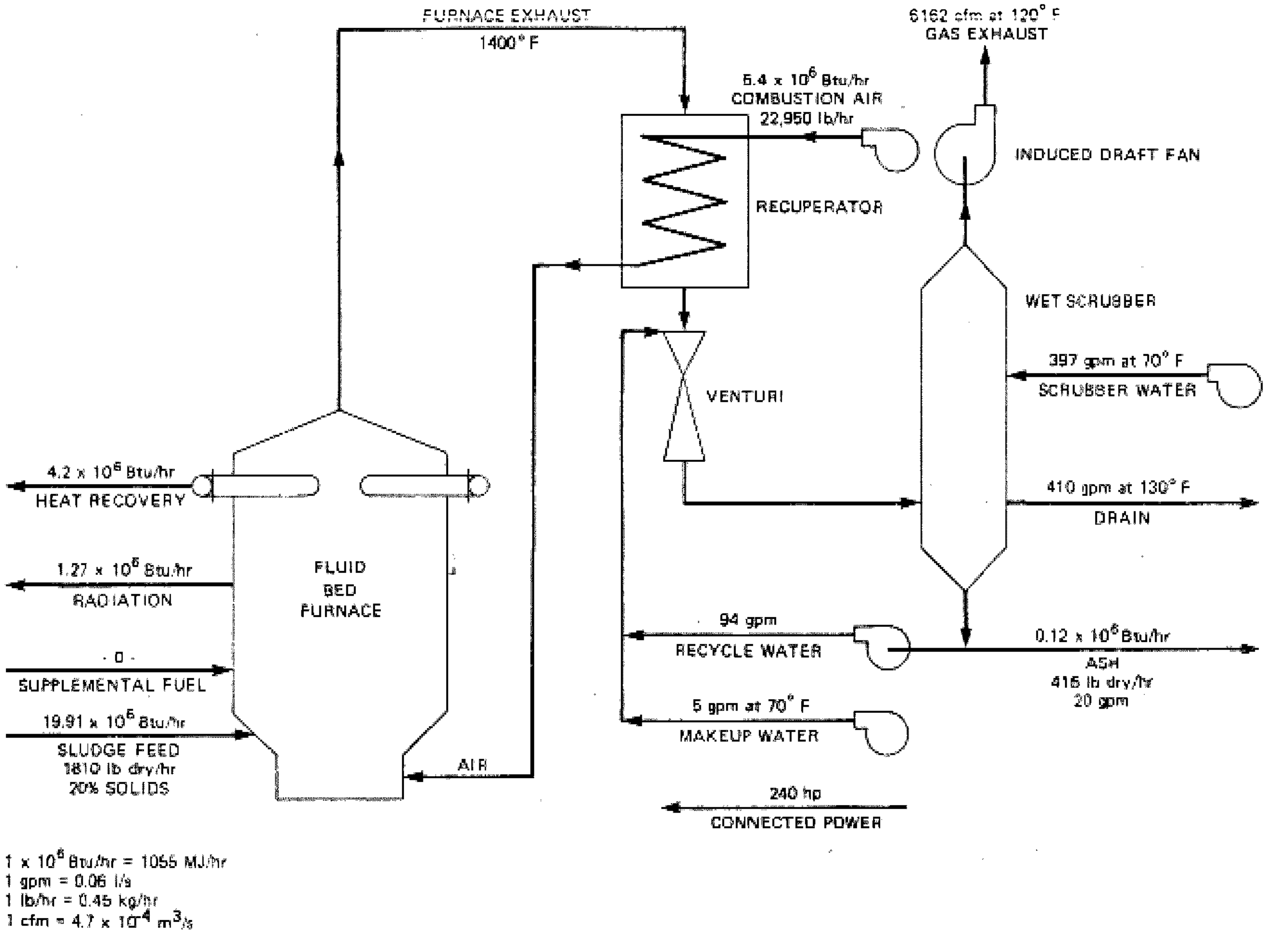


FIGURE 11-25

DESIGN EXAMPLE: HEAT AND MATERIAL BALANCE IN A FLUID BED FURNACE

Contracts for disposing of the wet ash must be established. Methods for transporting the ash slurry, conveying it to trucks at the plant site, and discharging it from the trucks at the disposal site must be investigated and designed.

Options for using available excess heat should also be examined. As shown in Table 11-16, 4.2×10^6 Btu per hour (4.4 GJ/hr) are available for use. However, heat is available only intermittently and not necessarily at the time it is most needed. Another approach is to transfer the heat to hot water tanks and use the heated water for space heating. Alternatively, the heat can be utilized in an absorption refrigeration unit to produce chilled water. This water can be stored and used to satisfy subsequent space cooling demands.

Other design considerations to be investigated include but are not limited to:

- Ash dewatering methods
- Ash hauling by owner or by separate contractor
- Type of auxiliary equipment such as sludge conveyors, fans, and feed equipment
- Heat recovery methods
- Electrical distribution
- Control philosophy
- Sophistication of instrumentation and control
- Supplemental fuel availability and storage (for start-up and problem periods)
- Area clearance, including access platforms
- Furnace housing requirements
- Structural requirements, for example, seismic and wind factors
- Noise levels and other safety requirements
- Heating, ventilating, and cooling the area near the furnace
- Spare parts
- Level and quality of staffing

These points relate only to the installed system. An important consideration is the interfacing of the existing plant with the construction of the furnace. All systems and details relating to the furnace should be discussed with the furnace manufacturer and, in some cases, made the responsibility of the manufacturer. For example, the combustion air fans, the recuperator (if used), the heat recovery boiler (if used), scrubbers, and some or all of the controls should be part of the total contract.

11.4 Starved-Air Combustion

Starved-air combustion (SAC) has been demonstrated to be an effective method for burning sludge in a furnace (17-20,22,24, 26,29,30). Strict air quality standards can be met with SAC, and large amounts of supplemental fuel are not required.

The key to SAC is the use of less than theoretical quantities of air in the furnace--30 to 90 percent of stoichiometric requirements. This makes SAC more fuel-efficient than incineration in an MHF. This is shown on Figure 11-26. When a SAC-MHF is combined with an afterburner, an overall excess air rate of 25 to 50 percent can be maintained, as compared to an excess air rate of 75 to 200 percent for multiple-hearth incinerator with an afterburner.

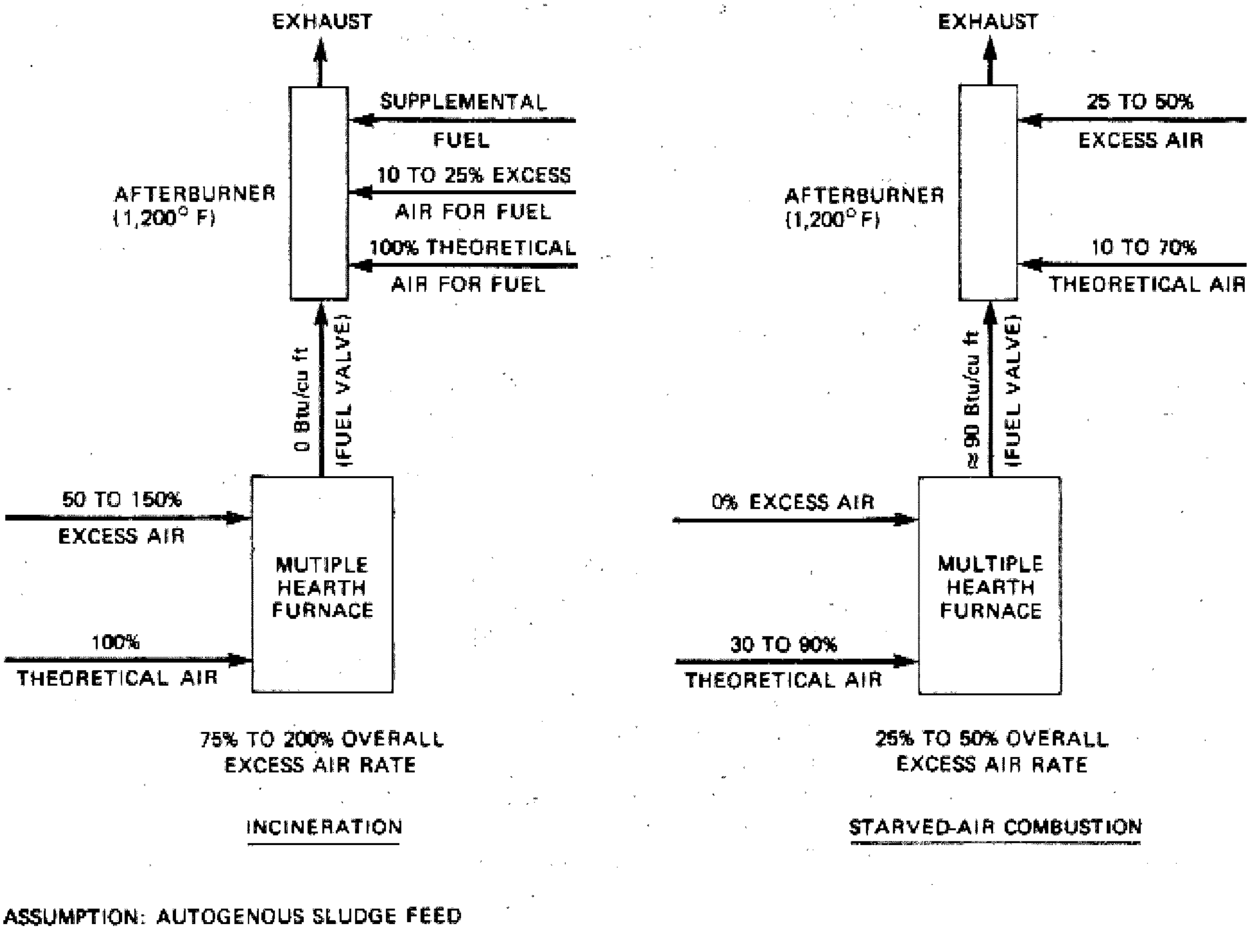


FIGURE 11-26

COMPARISON OF EXCESS AIR REQUIREMENTS: INCINERATION IN A MULTIPLE-HEARTH FURNACE VS. STARVED-AIR COMBUSTION

SAC is, in effect, incomplete combustion. The reaction products are combustible gases, tars, and oils, and a solid char that can have an appreciable heating value. The relative proportion of each varies with the amount of heat applied and the feed moisture. Generally, higher reaction temperatures yield simpler products and greater quantities of low heating value gas. This is at the expense of combustible solid products (25).

The low heating value gases may be burned, and the heat generated can be recovered and used beneficially. Alternatively, the gas may be cooled and stored for subsequent off-site use. The most effective utilization appears to be the burning of the total gas stream, with subsequent recovery of portions of the heat generated. Off-site use appears to be impractical because:

- The gas fuel value is low. Thus, delivery of any significant quantity of energy requires the transport of very large volumes of gas.
- Cooling of the gas for off-site use would result in permanent loss of much of its heat content.
- The condensates (tars, oils) produced when the gas is cooled are high strength and corrosive. Containing the condensates and disposing of them are significant problems.
- The condensates themselves have significant heat values. The heating values of the gas is diminshed when condensates are removed.

In full-scale test work (17), the SAC combustible exhaust gas was found to have a heating value of 90 Btu/standard dry cubic foot (3.4 MJ/m^3). The gas contained hydrogen, carbon monoxide, carbon dioxide, methane, ethylene, butane, nitrogen, oxygen, water, and some higher hydrocarbons.

SAC ash may contain combustible material; the amount depends upon furnace operation. SAC reduces sludge to an ash containing from 3 to 30 percent combustibles, including up to 20 percent fixed (elemental) carbon. More combustibles can be released to the gas stream by adding more air, oxygen, or steam to the lower part of the furnace. This has the advantage of transferring part of the heat in the residue to the gas stream. However, the transfer leaves the residue depleted in heat value. In some circumstances, it may be better not to burn out the residue completely. Conceivably, char could be used as an adsorbent or as a filter aid for sludge conditioning prior to dewatering.

The operating temperature of the furnace can be controlled within a wide range. The lower temperature limit is the point when the rate of decomposition of high molecular weight organic compounds becomes too low, about 1,300°F (704°C). The upper temperature limit is defined by the point at which there is ash melting or damage to refractories, about 1,800°F (982°C) (22). One temperature consideration is that vaporization of heavy metals must be minimized, since it is difficult to remove heavy metals from the gas stream with conventional scrubbing equipment. It is therefore preferable to burn the sludge at as low a temperature as possible. Full-scale test work (17) and other published data (18,19, and 20) indicate that 1,500°F (816°C) appears to be a reasonable operating temperature for minimum heavy metal vaporization.

Fluid bed, electric, and cyclonic furnaces could also be operated in a SAC mode. To date, none has been operated in this manner with a sludge feed. Operation in a SAC mode is particularly well suited to the MHF. There appears to be little incentive to operate the FBF in this mode because (1) excess air rates for SAC and the FBF are about the same, and (2) an afterburner would be required for a converted MHF whereas afterburning is not needed where the FBF is used in the incineration mode. Several types of furnaces, including an FBF (21), have been operated in the starved-air combustion mode on wood wastes to produce charcoal.

11.4.1 Development and Application

Starved-air combustion of sludge, and/or refuse-derived fuel, was successfully demonstrated in a full-scale test at the Central Contra Costa Sanitary District's wastewater treatment plant in Concord, California (17). The use of refuse-derived fuel is discussed in Section 11-5. The furnace and an afterburner were operated at 1,400°F (760°C) without supplemental fuel addition. The feed was primary and trickling filter sludge from a mostly domestic wastewater. The combined sludge had a heating value of 9,000 Btu per pound (20.9 MJ/kg) of combustible solids, a combustible solids content of 75 percent, and a feed sludge solids concentration of 24 percent (17). The Concord SAC reactor was a converted six-hearth, 16-foot 9-inch (5.1 m) diameter MHF. Dewatered sludge was burned by using approximately 50 percent of the theoretical air requirement, and an exhaust gas was produced with a heating value of 90 Btu per standard dry cubic foot (3,353 MJ/m^3). All of the exhaust gas was burned in an afterburner at 1,400°F (760°C). The resulting SAC ash contained 30 percent combustibles, of which 20 percent were fixed carbon. Other important results and conclusions of this two-month SAC test program were:

- Starved-air combustion was easier to control than incineration (the furnace was also run in an incineration mode).
- Hearth temperature could be used to control the furnace, with air addition as the manipulated variable.
- Air addition to the furnace should be automatically controlled.
- Particulate production per pound of solids fed was about 50 percent lower than conventional incineration.
- The completeness of the reaction depends upon the amount of air fed, not on temperature.
- The most corrosion resistant alloys for high temperature conditions were Type HK stainless steel and Inconel 690. For low temperature conditions the most corrosion resistant alloys were Hastelloy C-176 and Inconel 625.

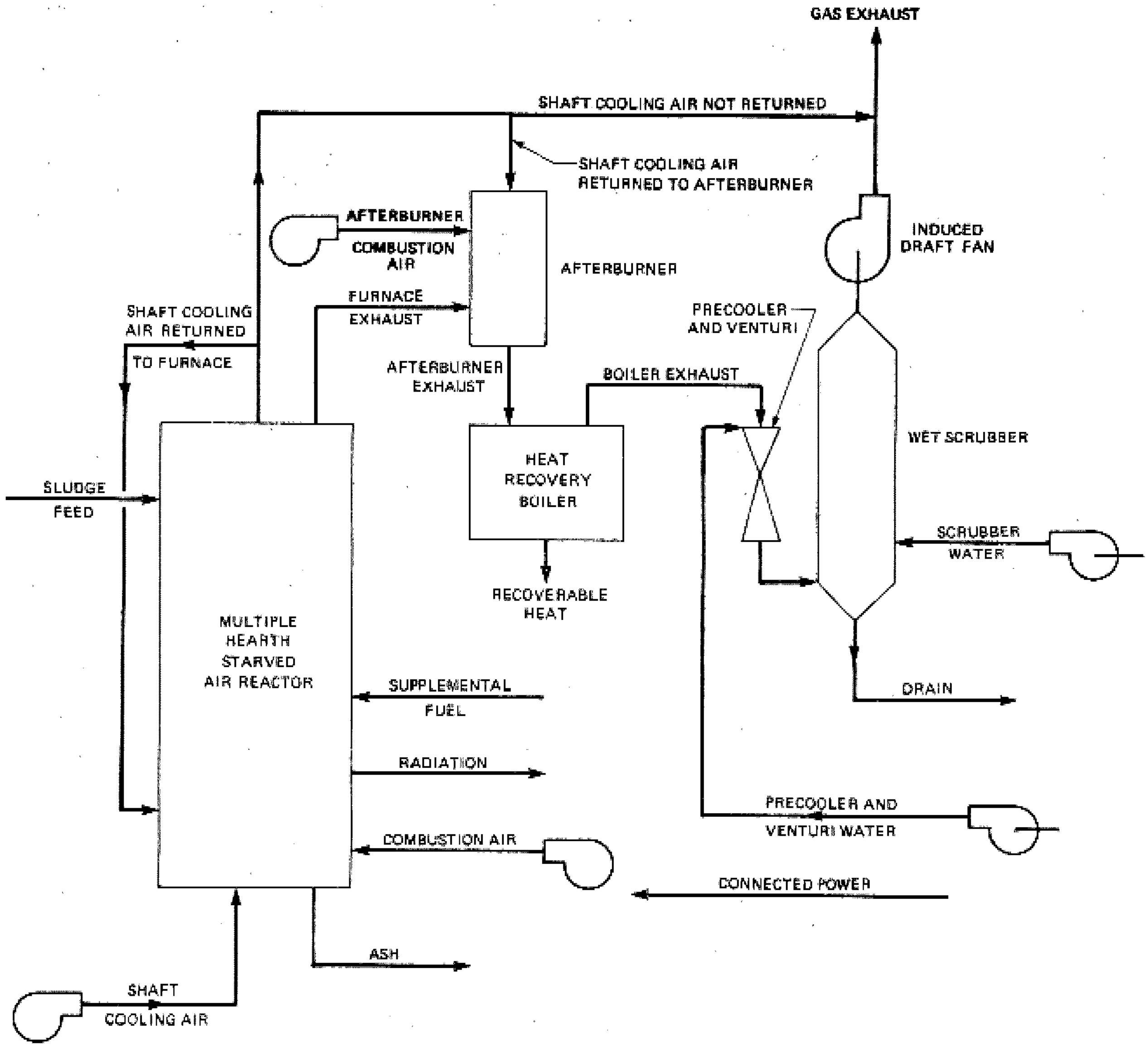


FIGURE 11-27

FLOWSHEET FOR STARVED-AIR COMBUSTION IN A MULTIPLE-HEARTH FURNACE

A flowsheet for an MHF operated as a SAC reactor is provided in Figure 11-27. Comparison with Figure 11-9 shows the difference to be the addition of an afterburner. Heat and material balances for the hypothetical treatment plant alternatives (Table 11-8) are presented in Table 11-17. Table 11-18 takes selected data from the heat and material balances previously presented to permit direct comparison of SAC with incineration options. Direct comparisons are made for an autogenous sludge, and feed rates to all systems are identical except for that to the cyclonic furnace. SAC appears to have an advantage overall

TABLE 11-17

HEAT AND MATERIAL BALANCE FOR STARVED-AIR COMBUSTION OF SLUDGE IN A MULTIPLE-HEARTH FURNACE[a]

Stream	Alternative (all 40 percent solids)		
	IB 5 MGD	IIB 15 MGD	IIIB 50 MGD
Furnace design			
Diameter, ft-in.	12-9	14-3	16-9
Number of hearths	6	7	8
Hearth loading rate, lb wet solids/sq ft/hr	12.1	12.0	11.4
Sludge feed			
Lb dry solids/hr	2,131	3,201	5,064
Heat value, 10^6 Btu/hr	7.35	10.73	16.90
Volatile solids, percent dry solids	65	65	65
Supplemental fuel	0	0	0
Combustion air			
Mass, lb/hr	0[b]	780[b]	1,500[b]
Temperature, °F	0	60	60
Shaft cooling air			
Mass, lb/hr	9,178	10,095	15,602
Shaft cooling air return			
Mass at 350 °F, lb/hr	6,480	8,640	13,380
Shaft cooling air to stack			
Mass at 325 °F, lb/hr	0	0	0
Shaft cooling air to afterburner			
Mass at 350 °F, lb/hr	2,698	1,455	2,222
Ash			
Mass, lb/hr	787	1,181	1,869
Temperature, °F	500	500	500
Heat value, 10^6 Btu/hr	0.23	0.34	0.54
Radiation			
Heat loss, 10^6 Btu/hr	0.44	0.62	0.94
Furnace exhaust			
Mass at 800 °F, lb/hr	11,010	16,250	25,658
Heat value, 10^6 Btu/hr	6.82	10.16	16.05
Afterburner combustion air			
Mass at 60 °F, lb/hr	4,382[c]	8,805[c]	14,098[c]
Afterburner exhaust			
Mass, lb/hr	17,368	26,537	42,041
Temperature, °F	1,495	1,495	1,495
Heat value, 10^6 Btu/hr	12.76	19.18	30.04
Boiler exhaust			
Heat value at 500 °F, 10^6 Btu/hr	6.76	9.18	13.04
Recoverable heat			
70 percent efficiency, 10^6 Btu/hr	4.2	7.0	11.9

[a]All data supplied by the manufacturer.

[b]In addition to shaft cooling air returned to furnace.

[c]In addition to shaft cooling air returned to afterburner.

[d]Costs as of early 1978.

1 ft = 0.30 m
1 in. = 0.02 m
1 lb/sq ft/hr = 4.9 kg/m^2/hr

1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 MGD = 0.044 m^3/s

TABLE 11-17

HEAT AND MATERIAL BALANCE FOR STARVED-AIR COMBUSTION OF SLUDGE IN A MULTIPLE-HEARTH FURNACE[a] (Continued)

Stream	Alternative (all 40 percent solids) IB 5 MGD	IIB 15 MGD	IIIB 50 MGD
Precooler and Venturi water feed			
Flow at 70 °F, gpm	51	77	121
Scrubber water feed			
Flow at 70 °F, gpm	102	153	243
Scrubber drain			
Flow, gpm	160	240	380
Temperature, °F	98	98	98
Gas exhaust			
Mass, lb/hr	14,280	21,480	34,080
Temperature, °F	120	120	120
Heat value, 10^6 Btu/hr	4.62	5.96	7.94
Connected power			
Horsepower	78	123	218
Installed cost, thousand dollars[d]	1,400	1,600	2,300

[a]All data supplied by the manufacturer.
[b]In addition to shaft cooling air returned to furnace.
[c]In addition to shaft cooling air returned to afterburner.
[d]Costs as of early 1978.

1 ft = 0.30 m
1 in. = 0.02 m
1 lb/sq ft/hr = 4.9 kg/m^2/hr
1 lb/hr = 0.45 kg/hr

1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 MGD = 0.044 m^3/s

but the FBF in terms of air required, as indicated by lesser exhaust flow rates. SAC has less connected horsepower than the other options, and except for the FBF, higher exhaust temperatures and thus, greater potential for energy recovery.

Additional details of the test work and SAC application can be found in the literature (8,17-30,65,66,67). Additional information can also be gained by working with the furnace manufacturers.

11.4.2 Advantages and Disadvantages of SAC

Test work, much of which is still underway, shows that SAC in an MHF using sludge alone has many advantages over incineration or other combustion processes.

TABLE 11-18

HEAT AND MATERIAL BALANCE COMPARISON OF STARVED-AIR COMBUSTION AND INCINERATION

Item	Multiple-hearth incinerator[a]	Fluid bed furnace[b]	Electric furnace[c]	Cyclonic furnace[d]	Starved-air combustion - multiple hearth[e]
Alternative IA					
Sludge feed, lb dry solids/hr	1,806	1,806	1,806	1,806	-
Supplemental fuel, 10^6 Btu/hr	2.64	2.80	2.98[f]	2.48	-
Furnace exhaust					
Mass, lb/hr	30,817	19,353	26,351	30,692	-
Temperature, °F	800	1,400	750	1,420	-
Recoverable heat 70 percent efficiency, 10^6 Btu/hr	1.89	3.50	1.37	2.97[g]	-
Connected power Horsepower	238	218	22[h]	175	-
Alternative IB					
Sludge feed, lb dry solids/hr	2,131	2,131	2,131	1,806[i]	2,131
Supplemental fuel, 10^6 Btu/hr	0	0	0	0	0
Furnace exhaust					
Mass, lb/hr	32,123	16,250	29,372	23,765	17,638
Temperature, °F	1,000	1,650	1,200	1,411	1,495
Recoverable heat 70 percent efficiency, 10^6 Btu/hr	2.31	6.2	3.85	4.63	4.20
Connected power Horsepower	93	162	25[h]	125	78
Alternative IIB					
Sludge feed, lb dry solids/hr	3,201	3,201	3,201	2,712	3,201
Supplemental fuel, 10^6 Btu/hr	0	0	0	0	0
Furnace exhaust					
Mass, lb/hr	48,434	23,576	44,064	35,675	26,537
Temperature, °F	1,000	1,650	1,200	1,421	1,495
Recoverable heat 70 percent efficiency, 10^6 Btu/hr	5.04	9.40	5.81	7.01	7.00
Connected power Horsepower	178	234	40[h]	190	123
Alternative IIIB					
Sludge feed, lb dry solids/hr	5,064	5,064	5,064	4,292	5,064
Supplemental fuel, 10^6 Btu/hr	0	0	0	0	0
Furnace exhaust					
Mass, lb/hr	77,643	38,620	69,732	57,424	42,041
Temperature, °F	1,000	1,650	1,200	1,420	1,495
Recoverable heat 70 percent efficiency, 10^6 Btu/hr	8.05	12.7	9.18	11.11	11.90
Connected power Horsepower	238	350	60[h]	290	218

[a] See Table 11-9.
[b] See Table 11-11.
[c] See Table 11-12.
[d] See Table 11-13.
[e] See Table 11-17.
[f] Infrared heaters (kW = 10,600 Btu to allow for generating efficiency).
[g] Recuperator only.
[h] Does not include power requirements for infrared heaters.
[i] Based data used by manufacturer is different from that for other furnaces.

1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr

The SAC process provides a greater solids throughput because of the higher allowable hearth loading rates. (This assumes that a portion of the combustibles remain in the ash.) Operation of a multiple-hearth furnace with SAC permits hearth loading rates 30 to 50 percent higher than an optimum incineration mode. This can be explained in terms of heat release and gas velocity, although other factors also affect loading rate. In incineration, the heat liberated in the furnace by combustion of the feed solids must be limited to prevent high-temperature damage to the furnace refractories. Under SAC, heat liberation is minimized in the furnace by air control with combustibles passing out in a gas form to an auxiliary combustion chamber, or afterburner. The afterburner which has no moving mechanical parts, can be designed for the high temperatures. Thus, with the two-stage combustion process which occurs under SAC, high furnace temperature is not a limiting condition. Gas velocity is another factor which affects hearth loading rate. An excessive gas velocity entrains large quantities of solids particles in the furnace, leading to gas cleanup difficulties. With SAC, considerably less air is used in the furnace than with incineration, and this can be traded-off against the increased volume of combustible gases created by higher hearth loading rates. Therefore, for a fixed maximum gas velocity, a greater hearth loading rate can be applied with SAC than with incineration.

A second advantage offered by SAC is reduced fuel usage when afterburning is required. Even when it is possible to dewater the sludge feed to an autogenous state, (eliminating the need for supplemental fuel to the furnace), a considerable quantity of fossil fuel is still required for the afterburner in an incineration mode. Essentially no fuel is required for the afterburner in an SAC mode.

SAC offers more stable operation and ease of control, with minimal furnace response to feed changes. With incineration, increasing or decreasing the feed rate results in a corresponding rise or fall in hearth temperature since the solids combustion rate increases or decreases. With SAC, the extent of the heat-generating combustion reactions are limited by the available oxygen supply. Fluctuations in feed rate will not change the temperature level because it does not change the amount of combustion occurring, provided air rate does not change.

A fourth advantage of SAC over incineration is that it produces fewer air emissions. SAC's lower furnace gas velocity, for the same solids loading rate, results in less particle entrainment and reduced particulate emissions. During full-scale tests at Concord, particulate production with SAC was about 50 percent less than incineration under equal solids feed conditions (17, 18). Furthermore, particulates leaving the furnace were larger than those from incineration. These particulates are more easily removed by cyclones or other simple gas cleanup equipment. At Concord, nitrogen oxide and sulfur oxide emissions also appeared to be lower with SAC. It is probable that when organic nitrogen is oxidized, one of the reaction products is nitrogen oxides. The reaction is illustrated for NO:

$$\text{Organic-N} + O_2 \longrightarrow NO + H_2O$$

Thus, incineration of sludge, which contains a fairly large organic nitrogen fraction, produces nitrogen oxides. When organic nitrogen is subjected to SAC, however, little organic-N is converted to nitrogen oxide because little oxygen is available. The organic nitrogen is instead converted to ammonia. The ammonia, when oxidized (for example, in the afterburner) is converted to nitrogen gas and water.

$$4NH_3 + 3O_2 \longrightarrow 2N_2 + 6H_2O$$

As long as afterburner temperatures are maintained below approximately 1,600°F (871°C), conversion of N_2 to nitrogen oxide is also minimized. Thus, the key to lower nitrogen oxide production with SAC appears to be its ability to direct organic nitrogen destruction toward ammonia formation, rather than to oxide formation.

Data supporting the observation of low sulfur oxide emissions in the Concord tests are limited. Measurements indicate that much of the sulfur in the feed solids ends up in the ash (17). With incineration, most of the feed sulfur is delivered to the stack.

Other advantages of SAC include the fact that essentially all equipment needed is currently available and has a long performance history, and that most existing MHFs can be easily retrofitted to operate in a SAC mode.

Disadvantages of SAC should also be considered in design. The afterburner requirement can limit use of SAC in existing installations for several reasons. The afterburner is normally a large chamber, and space may not be available. Floor loadings of existing buildings can easily be exceeded by a large refractory-lined device. Supplemental fuel and air must be supplied to the afterburner, requiring additional space for piping and equipment.

A second disadvantage is that SAC requires more instrumentation than does incineration. Proper control is essential for good SAC operation; therefore, temperature controllers must be included on each hearth to control air feed rate. Draft and other common incinerator instrumentation must also be provided and maintained.

If for some reason the furnace exhaust gases have to bypass the afterburner, they may create emission violations. Furnace exhaust gases are high in pollutants, such as hydrocarbons and other noxious products of incomplete combustion. They could flare in the atmosphere, causing stack damage. Also, these gases are corrosive. All construction materials in the gas stream must be properly selected, as described previously. Corrosion results found at the full-scale test in Concord, California, are found in the literature (17).

Additionally, combustibles in the SAC ash may create ultimate disposal problems. For example, in a landfill, they may not be as inert as incinerator ash.

11.4.3 Conversion of Existing Multiple-Hearth Incineration Units to SAC

One of the greatest advantages of SAC is that most existing units can be converted to operate as SAC reactors. This retrofitting involves relatively few changes. The costs and benefits are site-specific. One definite incentive for conversion is that the existing unit may be able to handle increased sludge loads without the addition of more incinerators. This incentive is demonstrated in a design example presented later in this section. Assuming an increase in solids loading of approximately 30 percent, the basic changes necessary are:

CHANGE	REASON
Add an afterburner (if existing system has an afterburner, its size may have to be increased). If furnace is large enough, top hearth may be used as an afterburner; however, refractories must be examined.	Required to burn combustible fuel gas prior to exhaust.
Add combustion air flow control and temperature controllers.	Required to control SAC process.
Possibly replace combustion air fan.	May be required to control reduced air flow rate.
Modify induced draft fan--may need change only in speed or damper position.	Required because total unit, including afterburner, uses approximately 50 percent excess air, while an MHF incinerator uses, including afterburner, 75 to 200 percent excess air. See Figure 11-26.

CHANGE	REASON
Review and modify venturi and wet scrubber.	Required to maintain high performance with lower air flows. Also may need precooler section if boiler is not in process train.
Add additional emission control equipment.	Required depending upon local air emission control regulations regarding applicability of new source performance standards. Modification of process may change applicable standards.
Review furnace system and and replace remote instrumentation.	Good practice for any major process revision.
Generally "tighten up" furnace system.	SAC process depends on good air control. Peak and poke holes must be modified along with other openings into the furnace to reduce uncontrolled air leakage into the furnace.

With these modifications and any others found necessary during the review of the site-specific system, the retrofitted MHF system will be suitable for SAC operation.

11.4.4 Design Example: Retrofit of an Existing Multiple-Hearth Sludge Incinerator to a Starved-Air Combustion Reactor

A 20-MGD (0.88-m^3/s) domestic wastewater treatment plant in the Midwest has been incinerating primary and waste-activated sludge in two multiple-hearth furnaces. All sludge is thickened prior to dewatering on vacuum filters that produce a 25 percent solids feed cake. Polymers are used in the vacuum filters. The ash from the furnaces is sluiced to ash holding ponds, and the supernatant is recovered and returned to the plant influent sewer. Stabilized ash is removed from the ponds at least once a year and hauled to the local landfill.

One furnace is normally required for sludge reduction; however, the original design provided 100 percent redundancy. The plant is currently overloaded and both multiple-hearth furnaces are used simultaneously about three months of the year.

Substantial growth in wastewater flows are anticipated in the next four years. Planning for an 10-MGD ($0.44\text{-}m^3/s$) expansion is currently underway. The design will handle projected flows through 1988. In addition, new air emission regulations were recently promulgated limiting hydrocarbon, carbonyl, and carbon monoxide emissions to about half of the current incinerator emissions. The city has been given notice to correct this situation or be subject to fines levied by the local air quality management district (AQMD). A time extension to review and correct this problem has been granted to the city. Data for the existing plant are shown in Table 11-19

TABLE 11-19

DESIGN EXAMPLE: WASTEWATER TREATMENT PLANT OPERATING DATA

Parameter	Value
Plant operating conditions	
Design flow, MGD	20
Total solids, lb/day dry basis	40,800
Volatile solids, percent of dry solids	75
Furnace operating conditions	
Operating hours/week	168
Loading rate, lb/hr dry basis	1,700
Solids content of feed, percent dry weight	25
Loading rate, lb/hr wet basis	6,800

1 MGD = 0.044 m^3/s
1 lb/day = 0.45 kg/kg
1 lb/hr = 0.45 kg/hr

11.4.4.1 Approach

The city retained a consultant to prepare a facilities plan/ project report to obtain Construction Grants funding for a plant expansion to 30-MGD ($1.32\text{-}m^3/s$). Because of the urgency of the air emissions problem, the city authorized the hiring of air pollution experts to assist the consultant in developing an interim plan consistent with the goals of the expansion.

Following several detailed design estimates, afterburning at 1,200°F (649°C) for one-half second was determined to be the most cost-effective solution. This approach was also felt to guarantee a continuous and dependable operation while satisfying all regulations.

Since afterburning was proposed, it was also decided to study SAC. SAC could possibly increase existing furnace capacity and/or reduce the equipment to be added. Prior to review of SAC, it was determined that, in the incineration mode, each furnace would require an afterburner, and that a new furnace and afterburner would be required for the plant expansion to 30-MGD (1.32-m^3/s).

11.4.4.2 Preliminary Design

Two experienced multiple-hearth furnace manufacturers were provided the data in Table 11-19. Detailed heat and material balances were developed for incineration and starved-air combustion--both followed by external afterburning. The schemes used the existing vacuum filters to provide a feed cake of 25 percent solids. Also, each manufacturer was to analyze two additional cases that entailed use of improved dewatering equipment to produce a feed cake solids content of 35 percent. Both of these cases used SAC, but one had an external afterburner and the second used the top hearth of the present furnace as the afterburner. The manufacturers were asked to use the existing furnace to determine the capacity of each of the four systems. The cases considered were as follows:

Case I — Add an external afterburner and heat recovery boiler to each furnace. One additional furnace is required to satisfy future loading.

Case II — Convert existing furnaces to SAC. Add an external afterburner and heat recovery boiler to each furnace. One additional furnace is required to satisfy future loading.

Case III — Convert existing furnaces to SAC. Add an external afterburner and heat recovery boiler to each furnace. Sludge feed rate calculated using allowable rates for SAC with improved dewatering equipment (35 percent solids). Note that afterburner temperature is 1,430°F (777°C). No additional furnaces required for future loading.

Case IV — Convert existing furnaces to SAC and use top hearth as an afterburner. Add a heat recovery boiler to each furnace. Sludge feed rate calculated from allowable rates for SAC with improved dewatering equipment (35 percent solids) and desired afterburner temperature of 1,200°F (649°C). No additional furnaces are required for future loading.

Table 11-20 shows a summary of the manufacturer's calculations for the four cases and the existing condition. An interesting comparison can be made between Cases I and II. Both cases use an afterburner and recover heat but Case II utilizes SAC. Heat recovery gains by using SAC are impressive. The city would save 1.33 x 10^6 Btu per hour (1.40 GJ/hr) by using SAC, which would produce an annual fuel savings of slightly

TABLE 11-20

DESIGN EXAMPLE: HEAT AND MATERIAL BALANCES FOR MULTIPLE-HEARTH FURNACES

	Existing condition	Case I	Case II	Case III	Case IV
Type of operation	Incinerator	Modified incinerator	SAC[b]	SAC[b]	SAC[b]
Furnace design					
Number of furnaces	2	3[c]	3[c]	2[c]	2[c]
Diameter, ft-in.	16-9	16-9	16-9	16-9	16-9
Number of hearths	7	7	7	7	7[d]
Hearth loading rate, lb wet solids/sq ft/hr	7.0	7.0	7.0	10.2	10.2
Afterburner	None	External	External	External	Internal (top hearth)
Sludge feed					
Lb dry solids/hr	1,700	1,700	1,700	3,473	2,957
Heat value, 10^6 Btu/hr	12.75	12.75	12.75	26.05	22.18
Volatile solids, percent dry solids	75	75	75	75	75
Feed solids, percent	25	25	25	35	35
Afterburner supplemental fuel					
Mass, lb/hr	N.A.	189	128	0	0
Heat value, 10^6 Btu/hr	N.A.	3.77	2.44	0	0
Furnace combustion air					
Mass at 60 °F, lb/hr	17,833	17,833	9,822	12,507	9,867
Shaft cooling air					
Mass, lb/hr	15,939	15,939	15,939	15,939	15,939
Shaft cooling air return to furnace					
Mass at 350 °F, lb/hr	13,548	13,548	9,840	12,480	9,867
Shaft cooling air to stack					
Mass at 350 °F, lb/hr	2,391	2,391	5,919	0	0
Heat value, 10^6 Btu/hr	0.35	0.35	1.09	0	0
Shaft cooling air to afterburner					
Mass at 350 °F, Btu/hr	N.A.	0	180	3,660	6,072
Ash					
Mass, lb/hr	425	425	478[e]	975[e]	866[e]
Heat value, 10^6 Btu/hr	0.04	0.04	0.14	0.28	0.25
Radiation					
Heat loss, 10^6 Btu/hr	0.29	0.29	0.29	0.29	0.29

N.A. - Not applicable.

[a] All data supplied by the manufacturer.
[b] SAC - Starved-air combustion.
[c] Number of furnaces required in 1988 (30 MGD), for increased sludge quantities with one furnace on standby.
[d] Note, top hearth is afterburner, therefore, not included in hearth loading calculations.
[e] Includes combustible heat content.
[f] Existing system does not include boiler.

1 ft = 0.30 m
1 in. = 0.02 m
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 MGD = 0.044 m^3/s

TABLE 11-20

DESIGN EXAMPLE: HEAT AND MATERIAL BALANCES FOR MULTIPLE-HEARTH FURNACES (Continued)

	Existing condition	Case I	Case II	Case III	Case IV
Type of operation	Incinerator	Modified incinerator	SAC[b]	SAC[b]	SAC[b]
Furnace exhaust					
Mass at 800 °F, lb/hr	24,209	24,209	16,145	21,454	17,448
Heat value, 10^6 Btu/hr	12.07	12.07	11.23	14.87	10.55
Afterburner combustion air					
Mass at 60°F, lb/hr	N.A.	2,555	4,296	11,534	10,989
Afterburner exhaust					
Mass, lb/hr	N.A.	26,764	19,366	32,987	28,437
Temperature, °F	N.A.	1,200	1,200	1,430	1,200
Heat value, 10^6 Btu/hr	N.A.	15.84	14.05	24.24	21.64
Boiler exhaust					
Heat value at 400 °F, 10^6 Btu/hr	N.A.	9.51	8.78	13.92	12.89
Recoverable heat					
70 percent efficiency, 10^6 Btu/hr	2.24[f]	4.43	3.69	7.22	6.13
Precooler and Venturi water feed					
Flow at 70 °F, gpm	51	51	45	65	65
Scrubber water feed					
Flow at 70° F, gpm	243	243	282	456	456
Scrubber drain					
Flow, gpm	306	306	338	536	532
Gas exhaust					
Mass, lb/hr	21,368	20,759	15,480	26,220	27,837
Temperature, °F	120	120	120	120	120
Heat value, 10^6 Btu/hr	6.35	7.53	4.11	8.52	2.64

N.A. - Not applicable.

[a]All data supplied by the manufacturer.

[b]SAC - Starved-air combustion.

[c]Number of furnaces required in 1988 (30 MGD), for increased sludge quantities with one furnace on standby.

[d]Note, top hearth is afterburner, therefore, not included in hearth loading calculations.

[e]Includes combustible heat content.

[f]Existing system does not include boiler.

1 ft = 0.30 m
1 in. = 0.02 m
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr
1 gpm = 0.06 l/s
1 MGD = 0.044 m^3/s

over $30,000 at $2.70 per 10^6 Btu ($2.60 per GJ). However, it appears that this savings would not justify the conversion when compared with the large capital expenditure.

Cases III and IV both use SAC, but start with a cake that has been dewatered to 35 percent solids. Recoverable heat quantities are far higher than for Cases I and II. Case IV, which does not use an external afterburner has a capital cost advantage over Case III. Also, the system could easily handle the expected sludge loads through the design year. The fuel savings would be almost $90,000 per year, and the energy generated would be sufficient to save another $250,000 per year (at 10,600 Btu/kWhr [11.18 MJ/kWhr] and $0.05/kWhr). These savings alone would justify capital expenditures of over $3,600,000 (20 years at 7 percent per year). In addition, there would be a capital savings because a third furnace would not be required.

After receiving detailed cost estimates, the city authorized the Case IV design. The flowsheet is given on Figure 11-28.

11.5 Co-Combustion of Sludge and Other Material

The net fuel value of sludge depends on the fraction of its total combustible solids, the fuel value of those combustible solids (generally about 10,000 Btu per pound [23.24 MJ/kg]), and the amount of water present. Wastewater treatment plant sludge generally has a high water content and, in some cases, fairly high levels of inert materials. As a result, its net fuel value is often low. Autogenous combustion of wastewater treatment plant sludge is generally only possible when the sludge solids content is 30 to 35 percent or greater. These solids contents are often difficult to achieve by conventional dewatering techniques; consequently, supplemental fuel is required for the combustion operation. If sludge is combined with other combustible materials in a co-combustion scheme, a furnace feed can be created that has both a low water concentration and a heat value high enough to sustain autogenous combustion and may be cost-effective.

11.5.1 Co-Combustion with Coal and Other Residuals

Many materials can be combined with sewage sludge to create a furnace feed with a higher heat value than sludge. Some of these materials are coal; municipal solid waste; wood wastes; sawdust; textile wastes; and agricultural wastes, such as corn stalks, rice husks, and bagasse (68, 69). Virtually any material that can be burned can be combined with sludge in a co-combustion process. An advantage of co-combustion is that a municipal or industrial waste material can often be disposed of while providing an autogenous sludge feed, thereby solving two disposal problems.

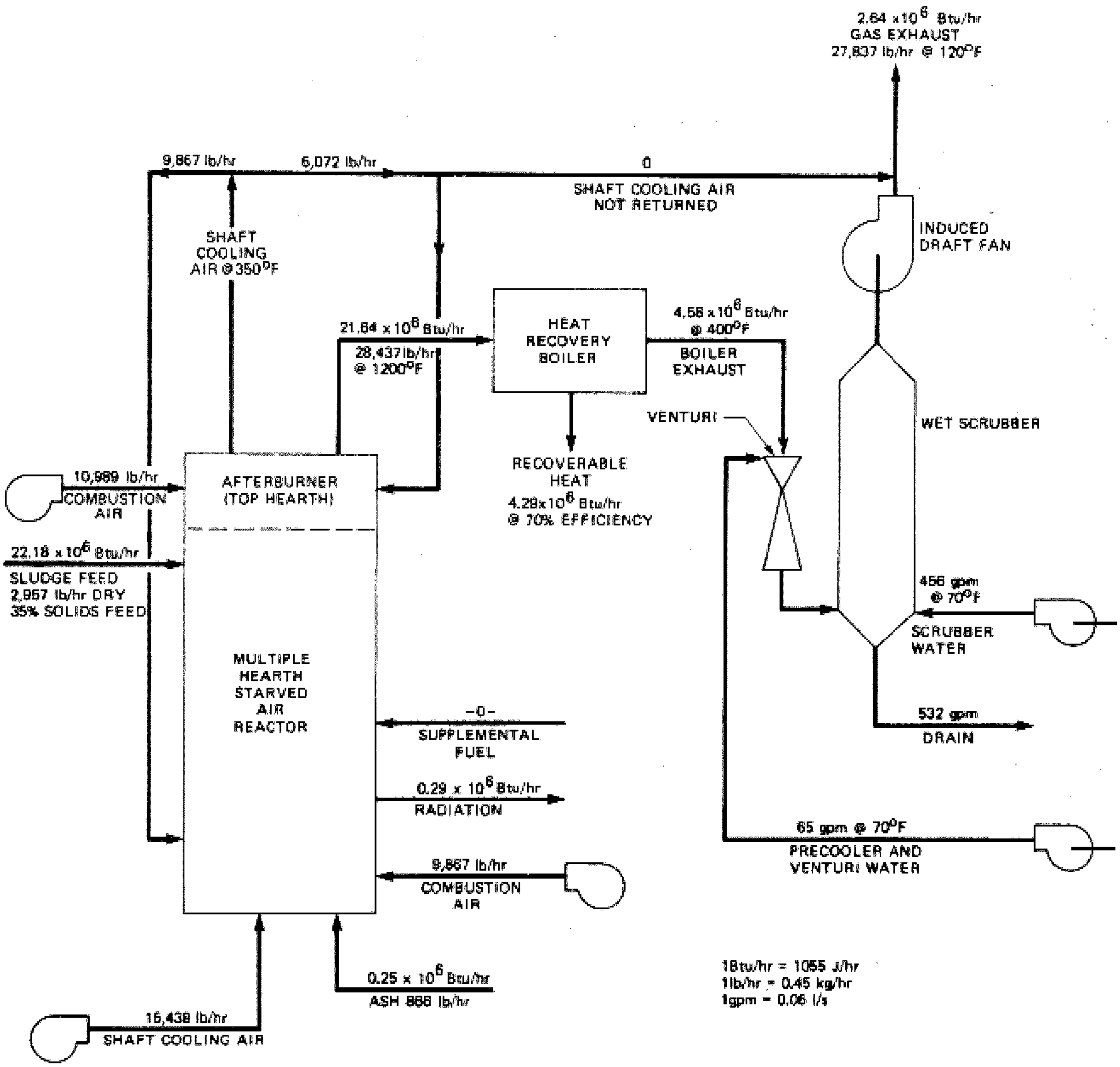


FIGURE 11-28

DESIGN EXAMPLE: STARVED-AIR COMBUSTION IN A MULTIPLE-HEARTH FURNACE

Recent studies have shown that the addition of pulverized coal to liquid sludge prior to dewatering can markedly increase the cake solids content (70-73). A drier filter cake is produced; thus, the net heat value of the sludge-coal mix is much greater than if the coal were added to the filter cake following filtration. Also, the sludge-coal mix is homogenous, which leads to better combustion. It may be possible to reduce the amounts of inorganic filter aids (lime, ferric chloride) required and produce an autogenous feed. This approach may become appropriate in many plants that are close to coal mines or coal-fired power stations. Coal, however, is not a waste material, and its use to improve filtration and increase the fuel value of the furnace feed is not as desirable as using a combustible waste for these purposes. Two plants, one in Rochester, New York, and an other in Vancouver, Washington, are experimenting with sawdust as a filter aid prior to combustion. The results to date have been very good, but detailed data are not available. Minneapolis has tried using woodchips as a supplemental fuel (70).

11.5.2 Co-Combustion with Mixed Municipal Refuse (MMR)

Currently there are more than twenty sludge and mixed municipal refuse (MMR) co-combustion systems, including incineration, pyrolysis, and starved-air combustion, that are being operated, tested, or demonstrated in full-scale plants (74-77). The systems described in this section have been operated at full-scale and have been developed sufficiently to be implemented whenever they prove cost-effective.

There are two basic approaches to co-combustion of sludge with MMR: (a) use of refuse combustion technology by adding dewatered or dried sludge to an MMR combustion unit, and (b) use of sludge combustion technology by adding raw or processed MMR as a supplemental fuel to the sludge furnace. Table 11-21 illustrates the commonly used approaches to co-combustion.

TABLE 11-21

CONVENTIONAL APPROACHES TO CO-COMBUSTION OF WASTEWATER SLUDGE AND MIXED MUNICIPAL REFUSE

Mixed municipal refuse technology

- Grate-fired (refractory or waterwalled)
  - Sludge dried via flue gases
  - Sludge dried via steam from furnace
  - Sludge added directly to furnace
- Vertical packed bed reactors (sludge added to bed)
  - Air (Andco-Torrax)
  - Oxygen (PUROX^{TM}, a Union Carbide System)

Sludge technology

- Multiple-hearth
  - Incineration
  - Starved-air combustion
- Fluid bed

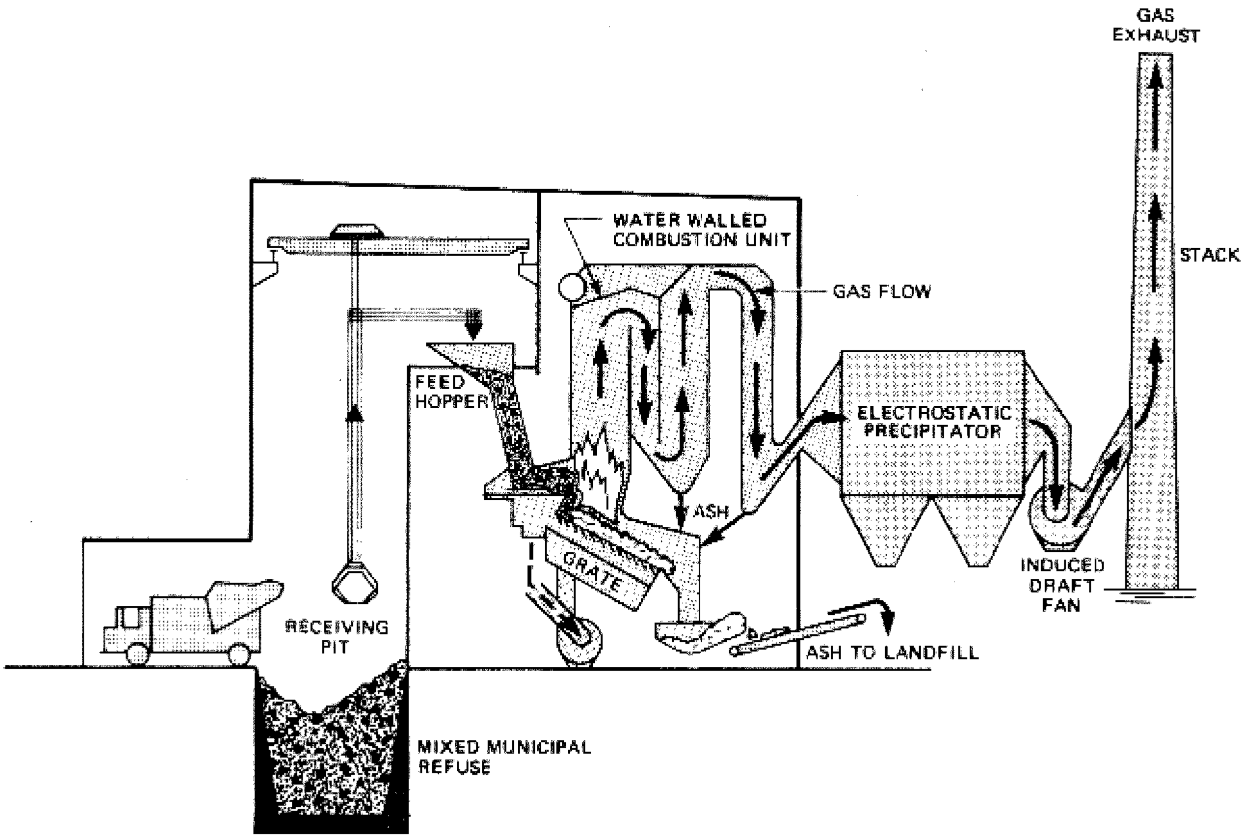


FIGURE 11-29

TYPICAL GRATE-FIRED WATERWALLED COMBUSTION UNIT

11.5.2.1 Refuse Combustion Technology

Historically, grate-fired refractory and waterwalled combustion units have been used to burn raw mixed municipal refuse. Figure 11-29 illustrates this approach. This practice is common throughout Europe, where there are several hundred installations. When sludge disposal became a problem, the first approach was to burn the sludge with the refuse. The quantity of sludge was normally small compared to the refuse. This was attempted in several locations, but efforts were generally unsuccessful, with failures due to the following problems:

- Uniform mixing of sludge and refuse was difficult to accomplish on a large scale. Poorly mixed feeds produced alternate "hot" and "cold" feeds, resulting in erratic furnace operation.

- Biodegradation of materials in the refuse/sludge holding bins caused unacceptable odors. Detention times in these bins are often several days long, which is sufficient for biological action to be established.

- High moisture content of the sludge and inadequate furnace detention times sometimes caused non-autogenous combustion and wet residues.

However, as previously stated, several systems currently in operation have been designed specifically to incinerate MMR with sewage sludge (78). A number of these are described below.

Sludge Drying via Steam Generated by Furnace

Several grate-fired, waterwalled combustion units in Europe are presently incinerating refuse and sewage sludge. At Dieppe, France, 54 tons (49 t) of MMR and 21 tons (19 t) of dried sludge are incinerated daily (79). Digested sludge with a solids content of four percent is pumped from the wastewater treatment plant and dried with 350°F (177°C) process steam in two thin-film evaporators to a solids content of 55 percent. The vapors generated are returned to the furnace. The dried sludge is conveyed to the charging chutes of the furnace and is mixed with the solid waste from the receiving pit. A small plant at Brive, France (80), is similar to that at Dieppe, except that it uses raw sludge.

Sludge Drying via Furnace Flue Gases

A waterwalled combustion unit at the Krefeld plant near Dusseldorf, Germany, processes 600 tons (544 t) of MMR and 45 tons (41 t) of dry wastewater solids daily (75-77,81). The facility generates electricity for the wastewater treatment plant and incineration facility and exports hot water for use in the community. Raw sludge, with a solids content of 5 percent, is pumped from the wastewater treatment plant to the disposal facility. The sludge is centrifuged to a solids content of 25 percent and then flash-dried in a vertical-shaft flash-drying chamber with 1,500°F (816°C) flue gases at from the refuse combustion unit. The powdered sludge is then injected into the furnace immediately above the top of the flame (suspension firing). The facility has been in operation for four years.

Two plants in the United States use flue gases generated in grate-fired, refractory-walled combustion units to dry waste-water solids prior to combustion with MMR (74). In Ansonia, Connecticut, sludge with four percent solids is dried in a disk-type, co-current spray dryer with 1,200°F (649°C) incinerator flue gases. Dried sludge and vapors are injected into the incinerator for suspension burning. The plant capacity is 200 tons (181 t) per day of solid waste. Presently, the sludge is not being incinerated but used as a soil conditioner. Holyoke, Massachusetts, uses a similar incinerator and averages 250 tons (227 t) per week of refuse and 19 tons (17 t) per week of dry sludge throughput. However, the sludge is dewatered to 28 percent solids prior to drying in a rotary unit using hot flue gases. Dried sludge and vapors are added to the furnace above the combustion zone.

Sludge Added Directly to Furnace

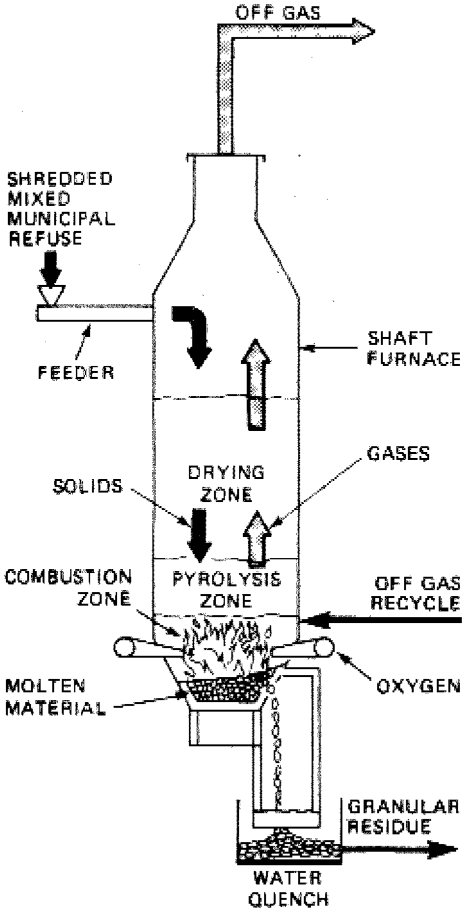
Recently at Norwalk, Connecticut, a process was tested in which a stoker-fired incinerator was used to co-combust sludge and refuse (82,83). In this project, sludge with a solids content of five percent was sprayed onto the front wall of the charging chute to form a thin sludge layer on top of the refuse. The sludge layer dries and burns during the 30-minute residence time in the combustion unit. This process has been incorporated into the design of a plant at Glen Cove, New York, that will burn a mixture of 25 tons (23 t) per day of sludge (20 percent solids content) and 175 tons (159 t) per day of mixed municipal refuse. The plant is designed to produce 2.2 megawatts of power, sufficient to meet the demands of the wastewater treatment plant and the incineration facility. Construction of the Glen Cove facility is scheduled to be completed in 1982.

Vertical Packed Bed

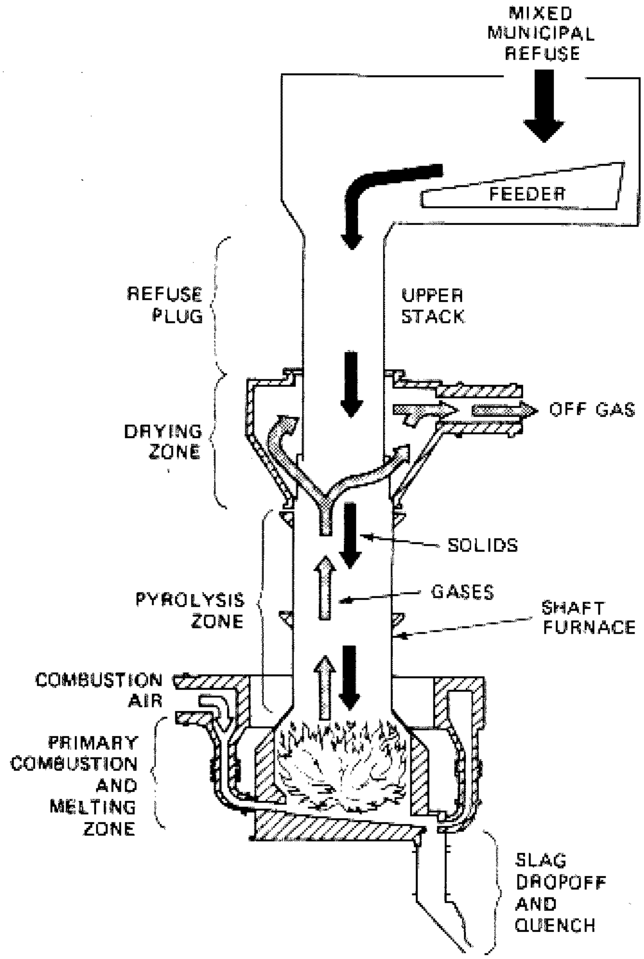
There are two vertical packed bed, solid waste, starved-air combustion systems currently available in the United States: Andco-Torrax and PUROX^tm (see Figure 11-30).

The Andco-Torrax system (84, 85) is a vertical shaft, slagging type furnace in which unprocessed municipal solid waste is charged into the unit from the top. The refuse is burned at the bottom of the ram at 3,000°F (1,649°C) by the addition of small quantities of air heated by countercurrent heat exchange with the afterburner exhaust. The combustible off-gases are afterburned at 2,000°F (1,093°C) and processed by electrostatic precipitators. Wet sludge has been added to an existing 75 ton (68 t) per day system, but detailed test data are not presently available.

The PUROX system, a trademark of Union Carbide, is a vertical furnace for combustion of a processed refuse (86, 87). Processing includes shredding and ferrous metal separation. The PUROX system uses pure oxygen rather than air. The refuse is burned at 3,000°F (1,649°C), and a fuel gas is produced that has a heat value of 385 Btu per standard dry cubic foot 14.3 MJ/m^3 dry). The molten slag produced at the high combustion temperature is primarily inert silica. A processed refuse and sludge mixture was successfully run through the test unit for two months at South Charleston, West Virginia (87). Average wet test feed rates were 90 tons (82 t) per day. Test data indicated that the refuse-to-sludge ratio was 4.26:1. Lower ratios were not tested because the availability of sludge was limited. The pure oxygen feed rate was approximately 0.2 tons of oxygen per ton (0.2 t O_2/t) of feed. Fuel gas production and quality, and slag production and quality from mixed refuse-sludge feeds, did not differ radically from that of pure refuse combustion in the PUROX reactor. Heavy metals in the sludge were trapped in the slag and were not discharged with the exhaust gases.



PUROX[sm] REACTOR
(COURTESY OF UNION CARBIDE CORPORATION)



ANDCO-TORRAX REACTOR
(COURTESY OF ANDCO INCORPORATED)

FIGURE 11-30

VERTICAL SHAFT REACTORS

11.5.2.2 Sludge Combustion Technology

The most widely used sludge combustion methods are the multiple-hearth and fluid bed furnace. Both types of units have successfully burned refuse. Although the electric furnace and the cyclonic furnace appear to be capable of refuse and sludge combustion, no full-scale work has been done to date. Figure 11-31 presents requirements for sustaining autogenous combustion when sludge is mixed with refuse.

Multiple-Hearth Incineration

Several plants in Great Britain and Europe have been practicing co-incineration in multiple-hearth furnaces for several years. However, serious problems such as severe erosion of the hearths, poor temperature control, refractory failures, and air pollution,

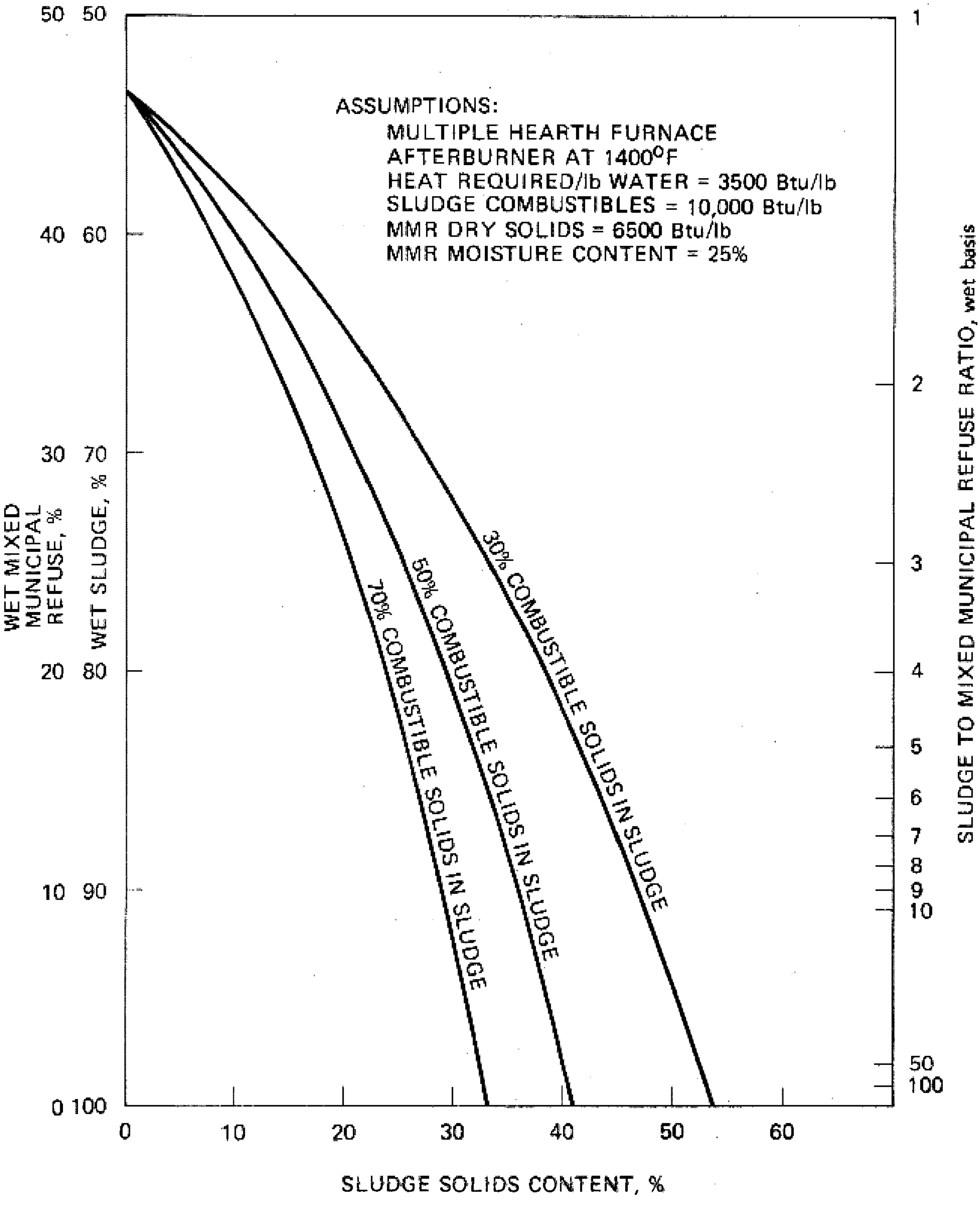


FIGURE 11-31

AUTOGENOUS COMBUSTION REQUIREMENTS FOR CO-DISPOSAL

have been experienced (88). All of these problems appear to be a direct result of poor solid waste processing prior to addition into the furnace. Poor pre-processing causes extreme variations in feed heat value, which in turn causes wide and uncontrollable temperature fluctuations in the furnace. These result in refractory failures and air emission problems.

These problems were resolved in test work conducted at the Central Contra Costa Sanitary District wastewater treatment plant at Concord, California (17). All refuse was shredded, air-classified, and screened prior to use. This provided a feed which was relatively free of metals and had a reasonably consistent heating value, as well as a consistent particle size. When the furnace was operated in an incineration mode, none of the problems encountered in Great Britain or Europe were experienced, but temperature control was still difficult. This was corrected by operating the furnace in a SAC mode. This work and the European experience indicates that for MHF furnaces pre-processing of municipal refuse is required and SAC of refuse and sludge is preferred over MHF incineration.

Multiple-Hearth, Starved-Air Combustion

Co-combustion of sludge with processed municipal solid waste was first successfully performed by SAC in a multiple-hearth furnace during a small-scale test in November 1974 at Burlingame, California (89). A full-scale prototype test was later implemented at Concord, California (17). A flow diagram of the test system is given on Figure 11-32. The test SAC-MHF burned a combination of wastewater sludge and refuse-derived fuel (RDF) in several ratios varying from 100 percent sludge to 100 percent RDF.

Municipal refuse was shredded, air-classified, and screened to produce a refuse-derived fuel. The RDF had a heating value of 7,500 Btu per pound (17.4 MJ/kg) of dry solids and a moisture content of 25 percent. A combined feed rate of up to 10,000 pounds per hour (4,540 kg/hr) was applied to the 6-hearth, 16-foot 9-inch (5.1-m) diameter SAC-MHF. Because of the addition of RDF, the heat value of the feed was greatly increased as compared to sludge alone. This produced a fuel gas heat value averaging 136 Btu per standard dry cubic foot (5.07 MJ/m^3 dry) and afterburner temperatures up to 2,500°F (1,371°C). Stable furnace control was achieved by regulating the addition of air to maintain hearth temperature.

Results of the test indicate that to maximize energy conversion, RDF should be fed to a mid-furnace hearth, and sludge to the top or second hearth. In other words, the point of sludge addition remains as in conventional systems, and the RDF is treated like any other fuel and added to the combustion zone. The ash handling system must be capable of handling small amounts of metal. Test results indicate that autogenous combustion of a 16 percent solids sludge cake can be accomplished with an RDF-to-sludge wet ratio of 1:2.

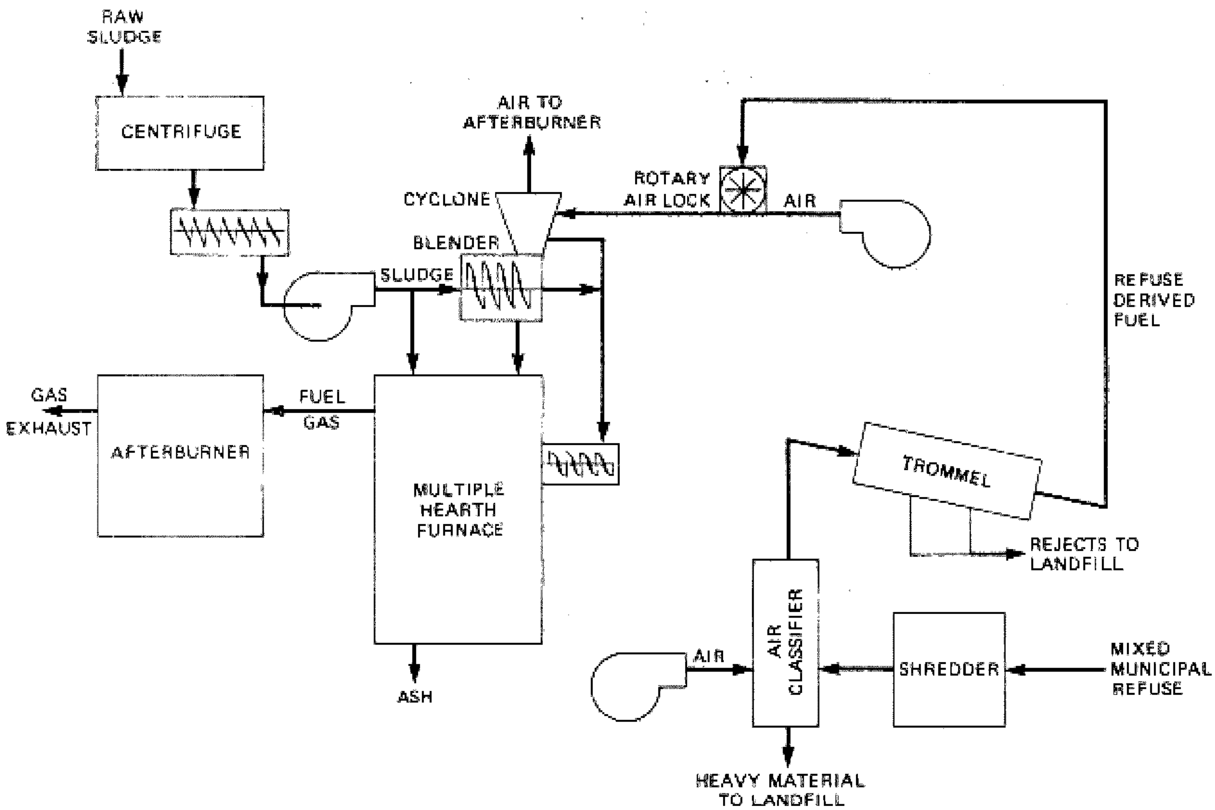


FIGURE 11-32

FLOWSHEET FOR CO-COMBUSTION FULL SCALE TEST AT THE CENTRAL CONTRA COSTA SANITARY DISTRICT, CALIFORNIA

This type of system is being reviewed for several plants, with implementation expected for the Central Contra Costa Sanitary District and the City of Memphis, Tennessee.

The flow sheet for a multiple-hearth furnace used for combustion of sludge and solid waste is similar to Figure 11-27, except that a refuse-derived fuel is added to the middle hearth(s). Heat and material balances for the hypothetical treatment plant alternatives (Table 11-8) are presented in Table 11-22. The effect of a 20 percent sludge solids feed versus a 40 percent sludge solids feed is again exhibited. An important item in this table is the recoverable heat, which is four times greater than that for other sludge-only combustion processes (see Table 11-18). This shows the effect of the addition of refuse-derived fuel. Also, in Case IIB, note the effect of excess air on the afterburner temperature. With 40 percent excess air, a temperature of 2,450°F (1,343°C) would be expected (consistent with Cases IB and IIB); however, a temperature of 1,800°F (982°C) occurs with an excess air rate of 150 percent.

Specific information specifically concerning co-combustion by SAC in a MHF can be found in the literature (8,17,18,35,69,74-77,81, 89-96).

TABLE 11-22

HEAT AND MATERIAL BALANCE FOR CO-COMBUSTION BY STARVED-AIR COMBUSTION IN A MULTIPLE-HEARTH FURNACE[a]

	Alternative					
Stream	IA 5 MGD 20 percent solids	IB 5 MGD 40 percent solids	IIA 15 MGD 20 percent solids	IIB 15 MGD 40 percent solids	IIIA 50 MGD 20 percent solids	IIIB 50 MGD 40 percent solids
Furnace design						
Diameter, ft-in.	22-3	16-9	25-9	18-9	25-9	22-3
Number of hearths	6	7	6	8	9	8
Hearth loading rate, lb wet solids/sq ft/hr	11.4	10.8	11.8	11.3	12.5	12.1
Sludge feed						
Lb dry solids/hr	1,806	2,131	2,713	3,201	4,292	5,064
Percent of total furnace feed	50	50	50	50	50	50
Volatile content, percent[c]	77	65	77	65	77	65
RDF feed						
Lb dry solids/hr	7,224	4,267	10,850	6,400	17,172	10,128
Percent of total furnace feed	50	50	50	50	50	50
Volatile content, percent[c]	84	84	84	84	84	84
Percent moisture	20	20	20	20	20	20
Combined feed rate						
Total lb wet solids/hr	18,060	10,664	27,126	16,000	42,930	25,320
Heat value, 10^6 Btu/hr	20.28	11.12	30.71	16.38	47.29	25.53
RDF to sludge ratio, wet basis	1:1	1:1	1:1	1:1	1:1	1:1
Furnace combustion air, lb/hr	12,753	7,320	19,316	10,782	29,747	16,806
Excess air rate, percent[d]	40	40	40	40	40	150
Ash						
Mass, lb/hr	1,749	1,589	2,627	2,384	4,158	3,772
Heat value, 10^6 Btu/hr	0.50	0.46	0.76	0.69	1.20	1.09
Afterburner combustion air						
Mass, lb/hr	34,123	25,867	51,049	39,065	81,838	112,888
Afterburner exhaust						
Mass, lb/hr	63,186	42,260	94,861	63,461	150,355	151,240
Heat value, 10^6 Btu/hr	63.27	42.80	95.27	64.29	150.9	101.8
Temperature, °F	2,290	2,457	2,294	2,458	2,294	1,800
Radiation						
Heat loss, 10^6 Btu/hr	1.62	1.12	2.33	1.61	3.57	2.45
Recoverable heat 70 percent efficiency, 10^6 Btu/hr	23	20	42	26	70	42
Connected power						
Horsepower	555	343	725	418	725	555
Installed cost, thousand dollars[e]	2,800	2,200	3,000	2,400	3,500	3,000

[a]All data supplied by the Eimco BSP Division of Envirotech Corporation.

[b]Solids for B alternatives (40 percent solids feed), larger than A alternatives (20 percent solids feed).

[c]Sludge volatiles heat value 10,000 Btu/lb: RDF volatiles heat value 8,500 Btu/lb.

[d]For total system - furnace and afterburner.

[e]Costs as of early 1978.

1 MGD = 0.04 m^3/s
1 ft = 0.3 m
1 in. = 0.02 m
1 lb/sq ft/hr = 4.9 $kg/m^2/hr$
1 lb/hr = 0.45 kg/hr
1 x 10^6 Btu/hr = 1,055 MJ/hr

Fluid Bed

Municipal solid waste and wastewater sludge have been co-incinerated in a fluid bed furnace in Franklin, Ohio, since 1971 (97). In the solid waste separation process, a wet pulper removes ferrous metal and heavy solids from 150 tons (136 t) per day of shredded refuse. Fiber is recovered from the pulper effluent by selective screening and elutriation. All unrecovered residuals from the fiber-recovery step are conveyed to a barrel thickener. Sludge from a 2.5-MGD (0.11-m^3/s) secondary wastewater treatment plant is added to the thickened residuals, and the combined stream is dewatered in a cone press to a solids content of 45 percent before injection into the furnace. The furnace feed is blown into the bed about one foot over the tuyeres. Because heavy inert materials accumulate within the bed, there is buildup in bed volume, and a small amount of bed material must be removed periodically from the furnace. The preparation steps reduce the amount of noncombustible material in the furnace feed to between three and six percent and the feed size to 1/2 inch (1.27 cm) or less (97).

In a conventional dry shredding and separation operation, the feed stock would not be as uniform as it is at the Franklin facility. If the feed to the fluid bed furnace is not uniform in both size and density, heavy material tends to sift downward through the bed. This material must be removed quickly or it could upset the air flow through the bed. Systems have been developed to remove settled, noncombustible material continuously from the bed.

An FBF system using sludge cake and RDF produced by a dry processing approach was constructed in Duluth, Minnesota, and the shakedown operations began in 1979. A process flowsheet of the system is presented on Figure 11-33.

11.5.3 Institutional Constraints

Co-combustion of sewage sludge with municipal solid waste is a viable and socially beneficial approach to solids disposal problems. Not only are both wastes disposed of in an environmentally acceptable manner, but benefits can be accrued by utilizing the waste heat or combustible exhaust gases for energy conservation. Cost-effectiveness, however, is very site-specific, and in general, co-combustion systems are not economically feasible without federal and state funding (81,98,99). This is due to the relative costs of disposal and relative quantities of the feed material involved. For example, solid waste quantities, dry basis, are approximately ten times that of sludge quantities and can be disposed of at one tenth the cost of sludge. Therefore, sludge disposal costs have a significant impact on solid waste operations, yet solid waste is too costly on a unit energy basis to supplement fossil fuels. To assist in funding, the federal government has adopted guidelines for allocating costs for co-combustion systems (100). As solid waste disposal and fossil fuel costs increase and funding becomes more available, co-disposal economics will become favorable in more applications. Although the technical feasibility of co-combustion of sludge and solid waste has been demonstrated, there remain a number of institutional constraints that may have to be resolved prior to implementation of a large scale co-combustion project. Because full-scale operations are limited and the technology is growing, risk analyses should be conducted. These analyses would provide authorities with a basis for making a decision and with an understanding of the impacts of that decision (101).

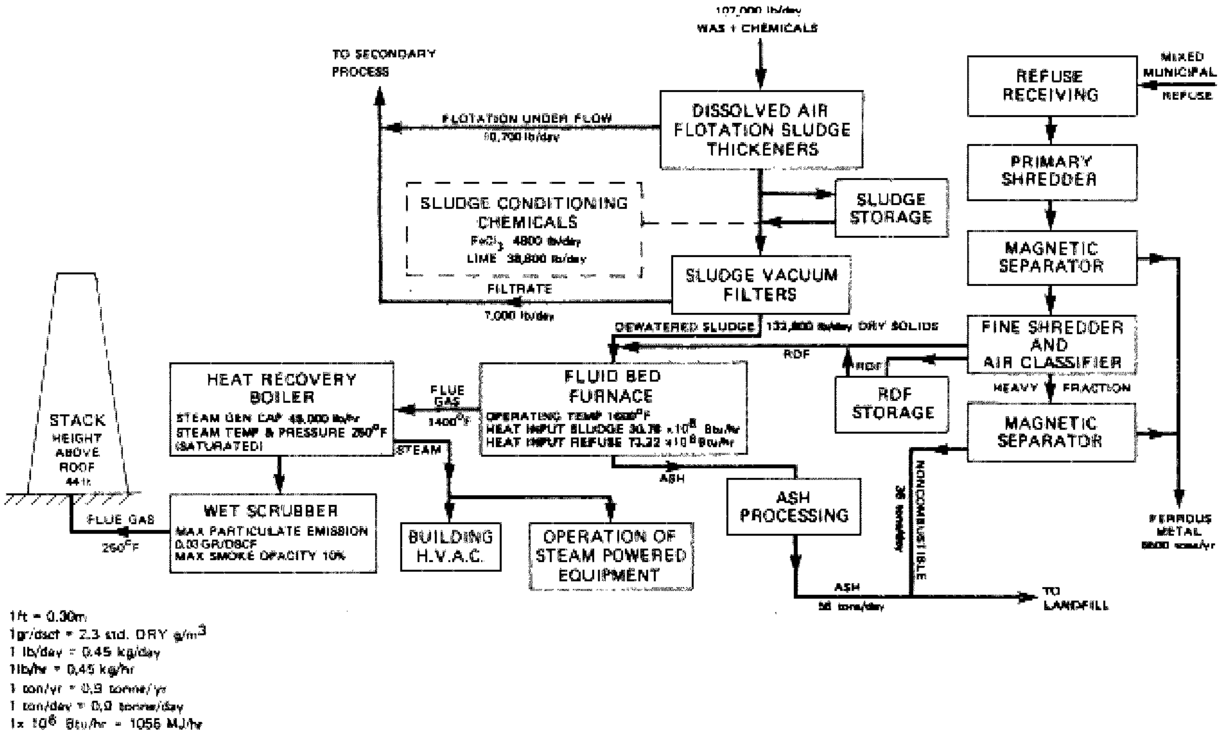


FIGURE 11-33

FLOWSHEET FOR CO-COMBUSTION AT THE WESTERN LAKE SUPERIOR SANITARY DISTRICT, DULUTH, MINNESOTA

In many localities, wastewater treatment and solid waste disposal are controlled by different governmental agencies. Many communities have contracts with private firms for refuse handling and disposal that release ownership of the refuse to the contractor. In such cases, the municipality is not able to do as it wishes with the refuse. Some contracts are long term, lasting 15 to 20 years. Although there have been legal opinions that these agreements can be modified for the benefit of the public, these opinions have not been tested in court. In recent waste disposal contract negotiations, local governments have attempted to retain ownership of the refuse, with the private firm acting strictly as a collector and hauler. Retaining ownership of the waste material would simplify resource recovery operations.

Consolidation of the governmental agencies responsible for solid and liquid waste disposal would also simplify disposal operations as they relate to co-disposal. With more emphasis on co-combustion techniques by both federal and state agencies, serious institutional problems may be resolved by governmental interaction with local agencies.

11.5.4 Conclusions about Co-Combustion

Of all areas of technological growth in combustion, co-combustion may have the greatest potential (81,102, 103) for use. Co-combustion is a relatively new venture, and its use must be thoroughly researched and tested, and project economics evaluated. Many solid waste projects have failed for economic reasons. Additionally, institutional requirements must be satisfied before the project can reach fruition.

11.6 Related Combustion Processes Used in Wastewater Treatment

Several high temperature processes are used in wastewater treatment plants for purposes other than wastewater sludge reduction. These processes include reduction of other wastewater solids such as screenings, grit, and scum, and also the regeneration of chemicals such as lime and carbon. High temperature equipment configurations are basically the same as those discussed in Sections 11.3 and 11.4, but some new types of furnaces are introduced in the sections that follow.

11.6.1 Screenings, Grit, and Scum Reduction

Besides sludge, other solids produced in a wastewater treatment plant (screenings, grit, and scum) can be processed in high temperature systems. Some of the unique operating problems presented by these materials are described below:

- Screenings tend to clog feed mechanisms and should be shredded before being fed to the incinerator. Bulky and non-combustible materials should be removed and disposed of in a landfill.

- Grit is often odorous, extremely abrasive, normally contains fairly large quantities of organics, and is relatively dry, thus making it autogenously combustible in many cases. Because of the odors, high temperature disposal tends to be the desirable stabilization method.

- Scum and grease are very difficult to handle because of their adhesive properties; however, they have a very high heating value up to 16,700 Btu per pound (37.8 MJ/kg) of dry solids (Table 11-2) (104). Air flow must be adequate to assure that the scum is totally burned; if it is not, the furnace will smoke. To provide thorough mixing and thus proper burning, the scum and air should be injected into the furnace at the same point. Scum has been fed through atomizers, but this feed system was not totally effective because the resulting vapors and smoke have been difficult to control (105).

A separate furnace may be difficult to justify for any one of the above materials because their quantities, as compared with sludge, are small. In some cases, the material can be blended with feeds and disposed of in existing sludge furnaces. Burning of the residues will not usually cause capacity problems. Although scum can provide considerable heating value, it can also create significant problems with smoking and hot spots. The latter may damage refractory material. Screenings and grit can also create hot spots, but they generally cause considerably fewer problems than scum.

Complete mixing of feeds can eliminate hot spots due to nonhomogeneity, but mixing is often difficult to achieve. The location of the mixing step is also a serious concern. When combined with sludge before dewatering, screenings, grit, or scum can cause dewatering equipment problems. These can include excessive wear, filter blocking, and poor dewatered cake release. On the other hand, it is difficult and costly to produce a homogeneous mixture when materials are combined after dewatering.

Since the materials are removed separately and require different dewatering techniques, they may in many instances be disposed of more appropriately by means other than high temperature processing. Several plants have provided digestion for sludge, and incineration for screenings, grit, and scum, with sludge gas used as the fuel for the furnace. Other plants have provided separate furnaces for scum reduction. In one plant, a separate furnace was provided for screenings only.

Furnaces for screenings, grit, and scum in small plants (less than 10 MGD [0.44 m^3/s]), tend to be single-chamber batch operations with little or no air emission control devices. However, high excess air rates and large quantities of fuel are used to make the burning relatively clean and odor-free. Such an operation is costly. For large plants, the furnaces described in Sections 11.3 and 11.4 are used. However, while several multiple-hearth furnaces are used successfully for scum (106), a starved-air combustion operation is desirable to control the combustion process and prevent serious temperature excursions, localized hot spots, and smoking--all typical problems when scum is burned.

To address the problem of scum burning, Nichols Engineering and Research Corp. has developed a furnace specially suited for high energy liquids that are lighter than water, such as grease, waste oils, and scum. Their WATERGRATE^{tm} furnace is shown on Figure 11-34. It is a two-chamber, refractory-lined furnace that uses water as the feed grate. As the material is burned, the ash sinks and is removed. The lower chamber is a reducing furnace (starved air), and the resulting combustible gases are burned in the upper chamber, which functions as an afterburner, thereby permitting better control of the process. More than ten units have been installed and are operating. Some have experienced severe problems with scum transport and feed systems external to the furnace.

Other small, modular furnaces (see Section 11.7) have considerable potential for screening, grit, and scum reduction, provided that pollution control devices are adequate to meet strict air emission codes. USEPA and the State of California have been conducting several tests on modular furnaces to determine expected air emission levels (107).

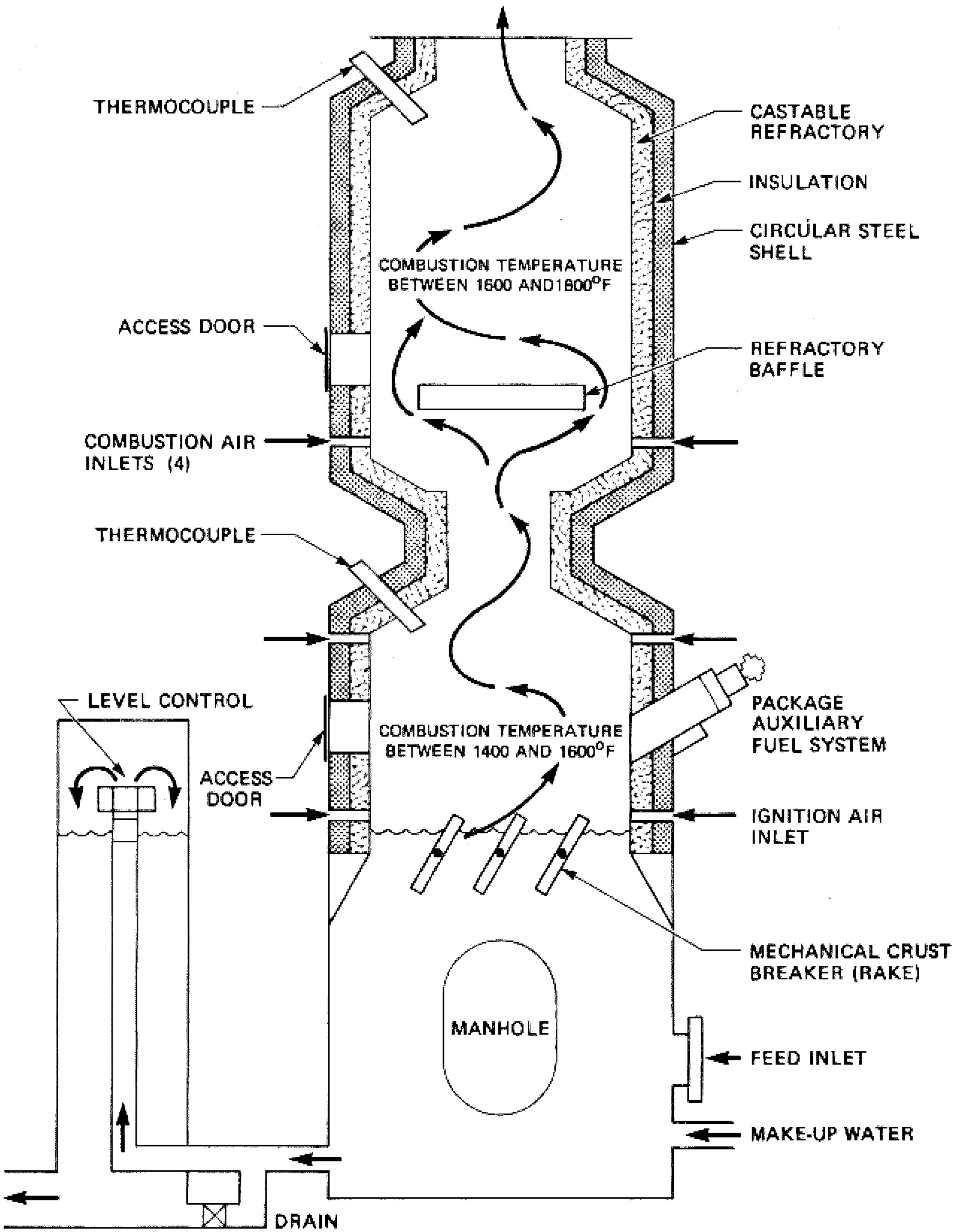
11.6.2 Lime Recalcination

Lime is often used to remove phosphorus, suspended solids, and trace metals from wastewater. It is generally added prior to primary clarification (108,109) or following a biological process (108,110). Often, energy and economic analyses indicate lime recovery and reuse to be viable, since net lime requirements are lower and the mass of solids for disposal is less when recovery is practiced. There is considerable experience with the recalcining and reuse of lime from water treatment plants. These techniques, with suitable modifications, are also used to recover lime in wastewater applications.

In the liquid process, the bulk of the lime reacts to form calcium carbonate ($CaCO_3$). The resultant slurry, commonly called lime sludge, can be thermally processed for recovery of calcium oxide (quicklime or CaO), while simultaneously oxidizing any entrapped organic solids. The recalcining reaction is:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2 \qquad \text{11-17}$$

The economics of lime recalcination as a chemical recovery process depend upon a number of variables: efficiency of rejection of inert material, moisture content of feed material, thermal efficiency of the drying and recalcining system, capture of CaO as a usable product, and reactivity (capture of CaO) in the product (111).



COURTESY NICHOLS ENGINEERING AND RESEARCH CORPORATION

FIGURE 11-34

CROSS SECTION OF THE WATERGRATE™ FURNACE FOR SCUM INCINERATION

Economies are realized when lime is recovered and reused, since net lime requirements and the amount of material to be disposed of are drastically reduced. However, lime recovery is expensive and always energy-intensive because recalcining is endothermic. Generally, wastewater lime sludges are low in organic material (volatiles) that can contribute to the heat value of the sludge, so supplemental fuel requirements to calcine the wet sludge cake are substantial. The major operating cost of recalcination is supplemental fuel. Fuel cost can be minimized by control of excess air at a rate no greater than that required to assure complete combustion and completion of the chemical reaction. Fuel costs may also be lowered by reducing the water content of the feed. An overall economic balance must be made to determine if the fuel savings exceed the added cost of dewatering.

Complete recovery of spent lime cannot be expected for several reasons. Lime sludge contains inert materials that must be wasted from the system or the quantity of sludge to be handled will build-up infinitely. Magnesium hydroxide and calcium phosphate are precipitated along with $CaCO_3$ and should be removed prior to recalcination to reduce recycle of inerts. Complete rejection of $Mg(OH)_2$ and other inerts, such as silica, can never be achieved. However, wet and dry classification steps can limit recycle of inerts, thus providing a relatively clean product. These classification steps necessarily reject some $CaCO_3$ and CaO, so that the recovery of available lime is limited to 60 to 77 percent (108,112).

Three high temperature systems have been used for lime recalcination: the multiple-hearth furnace, the fluid bed furnace (pellet bed and sand bed), and the rotary kiln calciner. It has also been claimed that the electric furnace has the capability to recalcine, but no installations exist. The multiple-hearth furnace is most frequently used in wastewater treatment plant sludge recalcining, while the fluid bed furnace is typically used in water treatment plants. Both the rotary kiln and the fluid bed are widely used on industrial sludge, primarily by the pulp and paper industry. As with other high temperature processes, opportunities for energy conservation and heat recovery are available. A detailed discussion of lime recalcination is beyond the scope of this chapter. More information is available in the literature (108-119).

11.6.3 Activated Carbon Regeneration

The use of activated carbon for removal of organic contaminants from water and wastewater is an established practice. In most applications, regeneration and reuse of spent carbon are required for overall cost-effectiveness. Most carbon absorption processes use granular carbon in packed columns. There is a growing interest in the addition of powdered carbon to unit processes such as activated sludge systems. Table 11-23 summarizes the methods available for carbon regeneration (reactivation).

TABLE 11-23

CARBON REGENERATION METHODS (120)

	Granular	Powdered
Thermal		
Multiple-hearth	X	X
Fluid bed	L	X
Transport reactor	NA	X
Rotary kiln	X	L
Indirect heated vertical moving bed	X	NA
Radiant heated belt reactor	X	X
Chemical		
Wet air oxidation	NA	X
Chemical oxidation	X	NA
Solvent extraction	X	NA
Acid or base extraction	X	NA
Biological regeneration	L	L

X = has been done on pilot or full-scale.
L = limited success
NA = not attempted.

Typical granular and powdered carbon systems are briefly summarized below. Also, the JPL process for carbon reactivation in a wastewater treatment plant is discussed.

11.6.3.1 Granular Carbon Systems (GAC)

Regeneration of granulated carbon (121,122) is usually conducted in a multiple-hearth furnace in five steps: dewatering the slurry to about 50 percent solids, drying the carbon, pyrolyzing the absorbed organics, oxidizing the pyrolysis residue (carbon reactivation), and quenching the reactivated carbon in water and washing it to remove fines.

In a multiple-hearth furnace, about 30 minutes are required for regeneration, with dwell times of 15 minutes for drying, 5 minutes for pyrolysis, and 10 minutes for reactivation. Loading rates for multiple-hearth furnaces must be adjusted to provide about 1 square foot (0.09 m^2) of hearth area per 40 pounds (18 kg) of spent carbon per day. The off-gases from a carbon regeneration furnace are relatively high in carbon particles and unburned organics. Afterburning and wet scrubbing are suggested. The injection of steam at 1 pound per pound of carbon (1 kg/kg) reduces the apparent density of the carbon and increases the iodine number. Heat required for the process, including steam but excluding any afterburner fuel requirements, is approximately 4,250 Btu per pound (9.88 MJ/kg) of carbon regenerated. Further details on the MHF regeneration process can be found in the literature (123).

The electric furnace is also becoming an alternative for granular carbon regeneration, with several units either under construction or in the planning stages. A test unit is being installed in Pomona, California, to develop detailed long-term data.

11.6.3.2 Powdered Activated Carbon (PAC)

During the regeneration of powdered carbon, organics must be removed from the micropores, and since PAC is generally associated with excess waste biomass, these solids must be incinerated simultaneously (120,124). Also, PAC is much smaller in particle size than GAC and must be handled with care during combustion to prevent excessive losses and excessive loadings of particulates on emission control systems.

Multiple-hearth systems have been used successfully to regenerate PAC (123,125). MHF-regenerated carbon appears to be of virgin quality and has been reused in a 40-MGD (1.75-m^3/s) plant. Available data on a 50-gpm (30-l/s) pilot plant indicate similar results with fluid bed technology (126).

Use of the transport reactor has been demonstrated on a 10-ton-per-day (9-t/day), full-scale facility with a recovery of 80 to 90 percent of the spent carbon. This reactor is a fast co-current thermal plug flow system (127,128). The unit is operated for regeneration of spent carbon from corn syrup manufacturing.

11.6.3.3 Jet Propulsion Laboratory Activated-Carbon Treatment System (JPL-ACTS)

Extensive laboratory and pilot testing by the Jet Propulsion Laboratory in Pasadena, California, has led to the development of an activated carbon treatment system for wastewater (129,130). The system is based on starved-air combustion of sludge. All PAC used in this process is produced by the SAC of sewage sludge and lignite coal. The system was tested for the Orange County Sanitary District in a 1-MGD (0.04 m^3/s) pilot plant at Huntington Beach, California.

The flowsheet for the Orange County plant is shown on Figure 11-35. Sludge from the primary sedimentation tank is dewatered in a filter press to 35 percent solids. The sludge cake is flash-dried to 90 percent solids before passing into the rotary kiln. Activated carbon and ash are generated by starved-air combustion of the carbon-sludge solids. Activated carbon-ash mixture is fed back to the secondary clarifier to complete the carbon cycle. A portion of the carbon-ash is purged from the kiln to prevent build-up of inert materials. The energy value of the purged carbon can be recovered in a separate furnace.

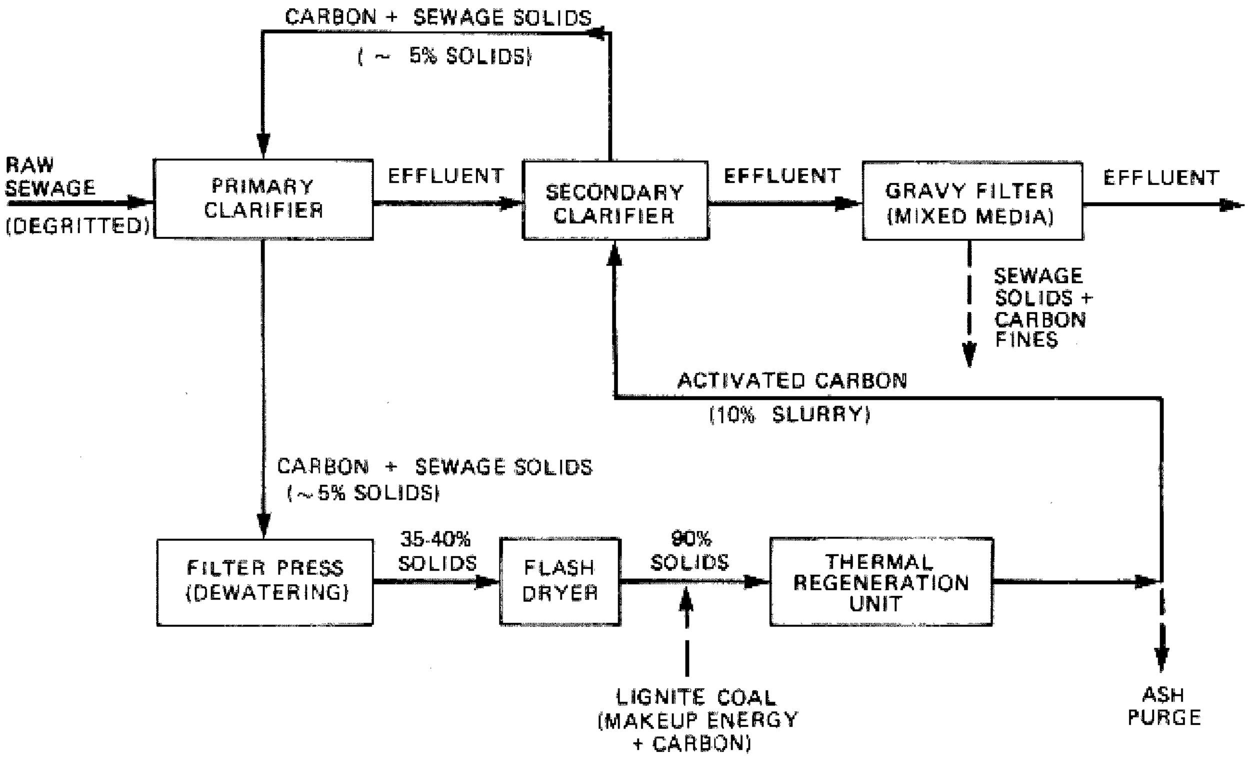


FIGURE 11-35

JPL ACTIVATED CARBON TREATMENT SYSTEM (129)

Various practical problems (primarily corrosion at high temperatures) associated with the kiln and flash-dryer have caused the developers to substitute a multiple-hearth furnace for these two system elements. No actual test work with the MHF has been done to date.

Activated carbon makeup requirements are dependent on adsorption characteristics. Under some circumstances, the carbonized sludge can satisfy the makeup requirements. Otherwise, activated carbon makeup is necessary. Lignite coal is a source of low ash carbon with an adsorptive capacity comparable to commercial activated carbons. Lignite coal also provides, at low cost, the necessary makeup energy to the system.

Preliminary economic studies by the developers indicate that the JPL-ACTS process for wastewater treatment is competitive with activated sludge for plant flows exceeding 175 MGD (7.67 m^3/s).

11.7 Other High Temperature Processes

There are a number of high temperature conversion processes that differ substantially from those previously discussed. Some are presently being used for combustion or co-combustion of wastewater sludge, and others are claimed suitable for sludge processing. These processes include:

- High pressure/high temperature wet air oxidation
- REACTO-THERM[tm] (Met-Pro Corporation, Systems Division)
- Modular controlled-air incinerators for co-disposal (Consumat, Kelly, and others)

Also, numerous thermal processes are being developed, mainly of the pyrolysis or starved-air combustion type; which are applicable to wastewater sludge or mixtures of sludge and solid waste (Table 11-24). These processes are potentially important because they produce a high heating value fuel gas that may be directly usable in existing furnaces and burners. Of the true pyrolytic processes (thermal decomposition in the absence of air), only the Pyro-Sol process appears to be sufficiently developed to be considered here for co-disposal and perhaps sludge disposal. Some of the processes shown in Table 11-24 have been discussed previously (PUROX and Andco-Torrax). Other developing processes with potential for sludge burning include the Bailie process, the Wright-Malta process, and Molten Salt pyrolysis.

11.7.1 High Pressure/High Temperature Wet Air Oxidation

Any burnable substance may be oxidized in the presence of water at a sufficiently high temperature (flameless combustion). Therefore, this process can be an alternative to incineration while providing a similar ash residue (134).

The high pressure/high temperature wet air oxidation process (HPO) is similar to thermal conditioning, except that higher temperatures and pressures and much more air are used to effect complete oxidation. Figure 11-36 is a composite representation of results of wet oxidation for a typical sewage sludge, showing volatile solids content or COD content in the solid phase and the total sludge as a function of total oxidation in both phases. The vertical distance between the two curves is the content in the liquid phase. Up to about 50 percent total oxidation, reduction in the volatile solids or COD in the liquid phase are minimal; above 50 percent, the volatile solids and COD of both phases are reduced to low values. At 80 percent total oxidation, about 5 percent of the original total volatile solids in the sludge is in the solid phase and 15 percent is in the liquid phase.

TABLE 11-24

BASIC TYPES OF PYROLYSIS, THERMAL GASIFICATION, AND LIQUEFACTION REACTORS - NEW, DEMONSTRATED, OR UNDER DEVELOPMENT (131,132,133)

Solids flow and bed conditions	Examples of processes, developers, R&D programs	Feedstock	Main products: Fuels or char materials	Main products: Steam
Vertical-flow reactors				
Moving packed bed (gravity solids flow; also called fixed bed)	Forest Fuels Mfg., Inc. (Antrim, N.H.)	FAR[a]	-	X
	Battelle Northwest (Richland, WA)	Refuse	X	X
	American Thermogen (location unknown)	Refuse	-	X
	Andco/Torrax Process (Buffalo, NY)	Refuse	-	X
	H.F. Funk Process[b] (Murray Hill, NJ)	Refuse	X	-
	Tech-Air Crop/Georgia Inst. Tech. (Atlanta, GA)	FAR	X	-
	Union Carbide Purox Process (Tonawanda, NY)	Refuse, FAR	X	-
	Motala Pyrogas (Sweden)	Refuse	X	-
	Urban Research & Development (E. Granby, CT)	Refuse	X	-
	Wilwardco, Inc. (San Jose, CA)	FAR, sludge	X	-
	U. of California (Davis, CA)	FAR	X	-
	Foster Wheeler Power Products (London, England)	Refuse, tires	X	-
	Destrugas Process (Denmark)	Refuse	X	-
	Koppelman Process (Encino, CA)	FAR	X	-
Moving stirred bed (gravity solids flow)	BSP/Envirotech (Belmont, CA)	Sludge, refuse	X	X
	Nichols Research & Engr. (Belle Mead, NJ)	Sludge, wood	X	X
	Garrett Energy Research & Engr. (Claremont, CA)	Manure	X	-
	Hercules/Black, Crow & Eidsness (Gainesville, FL)	Refuse	X	-
Moving entrained bed (may include mechanical bed transport)	Occidental Petroleum Co./Garrett Flash Pyrolysis Process (La Verne, CA)	Refuse	X	-
Fluidized reactors	Copeland Systems Inc. (Oak Brook, IL)	Sludges	X	-
	Coors Brewing Co./U. Of Missouri (Rolla, MO)	Refuse, FAR	X	-
	Energy Resources Co. (ERCO) (Cambridge, MA)	Refuse, FAR	X	-
	Hercules/Black Grow & Eidsness (Gainesville, FL)	Refuse	X	-
	Bailie Process/Wheelabrator Incin. Inc. (Pittsburgh, PA)	Refuse	X	-
	A.D. Little Inc./Combustion Equipment Assoc. (Cambridge, MA/New York, NY)	Refuse	X	-
Horizontal and inclined flow reactors	Devco Management Inc. (New York, NY)	Refuse	-	X
Tumbling solids bed	Monsanto Landgard/City of Baltimore, MD Watson Energy Systems (Los Angeles, CA)	Refuse	X	X

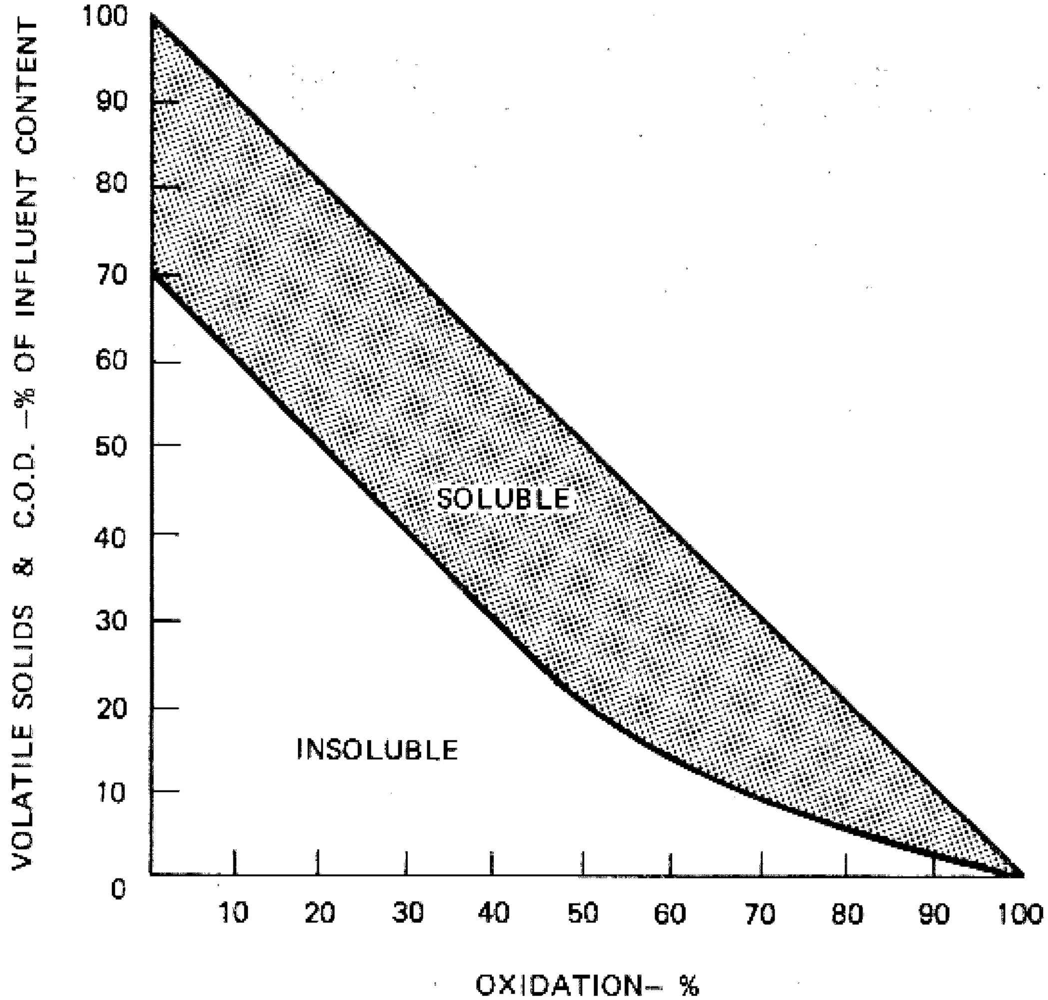
TABLE 11-24

BASIC TYPES OF PYROLYSIS, THERMAL GASIFICATION, AND LIQUEFACTION REACTORS - NEW, DEMONSTRATED, OR UNDER DEVELOPMENT (131, 132, 133) (Continued)

Solids flow and bed conditions	Examples of processes, developers, R&D programs	Feedstock	Main products: Fuels or char materials	Main products: Steam
Horizontal and inclined flow reactors (continued)	Ecology Recycling Unlimited, Inc. (Santa Fe Springs, CA)	Refuse	X	-
	Pyrolenergy System/Arcalon (Amsterdam)	Refuse, FAR	X	-
	Pan American Resources, Inc. (West Covina, CA)	Refuse, FAR	X	-
	Kobe Steel (Japan)	Tires	X	-
	JPL/Orange County, CA (Fountain Valley, CA)	Sludge	X	-
	Rust Engineering (Birmingham, AL)	Refuse, sludge	X	-
	Tosco Corp/Goodyear Tire and Rubber (Los Angeles, CA/Akron, OH)	Tires	X	-
Agitated solids bed	Deco Energy Co. (Irvine, CA)	Tires	X	-
	Enterprise Co. (Santa Ana, CA)	Refuse	X	-
	Kemp Reduction Corp. (Santa Barbara, CA)	Refuse, FAR	X	-
	PyroSol (Redwood City, CA)	Fluff from scrapped autos	-	X
Static solids bed	Thermex, Inc. (Hayward, CA)	Tires	X	-
Molten metal or salt beds				
Floating solids bed (horiztonal flow)	Michigan Tech. U. (Houghton, MI) (Puretech Pyrolysis System)	Refuse, FAR	X	-
Mixed molten-salt bed (various possible flow schemes)	Battelle Northwest (Richland, WA)	Refuse	X	-
	Anti-Pollution Systems, Inc. (Pleasantville, NJ)	Refuse, sludge	X	-
Multiple-reactor systems				
Combined entrained-bed/static-bed reactor system	U. of California (Berkeley, CA)	Pulping liquor	X	-
Combined moving packed-bed/entrained-bed reactor	Battelle Columbus Laboratories[b] (Columbus, OH)	Paper, biomass	X	-
Combined mechanically conveyed static-solids-bed/moving packed-bed reactor	Mansfield Carbon Products, Inc. (Gallatin, TN)	Refuse	X	-

[a]Forestry and/or agricultural residues.

[b]Pressure above atmospheric.



COURTESY ZIMPRO INC.

FIGURE 11-36

VOLATILE SOLIDS AND COD CONTENT OF HEAT TREATED SLUDGE

The degree to which organic materials are oxidized is a function of temperature, reaction time, and quantity of air (or oxygen) supplied. The process may be applied to dilute suspensions of sludge requiring only thickening. However, the solids content should be four to six percent to minimize reactor volume requirements and to maintain a thermally self-sustaining reaction. Solids concentrations greater than about 10 percent create problems with mixing and consequent mass transfer of the oxygen. There is insufficient data to indicate any advantage from use of pure oxygen rather than air as the oxidant source.

The high pressure/high temperature wet air oxidation process is shown schematically in Figure 11-37. Thickened sludge, at about six percent solids, passes through a grinder to reduce the size of all feed solids to less than 1/4 inch (0.64 cm).

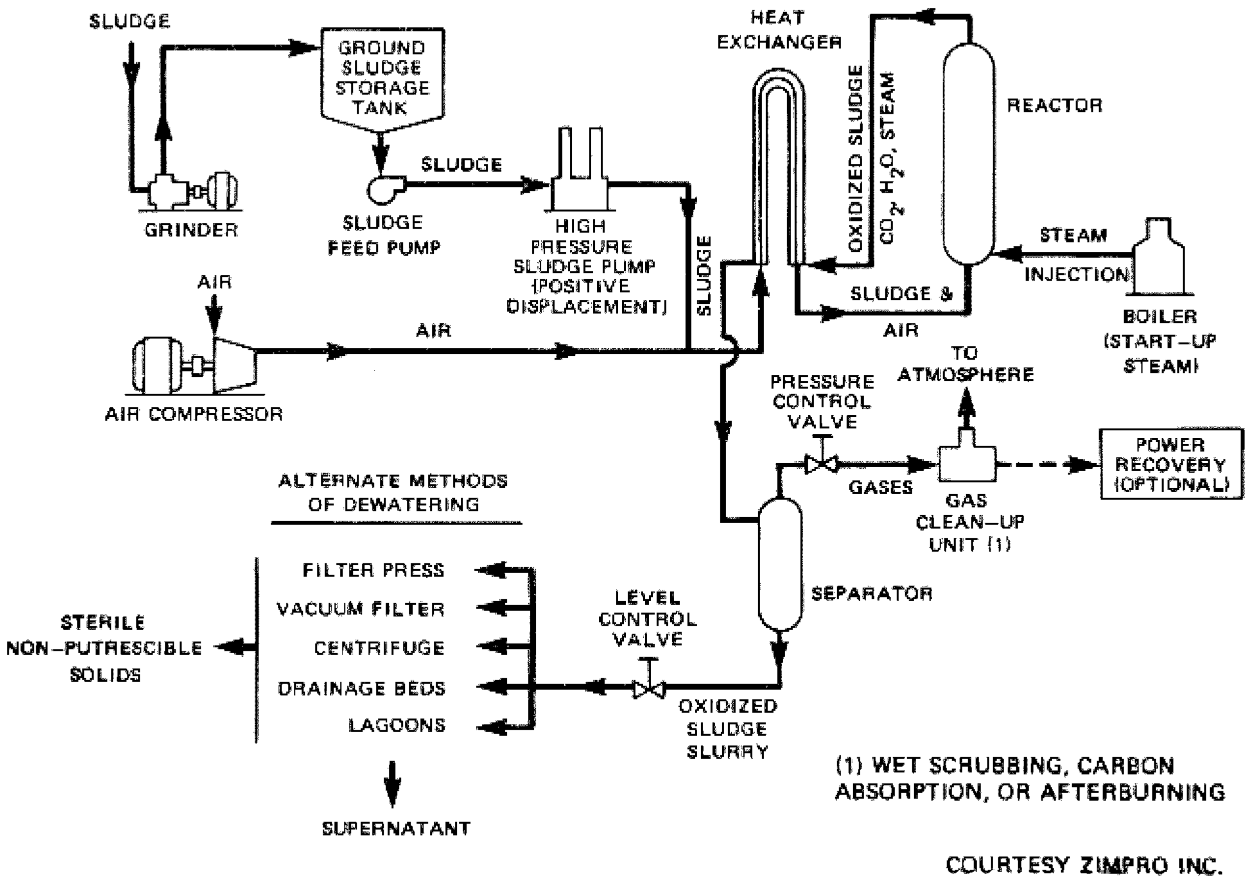


FIGURE 11-37

FLOWSHEET FOR HIGH PRESSURE/HIGH TEMPERATURE WET AIR OXIDATION

The slurry is then pressurized. The air quantity supplied is the stoichiometric amount required for complete oxidation of the combustible sludge solids (about 7.5 lb per 10,000 Btu) (2 g/J). The pressure applied must be sufficient to prevent the water from vaporizing at the temperature selected for the reaction.

The sludge-air mixture is then passed through a heat exchanger, where it is heated to close to the desired reaction temperature by the reactor effluent stream and introduced into the reactor for oxidation. Temperatures and pressures up to 500°F (260°C) and 1,000 to 1,800 psig (6,895 to 12,411 kN/m^2) are used with detention times of 40 to 60 minutes. The oxidized slurry is then cooled in the heat exchanger, gases are removed in a vapor-liquid separator, and the gases are reduced to atmospheric pressure through a pressure control valve. The gases are processed to eliminate odors. They consist mainly of oxygen, nitrogen, carbon dioxide, and water vapor. Nitrogen oxides are formed from the organic nitrogen present in the feed, but no nitrogen is fixed from the air. Elemental sulfur, hydrogen sulfide, and organic sulfur compounds are oxidized to sulfate (SO_4). Gas clean-up methods have included wet scrubbing, activated carbon absorption, afterburning with fossil fuel, and catalytic oxidation. With the last two methods, energy recovery is possible through use of heat recovery boilers, gas-liquid heat exchangers, and similar methods (135-137).

Slurry from the gas-liquid separator is removed through a liquid-level control valve and dewatered for final disposal. At high degrees of oxidation, the residual solids resemble ash from thermal incineration and are easily dewatered to a high solids content by conventional means (settling, centrifugation, or vacuum filtration).

The liquid phase is recycled to the treatment plant or given separate treatment for reduction of the residual soluble organics. Treatment and effects of this liquid stream are discussed in Chapter 16.

High pressure/high temperature wet air oxidation processes generate excess heat when they operate with a high heating value sludge and an adequate solids content (approximately six percent). Still, a source of high pressure steam (separate boiler or an existing plant system) must be provided for start-up.

There are over ten HPO systems in operation on sewage sludge in the United States. The most notable of these are Rockland County and Rensselaer, New York, and Akron, Ohio. These units operate at approximately 500°F (260°C) at pressures of 1,000 to 2,000 psi (6,895 to 13,790 kN/m^2). The capacities of the units as well as the sludge oxidized are very different in each of these plants Rockland County processes 12.4 tons per day (11.3 t/day) of a mixed digested primary plus waste-activated sludge. The Akron facility (Botzum Plant) oxidizes 50 tons per day (45 t/day) of waste-activated sludge. The Rensselaer facility oxidizes a more conventional mixture of primary plus waste-activated sludge.

Shutdowns with HPO systems are associated with the high pressures involved, heat exchanger scaling and corrosion, and required supernatant liquid treatment. The HPO process may provide a good system for oxidation of toxic and hazardous waste materials, and research in this area is under way (138).

Lack of extensive operating data prevents reliable estimation of the cost of HPO as a means to sludge disposal. It appears that if equipment maintenance and replacement costs are reasonable, the costs would be competitive with thermal processing. The only additional element of cost is treatment of the recycle stream. Electrical energy requirements are shown in Figure 11-38. Additional information can be found in the literature (134-139).

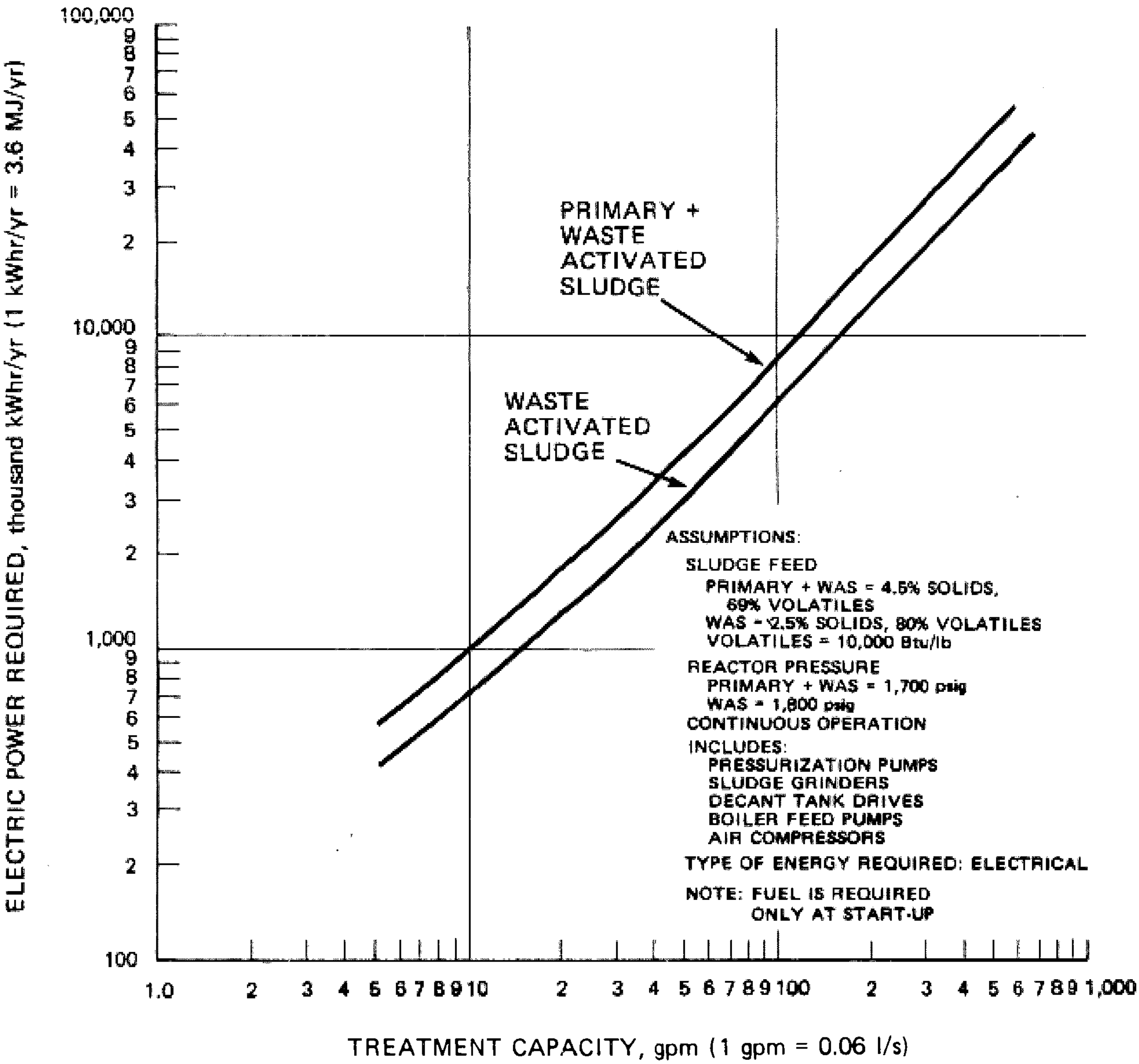


FIGURE 11-38

WET AIR OXIDATION - ELECTRICAL ENERGY REQUIREMENTS (36)

Another HPO unit presently being tested for feasibility with a feed of sewage sludge is the Vertical Tube Reactor (VTR). This is a deep-well type of process in which the required pressure is obtained simply by the depth of the well. The Municipal Environmental Research Laboratory of USEPA is conducting test work with a VTR system in Colorado. Data should be available in 1980.

11.7.2 REACT-O-THERM^{tm}

This is a three-stage combustion device with SAC in the first two stages followed by complete combustion in the third stage. This proprietary system developed by Met-Pro Corporation, Systems Division, is unique in that auxiliary fuel and air are burned in the primary combustion chamber (first stage) and the resulting gases pass into the rotary chamber, where the sludge is burned. The interior design of the rotary kiln second stage recovers the heat generated in the first stage and transmits this heat through a stainless steel helix and chains to the sludge. The residue, which contains some combustibles, is deposited into a fixed, cylindrical ash chamber, where it is removed by an auger. The gases from the rotary chamber flow into the secondary combustion chamber (third stage), and air and fuel are added as required to complete the combustion of the gases and destroy odors prior to discharge to atmosphere. The unit is available as a complete, skid-mounted package (see Figure 11-39). The unit is primarily designed for low-volume applications (50 to 300 gallons per hour of wet sludge [0.05 to 0.30 l/s]). Two units are presently operating on a physical-chemical sewage sludge in Prudhoe Bay, Alaska.

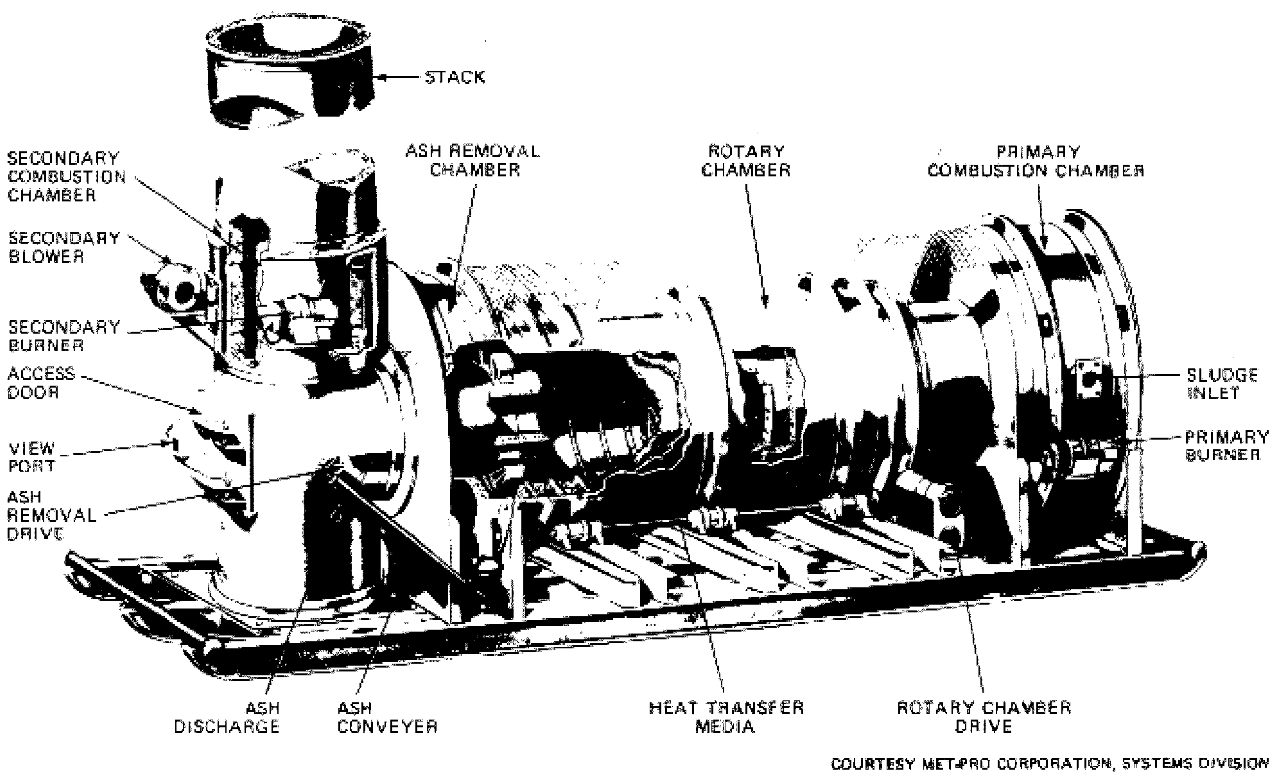


FIGURE 11-39

REACT-O-THERM^{tm} SLUDGE/LIQUID WASTE DESTRUCTION

Detailed heat and material balances are available from the manufacturer for specific applications. Emission test data from the manufacturer indicate that the unit, operated at rated conditions, can meet USEPA's New Source Performance Standards. However, the New Source Review Rule may be applicable in some areas and Best Available Control Technology (BACT) may be required.

11.7.3 Modular Starved-Air Incinerators

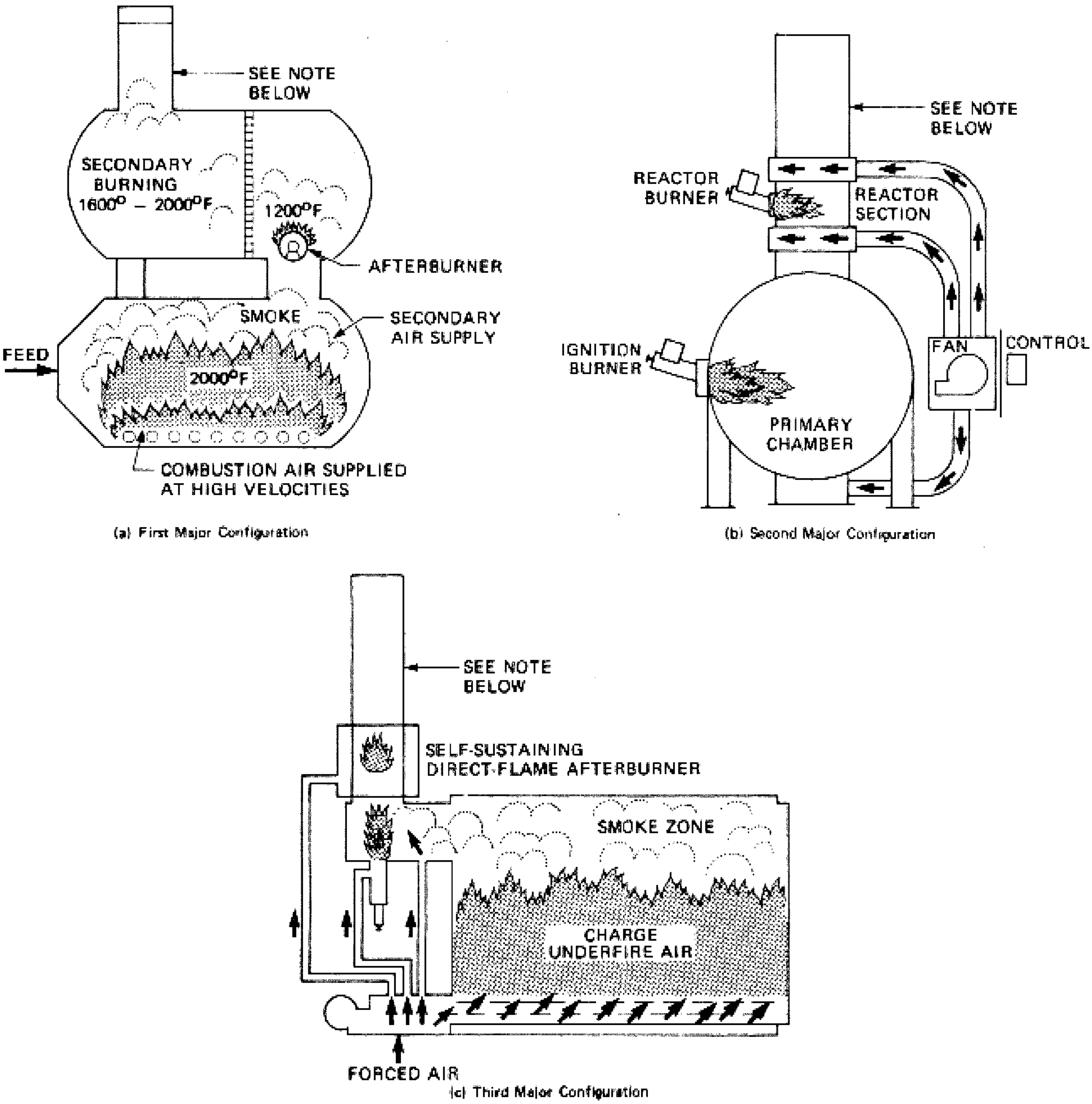
Modular controlled-air incinerators are static, and contain two-chambers. The first chamber is operated by starved-air combustion, and the gaseous products of combustion are passed to the second chamber where combustion is completed and odors are destroyed (see Figure 11-40) (107). A number of these incinerators have been installed for municipal and industrial solid waste. There are also units under study for co-disposal of municipal refuse and sewage sludge (141). There are no known installations (or test data) for sludge alone. However, the unit appears to be suitable for sludge reduction. The units are available in modules from 60 pounds per hour (27 kg/hr) to 250 tons per day (227 t/d). Equipment manufacturers (Consumat, Kelley, and others) state that USEPA New Source Performance Standards can be met without additional air pollution control equipment; however, the New Source Review Rule may be applicable in some areas and BACT may be required. A test program being funded jointly by the EPA and the State of California is currently underway at Little Rock, Arkansas, to obtain definitive air emission data on municipal solid waste incineration. Further information on controlled-air incinerators is included in the literature (107,140-145).

11.7.4 Pyro-Sol^{tm} Process

The Pyro-Sol process is a pyrolysis project presently operating on solid waste. In the Pyro-Sol process, waste is fed to a pyrolysis unit which, in the absence of oxygen and in the presence of heat, causes chemical decomposition of the waste. Products of the process are a gas and char/ash residue. A 50 to 75-ton per day (45 to 68 t/d) (MMR), full-scale plant is in operation in Redwood City, California. A flowsheet of that system is presented in Figure 11-41.

The process is autogenous, but heat-up and standby energy is provided by natural gas. A portion of the produced gas is burned in eight radiant heat tubes to provide heat for the endothermic pyrolysis process. The solids are fed by an airlock and moved through the furnace by means of a vibrating conveyor.

The resulting gas (largely hydrogen [H_2] and carbon monoxide [CO]) exits from the pyrolyzer at approximately 1,100°F (543°C) and less than 0.5 inches of water column (125 N/m^2) and enters



NOTE: STACK TO ENERGY RECOVERY EQUIPMENT
AND/OR EMISSION CONTROL DEVICE
(IF NECESSARY)

FIGURE 11-40

MODULAR CONTROLLED-AIR INCINERATOR CONFIGURATIONS (140) a dry cyclone where the particulate matter larger than 10 microns is removed. The hot gas is pulled through a wet scrubber/quencher where the remaining particulates are removed. The small amount of water that circulates to the scrubber/quencher, receives primary and secondary treatment, including filtration, before disposal to the plant sewer or to an on-site treatment plant. The scrubbed gas has a heating value of 400-500 Btu/cu ft (14.9 to 18.6 MJ/m^3).

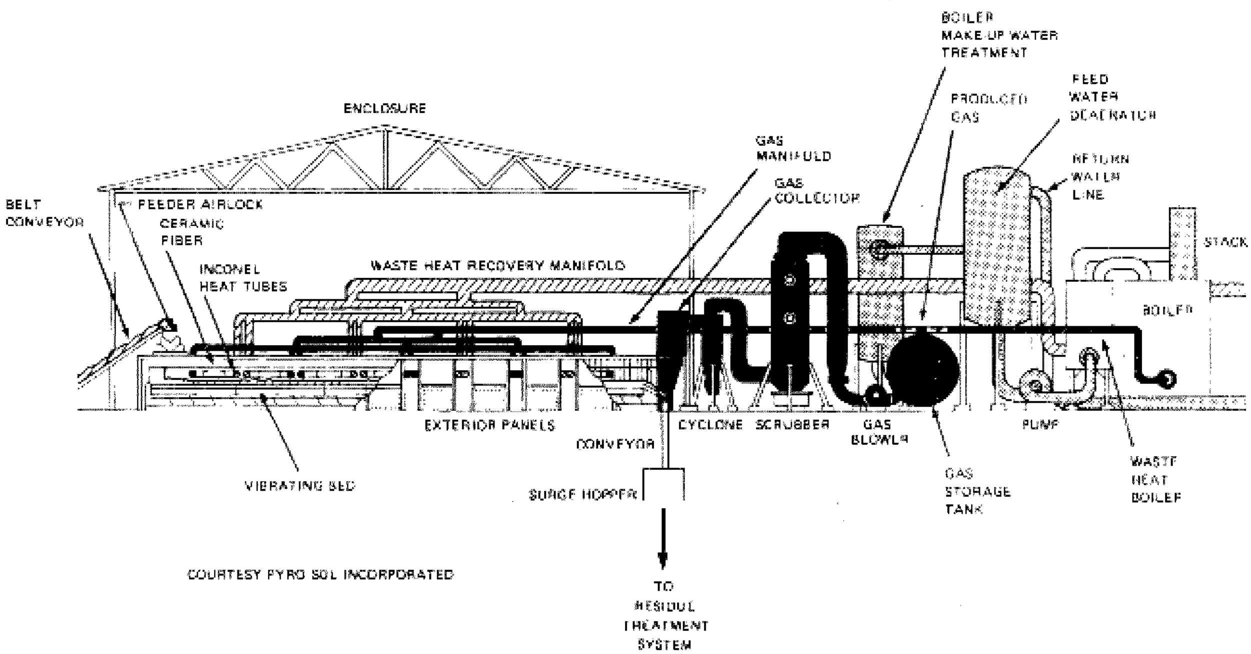


FIGURE 11-41

PYRO-SOL LIMITED PYROLYSIS SYSTEM

The gas is transferred to a surge tank and fed from there to a steam boiler. The steam can be used as process steam or to drive a turbo-generator.

Pyro-Sol, with feeds of up to 50 percent moisture, can achieve a net energy production of 60 percent of the input heat value in the fuel gas. Due to the high recovery of input heat value with relatively wet cakes, as compared with normal solid waste, this process should be amenable to co-disposal and possible sludge combustion.

11.7.5 Bailie Process

The Bailie Process integrates a combustion fluid bed furnace with a pyrolysis fluid bed reactor (146-147). The process, shown on Figure 11-42, involves feeding solid waste into the pyrolysis fluid bed reactor. The endothermic pyrolysis reaction is maintained in the 1,300 to 1,500°F (704-816°C) range by recycling hot fluidized sand from the combustion reactor. The fuel for the combustion reaction is contained in the same recycle from the pyrolytic reactor and from char collected in the combustion and pyrolysis gas cyclones. Some of the pyrolysis gas is returned to the pyrolytic reactor to control reaction kinetics. Both excess pyrolysis gas and char may be recovered.

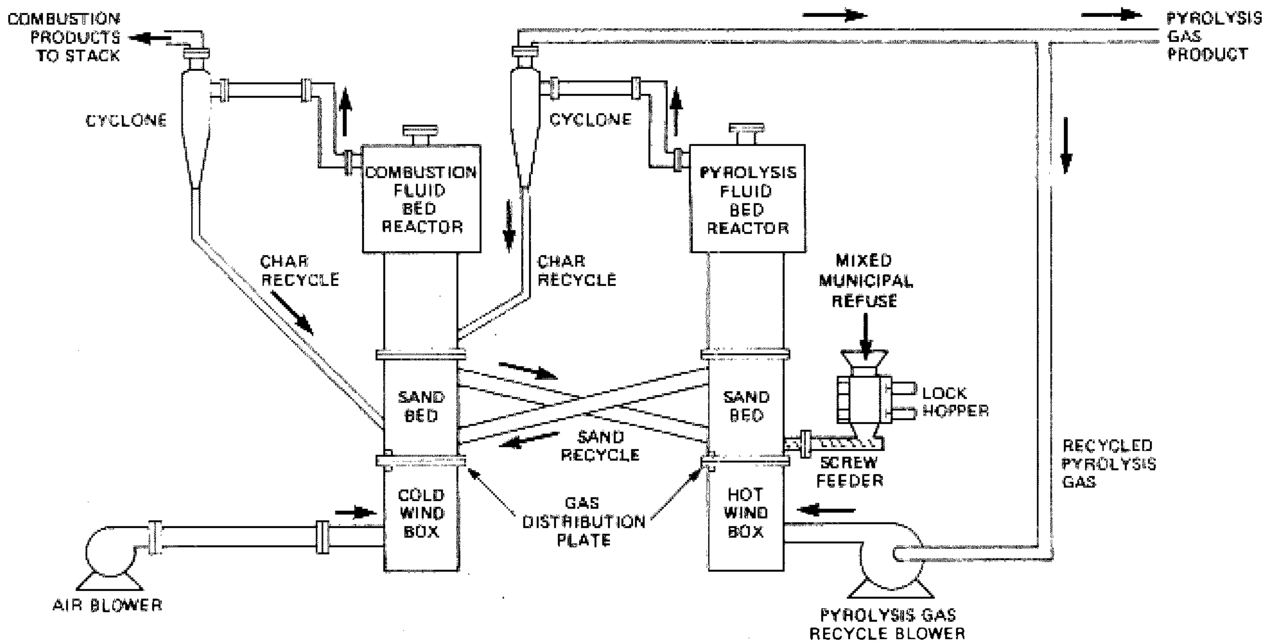


FIGURE 11-42

BAILIE PROCESS FLOWSHEET (146)

The Bailie Process is a potentially important method of sewage sludge pyrolysis. Less auxiliary fuel is needed for incineration of the sludge, and a number of energy recovery options are available. Heat from the off gases can be recovered and a combustible fuel gas is generated.

The Bailie Process is patented and has been piloted. No full-scale test has been conducted, but the manufacturer states that one is planned in the near future.

11.7.6 Wright-Malta Process

The Wright-Malta Corporation (W-M) is developing a pressurizied rotary kiln gasifier-gas turbine system for generating electric power from municipal solid waste and wastewater sludge (148,149). Figure 11-43 shows the process in terms of energy flows. The pressurized gasifier produces a hot, low heat value fuel gas that is combusted and fed directly to the gas turbine. The turbine drives an electrical generator and the associated air compressor. The hot exhaust is used to preheat the sludge and to raise steam temperature in a heat recovery boiler. The steam is superheated and passed back to the kiln, where it cools and condenses, supplying heat for the gasification process.

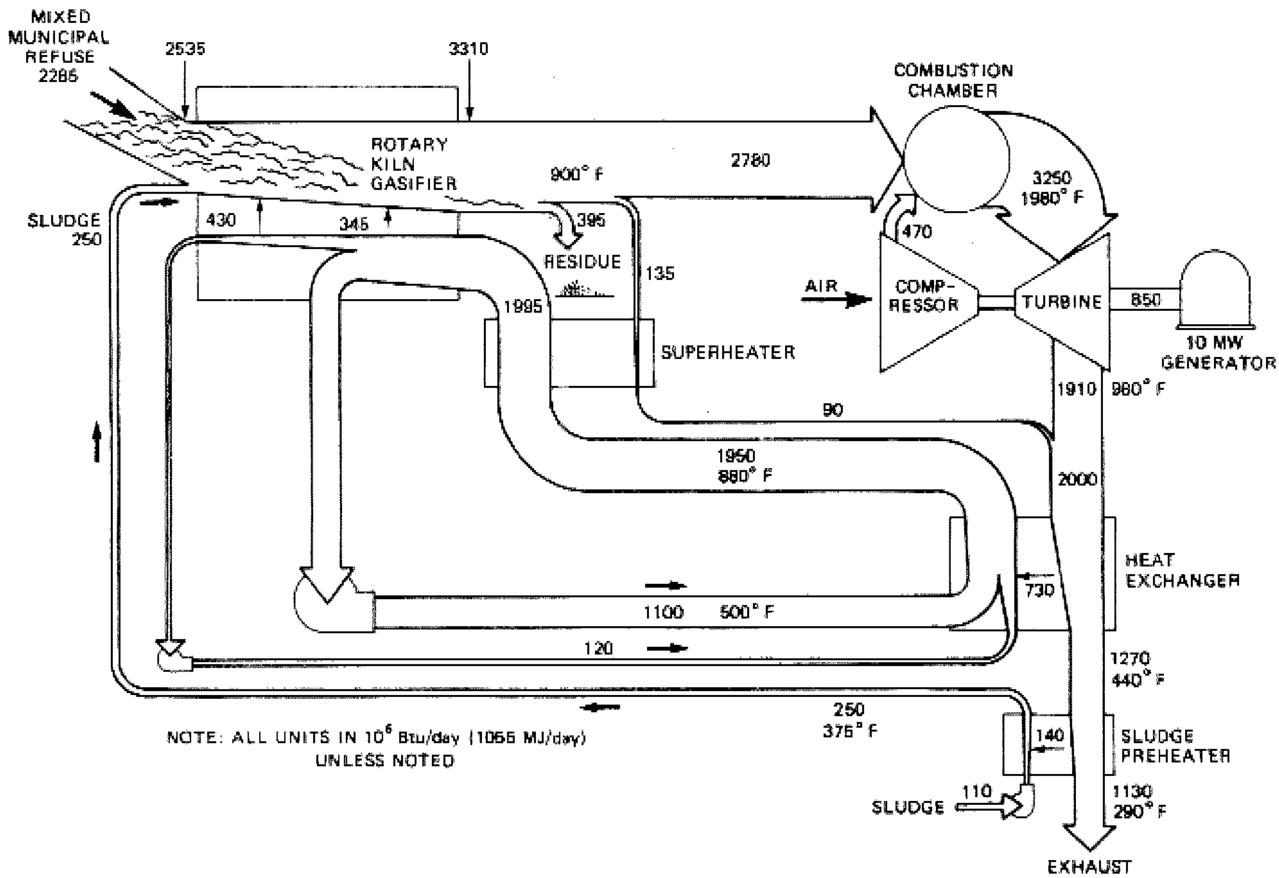


FIGURE 11-43

WRIGHT-MALTA PROCESS FLOWSHEET (150)

Wastewater sludge contributes about four percent of the organic fuel to the system. At the pressures involved, the water evaporated from the sludge provides motive force for the turbine in addition to the products of combustion from the fuel gas produced. The cycle is comparable to the combined cycle system used in electrical power generation, where hot gas turbine exhaust flows to a boiler to produce steam. The turbine exhaust in the W-M process generates steam in the kiln. This steam, along with the burned fuel gas, drives the turbine. The resulting fuel efficiency is close to the combined cycle efficiency. This process appears ideal for very moist fuels, and the high moisture content of the sludge is beneficial. The Wright-Malta process has been operated in a batch mode on a bench scale. Further progress depends on develpment of a rotary kiln that can be operated at high pressures and temperatures.

11.7.7 Molten Salt Pyrolysis

Bench-scale studies were conducted by Battelle-Pacific Northwest Laboratories on the pyrolysis of refuse in molten sodium carbonate (150). The products of reaction were studied for different conditions with steam, air, and oxygen as the gasification agents. While the processing of municipal refuse in the molten salt (sodium carbonate) reactor was found to be technically feasible, the lack of a cost-effective method of ash removal and the problems of refractory degradation have hindered further development. This type of process is not new. However, no information is available as to the applicability of the process to sludge disposal.

11.8 Air Pollution Considerations

In any combustion process, air emissions are a major concern and may be the most difficult and costly environmental consideration to satisfy. On the federal level, the USEPA has established standards of performance for municipal incinerators (solid waste) and wastewater sludge incinerators. In co-combustion schemes involving municipal solid waste and wastewater sludge, both standards will probably apply, with allowable emissions being prorated according to the fractions of energy in the solid waste and in the sludge. In September, 1978, the USEPA published proposed emission standards for new, modified, or reconstructed electric utility steam generating units that burn fossil fuel or a combination of fossil fuels and other fuels such as solid wastes. These guidelines offer some indication of air pollution requirements in co-combustion schemes.

Generally, these guidelines indicate that new sludge furnaces will have to comply with the following standards:

- National Ambient Air Quality Standards (State Implementation Plans).
- National Emission Standards for Hazardous Air Pollutants, subparts A and E.
- Standards of Performance for New Stationary Sources, parts A, O, and probably E, if co-combustion is proposed.
- New Source Review Rule.

- Regulations Pertaining to Prevention of Significant Deterioration of Air Quality.

In all cases, the minimum standards are set by the USEPA. However, state and local jurisdictions may promugate stricter standards.

A basic problem in evaluating any emission is predicting the effect on the overall air basin. Projecting emissions and estimating resulting air quality is, at best, an imperfect science. Air basins in which critical air quality levels are consistently exceeded have been studied in depth and have been the object of mathematical modeling. The results of these efforts have been mixed.

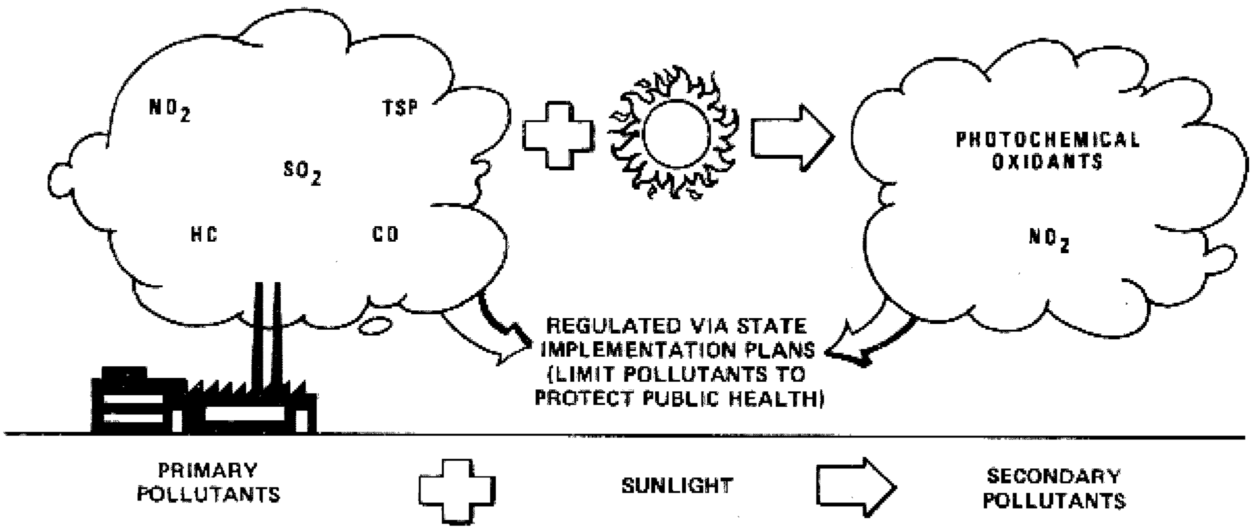
11.8.1 National Ambient Air Quality Standards (NAAQS)- State Implementation Plans (SIP)

Federal air quality regulations are derived from the Clean Air Act Amendments of 1970, the Energy Supply and Environmental Coordination Act of 1974, and most recently, the Clean Air Act Amendments of 1977 (151). The NAAQS established threshold levels of air pollutants below which no adverse effects would occur. These levels were designed to provide an adequate margin of safety so as to protect the public health.

Air pollutants are classified into two groups: primary pollutants and secondary pollutants. Primary pollutants are those emitted directly from sources, while secondary pollutants are formed by chemical and photochemical reactions of primary pollutants with the atmosphere, as shown on Figure 11-44. Primary pollutants include carbon monoxide (CO), hydrocarbons (organic gases), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), total suspended particulates (TSP) and lead (Pb). Photochemical oxidants and nitrogen dioxide (NO_2) are the principal secondary pollutants. These form a visible brown-yellow haze. The quantity of secondary pollutants is dependent on the availability of sunlight as much as on the availability of primary pollutants. Health effects of contaminants are summarized in Table 11-25.

The 1970 Amendments to the Clean Air Act required each state to develop its own State Implementation Plans (SIP) to meet the federal standards by 1975 or 1977, the date dependent on the severity of the state air quality problems. The 1977 Amendments extended the attainment deadlines and detail some appropriate control measures. For those areas which have not yet attained NAAQS, states must have approved implementation plan revisions by July 1, 1979, which provide for attainment by December 31, 1982. If a state demonstrates that such attainment is not possible, it must submit a second plan revision by December 31, 1982, which provides for attainment by December 31, 1987. For areas already meeting NAAQS standards, implementation plans must include a program to prevent significant deterioration of air quality.

The USEPA guidelines require the SIPs to provide for emission controls, transportation controls, source monitoring, ambient air quality monitoring, and procedure for review and approval of new sources of air pollution prior to construction. The USEPA has the authority to approve or disapprove these plans and to promulgate an acceptable plan if the submitted plan is disapproved. The USEPA, state air resources boards and local air quality management districts also have the authority to restrict issuance of permits for construction of stationary sources if emissions from that source would cause a violation of any air quality standards. This is accomplished by an emission offset policy. In both nonattainment and nondegradation areas, major stationary sources may be constructed only by permit and must at least meet applicable new source performance standards.



NATIONAL AMBIENT AIR QUALITY STANDARDS

(CLEAN AIR AMENDMENTS OF 1977)

FIGURE 11-44

AIR EMISSIONS

11.8.2 National Emission Standards for Hazardous Air Pollutants (NESHAPS)

Subpart A of NESHAPS (40 CFR 61) comprises general provisions covering definitions, applications, reporting, and waivers. Subpart E deals with mercury emissions and applies to all operations that burn or dry wastewater sludge. The NESHAPS standard (Federal Register, Vol. 40, No. 199, Tuesday, October 14, 1975) is currently seven pounds of mercury (3.2 kg) per 24-hour period for any source.

TABLE 11-25

HEALTH EFFECTS OF AIR POLLUTANTS (152)

Air quality level	TSP (24-hour), $\mu g/m^3$	SO_2 (24-hour), $\mu g/m^3$	CO (8-hour), mg/m^3	O_3 (1-hour), $\mu g/m^3$	NO_2 (1-hour) $\mu g/m^3$	Health effect descriptor	General health effects	Cautionary statements
	Pollutant levels							
Significant harm	1,000	2,620	57.5	1,200	3,750			
							Premature death of ill and elderly. Healthy people will experience adverse symptoms that affect their normal activity.	All persons should remain indoors, keeping windows and doors closed. All persons should minimize physical exertion and avoid traffic.
Emergency	875	2,100	40.0	1,000	3,000	Hazardous		
							Premature onset of certain diseases in addition to significant aggravation of symptoms and decreased exercise tolerance in healthy persons.	Elderly and persons with existing diseases should stay indoors and avoid physical exertion. General population should avoid outdoor activity.
Warning	625	1,600	34.0	800	2,260			
						Very unhealthful	Significant aggravation of symptoms and decreased exercise tolerance in persons with heart or lung disease, with widespread symptoms in the healthy population.	Elderly and persons with existing heart or lung disease should stay indoors and reduce physical activity.
Alert	375	800	17.0	400[c]	1,130			
						Unhealthful	Mild aggravation of symptoms in susceptible persons, with irritation symptoms in the healthy population.	Persons with existing heart or respiratory ailments should reduce physical exertion and outdoor activity.
NAAQS	260	365	10.0	240	a			
						Moderate		
50 percent of NAAQS	75[b]	80[b]	5.0	120	a			
						Good		
	0	0	0	0	a			

[a]No index values reported at concentration levels below those specified by "Alert Level" criteria.

[b]Annual primary NAAQS.

[c]400 $\mu g/m^3$ was used instead of the O_3 Alert Level of 200 $\mu g/m^3$.

11.8.3 Standards of Performance for New Stationary Sources (NSPS)

Subpart A of NSPS (40 CFR 60) involves general provisions covering definitions, performance tests, authority, and monitoring requirements. Subpart O is applicable to incinerators that burn municipal wastewater sludge and requires that particulates discharged cannot be in excess of 1.30 pounds per ton (0.65 kg/t) of dry sludge feed and that the gas discharged shall not have more than 20 percent opacity (154). For co-combustion, Subpart E is applicable to all incinerators with a charging rate greater than 50 tons per day (45 t/d) with municipal refuse comprising 50 percent or more of the charge. Subpart E requires that particulates discharged be no greater than 0.08 grains per standard dry cubic foot (0.18 g/m^3 dry) corrected to 12 percent carbon dioxide.

11.8.4 New Source Review Standards (NSR)

This regulation, 40 CFR 51.18, requires a preconstruction review of all new or modified stationary sources to determine if the source will meet all applicable emission requirements of the State Implementation Plans and the USEPA's Emission Offset Policy (44 CFR 3274, January 16, 1979).

The reviewing authority is usually a state agency that can apply stricter emission standards than the USEPA regulations. The state also sets emission offset required for stationery sources affected by the NSR. Federal law requires emissions offsets in areas where NAAQS are violated for a particular pollutant if:

1. The new source could, after installation of a pollutant control device, emit > 50 tons per year (45 t/yr) of the offending pollutant; or

2. Could emit >100 tons per year (91 t/yr) of the offending pollutant were there no pollution control device or were the existing device to fail.

State and local authorities may mandate a stricter criterion. In addition, the lowest achievable emission rate is required for any regulated source that mandates Best Available Control Technology (BACT).

The present definition of the term "potential emissions" is uncontrolled emissions or, those anticipated if the emission control device is bypassed or nonfunctional. This use of potential emissions in the regulations has a serious effect on which sources come under the perview of this regulation. For example, if only one ton per year (0.9 t/yr) of actual emissions were expected and the control device was 98 percent efficient, the "potential emissions" would be 50 tons per year (45 t/yr). The definition of "potential emissions" is the subject of pending court action, and this action is expected to be settled in late 1979.

11.8.5 Prevention of Significant Deterioration (PSD)

Regulation 40 CFR 52.21 limits increases in particulate and sulfur dioxide concentrations to specified increments above base levels measured in attainment areas. Data on total emissions for the entire air basin are required in order to evaluate incremental increases in specific emissions due to operation of any new or modified furnaces. If the potential emission rate of a regulated pollutant(s) exceeds 250 tons per year (227 t/yr) and the allowable emission rate exceeds 50 tons per year (45 t/yr), then this regulation must be used and public notice is required.

11.8.6 The Permit Process

Permits for construction and/or operation of processes that discharge gases to the atmosphere are the primary means for control of air emissions by a state and, in some cases, the local jurisdictions. Regulations applicable to a specific plant site must be thoroughly reviewed to determine if permits are required for the proposed project. Generally, sludge incineration and most other combustion operations require permits. The form and stages of permit requirements will vary considerably between state and local agencies and must be explored at that level. Federal permits for PSD regulations may be required. In the San Francisco Bay Area of California, for example, two stages of permits are required (154). These are:

- Permit to construct--to be applied for and granted before construction of a facility may proceed.
- Permit to operate--to be issued after construction and generally after point sources have passed stack emission tests.

11.8.7 Air Emissions Test Procedures

The criteria pollutants as defined in the Clean Air Act of 1977, are particulate matter, SO_2, NO_x, CO, hydrocarbons, and ozone. The USEPA has promulgated stack emission sampling and test procedures for these pollutants. However, state and local agency procedures may differ somewhat from those of USEPA and from each other. For example, some agencies define particulates as filterable particulate matter while others count the total catch (including condensible pollutants). For this reason, a measurement made under one jurisdiction may not be directly applicable to another.

11.8.8 Design Example

There are many regional and local variations in the rules, test procedures, and methodologies used to attain the NAAQS. Therefore, firm guidelines for procedures cannot be provided to encompass all areas of the nation. Designers must determine federal, state, and local requirements at an early project stage and meet with USEPA Regional officers and as well as state and local officials to negotiate changes or additions to the present regulations based on the project design, construction, and initial operation. This is just the start; contact must be continued with the USEPA Regional Offices, and state and local air quality management districts throughout the project. Also, the Federal Register and national and statewide newsletters should be monitored because they provide a good source for proposed changes in requirements.

The following design example provides a framework for project analysis. It is based upon experience with the San Francisco Bay Area Air Quality Management District (BAAQMD) which governs a nonattainment area. The BAAQMD generally promulgates rules more restrictive than federal requirements. This particular area was selected for the example since the local authority (BAAQMD) has developed a complex set of regulations that many areas may be using as guidelines.

The first step is to identify the applicable emission regulations (154-156) and then establish the requirements for emission control devices. These requirements are reviewed with several manufacturers to determine feasibility and cost before the device is incorporated into the design. The last step is the startup and testing of the control device and the receipt of a permit to operate. To maintain the operating permit, good plant monitoring, operations, and maintenance procedures are required.

11.8.8.1 Identify Applicable State and Local Regulations

New Source Review (NSR)

Combustion processes are subject to the NSR rule adopted by the California Air Resources Board (CARB) for application by the BAAQMD. NSR is required by the USEPA in the Bay Area and in other regions where clean air standards are violated. NSR governs the issuance of permits to construct new or modified stationary sources of air pollution.

The requirements apply only to facilities that would emit large amounts of pollutants. These requirements are that:

- The facilities must employ "best available (emission) control technology" (BACT), Section 1308(a)(154).
- The applicant must meet current air quality regulations regarding all sources of emission that it owns or operates in the Bay Area. Section 1307.1 (154).
- The applicant must offset proposed emission increases in NO_x, CO, and HC with more than equivalent restrictions at other sources in the region. Section 1309(a) (154).

The NSR rule is probably the most difficult environmental regulation facing the designer. The NSR rule requires that new stationary sources which emit pollutants above a certain criterion level be approved if they use BACT. The criterion levels are: 150 pound per day (68 kg/d) each for NO_x, SO_x, HC, and TSP; and 1,500 pound per day (681 kg/d) for CO. Below these levels, a permit may be granted without regard to NAAQS, and BACT need not be applied. A permit can be issued where BACT is used and the criterion is not met; however, the NSR rule allows no exemption from BACT.

Another requirement is that existing facilities owned or operated by the applicant must meet all air pollution regulations. Any wastewater treatment plant, or other facility operating under common ownership, must be upgraded to meet existing regulations before a new source can be added. Recent rulings make exemptions to this doubtful.

The third requirement of the NSR rule applies to stationary sources that will emit more than 250 pounds per day (114 kg/d) of NO_x, SO_x, HC, or TSP and more than 2,500 pounds per day (1135 kg/d) of CO. This requirement is intended to prevent the plant from contributing to violations or increased violations of the clean air standards. Since some standards in the Bay Area are already being violated, no sources with controlled emissions above this level can be built unless project proponents reduce emissions from another source, thus offsetting the air quality effects of the project. In other words, if BACT is employed, and if the emission level is above 250 pound per day (114 kg/d), the project cannot be built unless offsets are applied. The project proponents can offset the project's emissions by modifying other facilities to reduce emissions or by shutting down polluting facilities.

In the past, the BAAQMD has required that the offset facilities be in the vicinity of the proposed project so that the portion of the air basin surrounding the project receives the benefit of the offset. The rule also requires that the amount of emission reduction be slightly higher than the amount of emission increase anticipated from the project. The current offset amount is 1.2 times the emission. For example, an industry can purchase a paint shop presently discharging 500 pounds per day (227 kg/d) of hydrocarbons, close the shop, and credit the industry with: $500 \div 1.2 = 417$ pounds per day (184 kg/d).

The feasibility of offsets depends on the availability of suitable existing polluting plants, the cost of purchase or modification, and the public acceptability of the offset. If suitable plants are found, purchase of additional control devices to reduce emissions will probably be more politically acceptable than purchasing a privately owned facility and closing it down. The cost of any of these alternatives would be extremely high.

The alternative route for a large-scale plant would be to obtain an exemption from the offset portion of the new source review rule. The rule provides exemptions for a new stationary source that "represents a significant advance in the development of a technology that appears to offer extraordinary environmental or public health benefits or other benefits of overriding importance to the public health or welfare." An exemption granted by the BAAQMD would require concurrence of CARB and the USEPA. While an exemption may be provided, the likelihood that one would be given at the present time is slight. Facilities that potentially represent an advance in technology are normally reviewed at the USEPA headquarters in Washington, D.C., rather than locally.

The BAAQMD is seriously considering adoption of an NSR rule that would apply the offset requirement only to CO and HC, but not to NO_x. This is important to any combustion process proposed, because NO_x control is unproven and very costly. BACT would continue to apply as previously stated.

Prevention of Significant Deterioration (PSD)

The USEPA prevention of significant deterioration rule is designed to prevent increases in air pollutant concentrations that are below the national health standards in a particular air basin. This is in contrast to the New Source Review Rule designed to prevent increases in levels of air pollutants that already exceed standards. In the San Francisco Bay Area, levels for two pollutants, particulates and sulfur dioxide, are below or better than standards. If BACT is applied, as required by NSR, and if controlled emissions of SO_2 or TSP do not exceed the 50-ton per year (45-t/yr) criterion level, PSD will add no additional constraints.

New Source Performance Standards (NSPS)

Sludge incinerators will be subject to BAAQMD NSPS regulations. These limits are 1.30 pound per ton (0.65-kg/t) of dry solids, with gas discharge of not more than 20 percent opacity.

Limitation on Pollutant Concentrations

The BAAQMD requires, as do many other jurisdictions, that the concentration of major pollutants in the gas stream (NO_x, SO_x, HC, TSP, and CO) be limited to some maximum value. The limits established for the San Francisco Bay Area are shown in Table 11-26. If supplemental fuel is used in an incinerator, a correction is required to remove the product of combustion of the fuel from the calculation. Note that the concentrations shown in Table 11-26 are based upon concentrations per standard dry cubic foot (m^3 dry) corrected to a standard of six percent oxygen. This correction is applied in the design portion of this example, 11.8.6.3. Regulatory agencies vary in their treatment of these corrections, but generally, all require the gas volumes to be corrected to some standard concentration of CO_2 (usually 12 percent) or O_2 (usually six or nine percent). Some require a supplemental fuel correction, which can have a significant effect on the allowable emissions.

11.8.8.2 Establish Air Pollution Abatement Procedures

Requirements

The designer of an incineration facility must develop the following information about the flue gas characteristics before control devices can be designed: total flue gas flow rate, flue gas temperature, particle size distribution, chemical composition of emissions, corrosiveness of gas over the operating range, and moisture content.

TABLE 11-26

SAN FRANCISCO BAY AREA - MAXIMUM ALLOWABLE POLLUTANT CONCENTRATIONS (155)

Component[a]	Concentration[b]
Particulates	0.05[c]
SO_x	300[d]
NO_x	175[d,e]
HC[f]	25[d]

[a]BAAQMD Regulation 2.

[b]All concentrations per dry standard cubic foot corrected to 6 percent O_2.

[c]Grains/sdcf (2.3 std g/m^3).

[d]ppm.

[e]Fuel oil fired - there is no BAAQMD standard for solid fuel.

[f]Nonmethane hydrocarbons.

Until recently, municipal sewage sludge furnaces have been subject only to particulate emission controls. Therefore, limited basic data are available on emission rates of SO_x and NO_x from sewage sludge furnaces. Table 11-27 presents the available data on uncontrolled emissions from multiple-hearth furnaces.

The following calculations and discussions are based on Alternative IIIA (50-MGD [2.2-m^3/s] plant flow with a sludge solids concentration of 20 percent), as developed in Section 11.2.4 (Table 11-9). The incinerator considered is the multiple-hearth furnace (MHF) operated in the incineration mode. Auxiliary fuel is assumed to be natural gas. Where local regulations apply, the BAAQMD rules are used (see Section 11.8.8.1 and Table 11-26 and Figure 11-45). Figure 11-45 is excerpted from the BAAQMD rules. Installations under other jurisdictions will presumably have different regulations:

Step 1 - Calculate Uncontrolled Emissions of Criteria Pollutants

a. Quantity of dry sludge solids = 51.5 ton/day (46.7 t/d).

b. From Table 11-27, daily emissions are:

Particulates: $\frac{51.5 \text{ tons dry solids}}{\text{day}} \times \frac{33 \text{ pound}}{\text{ton dry solids}}$

= 1,700 pound/day (771.8 kg/d)

SO_2: $\frac{51.5 \text{ tons dry solids}}{\text{day}} \times \frac{1 \text{ pound}}{\text{ton dry solids}}$

= 51.5 pound/day (23.4 kg/d)

NO_x: $\frac{51.5 \text{ tons dry solids}}{\text{day}} \times \frac{5 \text{ pound}}{\text{ton dry solids}}$

= 257.5 pound/day (116.9 kg/d)

HC: $\frac{51.5 \text{ tons dry solids}}{\text{day}} \times \frac{1 \text{ pound}}{\text{ton dry solids}}$

= 51.5 pound/day (23.4 kg/d)

TABLE 11-27

UNCONTROLLED EMISSION RATES FROM MULTIPLE-HEARTH FURNACES (157)

Pollutant	Emission factor, lb/ton dry sludge solids
Particulates	33.0
SO_x	1.0
NO_x	5.0
Hydrocarbons	1.0
CO	0.0

1 lb/ton = 0.50 kg/tonne

Step 2 - Calculate Degree of Control Required to Meet NSPS

NSPS deals only with particulate emissions (other pollutants are covered by NSR).

a. NSPS = 1.3 lb particulates/ton (0.65 kg/t)

b. Allowable particulates: $\frac{1.3 \text{ pound}}{\text{ton}} \times \frac{51.5 \text{ ton solids}}{\text{day}}$

= 67 pound/day (30.4 kg/d)

c. Required particulate removal efficiency:

$$1 - \frac{67 \text{ pound day}}{1{,}700 \text{ pound day}} \times 100 \text{ percent} = 96.1 \text{ percent}$$

DIVISION 8 — CALCULATION METHODS AND GENERAL SAMPLING PROCEDURES

CHAPTER 1 — CALCULATIONS

§ 8100 Calculation of **emissions** of air contaminants shall be accomplished by the calculation methods prescribed in this Chapter 1, or by methods which yield equivalent results. All calculation methods not specifically prescribed in this regulation shall conform to accepted engineering practice.

§ 8110 Correction for the use of **auxiliary fuel** shall be as specified in § 8111, and correction to a basis of 6% oxygen by dry volume shall be as specified in § 8112. For the purposes of §§ 8111 and 8112 the term "measured volume" shall mean the emitted or metered volume to be corrected, expressed in **standard cubic feet.**

§ 8111 AUXILIARY FUEL CORRECTION. This calculation is intended to correct the measured volume to the volume which would have existed if the **auxiliary fuel** had not been introduced, and results obtained by this procedure shall be deemed to represent such correction. The method consists of four steps:

(a) Calculate the amount of oxygen required for stoichiometric **combustion** of the **auxiliary fuel,** at the rate of **combustion** occurring during the period of test.

(b) Calculate the composition and quantity of the products of such stoichiometric **combustion** in oxygen.

(c) Add, to the measured volume, the amount of oxygen calculated in step (a)

(d) Subtract, from the result of step (c), the volume of **combustion** products calculated in step (b); the result is the measured volume corrected for **auxiliary fuel** use.

EXAMPLE: Assume that the gases emitted from an operation using **auxiliary fuel** total 400,000 **standard cubic feet** during a test period, and have a composition as shown in the "measured" column of the tabulation below. Assume further that **auxiliary fuel** usage during the test is 6,000 **standard cubic feet** of methane, CH_4

(a) Stoichiometric **Combustion** of **Auxiliary Fuel**

$$\underset{6{,}000}{CH_4} + \underset{12{,}000}{2O_2} \longrightarrow \underset{6{,}000}{CO_2} + \underset{12{,}000}{2H_2O}$$

12,000 **standard cubic feet** of oxygen required.

(b) 18,000 **standard cubic feet** of combustion product.
6,000 **standard cubic feet** CO_2, 12,000 **standard cubic feet** H_2O

(c) 400,000 + 12,000 = 412,000

(d) 412,000 − 18,000 = 394,000 **standard cubic feet**

TABULATION OF VOLUME CHANGE (SCF)

Component	Measured	Correction	Final
CO_2	40,000	− 6,000	34,000
CO	8,000		8,000
O_2	21,600	+ 12,000	33,600
N_2	281,200		281,200
H_2O	49,200	− 12,000	37,200
Total	400,000	− 6,000	394,000

§ 8112 OXYGEN CORRECTION This calculation is intended to correct the measured concentration of an air contaminant to that which would exist if the same quantity of air contaminant were contained in a dry volume corrected to an oxygen content of 6%; and results obtained by this procedure shall be deemed to represent such correction. Where correction for the use of **auxiliary fuel** is applicable, the volume and composition resulting from the correction procedure of § 8111 shall be taken as the measured volume for purposes of this section 8112. The method consists of six steps:

(a) Subtract any water vapor content of the measured volume, to give a dry volume.

(b) Calculate the oxygen content of the measured volume as a decimal fraction of the dry volume obtained in step (a).

(c) From the figure 0.2095 (average atmospheric oxygen content) subtract the decimal fraction of oxygen as obtained in step (b).

(d) Divide the result of step (c) by 0.1495. (This is 0.2095 − 0.06.)

(e) Multiply the dry volume obtained in step (a) by the quotient obtained in step (d) to give the corrected dry volume on a 6% oxygen basis.

(f) Divide the weight of air contaminant, in grains, by the corrected volume obtained in step (e) to give the corrected concentration.

Example:
Assume an emitted gas composition as follows:

Component	% (Vol., wet)	% (Vol., dry)	SCF
CO_2	8.64	9.53	34,000
CO	2.03	2.24	8,000
O_2	8.53	9.42	33,600
N_2	71.36	78.81	281,200
H_2O	9.44	0.00	37,200
Total	100.00	100.00	394,000

Also assume the weight of air contaminant is 7.9 pounds.

(a) 394,000 − 37,200 = 356,800 SCF, dry volume

(b) $\frac{33{,}600}{356{,}800} = 0.0942$, volume fraction of oxygen

(c) 0.2095 − 0.0942 = 0.1153

(d) $\frac{0.1153}{0.1495} = 0.782$

(e) (0.782) (356,800) = 275,800 SDCF, at 6% oxygen, the corrected volume.

(f) $\frac{(7.9 \text{ lb})\ (7000 \text{ gr/lb})}{275{,}800 \text{ SDCF}} = 0.20$ gr/SDCF, the corrected concentration.

Where a concentration subject to this correction is based on a measured volume, the correction shall consist of multiplying the concentration by the ratio of the measured volume to the corrected volume obtained in step (e) above.

FIGURE 11-45

SAN FRANCISCO BAY AREA AIR QUALITY MANAGEMENT DISTRICT: AUXILIARY FUEL AND OXYGEN CORRECTION (155)

Step 3 - Select The Control Device for Satisfying NSPS

The actual selection of an emission control device is beyond the scope of this manual. Equipment selection can be quite involved and complex. Several excellent publications are listed in the references to provide a detailed understanding of emission control equipment (158-161). A number of publications are available in the literature for further detail on theory, specific furnaces, and combustion (1,4,8,9,11,12,14,17,23,38,46, 58,61,74,98,105,141,158-181). Additional sources for detailed information include furnace manufacturers, emission control device manufacturers, operating installations, and air quality control consultants.

In this design example, a venturi followed by a tray-type wet scrubber is selected. BAAQMD considers this equipment BACT.

Step 4 - Check Conformance with the New Source Review Rule (NSR)

a. The BAAQMD requires that all pollutants be below 150 pound per day (68.1 kg/d), except CO which is 1,500 pound per day (681 kg/d) (unless BACT is applied). As per Step 1, SO_2, HC, and CO meet this requirement, even as uncontrolled emissions and need not be considered further under NSR.

   Particulates and NO_x require BACT. Since the venturi and wet scrubber combination is considered BACT for particulates, the particulates criterion is satisfied.

   The venturi-scrubber combination will also reduce NO_x to a certain extent. The NO-NO_2 distribution in flue gas for sewage sludge incinerators is not well known. For general combustion, NO_2 content represents 10 to 20 percent of the NO_x and can be effectively removed by the wet scrubber. Assuming that a ten percent NO_2 component of NO_x is removed by scrubbing, the NO_x emission rate drops to 232 pounds per day (105 kg/d).

   At present, very few control processes are effective in reducing NO_x emissions. However, major research efforts are being made to solve the problem. The process with the best potential has been developed and tested in Japan only. It is a patented catalytic ammonia injection process which reduces NO_x by 90 percent. Current research in the United States has been conducted only on a small scale. Therefore, in effect, there are no fully developed, available NO_x control devices. Until full-scale systems for NO_x control are tested, an exemption or variance will probably be granted.

   Another potential way to reduce NO_x is via combustion-controlled processes such as SAC, reduction of excess air, and staged combustion. Firm data are not available with sewage sludge feed. Presently it is not known if the 150 pounds per day (68.1 kg/day) criterion for NO_x can be met by combustion control.

b. Check to see if emissions exceed the 250 pounds per day (114 kg/d) level at which offsets must be obtained. In this example, the levels are below 250 pounds per day (114 kg/d); thus offsets are not required.

Step 5 - Check that Concentrations of Criteria Pollutants Do Not Exceed Regulatory Standards

The objective is to calculate pollutant concentrations at some standard condition, so that the particulate emission can be compared with emissions from other sources on an equivalent basis. This correction is made by first calculating pollutant gas flow (under standard conditions), then calculating total standard exhaust gas flow and correcting the latter for auxiliary fuel. Finally, the pollutant concentrations are calculated to a six percent oxygen basis. A detailed calculation for hydrocarbons (HC) is presented below. It is assumed that HC are not removed in the wet scrubbing system.

a. Calculate the volumetric HC flow at standard temperature and pressure (STP). The volumetric flow rate of HC is calculated as:

$$\frac{51.5 \text{ pound HC}}{\text{day}} \times \frac{\text{pound mole HC}}{28 \text{ pound HC}}$$

$$\times \frac{359 \text{ cu ft}}{\text{pound mole at STP}} \times \frac{\text{day}}{1440 \text{ min.}}$$

$= 0.46$ standard cfm (2.17×10^{-4} std m^3/s)

It is assumed HC are ethylene with a molecular weight of 28.

b. Calculate exhaust gas flow at STP. The data in Table 11-28 are available. Off gas temperature and pressure are 800°F (427°C) and one atmosphere respectively. The pollutant (NO_x, SO_2, HC, CO, particulate) masses are small compared to the masses of the constituents in Table 11-28 and thus were ignored in calculating exhaust gas volume.

Total volumetric flow rate of the exhaust stream, wet basis; reduced to standard conditions:

$$= 44{,}403 \text{ scfm} \times \frac{60°F + 460°F}{800°F + 460°F}$$

$= 18{,}325$ scfm (8.65 std m^3/s)

Note: standard conditions are taken to be 60°F (16°C) and one atmosphere.

c. Correct for auxiliary fuel (See Figure 11-45 and Table 11-29). The intent of this calculation is to correct the measured exhaust gas volume to the volume that would have existed had auxiliary fuel not been introduced. Assume here that 100 scfm (4.72×10^{-2} std m^3/s) of natural gas was used. The combustion of 100 scfm (4.72×10^{-2} std m^3/s) of natural gas is depicted by the following equation:

$$\underset{100 \text{ scfm}}{CH_4} + \underset{200 \text{ scfm}}{2O_2} \longrightarrow \underset{100 \text{ scfm}}{CO_2} + \underset{200 \text{ scfm}}{2H_2O}$$

The auxiliary fuel correction procedure is:

1. Calculate the amount of oxygen, 200 scfm (0.09 std m^3/s) for stoichiometric combustion of auxiliary fuel.

2. Calculate the quantity of combustion products 300 scfm (0.14 std m^3/s).

3. Add the oxygen calculated, 200 scfm (0.09 std m^3s) to the measured gas volume 18,325 scfm (8.65 std m^3/s), then subtract the volume of combustion products calculated in Step 5c2, 300 scfm (0.14 std m^3/s). The sum, 18,225 scfm (8.60 std m^3/s), is gas volume corrected for auxiliary fuel (see Table 11-29).

d. Correct for oxygen (see Figure 11-45). The intent of this calculation is to correct the measured concentration of contaminant to that which would exist were the same quantity of contaminant contained in a dry volume, corrected to six percent oxygen. All calculations are based on the final flow rate at STP per Table 11-28. The procedure is as follows:

1. Subtract the volume of water vapor, 7,056 scfm (3.33 std m^3/s) from the final volume, 18,225 scfm (8.60 std m^3/s), to give the dry volume, 11,169 scfm (5.27 std m^3/s).

2. Calculate the oxygen content as a decimal fraction of the dry volume:

$$\frac{1{,}156 \text{ scfm}}{11{,}169 \text{ scfm}} = 0.1035 \ O_2$$

3. Subtract the decimal fraction calculated in Step 5d2 from the 0.2095 (average atmospheric oxygen content): 0.2095 - 0.1035 = 0.1060.

4. Divide the result of Step 5d3 by 0.1495 (this is 0.2095 - 0.06):

$$\frac{0.1060}{0.1495} = 0.709$$

5. Multiply the dry volume obtained in 5d1, 11,169 scfm (5.27 std m^3/s), by the quotient obtained in Step 5d4, 0.7090, to get the corrected dry volume on a six percent oxygen basis:

0.7090 x 11,169 scfm = 7,919 scfm (3.74 std m^3/s)

6. Divide the volumetric HC flow of Step 5a, 0.46 scfm (2.17×10^{-4} std m^3/s) by the corrected dry volume on a six percent basis to obtain concentration on a six percent basis:

$$\frac{0.46 \text{ scfm}}{7{,}919 \text{ scfm}} \times 10^6 = 58 \text{ ppm}$$

TABLE 11-28

DESIGN EXAMPLE: EXHAUST GAS DATA FROM A MULTIPLE-HEARTH FURNACE

Constituent	lb/hr	Percent of total gas volume	Actual CFM
CO_2	7,749	6.1	2,712
N_2	39,623	49.1	21,793
O_2	4,813	5.2	2,315
Water vapor	20,551	39.6	17,583
Total	72,736	100.0	44,403

1 lb/hr = 0.45 kg/hr
1 cfm = 0.028 m^3/min

TABLE 11-29

DESIGN EXAMPLE: AUXILIARY FUEL CORRECTION FOR A MULTIPLE-HEARTH FURNACE[a]

Component	Percent of total gas volume	CFM at STP	Correction	Final CFM at STP[b]
CO_2	6.1	1,119	-100	1,019
N_2	49.1	8,994		8,994
O_2	5.2	956	+200	1,156
Water vapor	39.6	7,256	-200	7,056
Total	100.0	18,325	-100	18,225

[a]See Step 5(c).
[b]STP = Standard temperature and pressure = 60°F (15.6°C) at one atmosphere.

1 cfm = 0.028 m^3/min

Step 6 - Compare Calculated Pollutant Concentrations Against Emission Standards (Table 11-30)

The emissions standard is 25 ppm. The HC limit is exceeded and afterburning will be required.

From similar calculations, the concentrations in Table 11-30 are obtained (corrected to six percent oxygen and auxiliary fuel, prior to afterburning).

None of the other pollutants (particulates, NO_x, SO_x) are in violation of concentration standards.

TABLE 11-30

DESIGN EXAMPLE: MULTIPLE-HEARTH FURNACE POLLUTANT CONCENTRATIONS AFTER SCRUBBING[a]

Pollutant	Concentration	Standard
Particulates, grains/sdcf	0.04	0.05
HC[b], ppm	58[c]	25
NO_x[d], ppm	147	175
SO_x[e], ppm	17	300

[a]Corrected for auxiliary fuel and to 6 percent oxygen.

[b]As ethylene.

[c]Does not include afterburning.

[d]As NO_2.

[e]As SO_2.

1 grain/sdcf = 2.3 std g/m^3

Step 7 - Summary

A venturi, wet tray-type scrubber and afterburning will satisfy all emission requirements except NSR requirements for NO_x. An exemption is expected for NO_x, since technology for NO_x removal is not sufficiently developed for field applications. Note that not all jurisdictions require auxiliary fuel and oxygen corrections. As shown, the corrections can have profound impacts. The type of control scheme required may hinge upon the regulatory agency's decision as to whether such corrections are necessary. The procedures used in Step 5 were taken directly from Regulation 2 of the BAAQMD Regulations (155).

11.9 Residue Disposal

The residues remaining after sludge combustion (ash, particulates from dry scrubbing, etc.) must be disposed of. Due to the drain of natural resources, the constructive utilization of residues, particularly ash, is undergoing considerable research. Because the ash concentrates the setteable material in wastewater, there is an interest in recovering valuable scarce metals such as gold. In Palo Alto, California, a firm is working on methods to recover such metals from the ash (182). In this case, recovery may be cost-effective, since the treatment plant receives the wastewater from many electronics firms and the scarce metal content is high. In general, however, there is no economical process to use ash; consequently, it is typically disposed of to a landfill.

Residues (ash) from the combustion of municipal wastewater solids generally contain high concentrations of trace metals. Leachate from sites where incinerator ash is landfilled must be controlled to prevent metal contamination of groundwater. Many states are beginning to classify disposal sites according to their relationship to nearby groundwater and the material to be landfilled. Tables 11-31 and 11-32 describe methods used by the State of California for classifying waste materials and disposal sites. Typically, wastewater sludge furnace ash requires a "protected" Class II-1 site and municipal refuse incinerator ash requires a hazardous fill site. These are described on Table 11-32. Outside these broad classifications, the ash will require sampling and analysis, including detailed review by state and local health agencies. A serious problem, however, is that no standard analyses or procedures are presently available that allow a particular ash to be classified (leachability of certain contaminants at various pH's and over different times). This type of analysis is expensive, and the results are difficult to interpret. No data base is available to compare the laboratory results with actual field conditions. Work is being done in this area and hopefully proper procedures and guidelines will be developed.

Detailed design and operating data are beyond the scope of this manual. More detailed discussions on landfilling ash and sludge landfilling procedures can be found in the literature (184,185,186).

TABLE 11-31

DESCRIPTION OF SOLID AND LIQUID WASTE CLASSIFICATIONS (183)

Group 1	Group 2	Group 3
Consist of or contain toxic substances and substances which could significantly impair the quality of usable waters. Examples include: • Saline fluids from water or waste treatment processes • Community incinerator ashes • Toxic chemical toilet waste • Industrial brines • Toxic and hazardous fluids • Pesticides or chemical fertilizers or their discarded containers • Other toxic wastes	Consist of or contain chemically or biologically decomposable material which does not include toxic substances nor those capable of significantly impairing the quality of usable waters. Examples include: • Garbage • Rubbish • Construction debris such as paper, cardboard, rubber, etc. • Refuse such as yard clippings, litter, glass, etc. • Dead animals • Abandoned vehicles • Sewage treatment residue such as solids from screenings and grit chambers, dewatered sludge, and septic tank pumpings • Infectious materials from hospitals or laboratories	Consist entirely of nonwater soluble, nondecomposable inert solids. Examples include: • Construction and demolition debris, asphalt paving, inert plastics, etc. • Vehicle tires • Industrial wastes such as clay products, glass, slags, tailings, etc

TABLE 11-32

CLASSIFICATION OF WASTE DISPOSAL SITES (183)

Class I	Class II	Class III
Class I disposal sites are those at which complete protection is provided for all time for the quality of ground and surface waters from all wastes deposited therein and against hazard to public health and wildlife resources. The following criteria must be met to qualify a site as Class I: (a) Geological conditions are naturally capable of preventing vertical hydraulic continuity between liquids and gases emanating from the waste in the site and usable surface or groundwaters. (b) Geological conditions are naturally capable of preventing lateral hydraulic continuity between liquids and gases emanating from wastes in the site and usable surface or groundwaters, or the disposal area has been modified to achieve such capability. (c) Underlying geological formations which contain rock fractures or fissures of questionable permeability must be permanently sealed to provide a competent barrier to the movement of liquids or gases from the disposal site to usable waters. (d) Inundation of disposal areas shall not occur until the site is closed in accordance with requirements of the regional board. (e) Disposal areas shall not be subject to washout. (f) Leachate and subsurface flow into the disposal area shall be contained within the site unless other disposition is made in accordance with requirements of the regional board. (g) Sites shall not be located over zones of active faulting or where other forms of geological change would impair the competence of natural features or artifical barriers which prevent continuity with usable waters. (h) Sites made suitable for use by man-made physical barriers shall not be located where improper operation or maintenance of such structures could permit the waste, leachate, or gases to contact usable ground or surface water. (i) Sites which comply with a, b, c, e, f, g, and h, but would be subject to inundation by a tide or a flood of greater than 100-year frequency may be considered by the regional board as a limited Class I disposal site.	Class II disposal sites are those at which protection is provided to water quality from Group 2 and Group 3 wastes. The types of physical features and the extent of protection of groundwater quality divides Class II sites into the two following categories: Class II-1 sites are those overlying usable groundwater and geologic conditions are either naturally capable of preventing lateral and vertical hydraulic continuity between liquids and gases emanating from the waste in the site and usable surface or groundwaters, or the disposal area has been modified to achieve such capability. Class II-2 sites are those having vertical and lateral hydraulic continuity with usable groundwater but for which geological and hydraulic features such as soil type, artificial barriers, depth to groundwater, and other factors will assure protection of the quality of usable groundwater underneath or adjacent to the site. The following criteria must be met to qualify a site as Class II: (a) Disposal areas shall be protected by natural or artificial features so as to assure protection from any washout and from inundation which could occur as a result of tides or floods having a predicted frequency of once in 100 years. (b) Surface drainage from tributary areas shall not contact Group 2 waters in the site during disposal operations and for the active life of the site. (c) Gases and leachate emanating from waste in the site shall not unreasonably affect groundwater during the active life of the site. (d) Subsurface flow into the site and the depth at which water soluble materials are placed shall be controlled during construction and operation of the site to minimize leachate production and assure that the Group 2 waste material will be above the highest anticipated elevation of the capillary fringe of the groundwater. Discharge from the site shall be subject to waste discharge requirements.	Class III disposal sites are those at which protection is provided to water quality from Group 3 wastes by location, construction, and operation which prevent erosion of deposited material.

Combustion Calculations—Molal Basis

LINE	Fuel Constituent	Per Fuel Unit, lb	Mol. Wt Divisor	Moles Fuel Constituent	O_2 Multiplier	O_2 Moles Theo Reqd	CO_2 + SO_2	O_2	N_2	H_2O	CO
	Fuel, O_2, and Air per Unit of Fuel						**Flue Gas (F.G.) Composition Moles per Fuel Unit (AF)**				
1	C to CO_2		12		1						
2	C to CO		12		.5						
3	CO to CO_2		28		.5						
4	C unburned, line k		12								
5	H_2		2		.5						
6	S		32		1						
7	O_2 (deduct)		32		1						
8	N_2		28			0					
9	CO_2		44			0					
10	H_2O		18			0					
11	Ash					0					
12	Sum	100.0									

O_2 and Air, Moles for Total Air = % (see line d at right)

LINE		
13	O_2 (theo) reqd = O_2, line 12	
14	O_2 (excess) = $\frac{T.A. - 100}{100} \times O_2$, line 12	
15	O_2 (total) supplied = lines 13 + 14	
16	N_2 supplied = 3.76 × O_2, line 15	
17	Air (dry) supplied = O_2 + N_2	
18	H_2O in air = moles dry air × $\frac{A}{B-A}$ *	
19	Air (wet) supplied = lines 17 + 18	
20	Flue gas constituents = lines 1 to 18, total	
21	*Note—for air at 80 F and 100% relative humidity, $\frac{A}{B-A}$ = 0.037 is often used as standard.	

Conditions—Assigned or Observed and Miscellaneous

Date

	LINE
Fuel Source Fuel Unit {100 lb, solid or liquid fuels; 100 moles, gaseous fuels	
Fuel Anal. as Fired (AF), % by Wt or Vol	a
C *H_2* *S* *O_2* *N_2* *H_2O* *Ash* *100.0*	b
CO_2 O_2 CO N_2 %†	c
Total air (T.A.) assigned or by ORSAT %	d
Lines f, g, h For Gaseous Fuels	e
Wt. fuel unit = Σ (moles each × mol. wt) lb	f
Mol. wt of fuel = line f ÷ 100	g
Density of fuel @ 80 F & 30 in. = $\frac{\text{line g}}{394}$ $\frac{\text{lb}}{\text{cu ft}}$	h
Fuel heat value, Btu/lb ††	i
Combustible in refuse, % "C"	j
Carbon unburned, lb/100 lb fuel = % ash in fuel × $\frac{\text{\% "C"}}{100 - \text{\% "C"}}$	k
Exit temp of flue gas, t_2 F	l
Dry-bulb (ambient) temp, t'_1 F	m
Wet-bulb temp F	n
Rel humid. (psychrometric chart) %	o
B*, barometric pressure, in. Hg	p
Sat. press. H_2O at amb temp, in. Hg	q
A*, press. H_2O in air, lines (o × q), in. Hg	r
Total Moles / Wet Flue Gas / Dry Flue Gas	s

Determination of Flue Gas and Combustible Losses in Btu per Fuel Unit (AF)

LINE		CO_2+SO_2	O_2	N_2	H_2O	CO	Total
22	Flue gas constituents						
23	Mc_p, mean, t_2 to t'_1 (for t'_1 =						
24	In dry flue gas = moles each, line 20 × Mc_p × ($t_2 - t'_1$)						
25	In H_2O in air = moles H_2O, line 18 × Mc_p × ($t_2 - t'_1$)						
26	In sens heat, H_2O in fuel = moles, lines (5 + 10) × Mc_p × ($t_2 - t'_1$)						
27	In latent heat, H_2O in fuel = moles, lines (5 + 10) × 1040 × 18						
28	Total in wet flue gas						
29	Due to carbon in refuse = line k × 14,100						
30	Due to unburned CO in flue gas = moles C to CO × 12 × 9,755						
31	Total flue gas losses + unburned combustible = lines 28 + 29 + 30 + radiation †††					Total	
32	Heat value of fuel unit = 100 × line i for solid and liquid fuels; 394 × line i × 100, for gaseous fuels						
33	**Total excess heat per fuel unit = line 32 − line 31**						

† Flue gas analysis by ORSAT. If CO is present in flue gases, a carbon balance is used to determine distribution of C, thus:
All C in fuel = C in flue gas constituents + C in refuse. Moles C in fuel = % C by analysis ÷ 12.
Moles C in refuse = line k÷12. Moles C in CO_2 = (moles C in fuel − moles C in refuse) x % CO_2 by ORSAT ÷ % (CO_2 + CO) by ORSAT.
Moles in C in CO = moles C in fuel − moles C in refuse − moles C in CO_2.

†† By Dulong formula (11-1) or by calorimetry.

††† Radiation assumed to be a fixed percent of line 28, normally 2 to 5 percent.

GENERAL NOTES:

- **See text for use of table.**
- **Refuse, as used in this table, is the residue (ash) from the process.**

1 lb = 0.45 kg
1 in. = 2.54 cm
1 Btu/lb = 2,324 J/kg
1 lb/cu ft = 16 kg/m³

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PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 12. Composting

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 12

COMPOSTING

12.1 Introduction

Although sludges have been composted as a minor constituent of refuse in many countries since the early 1900s, only since the early seventies has major attention been directed to composting of municipal wastewater sludges in the United States.

A major study of the composting of wastewater sludges was conducted at Salt Lake City from 1967 to 1969 (1). This work was followed in 1972 by research at pilot-scale wastewater sludge composting facilities at the USDA Agricultural Research Center at Beltsville, Maryland (2-4) and full-scale operations at County Sanitation Districts of Los Angeles County plant at Carson, California. Based on the operating experiences and developments at these plants, new projects were undertaken at Bangor, Maine (5); Durham, New Hampshire (6); and Windsor, Ontario (7). A number of other plants are in various phases of planning or development.

Sludge composting is the aerobic thermophilic decomposition of organic constituents to a relatively stable humus-like material (8). Environmental factors influence the activities of the bacteria, fungi, and actinomycetes in this oxidation decomposition process and affects the speed and course of composting cycles. The volatility and type of material, moisture content, oxygen concentration, carbon/nitrogen ratio, temperature, and pH are key determinants in the process (9). Sludge is not rendered totally inert by composting. The composting process is considered complete when the product can be stored without giving rise to nuisances such as odors, and when pathogenic organisms have been reduced to a level such that the material can be handled with minimum risk.

Compost produced from municipal wastewater sludges can provide a portion of the nutrient requirements for growth of crops. The organic matter in compost is particularly beneficial as a soil conditioner, because it has been stabilized, decomposes slowly, and remains effective for a longer time than the organic matter in uncomposted wastes. Composted sludge can improve the quality of soils containing excessive amounts of sand or clay as well as already more balanced soils. Improved physical properties include:

- Increased water content for sandy soils
- Increased water retention for sandy soils

- Enhanced aggregation
- Increased aeration for clay soils
- Increased permeability for clay soils
- Increased water infiltration for clay soils
- Greater root depth
- Increased microbial population
- Decreased surface crusting (10)

The persistence of organic chemicals, pathogenic organisms, or heavy metals in some composted sludges may restrict the use of the material for application to crops for human consumption (8,11). The composting process results in a significant nitrogen reduction within the wastewater sludge and, therefore, a reduced amount of nitrogen available to the soil and plants.

Processes for composting wastewater sludge differ from those for composting refuse. There are several principal advantages of sludge composting as compared to refuse composting. Sludge composting does not require the complex materials management and separation techniques necessary for most refuse composting operations. Municipal wastewater sludge is more uniform in composition causing less operating difficulties. The final composted mixture utilizing sludge is more suitable for marketing because it generally does not contain the plastics, metal, and glass commonly found in refuse compost. Sludge composting is often viewed as an alternative disposal method and does not have to be evaluated on profit-making potential as some refuse composting operations have been.

Classical and new solid waste composting techniques have been modified for sludge composting. These can be classified as:

- Unconfined processes
  - Windrow
  - Aerated static pile
    - Individual pile
    - Extended pile
- Confined processes

Unconfined processes are not enclosed, although a roof may be provided to protect the compost from precipitation. Unconfined processes make use of portable mechanical equipment such as front-end loaders or mixers for compost mixing and turning. Confined systems utilize a stationary-enclosed container or reactor for composting.

12.2 The Composting Process

Although each composting technique is unique, the fundamental process is similar. The basic process steps are as follows:

- If required, bulking agents for porosity and moisture control (for example, recycled compost, wood chips, etc.) or feed amendments for a source of limiting nutrients such as carbon (for example, sawdust, rice hulls, etc.) are added to the dewatered sludge to provide a mixture suitable for composting. The mixture must be porous, structurally stable, and capable of self-sustaining the decomposition reaction.

- A temperature in the range of 130° to 150°F (55° to 65°C) is attained to ensure destruction of pathogenic organisms and provide the driving force for evaporation, which reduces the moisture content.

- The compost is stored for extended periods after the primary composting operation to further stabilize the mixture at lower temperatures.

- Additional air drying (for example, windrowing) may be required if the cured compost is too wet for further processing.

- When bulking agents are reused, a separation operation is required.

Composting represents the combined activity of a succession of mixed populations of bacteria, actinomycetes, and other fungi associated with a diverse succession of environments. Moisture, temperature, pH, nutrient concentration, and availability and concentration of oxygen supply are principal factors which affect the biology of composting (12).

12.2.1 Moisture

Decomposition of organic matter is dependent upon moisture. The lowest moisture content at which bacterial activity takes place is from 12 to 15 percent; however, less than 40 percent moisture may limit the rate of decomposition. The optimum moisture content is in the range of 50 to 60 percent. If the mixture is over 60 percent water, the proper structural integrity will not be obtained.

Dewatered municipal sludges are usually too wet to satisfy optimum composting conditions. The moisture content can be reduced by blending the sludge with a dry bulking material or a recycled product, and dewatering the sludge to as great an extent as economically possible. The best approach for a particular site can be determined from a mass balance of the particular composting facility and by a site-specific economic analysis based on the mass balance results. Figure 12-1 illustrates the effect of the solids content of dewatered sludge on the required mixing ratio of wood chips to sludge by volume for one compost operation. The amount of wood chips needed for a 40 percent filter cake would be about one-fifth the amount required for a 20 percent solids cake. In addition to savings on wood chips, there would be a substantial reduction in material management costs and site sizes (13).

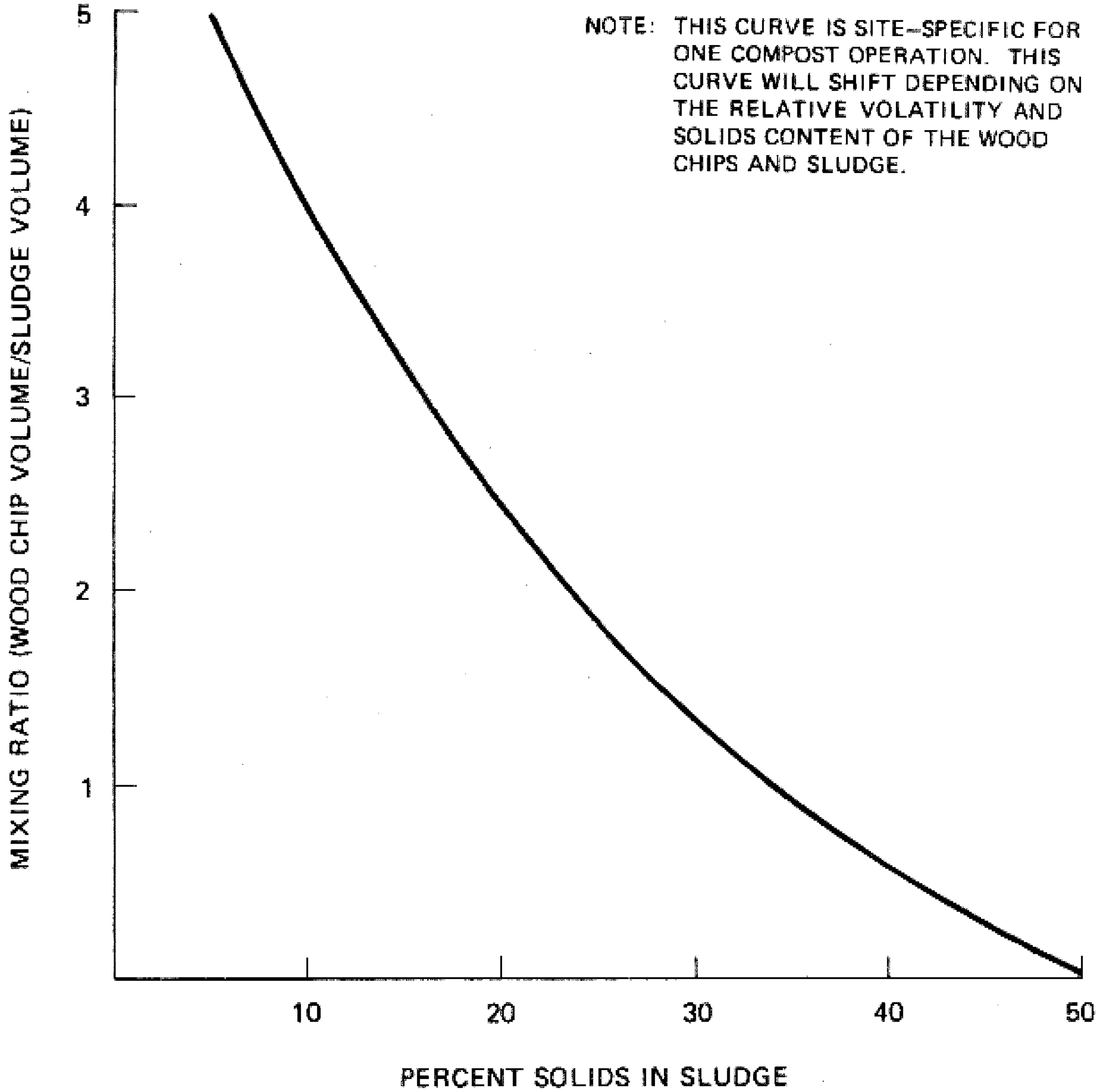


FIGURE 12-1

EFFECT OF SOLIDS CONTENT ON THE RATIO OF WOOD CHIPS TO SLUDGE BY VOLUME (14)

12.2.2 Temperature

For most efficient operation, composting processes depend on temperatures of from 130° to 150°F (55° to 65°C) but not above 176°F (80°C). High temperatures are also required for the inactivation of human pathogens in the sludge. Moisture content, aeration rates, size and shape of pile, atmospheric conditions, and nutrients affect the temperature distribution in a compost pile. For example, temperature elevation will be less for a given quantity of heat released if excessive moisture is present, as heat will be carried off by evaporation. On the other hand, low moisture content will decrease the rate of microbial activity and thus reduce the rate of heat evolution.

12.2.3 pH

The optimum pH range for growth of most bacteria is between 6 and 7.5 and between 5.5 and 8.0 for fungi (14). The pH varies throughout the pile, and throughout the composting operation, but it is essentially self regulating. A high initial pH resulting from the use of lime for dewatering will solubilize nitrogen in the compost and contribute to the loss of nitrogen by ammonia volatilization. It is difficult to alter the pH in the pile for optimum biological growth, and this has not been found to be an effective operation control.

12.2.4 Nutrient Concentration

Both carbon and nitrogen are required as energy sources for organism growth. Thirty parts by weight of carbon (C) are used by microorganisms for each part of nitrogen (N); a C/N ratio of 30 is, therefore, most desirable for efficient composting, and C/N ratios between 25 and 35 provide the best conditions. The carbon considered in this ratio is biodegradable carbon. Lower C/N ratios increase the loss of nitrogen by volatilization as ammonia, and higher values lead to progressively longer composting times as nitrogen becomes growth-rate limiting (12). No other macro-nutrients or trace nutrients have been found to be rate limiting in composting municipal wastewater sludge.

12.2.5 Oxygen Supply

Optimum oxygen concentrations in a composting mass are between 5 and 15 percent by volume (15). Increasing the oxygen concentration beyond 15 percent by air addition will result in a temperature decrease because of the greater air flow. Although oxygen concentrations as low as 0.5 percent have been observed inside windrows without anaerobic symptoms, at least 5 percent oxygen is generally required for aerobic conditions (12).

12.2.6 Design Criteria and Procedures

The basic criteria for successful composting are that the material to be composted be porous and structurally stable and contain sufficient degradable material so that the degradation reaction is self-sustaining (that is, heat released by oxidation of volatile material is sufficient to raise the mixture to reaction temperature and to bring it to required dryness). In this section, a procedure to meet these criteria of porosity, structural stability, and sufficient biodegradability will be discussed. An equally important design consideration is flexibility. A compost operation must be able to operate continuously even with changes in sludge solids content and volume. Changes in bulking agent supply and equipment failure must also be anticipated, and the design must be flexible to deal with these changes.

To obtain minimal assurance that the composting activity is proceeding properly, the temperature and oxygen content within the pile are constantly monitored. Equipment required to conduct this monitoring includes a portable, 0 to 25 percent, dry-gas oxygen analyzer which is used to measure the oxygen content; a probe-thermistor-type temperature indicator, with at least a 6-foot probe and scale reading from 32° to 212°F (0° to 100°C) is also needed. Additionally, monitoring of heavy metals, pathogens, and environmental parameters such as air and water quality ensures a safe and acceptable compost and composting operation. A comprehensive monitoring program is outlined in Table 12-1.

TABLE 12-1

SUGGESTED MONITORING PROGRAM FOR A MUNICIPAL WASTEWATER SLUDGE COMPOSTING FACILITY (17)

Activity/time	Component	Analysis	Frequency
Before composting	Sludge and bulking material	Heavy metals and PCB's	Monthly
During composting	Aerated pile or windrows	Acceptable time, temperature, dissolved oxygen relationships, that is, 131°F (55°C) and 5 to 15 percent oxygen content for 3 to 5 days.	Temperature and oxygen content measurements taken at least 6 days during first 2 weeks. (Additional measurements sometimes required to get true average).
After composting	Compost (prior to marketing)	Certain selected indicator heavy metals and pathogens.	Monthly or bimonthly depending on use of compost.
Site monitoring during entire operation	Personnel	Physical examination prior to employment and periodically thereafter.	Annually
		Protective equipment and clothing as needed.	Continuously
	Odors	Odor strength	Continuously, but especially during wet periods with temperature inversions and little to no wind.
		Odor filter pile effectiveness.	Continuously
		Log of odor complaints.	Continuously
	Dust	Assessment of particulate concentrations.	Continuously but especially during dry period under windy conditions
	Leachate and runoff	BOD and suspended solids.	Monthly, downwind at locations critical to public health concerns.
	Airborne spores	Numbers generated and transported.	Monthly
	Micrometeorological	Temperature at 5 ft (1.5 m) and 25 ft (7.6 m)	Continuously
		Wind speed	Continuously
		Wind direction	Continuously

Four locations for temperature and oxygen measurements at both ends of each pile are shown on Figure 12-2.

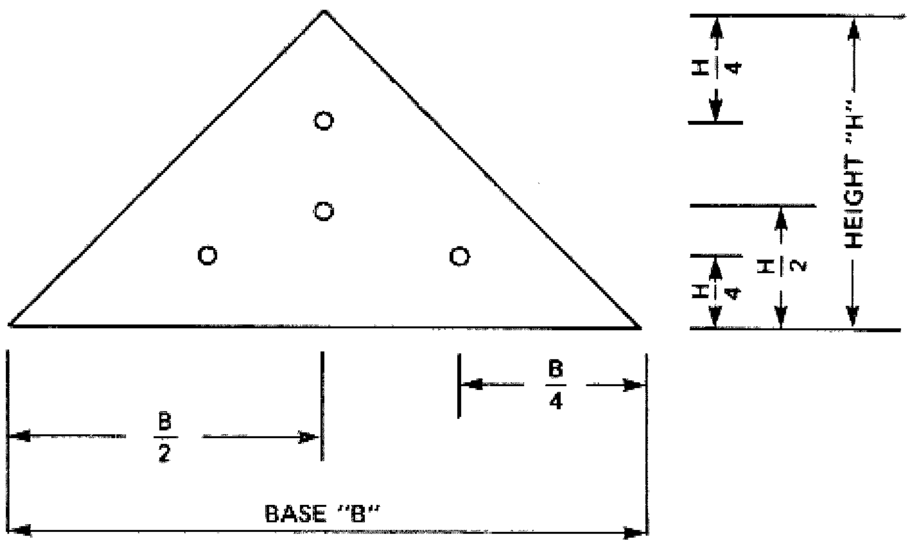


FIGURE 12-2

LOCATIONS FOR TEMPERATURE AND OXYGEN MONITORING AT ONE END OF A WINDROW OR INDIVIDUAL AERATED PILE

Haug and Haug (17) have shown the compost reaction is self-sustaining when the ratio W is $\leq$ 10. This ratio is defined as:

$$W = \frac{\text{mass of water in the initial compost mixture}}{\text{mass of organics degraded under composting conditions}}$$

In windrow and mechanical composting, porosity and structural stability are provided when the sludge is mixed with recycled compost product or bulking agent to obtain a solids concentration of approximately 40 to 60 percent. With aerated pile composting, a bulking agent such as wood chips is used to provide porosity and structural stability. When the composting process is complete, the bulking agents are generally screened out of the compost and recycled back to the mix point for reuse. The fine portion of the bulking agent is usually retained with the compost product because it passes through the screen with the finished compost. Fresh bulking agent must be added at the mix point to compensate for this material loss.

Mixture degradability can be adjusted by the addition of materials that contain high concentrations of degradable organic material. These materials are usually dry and reduce the ratio W by increasing the volatile fraction and decreasing the moisture fraction of the mixture.

Figure 12-3 shows a generalized mass balance diagram for the compost process. The recycle stream could consist of finished compost only (typical for windrow and mechanical methods), bulking agent only (typical for aerated pile methods) or a combination of bulking agent and finished compost. Amendment may also be added with bulking agent. The exact quantities of the various streams are dependent on the mass balance equations (12-1 and 12-2) derived from Figure 12-3 and the type of composting process utilized.

A set of equations can be developed from an analysis of the mass balance diagram. Two general equations have been arranged that apply to all composting methods. Equation 12-1 is used to determine the recycled compost or wood chip quantity and Equation 12-2 is used to determine the ratio W (17):

$$X_R = \frac{X_C(S_M-S_C) + X_A(S_M-S_A) + X_B(S_M-S_B)}{(S_R-S_M)} \qquad (12\text{-}1)$$

$$W = \frac{X_C(1-S_C) + X_A(1-S_A) + X_B(1-S_B) + X_R(1-S_R)}{X_C S_C V_C k_C + X_A S_A V_A k_A + X_B S_B V_B k_B + X_R S_R V_R k_R} \qquad (12\text{-}2)$$

Compost Processes With No External Bulking Agent

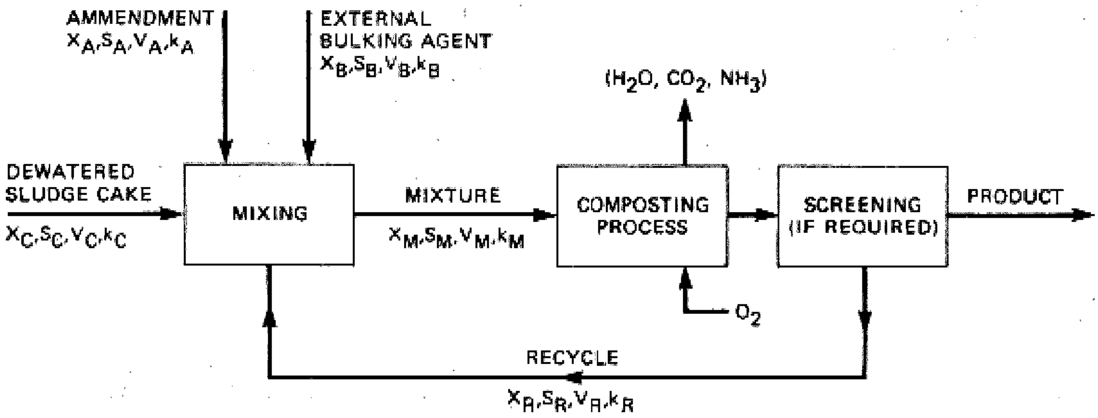
To design a compost facility employing no external bulking agent, the parameters $X_C, S_C, V_C, k_C, S_R, V_R, k_R$, and S_M must be determined analytically, assumed, or calculated. The wet weight of recycled compost (X_R) is calculated, assuming no amendment or external bulking agent addition ($X_A=X_B=0$), to provide a desired solids content of the mixture (S_M) in the 0.40 to 0.50 range:

$$X_R = \frac{X_C(S_M-S_C)}{(S_R-S_M)} \qquad (12\text{-}3)$$

Once X_R is determined for these conditions, the ratio W is calculated:

$$W = \frac{X_C(1-S_C) + X_R(1-S_R)}{X_C S_C V_C k_C + X_R S_R V_R k_R} \qquad (12\text{-}4)$$

If the ratio W is less than ten, the compost mixture has sufficient energy available for temperature elevation and water evaporation. The ratio number of ten is not absolute because climatic conditions affect the thermodynamic energy requirements. In a hot, arid climate, W may be higher because evaporation of water from the compost mass is increased by a high humidity



Note: RECYCLE is defined as finished compost for the windrow and mechanical systems and as recycled wood chips for the aerated pile system.

The exact value for these parameters must be determined from samples of the sludge, external bulking agent, amendment, and estimated for the recycle values unless otherwise known.

Process Variables and Range of Average Values (in Parenthesis)

X_C = Total wet weight of sludge cake produced/day.

X_A = Total wet weight of amendment/day.

X_R = Total wet weight of recycle/day.

X_B = Total wet weight of external bulking agent/day.

X_M = Total wet weight of mixture/day.

S_C = Fractional solids content of sludge cake (0.20 to 0.55).

S_A = Fractional solids content of amendment (0.50 to 0.95).

S_R = Fractional solids content of recycle (0.60 to 0.75).

S_B = Fractional solids content of external bulking agent (0.50 to 0.85).

S_M = Fractional solids content of mixture (0.40 to 0.50).

V_C = Volatile solids content of sludge cake, fraction of dry solids (0.40 to 0.60) - Digested; (0.60 to 0.80) - Raw.

V_A = Volatile solids content of amendment, fraction of dry solids (0.80 to 0.95).

V_R = Volatile solids content of recycle, fraction of dry solids (0.00 to 0.90).

V_B = Volatile solids content of external bulking agent, fraction of dry solids (0.55 to 0.90).

V_M = Volatile solids content of mixture, fraction of dry solids (0.40 to 0.80).

k_C = Fraction of sludge cake volatile solids degradable under composting conditions (0.33 to 0.56).

k_A = Fraction of amendment volatile solids degradable under composting conditions (0.40 to 0.60).

k_R = Fraction of recycle volatile solids degradable under composting conditions (0.00 to 0.20).

k_B = Fraction of external bulking agent volatile solids degradable under composting conditions (0.00 to 0.40).

k_M = Fraction of mixture volatile solids degradable under composting conditions (0.20 to 0.60).

FIGURE 12-3

SLUDGE COMPOSTING MASS BALANCE DIAGRAM

driving force and higher initial pile temperatures. In a cold climate, more biological energy is required to heat the pile to normal operating temperatures and thus W may have to be as low as seven to ten (17).

The ratio W can be reduced by adding amendment. The parameters S_A, V_A, and k_A are known. The amendment dry weight is assumed, and a new recycle compost mass (X_R) is calculated:

$$X_R = \frac{X_C\ (S_M-S_C) + X_A\ (S_M-S_A)}{(S_R-S_M)} \tag{12-5}$$

The ratio W is also recalculated:

$$W = \frac{X_C\ (1-S_C) + X_R\ (1-S_R) + X_A\ (1-S_A)}{X_C S_C V_C k_C + X_R S_R V_R k_R + X_A S_A V_A k_A} \tag{12-6}$$

If W is still not below ten, the quantity of amendment is increased and X_R and W are recalculated until the W requirement is satisfied.

If these guidelines are followed, a mixture with sufficient energy to compost will be produced. The actual values for the process parameters are site-specific and the most economical design is dependent on accurate information about the composting characteristics that affect the mass and thermodynamic balance.

Compost Processes Using External Bulking Agent

Design criteria for processes using external bulking agent are similar to those just described except that the recycle rate is calculated in a different manner. In the former process, the ratio of total bulking agent to sludge is specified without regard to the mixture's moisture content, since it is not as important as the structural integrity of the pile. The recycle rate, X_R, and makeup supply are calculated using Equations 12-7 and 12-8.

$$X_R = (1-f_2)\ f_1 X_C \tag{12-7}$$

$$X_B = f_1\ X_C - X_R \tag{12-8}$$

where f_1 is defined as the ratio of external bulking agent (recycle and makeup) to sludge

$$f_1 = \frac{X_R + X_B}{X_C}$$

and f_2 represents the fraction of total external bulking agent lost from the process by volatilization or because it remains with the finished compost.

$$f_2 = \frac{X_B}{X_B + X_R}$$

The values for f_1 and f_2 must be assumed based on operating experience at an existing facility. The range of values for f_1 are 0.75 to 1.25, and for f_2 are 0.20 to 0.40. Once these values are chosen, the amount of recycled bulking agent (X_R) and new external bulking agent (X_B) can be calculated using Equations 12-7 and 12-8.

The value of the ratio W is then calculated using Equation 12-2, indicating no amendment is used ($X_A = 0$). If W is less than or equal to ten, then the mixture has sufficient energy to compost. If W is greater than ten, two options for reducing the ratio are possible. More external bulking agent can be used (that is, f_1 is increased). If the bulking agent is more volatile than the sludge, W should be reduced. The recycle and makeup quantities of bulking agent must be recalculated and W determined again. If the bulking agent is of low volatile fraction, this approach will not work because W will be reduced only slightly. In this case, amendment must be added.

For any amount of amendment addition, the ratio W can again be calculated using Equation 12-2. Increasing the amount of amendment until W is below ten will result in the proper compost energy balance.

The operation at Bangor, Maine, successfully composts sludge by the aerated pile method in winter months. No amendment is used, and the ratio of external bulking agent (bark) to sludge by volume is 2.5:1. The value for W ranges from seven to ten at this operation (17).

The best means to determining the quantities of external bulking agent and amendment used will be a careful economic analysis of the process and accurate estimation of the process variables. Table 12-2 lists some of the density ranges for various compost materials as experienced at various compost facilities.

12.3 Unconfined Composting Systems

In the United States, the windrow and aerated static pile processes have been used almost exclusively for composting dewatered municipal wastewater sludges. The basic steps to be followed in these two processes are similar, but the processing technology for the composting stage differs appreciably. In the windrow method, oxygen is drawn into the pile by natural convection and turning, whereas in the static pile method, aeration is induced by forced air circulation.

TABLE 12-2

DENSITIES OF VARIOUS COMPOST BULKING AGENTS (13)

Material	Density, lb/cu yd
Digested sludge	1,500 to 1,700
Raw sludge	1,300 to 1,700
New wood chips	445 to 560
Recycled wood chips	590 to 620
Finished compost	930 to 1,040

1 lb/cu yd = 0.595 kg/m^3

12.3.1 Windrow Process

The windrow process is normally conducted in uncovered areas and relies on natural ventilation with frequent mechanical mixing of the piles to maintain aerobic conditions. In areas of significant rainfall, it may be desirable for operational reasons to provide a roofed structure to cover the windrows for composting sludge. The largest operating windrow process in the United States is located at the Joint Water Pollution Control Plant of the County Sanitation Districts of Los Angeles County in Carson, California.

In the windrow composting process, the mixture to be composted is stacked in long parallel rows or windrows. The cross section of the windrows may be trapezoidal or triangular, depending largely on the characteristics of the mobile equipment used for mixing and turning the piles. The width of a typical windrow is 15 feet (4.5 m) and the height is 3 to 7 feet (1 to 2 m).

Based on processing 20 percent solids sludge, land requirements for the windrow process are greater than for the aerated pile process. Colacicco estimates an extra 25 percent land usage for the windrow process based on windrows 5 feet (1.5 m) high and 7 feet (2 m) wide with a two-week composting period (18). Even more land would be necessary for the longer composting time experienced in the Los Angeles operations.

The mixing of a bulking agent with the wet sludge cake has enabled the windrow process to be used for composting digested dewatered sludge. Bulking agents may include the recycled composted sludge itself or external agents such as wood chips, sawdust, straw, rice hulls, or licorice root. The quantity of bulking agent is adjusted to obtain a mixture solids content of 40 to 50 percent. The use of a bulking agent also increases the structural integrity of the mixture and thus, its ability to maintain a properly shaped windrow. Porosity of the mixed material is greatly improved, which in turn improves the aeration characteristics. External bulking agents can also provide a source of carbon for the composting process. The carbon to nitrogen (C/N) ratio of digested activated sludge is in the range of 9 to 15:1. If wood chips are used as the bulking agent, the C/N ratio will be raised to approximately 20 to 30:1 in the composting mixture.

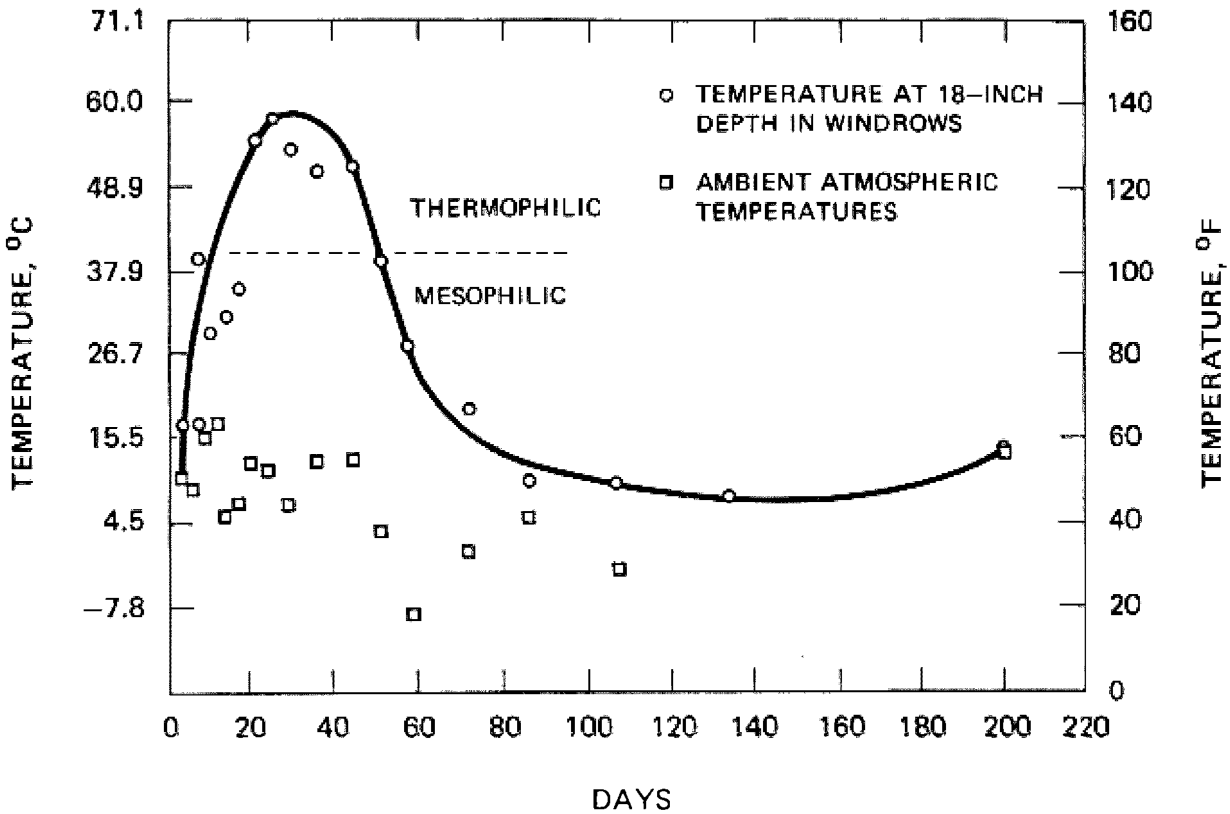
Convective air movement within windrows is essential for providing oxygen for the microorganisms. The aerobic reaction provides heat for warming the windrows. This causes the air to rise, producing a natural chimney effect. The rate of air exchange can be regulated by controlling the porosity and size of the windrow (2). The turning of the windrow also introduces oxygen to the microorganisms. This method of aeration can be expensive if used excessively to obtain high oxygen concentrations and may reduce the temperature within the windrow.

As a result of the biological decay process, temperatures in the central portion of the windrow reach as high as 150°F (65°C). Operating temperatures of about 140°F (60°C) may be maintained in the central portion of the windrow for as long as ten days. Temperatures in the outer layers are considerably cooler and may approach atmospheric conditions. During wet periods and winter conditions, maximum temperatures may only be 130° to 140°F (55° to 60°C). A high temperature maintained throughout the pile for a sufficient period of time is important to the control of pathogens (see Chapter 7). A satisfactory degree of stabilization is indicated by a decline in temperature, usually to about 113° to 122°F (45° to 50°C). These variations in temperature are illustrated in Figure 12-4.

Large-scale, 270 dry tons per day (243 t/day) processing of digested primary sludge (23 percent solids) using the windrow process, with recycled composted sludge as the bulking agent, has proven a viable method of sludge stabilization by the Los Angeles County Sanitation Districts. Successful operation of the windrow process using bulking agents such as wood chips and sawdust with digested primary and secondary sludge has also been achieved at Beltsville. This process has not proven suitable for composting unstabilized primary or secondary sludges. At Beltsville during early tests with windrows, undigested primary and waste-activated sludges were found to produce offensive odors (3). Also, composting of digested sludge did not kill all seeds, and these were present in the final product.

The Los Angeles County Sanitation Districts are currently composting digested, centrifuged primary sludge (23 percent solids) in windrows mixed with recycled composted sludge

(60 percent solids) in a 1:2.2 ratio (dry weight). A compost mixing machine is used to turn the mixture. Recycled compost is added to the sludge before the windrow is constructed. Each windrow must be turned two or three times a day for the first five days to mix the material completely, minimize odors, and ensure sufficient oxygen transfer. The sludge is then turned once a day for about 30 days, depending on weather conditions. Figure 12-5 shows a windrow being turned at Los Angeles.



1 in = 2.54 cm

FIGURE 12-4

TEMPERATURE PROFILE OF A TYPICAL COMPOST WINDROW (12)

Large, portable, heavy materials handling equipment is required for the windrow system. The Los Angeles operation requires four windrow mixing-turning machines capable of turning 3,400 tons per hour (3,084 t/hr) of a density of 1,890 pounds per cubic yard (1,120 kg/m^3). This is equivalent to a volume capacity of 3,600 cubic yards per hour (2,752 m^3/hr). Three machines operate continuously for two shifts a day. A fourth machine is required to provide backup whenever any of the others is being repaired. In case of rain all four machines must operate continuously.

FIGURE 12-5

TURNING A WINDROW AT LOS ANGELES COMPOST SITE

Sawdust, shredded paper, and wood chips were the external bulking agents used in the Beltsville windrow tests. Only shredded paper was found to be unsatisfactory (2). The windrow area at Beltsville was paved with 18 inches (0.46 m) of crushed stone to support heavy equipment and the windrow composter. The area was later paved with asphalt and then with concrete to assure positive leachate collection and to eliminate rock pickup from the collection equipment and damage to the screening equipment. To start the windrow, a layer of wood chips 15 inches (0.38 m) deep and 15 feet (4.5 m) wide was placed on the paved area. Sludge (20 to 25 percent solids) was distributed to the chips at a 1:3 volume ratio. The compost machine then mixed the sludge and chips. After several turnings, the two materials were thoroughly mixed. The windrow was turned five times a week, flattened after two weeks to a 12-inch (0.30 m) layer and harrowed for further drying, generally to greater than 65 percent solids. The material was then removed from the windrow area and stockpiled for an additional 30 days for curing purposes. Curing was required to improve compost quality and to further control pathogens. After curing, the composted mixture was distributed to local government agencies as screened or unscreened material. Wood chips separated during the screening operation were recycled and reused as bulking agent. The use of a bulking agent may substantially increase the cost of the composting process unless the bulking agent is itself a waste material (7). At Beltsville, a fresh supply of wood chips was required to make up for the estimated 25 to 30 percent lost in the composting process. Some of the bulking agent was consumed in the biological oxidation processes during composting, and a large portion was lost in the screening process.

12.3.1.1 Energy Requirements

Thermodynamic considerations in the composting of sludge are discussed in a recent article by Haug & Haug (17). As indicated previously, the reaction is self-sustaining when the ratio W is less than ten. Over 80 percent of the heat released by the biological reaction is used to evaporate moisture associated with the sludge.

In the windrow process, the only external energy requirements are gasoline for transportation, diesel fuel for operation of composting machines, and electricity for leachate treatment and site services, including lighting. In the Beltsville windrow tests, which used wood chips as a bulking agent, the following energy consumption figures have been estimated (18).

Operating Requirements
per dry ton per day (0.9 t/day) for a
10 to 50 dry ton per day (9 to 45 t/day) operation

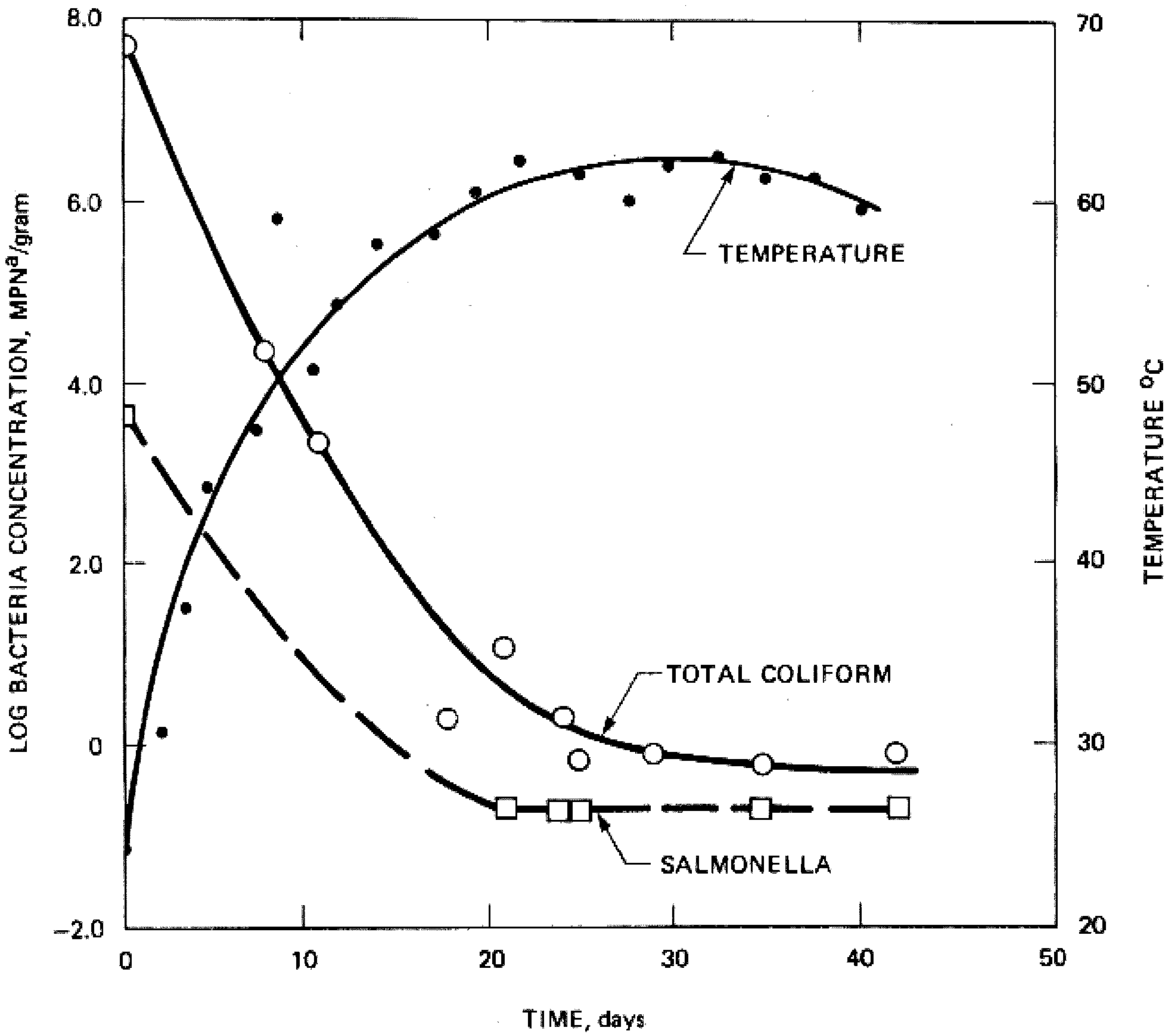
Labor	1.8 to 3.0 hours
Gasoline	1.1 gallons (4.5 l)
Diesel Fuel	3.3 to 4.0 gallons (13.5 to 16.5 l)
Electricity	3.0 to 8.0 kWhr (12 to 32 MJ)

Where finished compost is used as the bulking agent, and increased windrow turning frequency is practiced, a higher diesel fuel consumption should be expected.

12.3.1.2 Public Health and Environmental Impacts

Numerous studies have indicated that a community's wastewater contains organisms which reflect the local prevalent endemic diseases (19). The pathogens borne by wastewater are not entirely inactivated during conventional sludge digestion and drying techniques and may persist in the soil for extended periods of time. Figure 12-6 shows this time-temperature-destruction relationship of pathogens for windrows (20,21).

Intensive studies conducted by the Los Angeles County Sanitation Districts indicate that total coliform and Salmonella concentrations are rapidly reduced in the first ten days of composting in the interior of windrows. For interior samples, final compost coliform concentrations of less than one per gram have been attained, but higher values for exterior samples have been measured consistently. Very low levels of virus, parasitic ova, and Salmonella have been assayed in the majority of final compost samples.



[a] MOST PROBABLE NUMBER

1° C = 5/9 (°F-32)

FIGURE 12-6

DESTRUCTION OF PATHOGENIC ORGANISMS AS A FUNCTION OF TIME AND TEMPERATURE DURING COMPOSTING OF DIGESTED SLUDGE BY THE WINDROW METHOD

Recycling large quantities of finished compost as bulking agent provides good odor control for digested sludges, as long as process upsets are kept under control. Interruption of regular turning of the sludge may cause odor problems, since compost windrows quickly become anaerobic under these circumstances. Unpleasant odors may also be generated during periods of high rainfall, as well as by poor mixture control and inefficient mixing. In dry and windy areas, wetting of the compost windrows should be practiced to prevent excessive dust generation.

A drainage and collection system is required for stormwater runoff from the site because the contaminated water requires treatment. The runoff may be returned to the wastewater treatment plant. At Beltsville, a wooded area adjacent to the site was spray irrigated (2).

Workers at a compost site should avoid inhaling dust. Respiratory protection, such as breathing masks, should be worn in dusty areas, and the area should be sprinkled with water during dry periods. Although recent experiments have shown high concentrations of the fungus Aspergillus fumigatus, a secondary pathogen, to be airborne at sludge composting sites, preliminary data indicate that these higher spore levels are generally restricted to the immediate composting area and should not pose a significant health threat to surrounding residential, commercial, or industrial areas (22). However, individuals with a history of lung ailments should not work in composting operations. Research is continuing on potential health effects of exposure to the fungus A. fumigatus (23 to 27). For additional discussion, see Chapter 7.

12.3.1.3 Design Example

This design example illustrates the procedure for a 10 MGD (0.45 m^3/s) municipal wastewater secondary treatment plant. The dewatered, digested primary and secondary sludge (20 percent solids) is generated at the rate of one dry ton per million gallons (.00024 t/m^3). The compost facility will handle ten dry tons per day (9 t/day) at 20 percent solids, seven days per week. The values for the process design variables are similar to those reported for Beltsville. The availability and cost of amendments and suitable land for the operation will strongly influence the economic analysis of the project. This design example, however, does not consider these site-specific economic parameters.

The design of this windrow composting facility is based on the following assumptions:

- The water content and total weight of the compost mixture will be reduced by approximately 40 to 50 percent and volatile solids content will be reduced by about 20 to 40 percent. The density will decrease by 15 to 25 percent because of evaporation.

- The values for the process variables defined previously are assumed to be as follows:

$S_C = 0.20$	$S_R = 0.70$	$S_A = 0.90$	$S_M = 0.40$
$V_C = 0.50$	$V_R = 0.35$	$V_A = 0.90$	$V_M = 0.50$
$k_C = 0.45$	$k_R = 0.15$	$k_A = 0.50$	

- If the mixture has a high ratio of water to degradable organics by weight (W ratio greater than ten), amendment will be added to reduce W.

The amount of finished compost to be recycled can be calculated using Equation 12-3.

$$X_R = \frac{X_C\ (S_M - S_C)}{(S_R - S_M)} = \frac{50\ (0.04 - 0.20)}{(0.70 - 0.40)}$$

$$= 33.3 \text{ tons per day } (30.3 \text{ t/day})$$

This indicates that if a mixture moisture content of 40 percent is to be obtained, 0.67 tons (.67 t/t) of finished compost must be added to each ton (0.9 tonne) of sludge cake to be composted.

The ratio W is checked using Equation 12-4 in order to determine whether to compost.

$$W = \frac{X_C(1-S_C) + X_R(1-S_R)}{X_C S_C V_C k_C + X_R S_R V_R k_R}$$

$$= \frac{50(1-0.20) + 33.3(1-0.70)}{50(0.20)(0.50)(0.45) + 33.3\ (0.70)(0.35)(0.15)}$$

$$= 14.4$$

The calculated value for W is too high, indicating that amendment addition is required. Increasing the recycle rate to create a mixture of 50 percent solids (X_R = 50 tons per day [45 t/day]) would only lower W to 13.5, because the proportion of degradable organics does not increase significantly in the mixture.

Assuming that 1.0 ton (0.9 t) amendment per ten tons (9 t) of sludge cake are added to the mixture, the recycle rate can be calculated using Equation 12-5:

$$X_R = \frac{X_C(S_M-S_C) + X_A(S_M-S_A)}{(S_R-S_M)}$$

$$= \frac{50\ (0.40 - 0.20) + 5\ (0.40 - 0.90)}{(0.70 - 0.40)}$$

= 25.0 tons per day (22.7 t/day)

The amount of recycled compost has dropped from 0.67 tons per ton (0.61 t/t) to 0.5 tons per ton (0.5 t/t) of sludge cake. The ratio W is calculated using Equation 12-6:

$$W = \frac{X_C\ (1-S_C) + X_R\ (1-S_R) + X_A\ (1-S_A)}{X_C S_C V_C k_C + X_R S_R V_R k_R + X_A S_A V_A k_A}$$

$$= \frac{50(1-0.20) + 25(1-0.70) + 5(1-0.90)}{50(0.20)(0.50)(0.45) + 25(0.70)(0.35)(0.15) + 5(0.90)(0.90)(0.50)}$$

= 9.2

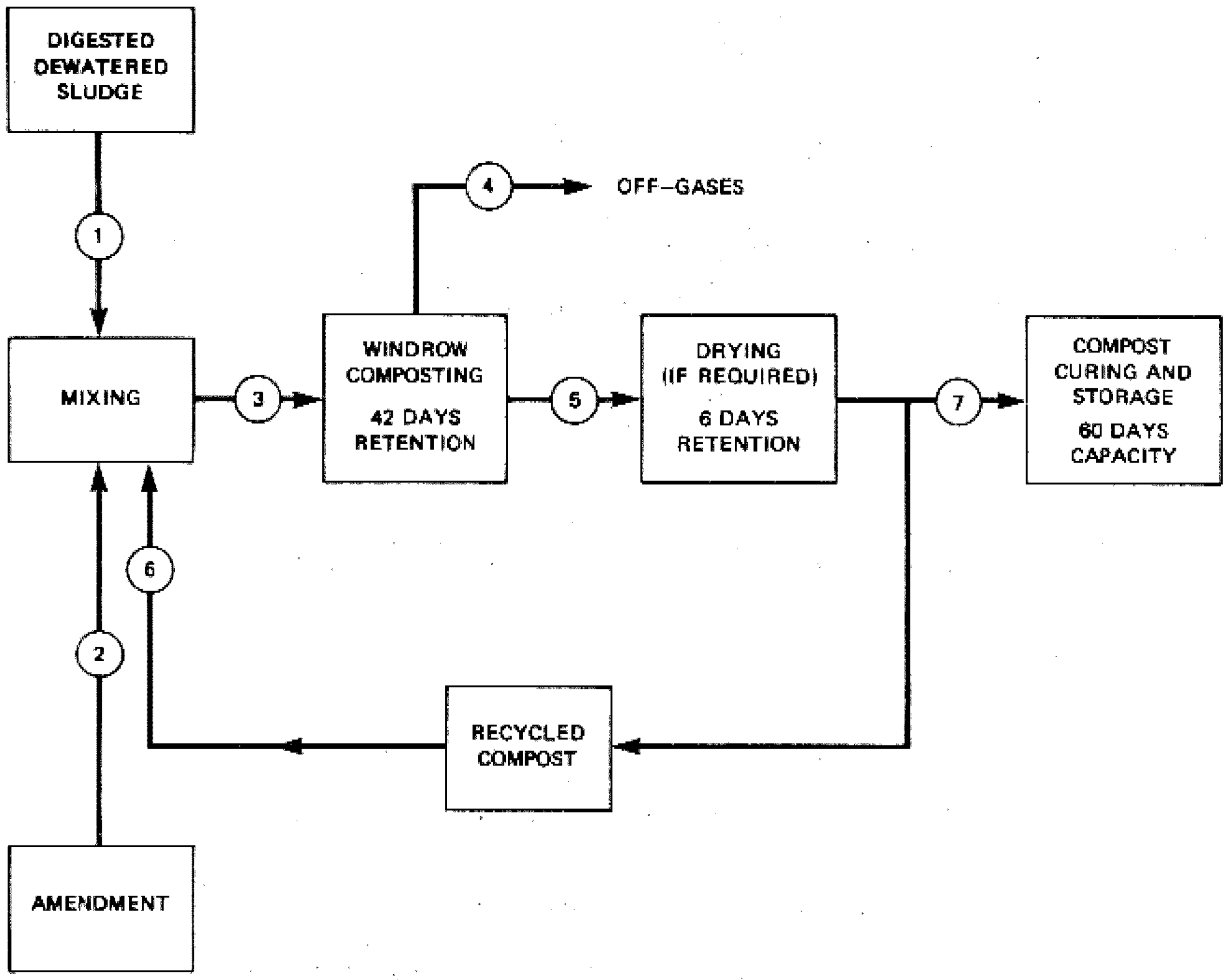
This mixture of sludge cake, recycled compost, and amendment is self-sustaining and will degrade properly. Figure 12-7 illustrates this process and shows the materials balance.

A 7-foot (2 m) high, 65-foot (20 m) long, windrow with a base of 15 feet (4.6 m) is constructed each day. Longer windrows can be made if the windrow is extended each day with the mixture to be composted. The final volume of composting at the end of six weeks of turning is approximately 65 percent of the original volume. In continuous operation there would be about 11 windrows, 250-feet (76 m) long.

Each windrow must be turned at least two times per day for the first five days to mix the materials completely, to minimize odors, and to insure sufficient oxygen transfer. After the initial five-day period, the windrows must be turned frequently enough to maintain the proper oxygen level and temperature in the composting material. This is dependent on weather conditions.

Other site operations must include a mixing area, maintenance and operations building, a curing area to stockpile the finished compost, and enough land area for handling all other site operations and for future expansion.

Equipment required for the operation includes a windrow turning machine; a front-end loader for site preparation, dismantling piles and loading transfer trucks; and transfer trucks to haul the sludge and amendment to the compost facility and to haul the finished compost away.



7 DAY PER WEEK OPERATION

LOCATION	WET TONS	PERCENT SOLIDS	DRY TONS	DENSITY (lb/cu yd)	VOLUME (cu yd)	PERCENT VOLATILE SOLIDS
1	50	20	10.0	1,600	63	50
2	5	90	4.5	1,000	10	90
3	80	40	32.0	1,300	123	50
4	41	–	5.0	–	–	–
5	39	70	27.0	1,000	78	35
6	25	70	17.5	1,000	50	35
7	14	70	9.5	1,000	28	35

1 ton = 0.907 tonne
1 lb/cu yd = 0.6 kg/m^3
1 cu yd = 0.76 m^3

FIGURE 12-7

PROCESS FLOW DIAGRAM - WINDROW COMPOSTING SLUDGE - 10 MGD ACTIVATED SLUDGE PLANT

Optimum windrow compost design will do the following:

- Minimize hauling and handling cost.
- Maximize use of existing equipment in the compost operation.
- Minimize the use of amendment which adds to the cost and is not recoverable.
- Maximize the solids content of the dewatered digested sludge cake to minimize the amount of recycled compost used for moisture control and also reduce the amount of amendment required. The cost of dewatering should not exceed the savings at the compost facility.

12.3.2 Aerated Static Pile Process

An aerated static pile system was developed in order to eliminate many of the land requirements and other problems associated with the windrow composting process and to allow composting of raw sludge. This system consists of the following steps: mixing of sludge with a bulking agent; construction of the composting pile; composting; screening of the composted mixture; curing; and storage. A diagram of an aerated pile for composting sludge is shown in Figure 12-8.

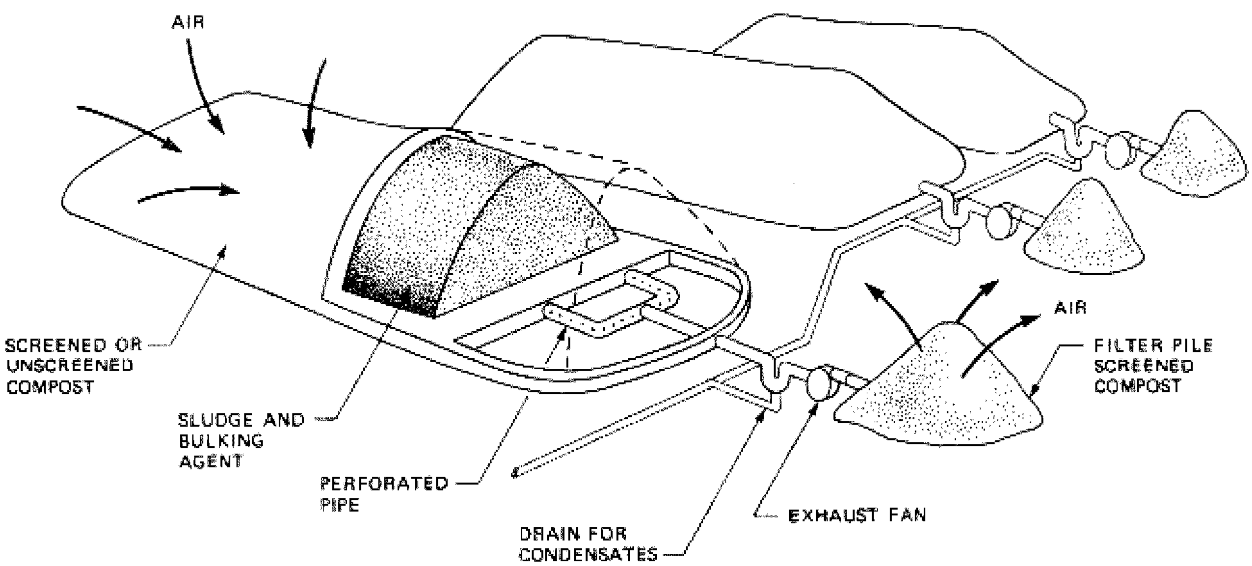


FIGURE 12-8

CONFIGURATION OF INDIVIDUAL AERATED PILES

The forced air method provides for more flexible operation and more precise control of oxygen and temperature conditions in the pile than would be obtained with a windrow system. Since composting times tend to be slightly shorter and anaerobic conditions can be more readily prevented, the risk of odors is reduced.

Two distinct aerated static pile methods have been developed, the individual aerated pile and the extended aerated pile.

12.3.2.1 Individual Aerated Piles

An individual aerated pile may be constructed in a manner similar to the Beltsville method, in which loop of perforated plastic pipe, 4 to 6 inches (10 to 15 cm) in diameter is placed on the composting pad, oriented longitudinally, and centered under the ridge of the pile under construction. In order to avoid short circuiting of air, the perforated pipe terminated at least 8 to 10 feet (2 to 3 m) inside the ends of the pile. A non-perforated pipe that extends beyond the pile base is used to connect the loop of perforated pipe to the blower. (See Figure 12-9).

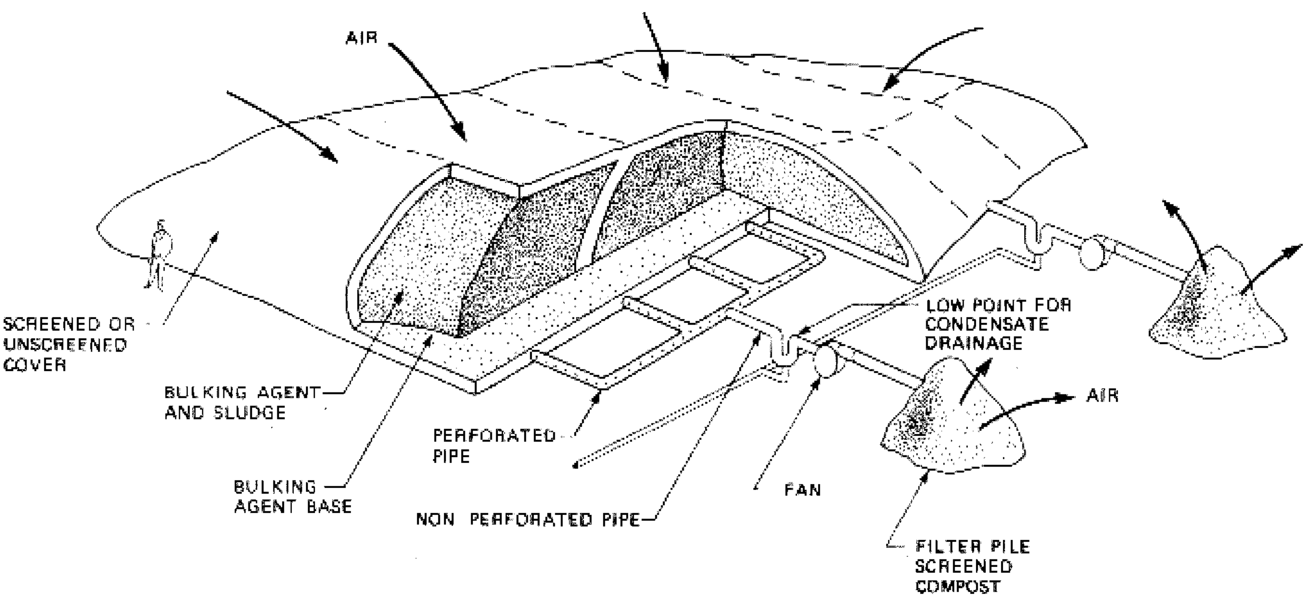


FIGURE 12-9

AERATION PIPE SET-UP FOR INDIVIDUAL AERATED PILE

A 6- to 8-inch (15 to 20 cm) layer of bulking agent is placed over both the pipes and the area to be covered by the pile. This base facilitates the movement and even the distribution of air during composting and absorbs excessive moisture that may otherwise condense and drain from the pile (19).

At Beltsville a mixer or front-end loader is used to mix one volume of sludge cake containing 22 percent solids and two volumes of bulking agent. The resulting mixture contains 40 percent solids and is placed loosely upon the prepared base by the front-end loader to form a pile with a triangular cross section 15 feet (4.6 m) wide by 7.5 feet (2.3 m) high.

The pile is then completely covered with a 12-inch (0.3 m) layer of cured, screened compost or an 18-inch (0.4 m) layer of unscreened compost. This outer blanket of compost provides insulation and prevents escape of odors during composting. Unstabilized sludge can generate odors during dumping and initial pile construction. Conditioning with lime during dewatering will minimize this, however. The non-perforated pipe is connected to a 1/3 horsepower (0.25 kW), 335 cubic feet per minute (158 l/s) blower that is controlled by a timer (28). Aerobic composting conditions are maintained if air is intermittently drawn through the pile. The timing sequence for the blower is 5 minutes on and 15 minutes off for a 56-foot (17 m) long pile containing up to 80 wet tons (73 t) of sludge. If the aeration rate is too high or the blower remains on too long, the pile will cool, and the thermophilic process will be inhibited (12).

The effluent air from the compost pile is conducted into a small, cone-shaped filter pile of cured, screened compost approximately 4 feet (1.2 m) high and 8 feet (2.5 m) in diameter where malodorous gases are absorbed. The odor retention capacity of these piles is inhibited if their moisture content is greater than 50 percent. The odor filter pile should contain one cubic yard (0.76 m^3) of screened compost for each four dry tons (3.6 t) of sludge in the compost pile. Filter piles are sometimes constructed with a 4-inch (10 cm) base layer of wood chips to prevent high back pressures on the blower.

Land area requirements are estimated at one acre per 3 to 5 dry tons (1.0 ha/6.7 to 11.2 t) of sludge treated. The lower figure includes space for runoff collection, administration, parking, and general storage. The actual composting area (mixing area, aerated piles, screening area, drying area, and storage area) is estimated to be one acre per 5 dry tons (1.0 ha/11.2 t) of sludge (19).

12.3.2.2 Extended Aerated Piles

To make more effective use of available space, another static pile configuration called the extended aerated pile has been developed. An initial pile is constructed with a triangular cross section utilizing one day's sludge production. Only one side and the ends of this pile are blanketed with cured, screened compost. The remaining side is dusted with only about an inch (0.5 cm) of compost for overnight odor control. The next day, additional aeration pipe is placed on the pad parallel to the dusted side of the initial pile. The pile bed is extended by covering the additional pipe with more bulking agent and sludge-bulking agent mixture so as to form a continuous or extended pile. This process is repeated daily for 28 days. The first section is removed after 21 days. After seven sections are removed in sequence, there is sufficient space for operating the equipment so that a new extended pile can be started. Figure 12-10 shows such a system. The area requirement of an extended pile system is about 50 percent less than that for individual piles. The amount of recycled bulking agent required for covering the pile and bulking agent used in the construction of the base is also reduced by about 50 percent. At Beltsville, research into extending aerated piles in both the vertical and horizontal directions is ongoing.

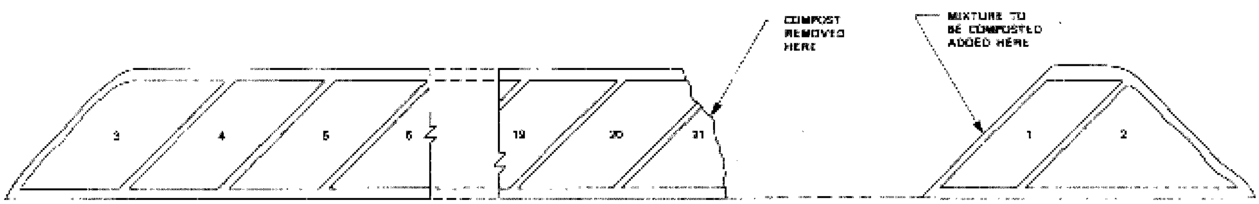


FIGURE 12-10

CONFIGURATION OF EXTENDED AERATED PILE

12.3.2.3 Current Status

The aerated pile system has proven effective on a full-scale basis at Beltsville, Maryland; Bangor, Maine; Durham, New Hampshire; Detroit, Michigan; and Windsor, Ontario. After start-up, mean temperatures in aerated piles are 176°F (70°C); and after stable conditions are achieved, minimum temperatures are usually 130°F (55°C). When the piles are constructed properly, neither excessive rainfall nor low ambient temperature adversely affect the composting process (28).

Currently most of the interest in composting of wastewater sludges is centered on this technique. The applicability of this system for the treatment of undigested sludges provides it with a significant advantage over the windrow method. Other advantages are superior odor control, greater inactivation of pathogenic organisms, and use of less site area. The aerated pile technique exposes all sludge to more uniform temperature. Capital costs are also lower for the aerated pile system, but operating costs tend to be higher because of the cost of the bulking agent. Comparisons of capital and operating costs using wood chips as bulking agent in aerated piles, as well as in windrows, are made by Colacicco (18). In experiments at Los Angeles County, it has been found necessary to follow this technique by windrow composting for 2 to 3 days to dry off the moisture. At other locations, the air flow is reversed without disruption of the pile as another means to reducing moisture content.

12.3.2.4 Oxygen Supply

Centrifugal fans efficiently provide the necessary pressure to move air through the compost and odor filter piles. Variation in the blower pressure is a necessity for optimum conditions and a site-specific operating parameter. The oxygen concentration in the pile should be maintained between 5 and 15 percent; this can be achieved with an aeration rate of about 500 cubic feet per hour per ton (15.6 m^3/hr/t) dry sludge. If the pile cools at this air rate, the air flow must be reduced. Aeration cycles of 20 to 30 minutes with the fan operating 1/10 to 1/2 of the cycle have proven satisfactory (19). While the fan is not operating, the natural convective chimney effect, typical of windrows, takes place. In the absence of forced aeration, this effect causes warming of the outer edges, destroying pathogens more effectively.

Moist air drawn through the pile condenses in the slightly cooler sections. When enough condensate accumulates, it will drain from the pile and leach material from the sludge. Condensed moisture which collects in the aeration pipes is removed by a water trap. This material must be collected and treated along with the contaminated rainfall runoff from the site, because it can become a source of odors if allowed to accumulate in puddles around the piles. Data is not available on combined leachate and condensate water characteristics; the quantity may, however, vary from 6 to 20 gallons per day (22 to 75 l/day) per pile containing 50 cubic yards (38 m^3) of sludge during dry weather (29). (Refer to Chapter 16 for further information.)

12.3.2.5 Bulking Agent

While bulking agents are in the aerated pile composting system, they serve primarily to maintain the structural integrity and porosity of the pile. The quantity of external bulking agent required is determined by the need for structural support and porosity. The requirements for moisture control are not as critical as adequate porosity; thus, sludge moisture can vary considerably as long as sufficient bulking agent is added to assure adequate porosity. The design factors discussed for windrows do not apply here (17).

Wood chips and other bulking agents also increase the volatile solids content of the composting mixture; volatility of new and recycled wood chips has been reported as 90 and 86 percent, respectively (18). The actual contribution of the wood chips to the compost mixture is limited because their composting rate is slower.

When wood chips are mixed with unstabilized sludge an average volatility of about 75 percent results; this is well in excess of the 40 to 50 percent volatility achieved in the mixture of digested sludge and recycled compost. Volatility content is therefore not a limiting factor in aerated pile composting of unstabilized sludge, as it can be in the digested sludge windrow system.

12.3.2.6 Energy Requirements

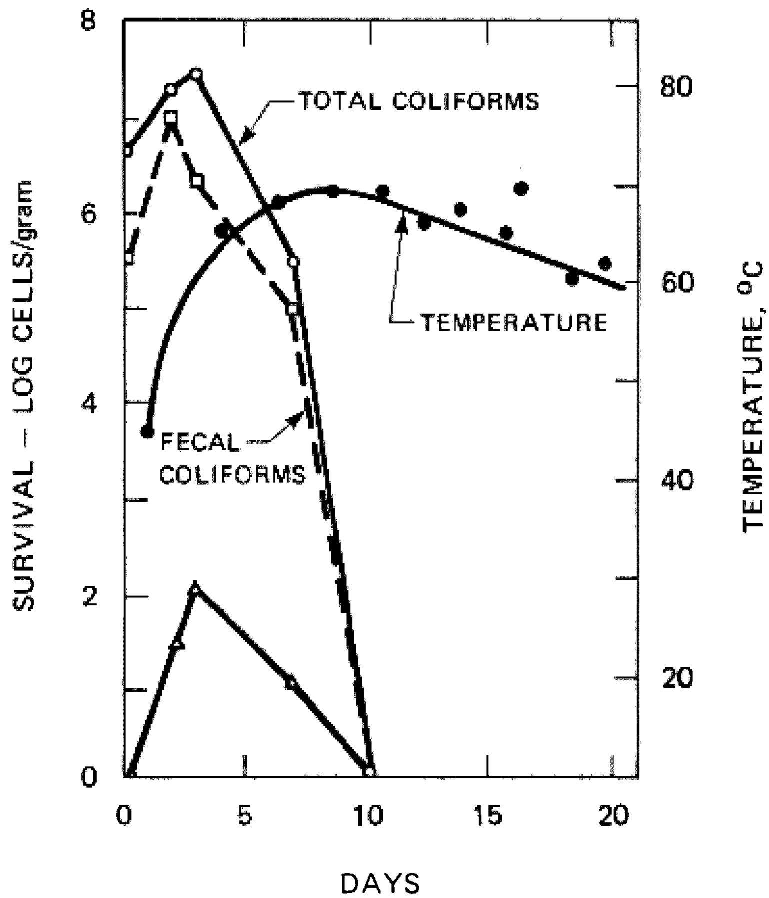
Energy costs for aerated pile composting are a small portion of the overall operating costs. The bulk of the overall energy requirement of the process is provided by the volatile solids in the composting mixture. A range of resources for labor, external bulking agent, gasoline for small vehicles, diesel fuel for the front-end loaders, and electricity usage for leachate treatment is listed below (18).

	Operating Requirements per dry ton per day (0.9 t/day) for a 10 to 50 dry ton per day (9 to 45 t/day) operation (20 percent sludge)
Labor	1.5 to 2.8 hours
Wood Chips	2 to 8 cubic yards (2.1 m^3)
Gasoline	1.1 gallon (4.1 l)
Diesel Fuel	2.7 to 3.5 gallon (10.2 to 13.2 l)
Electricity	7.5 to 17.5 kWhr (29.7 to 69.3 MJ)

12.3.2.7 Public Health and Environmental Impacts

Extensive studies have been made on the destruction of pathogens in aerated piles (30). Although Salmonella, fecal coliforms, and total coliforms initially increased in numbers, they were reduced to essentially undetectable levels by the tenth day of composting. Studies using "F" bacteriophage and virus as an indicator showed that the virus was essentially destroyed by the thirteenth day. However, survival of the virus did occur for some time in the blanket-compost interface where lower temperatures prevailed. Storage in a curing pile for 30 days will complete the destruction of viruses or reduce the numbers to an extremely low level (19). Studies have shown that the composting process in an aerated pile is essentially unaffected by low ambient temperatures or rainfall, which makes this system particularly well suited to operation under difficult climatic conditions (31). Figure 12-11 shows the time-temperature-destruction relationship of pathogens for aerated piles (20).

Odor control is the primary environmental consideration in the operation of an aerated pile composting system. Good odor control results from prompt mixing of sludge and bulking agent and formation of the aerated pile. In addition, lumps of material or puddles of liquid must not be allowed to remain in the mixing area. No thin spots or holes should be present in the compost blanket. There should be leakproof transport of aeration air between blower and odor filter pile. Moisture content within odor filter piles (Figure 12-12) should be kept below 50 percent. Condensate, leachates, and runoff from the piles must be collected and treated as quickly as possible. The compost should be adequately cured before it is removed from the area, and any unstabilized material should be recycled back into the composting process for further treatment.



1°C = 5/9 (°F − 32)

FIGURE 12-11

DESTRUCTION OF PATHOGENIC ORGANISMS AS A FUNCTION OF TIME AND TEMPERATURE DURING COMPOSTING OF UNDIGESTED SLUDGE BY THE AERATED PILE METHOD (20)

FIGURE 12-12

ODOR FILTER PILES AT BELTSVILLE

12.3.2.8 Design Example

This design example is based on a Beltsville-type sludge composting system utilizing existing technology and available design criteria. The example provided is specific to a 10 million gallon per day (0.45 m^3/s) municipal wastewater secondary treatment plant.

The weight and volume of sludge and bulking agent at various points in the process must be known so that the volumetric flow capacity of a composting facility can be determined. The basic design decisions include the bulking agent to sludge ratio and the ratio of new to recycled bulking agent.

The materials balance in this example is based on the following assumptions:

- Sludge to be composted is 50 wet tons per day (45 t/d) of undigested sludge, seven days per week, with no digestion.
- Wood chips are added to the wet sludge at the rate of 2 cubic yards of chips per cubic yard (2.0/m^3) of wet sludge.
- Three-fourths of the chips are recovered by screening and reuse.

- The water content and total weight of the compost mixture is reduced by approximately 30 to 40 percent and volatile solids content is reduced by about 10 to 15 percent. The density decreases 15 to 20 percent because of evaporation.

- The extended aerated pile system will be used.

Information on the bulk density of sludge is surprisingly scarce. Tests conducted at Beltsville for an engineering study of a large-scale composting facility provide some basic data on the bulk density of sludge and wood chip bulking agents. The following bulk densities are used in this design example (20):

Constituent	Bulk Density: Pounds per cubic yard	Bulk Density: kg/m^3
Dewatered Sludge (20% solids)	1,600	960
New Wood Chips	500	300
Recycled Wood Chips	600	360
Screened Compost	865	519
Unscreened Compost	1,000	600

It is also assumed that the process variables have the following values:

$S_C = 0.20$	$S_B = 0.70$	$S_R = 0.70$
$V_C = 0.75$	$V_B = 0.90$	$V_R = 0.80$
$k_C = 0.45$	$k_B = 0.10$	$k_R = 0.10$

Sludge composting will operate 5 days per week, 8 hours per day using the extended aerated static pile method. The volume to be composted per work day is as follows:

$$\frac{50 \text{ wet tons}}{\text{week day}} \times \frac{7 \text{ week-days}}{5 \text{ work-days}} = 70 \text{ wet tons per work day (63.5 t/work day)}$$

It is assumed that the dewatered sludge arrives on-site 5 days per week from the dewatering operation which runs only 5 days per week. Equalization storage to cover weekend operation of the plant is provided for sludge in the liquid state upstream from the dewatering process.

The amount of recycled and new wood chips can be calculated using Equations 12-7 and 12-8 and assuming f_1=0.75 and f_2=0.25;

$$X_R = (1-0.25)(0.75)70 = 39.4 \text{ tons per day } (35.7 \text{ t/day}).$$

$$X_B = (0.75)70 - 39.4 = 13.1 \text{ tons per day } (11.9 \text{ t/day}).$$

The ratio W can be calculated using Equation 12-2:

$$W = \frac{70(1-0.2) + 39.4(1-0.7) + 13.1(1-0.7)}{70(0.2)(0.75)(0.45) + 39.4(0.7)(0.9)(0.1) + 13.1(0.7)(0.8)(0.1)}$$

$$= 9.0$$

Since W is less than 10, no amendment addition is required.

The daily volume of the compost material is calculated using the assumed values previously stated:

Constituent	Mass tons/day	Volume cubic yards/day
Dewatered sludge	70	87.5
New wood chips	13.1	52.4
Recycled wood chips	39.4	131.3
Total	122.5 (111.1 t/day)	271.2 (206.8 m^3/day)

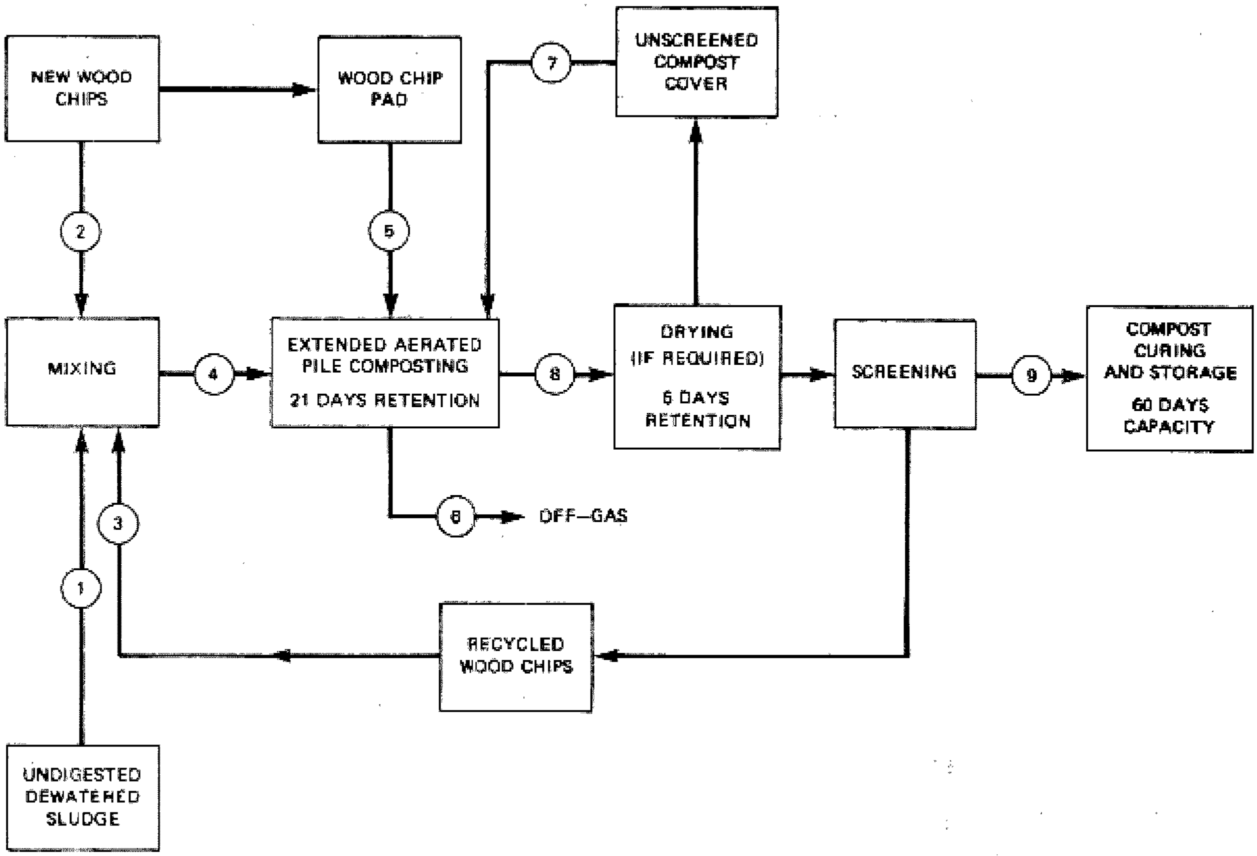
The pile will be 8 feet (2.4 m) high and 50 feet (15 m) long. Each day, the pile will be extended 18.5 feet (5.6 m). The amount of new wood chips required to construct a one-foot (0.3 m) thick pad for the compost is as follows:

$$\frac{(50 \text{ ft})(18.5)(1 \text{ ft})}{27 \text{ cu ft/cu yd}} = 34.3 \text{ cubic yards } (26.2 \text{ m}^3)\text{/day}$$

Unscreened compost is required each day to cover the pile. This layer will be 18 inches (0.46 m) thick:

$$\frac{(50 \text{ ft})(18.5 \text{ ft})(1.5 \text{ ft})}{27 \text{ cu ft/cu yd}} = 51.4 \text{ cubic yards } (39 \text{ m}^3)\text{/day}$$

Figure 12-13 is the process flow diagram for the extended aerated pile compost facility and summarizes the design materials balance.



5 DAY PER WEEK OPERATION

LOCATION	WET TONS	PERCENT SOLIDS	DRY TONS	DENSITY (lb/cu yd)	VOLUME (cu yd)	PERCENT VOLATILE SOLIDS
1	70	20	14	1,600	87.5	75
2	13.1	70	9.2	500	52.4	90
3	39.4	70	27.6	600	131.3	80
4	122.5	41	50.8	900	271.2	80
5	8.6	70	6	500	34.3	90
6	59.7	–	10.3	–	–	–
7	18.6	65	12	725	51.4	65
8	90	65	58.5	725	248.3	65
9	32	60	18.9	975	64.6	45

1 ton = 0.907 tonne
1 lb/cu yd = 0.6 Kg/m^3
1 cu yd = 0.76 m^3

FIGURE 12-13

PROCESS FLOW DIAGRAM FOR THE EXTENDED PILE COMPOST SLUDGE FACILITY - 10 MGD (0.44m^3/s) ACTIVATED SLUDGE PLANT

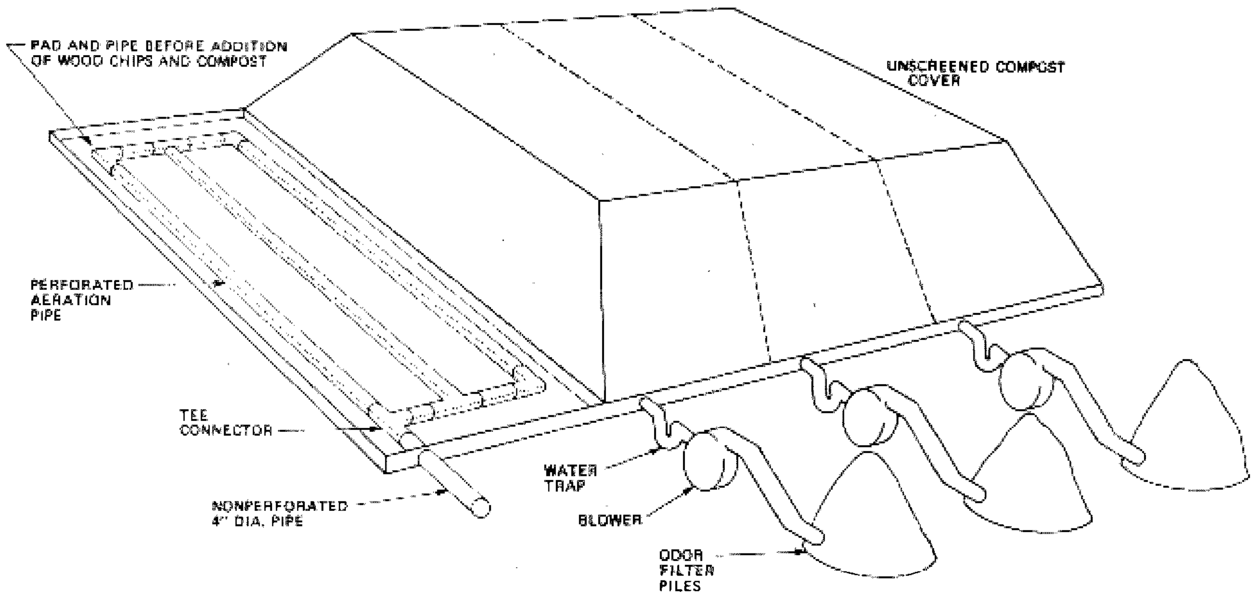
Approximately 250 feet (76 m) of 4-inch (10-cm) diameter perforated aeration pipe, 50 feet (15 m) of non-perforated pipe, three 4-inch (10-cm) tee connectors, and one blower/timer unit with weather protection and condensate collection system are required for each daily pile. Only one blower rated at 335 cubic feet per minute (158 l/s) will be used to draw air into the pile. In general, the blower should be rated at a minimum of 150 cubic feet per hour per wet ton (1.3 l/s/t) of sludge in the daily pile. Non-perforated pipe should be used to connect the aeration pipe loop to the blower. The exhausted air will be filtered in a pile of screened compost. The filter pile will contain at least one cubic yard of material per 30 wet tons (1 m^3/35.5 t) of sludge in the daily pile or 4 cubic yards (3 m^3) for this design. Figure 12-14 illustrates this design example. The minimal area requirements for various composting site components is as follows:

MINIMAL COMPOSTING AREA REQUIREMENTS

50 wet tons per day (45 t/day)
10 dry tons per day (9 t/day)

Function	Area Required: Square feet	Area Required: Square meters
Truck unloading and mixing	5,000	465
Composting (28 days)(50)(18.5)(1.15 excess)	30,000	2,792
Unscreened compost	10,000	931
Drying and screening	20,000	1,862
Compost curing and storage (60 day)(200 cu yd/day)(27 wet tons) (10 ft deep) + excess	33,000	3,071
New wood chip storage (60 day)(87 cu yd/day)(27 wet tons) (12 ft deep) + excess	15,000	1,396
Subtotal	113,000	10,517
Maintenance building, operations building and laboratory, Lunch room and locker room	4,000	372
Employee and visitor parking	5,000	465
Miscellaneous storage	1,000	93
Subtotal	10,000	930
Total	123,000	11,447

NOTE: 123,000 square feet (11,447 m^2) = 3 acres (1.14 ha). Land Utilization = 6.6 dry tons per acre (14.8 t/ha).



1 in = 2.54 cm

FIGURE 12-14

DESIGN EXAMPLE EXTENDED AERATED PILE CONSTRUCTION

The overall space required is about 3 acres (1.2 ha) which is 0.15 acres per ton per day (0.07 ha/t/day) of dry sludge solids composted. Reducing the bulking agent would decrease the area required.

Although porosity is the key factor for the aerated pile, control of moisture is important for a successful sludge composting system. The sludge should be dewatered or mixed with sufficient bulking agent to obtain enough porosity in the composting piles for optimum composting conditions. For optimum composting the composted mixture should have a solids content of not less than 40 percent or more than 50 percent. Figure 12-15 shows a compost pile as it is being taken down.

Approximately 8.5 cubic feet per minute (4 l/s/t) of air per ton of dry sludge solids in the pile is required. At Beltsville, this was delivered by a centrifugal fan operating at 5 inches differential water pressure (1.25 kN/m^2) (18). The Bangor, Maine system uses a 1/3 horsepower (0.25 Kw) blower rated at 335 cubic feet per minute (158 l/s) at 5 inches water pressure (1.25 kN/m^2) for each pile consisting of 50 cubic yards (38 m^3) sludge and 150 cubic yards (114 m^3) bulking agent (7).

The blowers are operated intermittently to maintain the oxygen level in the 5 to 15 percent range and to obtain as uniform a temperature as possible.

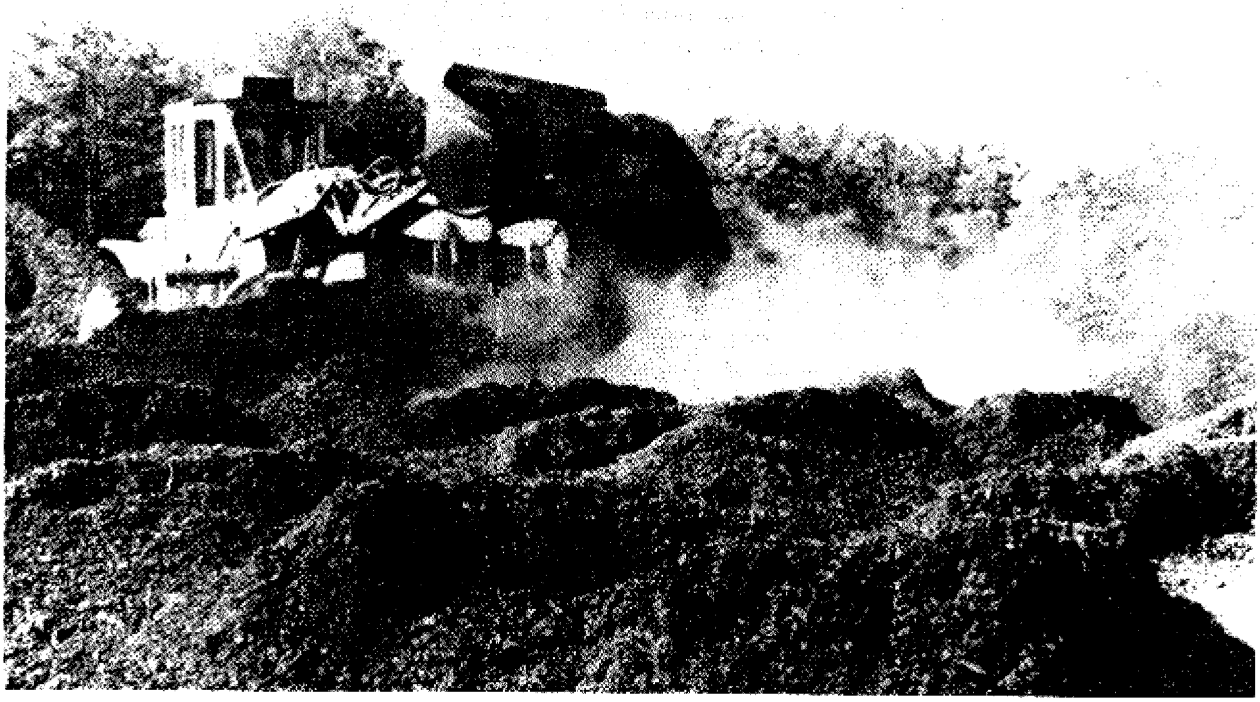


FIGURE 12-15

COMPOST PILES BEING TAKEN DOWN

For large composting systems, a permanent central blower system may be considered. A header pipe could be utilized to provide the necessary suction for each pile. Only one or two large blowers located in a covered area would be required. Although capital cost would be high because of the needed piping and control devices, the operation and maintenance costs of many individual blowers would be eliminated. On the other hand, a central blower system is not especially flexible. Since it is important to maintain the proper aeration rates in each pile, an air flow metering device will be required for each pile. A decision for or against a permanent system would be based on economic analysis and the need for system flexibility to handle changing composting conditions.

The composting area should be paved. Probably the most efficient design in a permanent facility involves the use of fixed aeration and drainage systems. The aeration piping and drainage system could be placed in trenches in the composting pad and the blowers placed in permanent protected structures and equipped with water traps and controls. The disadvantages of this type of combined system are the high initial cost and the reduced flexibility of operation. Possible elimination of the one-foot (0.3 m) wood chip pad and the disposable plastic pipe processed through the screens is a potential advantage of fixed trenches for the aeration pipes. Special precautions would be necessary to keep the centralized aeration piping and pile drainage trenches from clogging and to provide for condensate water drainage.

Odor filter piles should be replaced periodically. The filter piles are replaced every other month at Bangor; during cool weather the system has operated without significant odor problems and with no filter piles. At Beltsville, the odor filter pile is replaced each time the compost pile is dismantled.

After the piles are formed, they should be covered with a layer of compost or wood chips for insulation and to prevent the dust which is caused by excessive drying of the outer pile edges from blowing.

Most composting facilities use a base layer of bulking agent or unscreened compost to cover the aeration piping. However, the piles are now constructed at Bangor with no special base layer; the sludge-bulking agent mixture is placed directly on the aeration piping.

Rotary or vibrating screens are commonly used to separate wood chips for reuse. Compost containing wood chips with a moisture content of greater than 40 to 50 percent can be difficult to screen; the operation is therefore not conducted on rainy days. Allowance should be made for drying the compost if the solids content is less than 50 percent, and the screens should be sized to handle a large volume of compost during fair weather. Figure 12-16 is a photograph of the finished screened compost.

12.3.3 Case Studies (Unconfined Systems)

The four case studies chosen involve Los Angeles County Sanitation District, California; Beltsville, Maryland; Bangor, Maine; and Durham, New Hampshire. The Los Angeles system handles 80 to 120 dry tons per day (73 to 109 t/day). Beltsville composts approximately 14 dry tons per day (12.6 t/day), Bangor about 2 dry tons per day (1.8 t/day), and Durham around 3 dry tons per day (2.7 t/day).

12.3.3.1 Joint Water Pollution Control Plant, Carson, California

A large-scale windrow composting system was established in 1974 at the Joint Water Pollution Control Plant. This operation is currently composting 400 to 600 wet tons per day (364 to 545 t/day) of anaerobically-digested, polymer-conditioned, centrifugally dewatered, primary sludge with a 25 percent solids content (19). The sludge is transported to the nearby compost site in fifteen ton (13.5 t) sludge hauling trucks equipped with end discharge and conveyor bottom trailers, provided to make windrow construction relatively easy. Approximately 15 cubic yards (11 m^3) of finished compost are added to the truck along with the dewatered sludge. The wet and the dry materials are initially mixed in the truck. Complete mixing is subsequently provided by a compost turning machine in the windrow. Given the current consistency of the sludge and the type of equipment used, the windrows that can be constructed are about 3 feet (0.9 m) high and 10 feet (3.0 m) wide. Typically, each windrow is about 500 feet (451 m) long and is constructed with eight to ten truckloads of material. The windrows are placed on sixteen to eighteen foot (14.6 to 16.5 m) centers, leaving a clear aisle for the wheels of the turning machine.

FIGURE 12-16

FINISHED SCREENED COMPOST

When a windrow is first placed, it is turned twice to mix the wet cake with the dry compost. Thereafter, each windrow is turned once per day to maintain sufficient voids for the natural passage of air and to promote drying. The process can produce objectionable odors, particularly in the early part of the cycle and is likely to generate dust under moderately windy conditions.

In addition to being equipped with conveyor bottom trailors, the composting trucks have also been modified with extended sidewalls to increase their capacity, and sealed bottoms, so that they may be used to haul wet cake on public roads. At a production rate of 500 tons per day (450 t/day) of wet cake, about 25 hours of truck time are required each day to construct windrows. Four turning machines, each with a rated capacity of 3,400 tons per hour (3,084 t/hour), are available for the operation. They are relatively high maintenance items, and generally, only two or three are operated. With the current sludge production and a composting time of three weeks, about ten hours of machine time are required to turn all the windrows each day (32).

In addition, two loaders are used for loading dry sludge into the trucks; one crawler tractor is used for pushing windrows into stockpiles; one grader is used for road maintenance and cleaning between the windrows; and a water truck is used to control dust on the plant roads.

The composting operation takes place over a 10-hour day, 7 days per week and employs approximately twenty operators and mechanics, excluding the sludge haulers.

Kellogg Supply Company currently uses earth movers to transfer composted, dried sludge to a neighboring site. Kellogg has been highly successful in distributing and selling the compost as an organic soil conditioner.

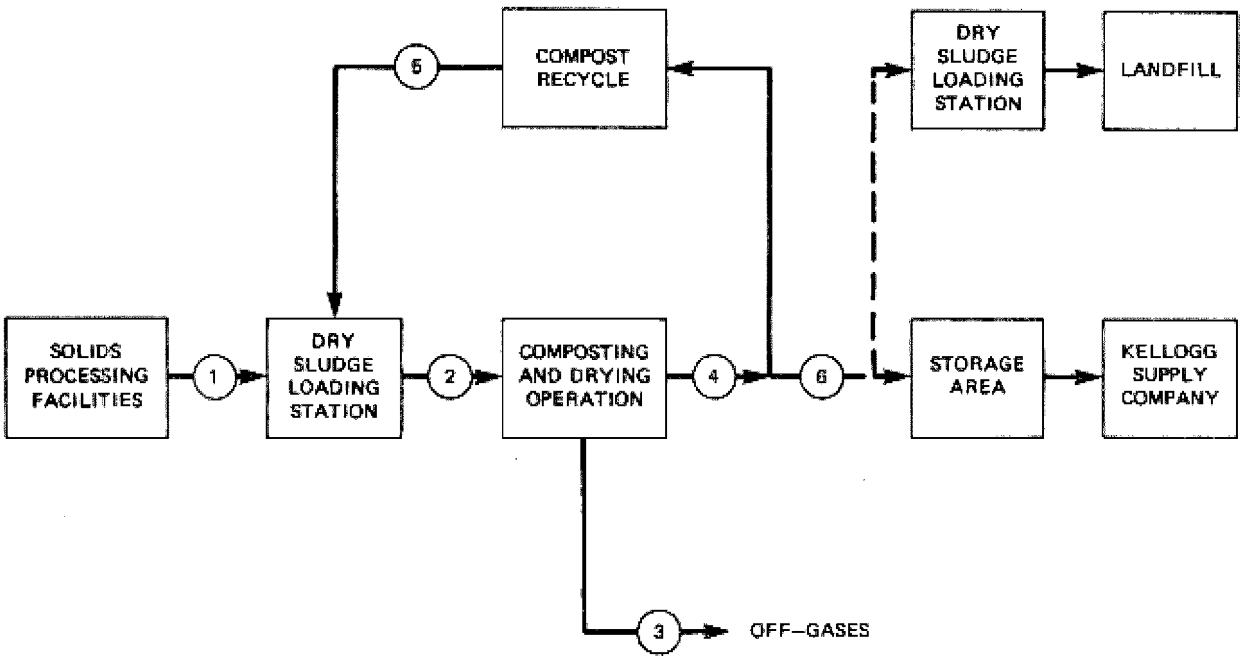
The composting operation of the County Sanitation Districts of Los Angeles County provides a good demonstration of the feasibility of sewage sludge composting on a large scale. Figure 12-17 illustrates the process flow for this operation.

12.3.3.2 Beltsville, Maryland

Many methods and concepts have been developed at Beltsville through the integration of experimental research and practical operation. The first method attempted at Beltsville was the windrow process. The windrows performed well when digested sludge was used, but odors developed when unstabilized, dewatered/combined primary and secondary sludge was composted by this method. The individual aerated pile method was developed by the Beltsville researchers to eliminate the odor problems associated with the windrow process.

The research programs demonstrated that either digested or undigested sludge can be composted in the aerated pile. Destruction of pathogens was much greater with aerated pile composting than with windrow composting (33,34). The extended aerated pile method was also developed at Beltsville to minimize composting area requirements.

The extended aerated static pile process is currently used in continuous, 5 day per week operation to compost 60 to 120 wet tons per day (54 to 109 t/day) of dewatered, unstabilized sludge (approximately 20 to 22 percent solids). The sludge is conditioned with lime and ferric chloride, dewatered and loaded into tractor-trailer dump trucks at the treatment plant during the night. Each truck holds 20 wet tons (18 t) and has a watertight rear door. Depending on the quantity of sludge to be composted, three to six trucks transport the sludge to the compost site in the morning. All of the sludge is delivered at once, which facilitates pile construction.



LOCATION	WET TONS PER DAY	PERCENT SOLIDS	DRY TONS PER DAY	DENSITY (lb/cu yd)	VOLUME (cu yd)	PERCENT VOLATILE SOLIDS
1	1,600	23	368	1,890	1,690	55
2	2,960	40	1,184	1,510	3,930	50
3	1,140	–	92	–	–	–
4	1,820	60	1,092	1,215	3,000	40
5	1,360	60	816	1,215	2,240	40
6	460	60	276	1,215	757	40

1 ton = 0.907 tonne
1 lb/cu yd = 0.6 Kg/m^3
1 cu yd = 0.76 m^3

FIGURE 12-17

COMPOSTING/DRYING SYSTEM - COUNTY SANITARY DISTRICTS - LOS ANGELES (18)

The extended pile is constructed on a concrete pad approximately 100 feet (30 m) wide and about 400 feet (122 m) long. The sludge is dumped onto the wood chips and mixed by a front-end loader, in a 2.5:1 chip to sludge volumetric ratio.

The composting area for each daily mixture is prepared by laying out aeration piping on the concrete composting pad and covering it with a 12-inch (0.3 m) layer of wood chips using a front-end loader. The compost mixture is then placed on the wood chip base using a front-end loader. The mixture is piled to a height of 8 feet (2.5 m), and the top and ends are then capped with an 18-inch (0.5 m) layer of unscreened finished compost or a 12-inch (0.3 m) layer of screened, finished compost. At the end of each day's operation, the side of the pile (which will have new material added to it the next day) is covered with a thin layer of compost. A pile containing 60 wet tons (54 t) of sludge and wood chips is approximately 8 feet (2.5 m) high, 12 feet (3.6 m) wide and 75 feet (23 m) long.

To insure proper aeration, a 1/3 horsepower (0.25 kW) blower, rated at 335 cubic feet per minute (158 l/s) at 5 inches differential water pressure (1.2 kN/m^2) is connected to the piping. The exhausted air is filtered through a 5 cubic yard (3.8 m^3) filter pile of screened compost for deodorization. The blower's is operation is controlled by a timer. Currently, blowers are operated for 8 minutes out of every 20 minutes.

At Beltsville, one blower is used to aerate 120 wet tons (109 wet t) of primary undigested sludge mixed with wood chips. One blower has proven sufficient for two piles when the sludge is brought to the site at a rate of 60 wet tons per day (54 t/day). Thus, only approximately 10 blowers and odor filter piles are required (excluding spare equipment) to operate a 21-day extended aerated pile facility.

Composted material is removed from the piles after 21 days. The compost pile is dismantled by a front-end loader and moved to the curing stockpile. The compost stays in the curing pile for at least 30 days and is not mixed before screening and off-site use. A mobile rotary drum screen separates the cured material, which must be at least 60 percent solids to screen properly. Finished, cured compost that is too wet to screen is placed in windrows and turned as frequently as possible for 2 to 3 days until it is sufficiently dry.

Leachate, condensate, and stormwater runoff are collected in a holding pond at the far end of the compost facility. When the level of the pond rises to a maximum allowable height, the water is pumped to a forested site and sprayed on the forest floor. Test wells at the compost site and at the land application site have indicated no groundwater contamination with the use of this system.

Additional research is being conducted at Beltsville on a modification of the aerated, extended pile process, called the extended high pile method. Since land area requirements can be reduced by increasing pile height, one pile in the shape of a pyramid has been constructed to a height of 18 feet (5.5 m). Aeration pipes are installed at three elevations in the pile--at the base, at 6 feet (2 m), and at 12 feet (4 m) above the base.

Those at the base and at 12 feet (4 m) levels operate at negative pressure while the pipe at the 6-foot (2 m) level operates at positive pressure. Tests are presently underway to determine the maximum height at which piles can be built and effectively aerated with pipes placed only at the base (35).

The Beltsville staff consists of eight full-time people, two administrative personnel and six operators, excluding the sludge transfer truck drivers. This number is more than actually needed for normal operations. The additional personnel are used for special operations and to support the research demonstration program. Each member of the operation staff is qualified on each piece of equipment and the staff is able to perform all preventive maintenance and much of the repair work. A list of equipment is shown on Table 12-3. All equipment has enclosed operator cabs so that dust and moisture do not interfere with the equipment operators.

TABLE 12-3

BELTSVILLE EQUIPMENT (15)

3	Terex rubber-tired front loaders, 4.5 cubic yards
5	Dump trucks, 20 ton
1	Rotary drum screen with power unit
1	Sweco screen
1	Fixed Toledo truck scale
1	Mobile office
1	Storage building
1	Covered building - compost test, concrete floor with aeration pipe in floor
1	Portable oxygen analyzer and temperature indicator and probe

1 cu yd = 0.76 m^3
1 ton = 0.907 t

Some of the finished compost is used by the USDA at its agricultural research center for other test programs. Most of the compost is provided free of charge to local public works departments who pick up the material at the Beltsville site.

The approximate material quantities used in the Beltsville operation are based on the following: annual undigested sludge cake (with a solids concentration of approximately 23 percent) input of 15,000 wet tons (13,605 t); ratio of 2.5:1 wood chip bulking agent to sludge cake by volume; and 5/8-inch (1.5 cm) screening of all compost for wood chip recovery and recycle of 75 to 80 percent; the wood chip loss/attrition rate at Beltsville is currently about 41 percent (36). In this example, the materials loss through composting and curing is estimated.

The building used for test purposes at Beltsville has a concrete floor with aeration piping built in. Channels 6 inches by 6 inches (15 cm x 15 cm) are recessed in the floor and the aeration piping is placed into them. The channels run the width of the building and are spaced 6 feet (2 m) apart along the length of the building. One end of the piping is connected to a header system and the other is closed off. One large blower draws air through the header system. Limited tests have suggested this arrangement will be proven successful, and a refined version of this system is being constructed at Durham, New Hampshire. The Beltsville structure is approximately 80 feet (24 m) wide and 240 feet (73 m) long. Composting is conducted in an 80 by 200 foot (24 by 61 m) area and the remainder is an enclosed and heated equipment storage and maintenance area.

The estimated and projected costs for this extended aerated pile operation are listed in Table 12-4. The cost for early composting operations included extensive testing, monitoring, and optimization. The cost per ton for this operation would be reduced if a facility were designed to operate continuously and to use the process as it has been optimized at Beltsville.

12.3.3.3 Bangor, Maine

In August 1975, composting operations began in Bangor to dispose of the sludge generated by the wastewater treatment plant. An average wastewater flow of 7 MGD (307 l/s) receives only primary treatment. The plant produces 2,500 wet tons per year (2,268 t/year) of lime conditioned vacuum-filtered sludge cake with an average solids content of 20 percent (5). The composting site selected by the City of Bangor is located about 3 miles (4.8 km) from the wastewater treatment plant.

Initially, the sludge was dumped onto a bed of bulking agent (wood bark) in the mixing area, mixed with a front-end loader, and formed into a compost pile. Currently, no base material is used; the sludge bulking agent mixture is placed directly on the pad and aeration pipes. Generally, one composting pile is constructed per week and typically consists of 40 to 60 cubic yards (30 to 46 m^3) of undigested primary and secondary sludge cake which is mixed in 1:2.5 ratio with about 120 to 180 cubic yards (91 to 137 m^3) of bulking agent. Bark with a less than 50 percent moisture content is used as the bulking agent.

The total area required for composting 3,000 cubic yards per year (2,280 m^3/year) of dewatered sludge at 20 percent solids is about 1.7 acres (0.7 ha). Precipitation, runoff, and condensate from the composting operation are channeled into a drainage ditch leading to the sanitary sewer line (Figure 12-18).

The base for the compost pile is prepared using 7-foot (2 m) lengths of perforated schedule 40 steel pipe, joined together by short pieces of plastic pipe. The city found that the short lengths of steel pipe can be removed from the pile without significant damage and reused many times. Longer pipes were used previously but were easily bent when pulled from the pile.

TABLE 12-4

BELTSVILLE ACTUAL AND PROJECTED OPERATING COSTS - 1977 DOLLARS (15)

	Actual 1976	Estimated October 1977 to September 1978 costs, dollars: 15,000 wet tons/yr	18,200 wet tons/yr[a,b]	45,500 wet tons/yr[a,b]
On-site operations				
Telephone and travel	3,971	1,300	1,300	1,300
Utilities	426	2,211	2,211	3,000
Fuel and oil	13,036	10,500	10,500	25,000
Sludge hauling	120,000	132,000	-	-
Labor including fringes	152,919	125,750	80,000	125,750
Miscellaneous contract services	112,942[c]	27,540	27,540	37,000
Wood chips[d]	73,145	144,000	144,000	350,000
Supplies and materials	32,176	22,250	22,250	35,000
Equipment insurance	3,955	4,000	4,000	4,000
Total, excluding off-site	512,570	469,551	291,801	581,050
Dry tons sludge/yr (23 percent solids)	3,450	3,450	4,200	10,500
Annual cost, dollars/dry ton sludge solids	149	136	69	55

[a]Excluding requirements of research work.

[b]Assume 50 percent of compost marketed unscreened and 70 percent recovery of bulking agent after screening finished compost.

[c]Includes screening performed by outside contract, screening now performed on site.

[d]When this analysis was conducted a wood chip attrition rate of 20 percent was used. 1979 analysis indicates that an actual value of 41 percent should be used for wood chip attrition. (36)

1 ton = 0.907 t

The city has used unscreened compost as the bulking agent in a number of piles. This has dramatically reduced requirements for new bulking material, and the city plans further tests.

The compost piles are constructed as high as the front-end loader can reach and capped with 1 to 2 feet (0.3 to 0.6 m) of unscreened compost. The finished pile is 10 to 12 feet (3 to 4 m) high. Each pair of compost piles is provided with one mechanical blower. Blowers are operated by timers.

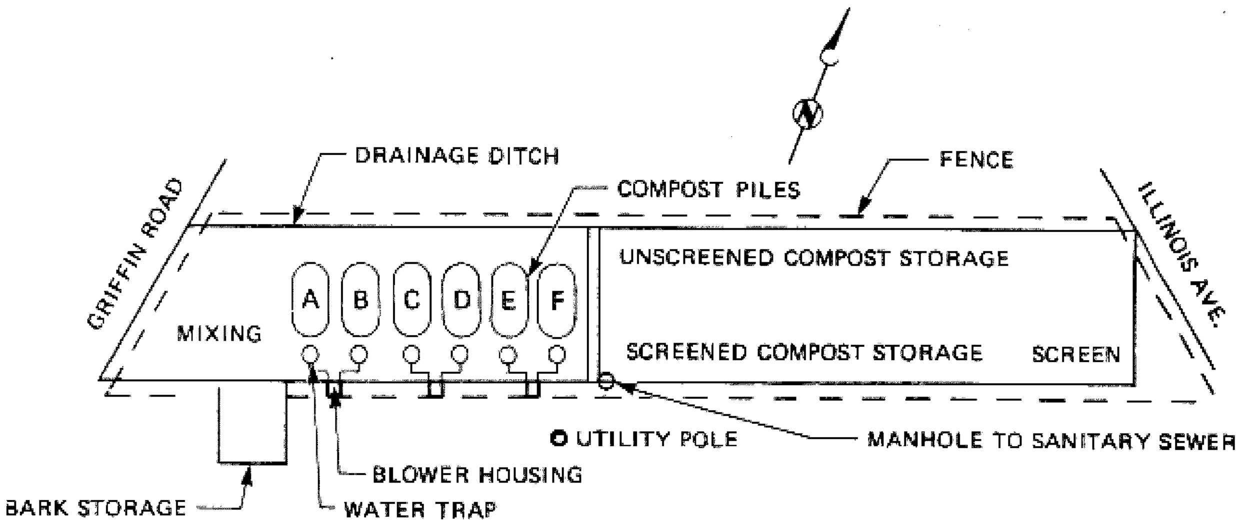


FIGURE 12-18

COMPOSTING SITE LAYOUT - BANGOR, MAINE (5)

During cold weather, all available heat must be conserved to bring the piles up to temperature. Recycled unscreened compost provides a warm bulking agent. The interiors of the wood bark storage piles are also sources of warm materials for mixing. Generally, if the compost pile mixture can initially be maintained at 39°F (4°C), the interior of the pile will warm up to normal composting temperatures much more readily than if the mixture falls below 39°F (4°C). Warm exhaust air recycled from an older composting pile into the new pile also helps for the first few days, but recycling should be discontinued after this period because it causes high moisture levels in the new pile. Increasing the unscreened compost blanket from 1 to 2 feet (0.3 to 0.6 m) during the winter also helped to retain more heat within the composting pile. The city purchased an air heater to provide initial heat to the piles.

The piles are composted for at least 21 days. Temperature and oxygen levels are monitored every two to five days during the compost cycle. Blower operating cycle is adjusted according to the performance of the pile. The aeration pipes, blowers, and moisture traps are checked for freezing during cold weather.

At the end of the composting cycle, the pile is dismantled, and another pile is usually constructed. The material removed from the pile is either used as the bulking agent for the new pile or transferred to curing.

Unstabilized sludge is not stored at the compost site. Generally, operations are scheduled so that sludge is dewatered and a compost pile is constructed once a week. The exact day of pile construction is varied depending on weather conditions. The city has been able to compost nearly all of the sludge produced, because it is prepared to construct the compost pile during good weather.

A Lindig rotary drum screen is used to separate compost prior to distribution. The drum is presently fitted with a one-inch (2.5 cm) mesh screen. City personnel are planning to construct a 5/8-inch (1.6 cm) screen assembly so that either size material can be produced. Tests performed at Bangor indicate that the screen is capable of handling about 20 to 25 cubic yards per hour (15 to 19 m^3/hr) of feed under the best conditions. Compost is put in the screen with a front loader. One loader operator and a laborer are required during screening operations.

Currently, operations at Bangor are performed by treatment plant personnel under the direction of the treatment plant superintendent. There are no full-time composting personnel because of the cyclical nature of the operations. Approximately 11 man-hours per week are required for a truck driver to deliver and unload sludge at the site. Sampling and monitoring for temperature and oxygen content require 10 man-hours per week. Pathogen and heavy metals monitoring is performed under contract with the University of Maine. Supervision and administration require about 15 man-hours per week. Annual equipment and labor requirements are shown in Table 12-5. The equipment used for composting operations is shown in Table 12-6. This equipment is provided by the city motor pool and is available for composting when needed.

TABLE 12-5

ESTIMATED ANNUAL LABOR AND EQUIPMENT REQUIREMENTS, BANGOR, MAINE (5)

Operation	Labor, hours	Equipment, hours
Composting		
labor	572	
front loader		468
Sludge hauling		
labor	468	
truck		468
Monitoring		
labor	520	
pickup		520
Administration		
labor	780	
Screening (8,000 cubic yards)		
labor	1,040	
screen		520
front loader		520
Maintenance		
labor	100	

1 cu yd = 0.76 m^3

TABLE 12-6

BANGOR EQUIPMENT (5)

1	Case W24B rubber-tired front loader, 4 cubic yard
1	Rubber-tired front loader, 1.5 cubic yard
1	Truck, sludge hauling
1	Mobile screen, Lindig
	Small tools, as required
	Miscellaneous vehicles as needed from motor pool

1 cu yd = 0.76 m^3

Approximate materials quantities for 1976 are shown in Table 12-7. This is based on an annual sludge input of 3,000 cubic yards (2,280 m^3) and a mixture of three parts bulking agent to one part sludge.

TABLE 12-7

BANGOR MATERIALS REQUIREMENTS FOR 2,170 WET TON (1,968 t) ANNUAL SLUDGE INPUT (5)

Limed raw primary sludge, wet tons	2,170
Solids, percent	23
Cubic yards, cu yd	3,000
Density, lb/cu yd	1,450
Dry tons	500
Static pile construction	
Sludge, cu yd	3,000
Bulking agent, cu yd	9,000
Pile cover, cu yd	1,560

1 ton = 0.907 t
1 cu yd = 0.76 m^3
1 lb/cu yd = 0.6 kg/m^3

12.3.3.4 Durham, New Hampshire

Durham, New Hampshire, provides primary treatment to approximately 1 MGD (44 l/s) of wastewater. About 15 wet tons (13.6 t) of unstabilzed, dewatered, primary sludge (20 percent solids) is produced each week. The treatment plant is being upgraded to secondary treatment capability, and this is expected to double the quantity of sludge generated.

In an effort to cope with current sludge production and to solve the problem of future sludge disposal, Durham investigated several sludge utilization and disposal alternatives. Landfilling had to be terminated because the landfill was reaching its maximum capacity and no other suitable land was available within the town limits. It was considered too costly and time consuming to obtain additional land in an adjacent town. Incineration was considered but rejected because previous experience with burning solid waste had been unsatisfactory.

A permanent composting facility was chosen (after an extensive pilot-scale investigation) as the sludge disposal alternative. It was determined that this facility would best meet the needs of the community for the following reasons (31):

- Estimated cost of the compost facility was 658,000 dollars, of which Durham, by virtue of state and Federal funding, would pay approximately 33,000 dollars.

- The compost facility would be an integral part of the wastewater treatment plant, and plant personnel could operate the facility.

- Sale of finished compost would help defray the operating costs.

- Composting returns a viable product to the land at a cost competitive with landfilling and incineration.

The new composting facility incorporates many innovations that reduce operation and maintenance problems. It should be recognized that since there are many innovations in this design that they are not a proven technology. The composting and all other outdoor operations will take place on a concrete pad which is easier to clean than a gravel base, prevents rocks from mixing with the compost, and is a better year-round working surface. The pad is sloped to allow runoff collection from the compost piles. The runoff is recycled to the treatment plant to provide protection for the surrounding land and streams. The pad is 250 x 152 feet (76 x 46 m), and is spacious enough for the screening operation.

The aeration pipes are placed in triangular troughs 6 inches (15 cm) deep which are recessed below the pad surface and covered with an aluminum grating, flush with the pad. Once the aeration pipe is in place, wood chips are used to fill up the remaining space in the trough under the grates. It is anticipated that chips directly under the grating will be changed occasionally, but the pipe will be used for an extended period of time. The sludge-wood chip mixture will then be placed directly on the concrete pad over the grates without any wood chip base. Figure 12-19 shows a cross section of an aeration trough with the aeration pipe.

A 4-foot retaining wall will be built along the edge of the composting area of the pad. This wall will be constructed to protect the blowers which will be located on the side away from the composting operation and to provide a positive backstop for front loader operations.

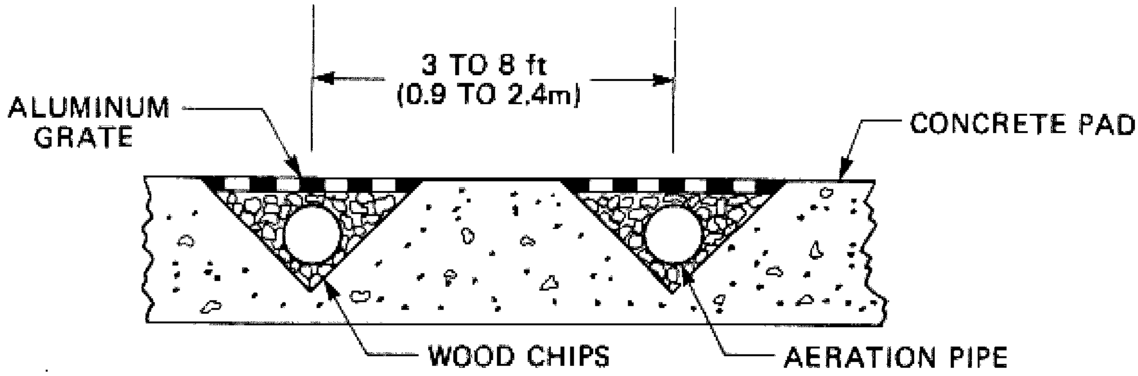


FIGURE 12-19

CROSS SECTION OF AERATION PIPE TRENCH
DURHAM COMPOST PAD DESIGN

The sludge processing building of the new secondary treatment plant will be placed adjacent to the composting pad. Primary and waste-activated sludges will be mixed together prior to coil vacuum filter dewatering to provide for more consistent operation. The mixing tanks for both primary and secondary sludge will be located in this building along with the conditioning chemicals, chemical feed equipment and coil filters. To provide flexibility in operation, the new plant will have a one-week liquid storage capacity for both activated sludge and primary sludge.

After the sludge is dewatered, a pug mill will mix it with wood chips fed from a hopper. A conveyor belt will transport the compost mixture from the building for pick-up by the loader and placement on the pad. The mixing operation is conducted inside the building to protect the operation from the weather. Coil filter personnel will operate the mixing process, thus minimizing personnel requirements.

Screening will be executed using a Lindig Rotary Screener with a material throughput capacity of 280 to 400 cubic yards per day (213 to 304 m^3/day). Screening capacity exceeds production requirements, so that the screen needs to be run only part of the time. This frees the screen and loader operators to undertake other tasks.

Storage bins for the composted material and chips will be placed directly against the composting pad such that the top of the bins are even with the pad. There will be four bins with a capacity of 1,200 yards (912 m^3) each. Three of the bins will be used for storing compost and one bin for the storage of wood chips. As the composted material is screened on the composting pad, the compost will drop into the bins for storage and curing. A conveyor will collect the wood chips and return them to the fourth bin for storage. The screen can be shifted to link the compost pile being dismantled with a storage bin (31).

The storage bins will be used for curing the compost and will have sufficient capacity for storage of all production during winter months when no distribution is planned. The bins will be unloaded after the sludge is cured for about four weeks. This two-yard (1.4 m^3) front-end loader will also build and dismantle the piles, feed the screen, load the chip hopper and trucks with the finished product, keep the pad free of ice and snow, and provide a backup for the mixing operation. A wood chipper and a seven-yard (5 m^3) dump truck for hauling purposes are other equipment to be used.

12.3.3.5 Cost Analysis

Comparing the cost of composting at different facilities is extremely difficult because local factors such as the weather, labor, and equipment are highly variable. Operations in warm, dry climates will require less bulking agent and probably be more successful with the screening process than operations in cold winter areas. Labor and bulking agent costs are a large portion of composting expenditures and vary widely according to geographic area.

A generalized annual operating cost analysis has been performed for an extended aerated pile system for an operation processing ten dry tons per day (9 t/day) of sludge based on the operations at the Beltsville facility (18, 34). This analysis is presented in Table 12-8. A 10 dry ton per day (9 t/day) compost site should handle the sludge generated by a secondary treatment plant from a community of 100,000 people. The site is assumed to be operating eight hours per day, seven days per week.

In 1976, when the original analysis was done, the operating cost was calculated to be 40 dollars per dry ton ($44.44/t). Although all prices have increased since then, the one item which is significantly more expensive is wood chips. In the analysis in Table 12-8, wood chip attrition had been estimated at 20 percent. Analysis done in 1979 indicates that 41 percent is the actual value. Wood chip costs have increased from the $3.50 per cubic yard ($4.61/m^3), the value indicated in Table 12-8, to a 1979 value of approximately $7.00 per cubic yard ($9.21/m^3). In addition cost for transporting sludge to the compost side must be included.

An analysis of the capital cost is not presented, because capital costs are site specific. The development cost of the site cannot be generalized, and the type of composting systems used, aerated pile or windrow, will largely influence the capital cost. The replacement cost of the equipment can be a large portion of the capital cost. The largest capital cost is usually the compost pad. The capital cost for all equipment and structures at Durham is estimated to be about $600,000. Durham's annualized cost is anticipated to be $80 per dry ton ($88/t) for capital and $60 per dry ton ($66/t) for operating. This makes the total annual cost for sludge composting at Durham $140.00 per dry ton ($154/t). This facility is highly mechanized and may represent one of the most capital-intensive composting operations. The operation at Bangor, however, utilizes a portion of an abondoned taxi way and uses the individual pile composting method. The capital costs for this facility are estimated at about $10 to $15 per dry ton ($11 to $16/t).

Except for wood chips and labor, the best approach for estimating annual operating costs for design purposes is to determine the costs from a similar compost facility operating in the same geographic area. Wood chip and labor costs must be determined for the specific site. Capital costs are best developed and annualized for the specific site chosen for the facility.

TABLE 12-8

FACILITY PROCESSING 10 DRY TONS (9 t) OF SLUDGE PER DAY [a] (1976 DOLLARS) (19,34)

	Dollars/yr	Dollars/dry ton	Percent of operating cost
Operations			
Wood chips at $3.50/cu yd[b]	35,000	9.60	23
Plastic pipe	12,200	3.34	8
Gasoline	2,300	0.63	1
Diesel	5,300	1.45	4
Electricity	1,500	0.41	1
Equipment maintenance	8,400	2.30	6
Equipment insurance	1,400	2.30	6
Pad, road maintenance	1,200	0.33	0.5
Water/sewer	500	0.14	0.5
Labor	77,500	21.23	52
Miscellaneous supplies	4,400	1.20	3
Total	149,700	41.01	100

[a]Based on the Beltsville operation and assumed to operate eight hours per day, seven days per week.

[b]In 1979 wood chips cost $6.50/cu yd at Detroit and $7.92/cu yd at Blue Plains. In addition the wood chip attrition rate went from an assumed 20 percent to a confirmed 41 percent. (36)

1 ton = 0.907 t
1 cu yd = 0.76 m^3

12.4 Confined Composting System

Mechanical composting is accomplished inside an enclosed container or basin. Mechanical systems are designed to minimize odors and process time by controlling environmental conditions such as air flow, temperature, and oxygen concentration.

12.4.1 Description of Process

The primary differences among mechanical composting systems are in the methods of process control. Some provide aeration by tumbling or dropping the material from one floor to the next. Others use devices which stir the composting mass. Tumbling the compost in a rotating cylinder is another approach. In addition, an endless belt is used to combine forced bottom aeration and stirring. Water is added to the composting mass at critical times to increase biological activity in some mechanical systems. Also, some mechanical composters can introduce heat to the composting mass to keep the composting reaction continuing at the optimum rate during cool weather.

The brief detention times which equipment manufacturers specify for mechanical composters do not allow adequate stabilization of the sludge. If shorter detention times are provided, a two- to three-month maturation period will be necessary to reduce the remaining volatile matter. Thus, the amount of time and total area required for mechanical processes approaches that for unconfined processes. Mechanical processes are more capital-intensive than unconfined processes. Currently only a few mechanical composting processes are operating in the United States and these are generally used to compost a mixture of refuse and wastewater sludge. A schematic of a typical confined composting process is shown on Figure 12-20.

12.4.2 Metro-Waste Aerobic Thermophilic Bio-Reactor

The Metro-Waste process utilizes a compost chamber and an endless belt to achieve adequate aeration. The endless belt lifts the composting material to a height of three feet (0.9 m), and drops it behind as it moves from one end of the bin to the other. A large fan introduces air into the mixture through a perforated floor in the compost chamber. A partial diagram of this system is shown on Figure 12-21.

This process, including environmentally controlled buildings, is available in module units of 10 dry tons per day (9 t/day) with retention capacities of 7 to 21 days (37).

12.4.3 Dano Bio-Stabilizer Plant

Figure 12-22 shows a typical layout of a Dano Bio-Stabilizer plant. The process makes use of a large, slowly rotating drum, the interior of which is equipped with vanes or baffles. Material is injected into one end of the machine, rotated slowly for one to three days, and ejected from the opposite end. Aeration is acccomplished by tumbling action. Air is injected into the interior of the drum to insure a constant supply of oxygen.

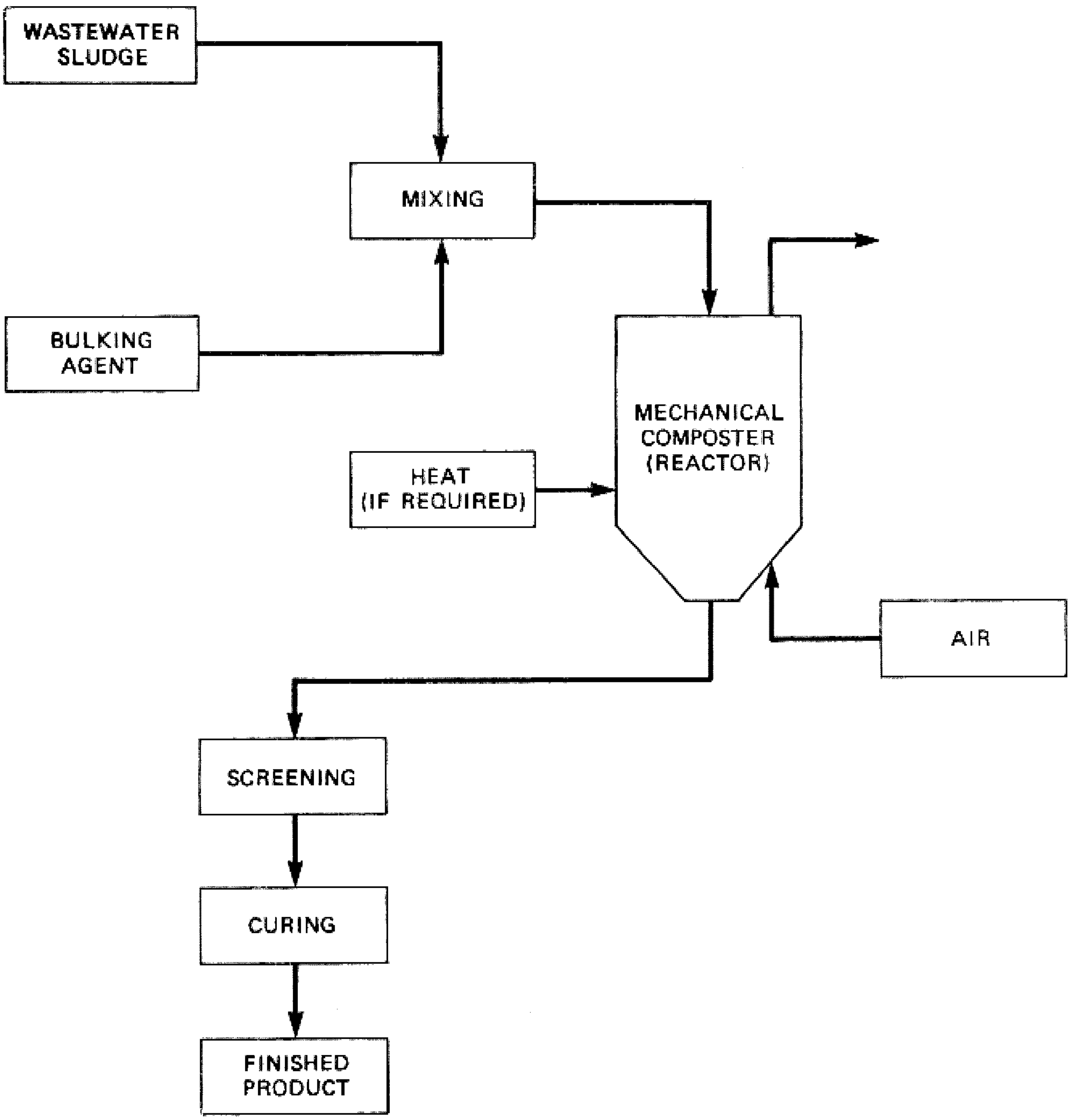


FIGURE 12-20

TYPICAL PROCESS FLOW
SCHEMATIC CONFINED COMPOSTING SYSTEM

The "maturation" or "curing" period for a Dano Bio Stabilizer can be reduced to one month if the material is turned occasionally (9). The Dano process is generally designed for refuse composting with sludge addition.

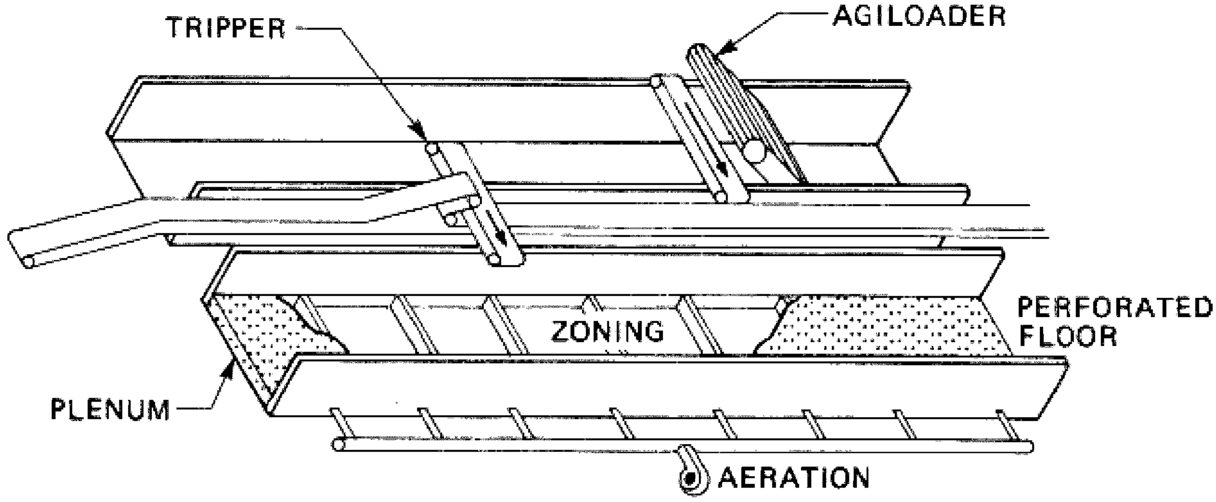


FIGURE 12-21

PARTIAL DIAGRAM
METRO - WASTE SYSTEM -
RESOURCE CONVERSION SYSTEMS, INC.

12.4.4 BAV Bio-Reactor

The BAV system composts municipal wastewater sludge in an upright cylindrical reactor. Sludge is mixed with finished compost, or other bulking agent such as sawdust, and the mixture is fed through the top of the cylindrical reactor. The composted mixture is drawn off the bottom of the reactor as new material enters from the top. The detention time in the reactor is between ten and fourteen days. Air is fed evenly throughout the reactor and the oxygen concentration is monitored by an electric measuring and regulating system. Municipal solid waste can also be composted with the sludge, but then the compost would require further processing to remove nonmagnetic metals and pieces of wood, glass, plastic, and other non-organic materials before it is ready for landscaping use. Figure 12-23 illustrates the BAV process.

12.5 European Composting Experience

Of the seven European countries recently surveyed for wastewater sludge composting practice, West Germany is the center of activity, with more than 30 operating plants (38). Sweden follows with 20, which are either in operation or in planning and design stages; Switzerland has nine; France has five; the United Kingdom has one; Italy and the Netherlands have none. These systems are located where wastewater sludge is the predominant waste component usually mixed with municipal solid waste. The number of sludge-only composting systems are few.

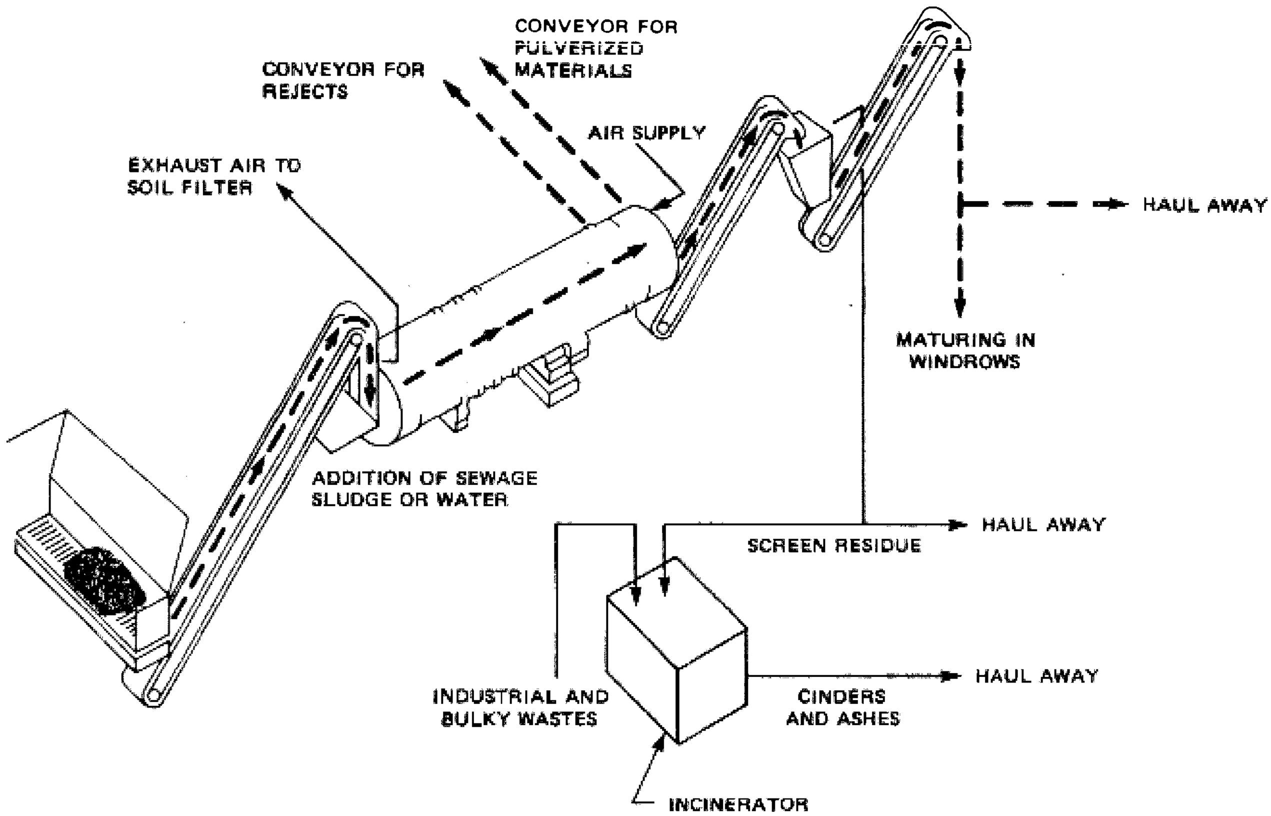


FIGURE 12-22

TYPICAL LAYOUT OF A DANO BIO-STABILIZER PLANT

The feasibility of composting wastewater sludge mixed with a bulking agent is established in Europe, but the future of general composting technology in Europe appears to depend on the market economics and continued public acceptance, rather than on technological improvements.

The predominant experience in Europe has been with enclosed mechanical systems. This is primarily a result of attempts to minimize compost facility area requirements. Table 12-9 lists the various operating European wastewater sludge composting processes.

Although numerous attempts were made from 1930 until the present, wastewater sludge is no longer composted in windrows without additives (sawdust, straw, bark) in Germany. Dewatered sludge, without additives, has a low porosity which impedes natural aeration. Strong, objectionable odors developed, and caused all attempts to be abandoned. The following illustrates recent composting experiences, in Germany, the United Kingdom, Sweden, and Switzerland (38).

West Germany

In the last three to five years in the Federal Republic of Germany, about 30 plants for the composting of wastewater sludge only have been built or are under construction. When all of these plants are in service, they together will be capable of managing the sludge from an equivalent population of 800,000. The fact that these 30 confined facilities can only together service the sludge from a population of 800,000, contrasts sharply with the fact that unconfined processes, such as the windrow operation in Los Angeles, or aerated static pile process in Washington, singularly each process equal to or greater than 800,000 population. In most cases, composting of wastewater sludge occurs with the help of bulking materials such as sawdust or straw. Currently, a research program is being conducted by the German Umweltbundesamt to determine whether these processes do indeed produce a pasteurized and pathogen-parasite-free product. Preliminary results of this research program, as yet unpublished, show that in some of these processes, pasteurization is incomplete and indeed some final composted products do contain both human and plant pathogens.

United Kingdom

As of 1978, only one operating plant located at Wanlip, near Leicester, is composting wastewater sludge in the United Kingdom. Although 10 to 15 years ago, municipal solid waste (MSW) composting in Dano rotating drums was common, most of the plants using these have shut down. In 1974, the Wanlip plant reopened, and it now processes 1,100 tons (1,000 t) of MSW mixed with 551 tons (500 tonnes) of digested wastewater sludge (five percent solids) each week. The product, packaged under the brand-name, "Lescost," is marketed with some success throughout Great Britain.

Sweden

In 1975, the Swedish parliament passed a resolution which emphasizes recycling through better solid waste management. With this resolution, 20 Swedish communities or regions are planning, or are in the process of constructing, composting plants. At present, less than one percent of the total MSW and wastewater sludge produced is recycled by a composting technique. According to recent estimates by the Swedish National Protection Board, in the next two years approximately seven percent of the total MSW and wastewater sludge produced will be recycled by composting methods.

Switzerland

Currently, there are nine composting plants in Switzerland, the newest of which went into operation in 1975 in Biel. All but one, in Uzwel, mix sewage sludge with MSW. In most cases, incineration and composting equipment are located side by side. The composting operation is used to dispose of sewage sludge. The incinerator burns most of the municipal waste and the rejects from the composting installation. Nearly all the plants use the Dano system for composting. The auxiliary mechanical machinery, such as hammermills, conveyors and screens, is usually produced by Buehler.

The construction of composting plants has almost ceased in European countries other than Sweden. Apparently most operating plants have difficulties in marketing the compost at a satisfactory price. It may well be, however, that careful operation of the plant and better marketing could improve sales of the compost. It appears very unlikely that a number of combined MSW/wastewater sludge composting plants will be built in the near future. One of the reasons is that the rejects of composting must be burnt (landfilling is, for reasons of space, not feasible in most relatively small European countries); therefore, an incinerator is necessary in any case. Building a larger incinerator instead of a combined system seems, in many cases, the simpler solution.

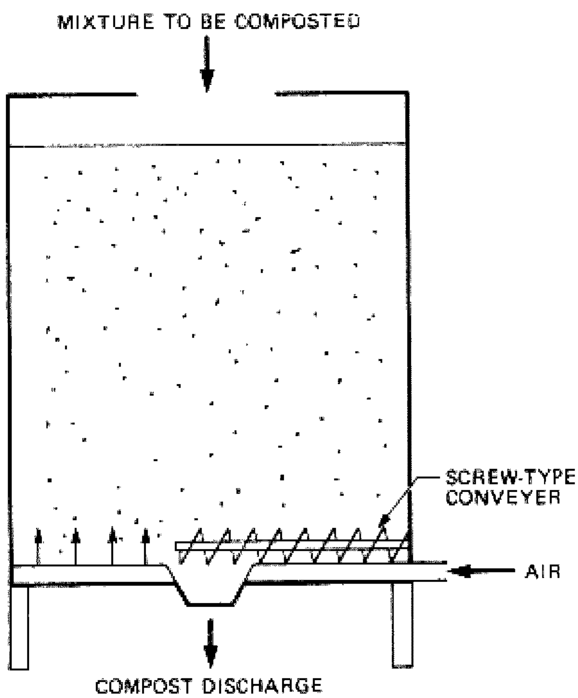


FIGURE 12-23

BAV BIOREACTOR

TABLE 12-9

EUROPEAN WASTEWATER SLUDGE COMPOSTING PROCESSES (38)

Category	Process	Number of operating plants
Within vessel	BAV	19
	Carel Fouche Languepin	1
	Roediger/Fermenttechnik	1
	Schnorr Valve Cell	2
	Societe General D'assainissement et de Distribution (SGDA)	1
	Triga	2
	Weiss	3
Windrow	BIO-Manure	1
	Hazemag	-
	PLM	-
Rotating drum	Buehler	9
	Dano	9
	HKS	2
Pressed brick	Brikollare	2
Fermentation cells	Prat	1

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EPA 625/1-79-011

PROCESS DESIGN MANUAL FOR SLUDGE TREATMENT AND DISPOSAL

Chapter 13. Miscellaneous Processes

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

September 1979

structure of the solids; a monolithic solid is much less subject to leaching than is a granular solid. However, monolithic solids may deteriorate if exposed to wet-dry or freeze-thaw cycles (11). Leaching tests to estimate long-term weathering resistance of the fixed solids are still being formulated (12). It should be emphasized that the information presented in this paragraph was derived from experience with sludges of an industrial origin. Experience with municipal sludges may be similar to that with some industrial ones.

TABLE 13-1

PARTIAL LIST OF FIXATION PROCESSES

Vendor	Process	Additives	Additive quantity, percent	References
Dravo Corporation	Synearth[a]	Calcilox[a] Thiosorbic[a] lime	7[b] 1[b]	3, 4
IU Conversion Systems, Inc.	Poz-O-Tec[a] Poz-O-Soil[a]	Lime	4[b]	3, 4, 5
Chemfix, Inc.	Chemfix[a]	Portland cement Sodium silicate	7[b] 2[b]	3, 4
TRW, Systems Group[c]	-	1, 2 - polybutadiene	3 - 4[d]	6
(nonproprietary)	Flyash-limestone	Fly ash Limestone	- -	4

[a]Registered trademarks. Process is in full-scale use on hazardous industrial sludge or flue gas desulfurization sludge or both.
[b]Additive as percent by weight of dry sludge solids for flue gas desulfurization sludge and fly ash at coal-burning power plants.
[c]Bench scale tests.
[d]Additive as a percent of dry sludge solids.

The cost of utilizing the chemical fixation process is affected by the degree of dewatering required, the type of fixation chemical(s) employed, and the method of mixing the chemical(s) and sludge. In addition chemical fixation processes are generally proprietary and require royalty payments. Therefore, schemes including chemical fixation are generally more expensive than conventional systems for processing municipal sludges. Consequently, applications of the chemical fixation process to municipal sludges will probably remain uncommon except when such sludges contain significant concentrations of heavy metals or other toxicants. Variables affecting the cost of fixation include:

- Availability of fly ash. Some processes use fly ash to reduce the need for other chemicals.
- Sludge dewaterability. Fixation costs increase with the amount of water present.

- Volume and mass of sludge to be treated.

- Physical properties required for the fixed sludge. A granular product tends to cost less than a monolithic product, for example.

- The degree to which the fixed product must resist leaching.

- Reactivity of the sludge with the fixation chemicals.

- Unit prices of treatment chemicals. In some cases, this factor is complicated by the fact that the chemicals are proprietary.

13.3 Encapsulation Process

Encapsulation is the encasing of sludge in an impervious, durable material. Encapsulation processes are expensive to employ but are a useful treatment alternative when the sludge contains significant concentrations of leachable toxic materials. As with fixation processes, there is little reported experience for the system with municipal sludges. The information presented here has been obtained from experience with industrially derived sludges. Two examples of encapsulation processes are discussed below.

13.3.1 Polyethylene Process

Encapsulation of a sludge with polyethylene has been investigated in the laboratory (6,13,14). This process involves putting a block, a 55-gallon (208 l) drum, or other container of sludge that has been treated by the chemical fixation process into a bed of polyethylene powder. The polyethylene is then heated to 350°F (180°C) so that it melts and fuses into a 1/4 inch (6 mm) thick seamless layer. The approximate amount of polyethylene required is 4 percent by weight of the sludge to be encapsulated. Polyethylene is tough and may be severely deformed without rupture. Leaching tests of several materials treated by the polyethylene process showed virtually no release of the chemical constituent.

The extremely high system temperatures cause water to evaporate at pressures up to about 130 psig (900 kN/m^2). Therefore, one of the following three stringent conditions must be met:

- The process must be carried out under pressure.

- The sludge must be sealed in vessels that are able to withstand an internal working pressure of 130 psig (900 kN/m^2) before the sludge is delivered to the encapsulation process.

- The sludge must be in a thoroughly dry form such as either sludge incinerator ash or heat-dried sludge.

13.3.2 Asphalt Process

Asphalt may be used to encapsulate wastes. In this process, the waste is mixed with asphalt at 300°F (150°C) in such a way that each individual particle is coated with asphalt. Moisture is removed as steam. The coated particles are then placed in 55-gallon (208 l) drums or other containers where they cool and form a solid, nonporous mass. The encapsulated product is highly resistant to leaching, mechanical damage, and bacterial attack. About one pound of asphalt is required for each pound of dry solids (15).

Asphalt encapsulation has been used in Europe on medium-level radioactive wastes since 1965. There is little United States operating experience, but European experience makes it possible to estimate costs for wastewater sludge applications. An installation with a capacity of five hundred 55-gallon (208 l) drums per year could handle about 84 tons (76 t) of dry sludge solids per year. Capital and operating costs are estimated at $1.45 million and $62,000 per year, respectively, at 1977 U.S. price levels. Amortizing capital over twenty years at 7 percent, the total cost is about $2,400 per ton dry solids processed ($2,600/t). This cost includes encapsulation machinery and associated building space, drums, drum storage, asphalt, steam, cooling water, and operating labor. It does not include engineering (except for engineering performed by the equipment supplier), sludge dewatering which precedes the encapsulation process, transportation and disposal of the finished product, treatment of contaminated steam that might be produced, or maintenance. Possibly, cost savings can be obtained from economies of scale and less rigorous conditions than those at nuclear power plants.

13.4 Earthworm Conversion Process

A novel municipal wastewater sludge treatment process uses earthworms (Oligochaete annelids). This system is often called "earthworm conversion," vermicomposting, or annelidic consumption (16). Vermicomposting is different from the conventional composting of wastewater treatment plant sludge. In the earthworm conversion process, the worms are provided an optimum environment to consume or metabolize the sludge and produce feces or castings. These castings may be used as a soil conditioner.

13.4.1 Process Arrangement

Earthworm conversion is basically a simple process, and a schematic diagram of it is shown on Figure 13-1. The process requires worm beds and a supply of worms. Generally, digested and dewatered sludge is put into the beds, although experiments are underway, where raw liquid sludge is placed in beds. If anaerobic digestion is used prior to earthworm conversion, additional pretreatment may be needed. A bulking agent such as wood chips may be useful in some cases for keeping the bed porous and aerobic, especially if moisture is high. Sludge is, however, generally applied without any bulking agent. A worm bed may take the form of a simple tray. Windrows similar to those for composting may also be used. After the worms have consumed the sludge, they must be separated from the castings. This may be done with an earthworm harvester, a drum screen that rotates on a nearly horizontal axis. Castings fall through the screen openings while worms tumble through the length of the drum. Table 13-2 contains some critical operational parameters for the earthworm conversion process.

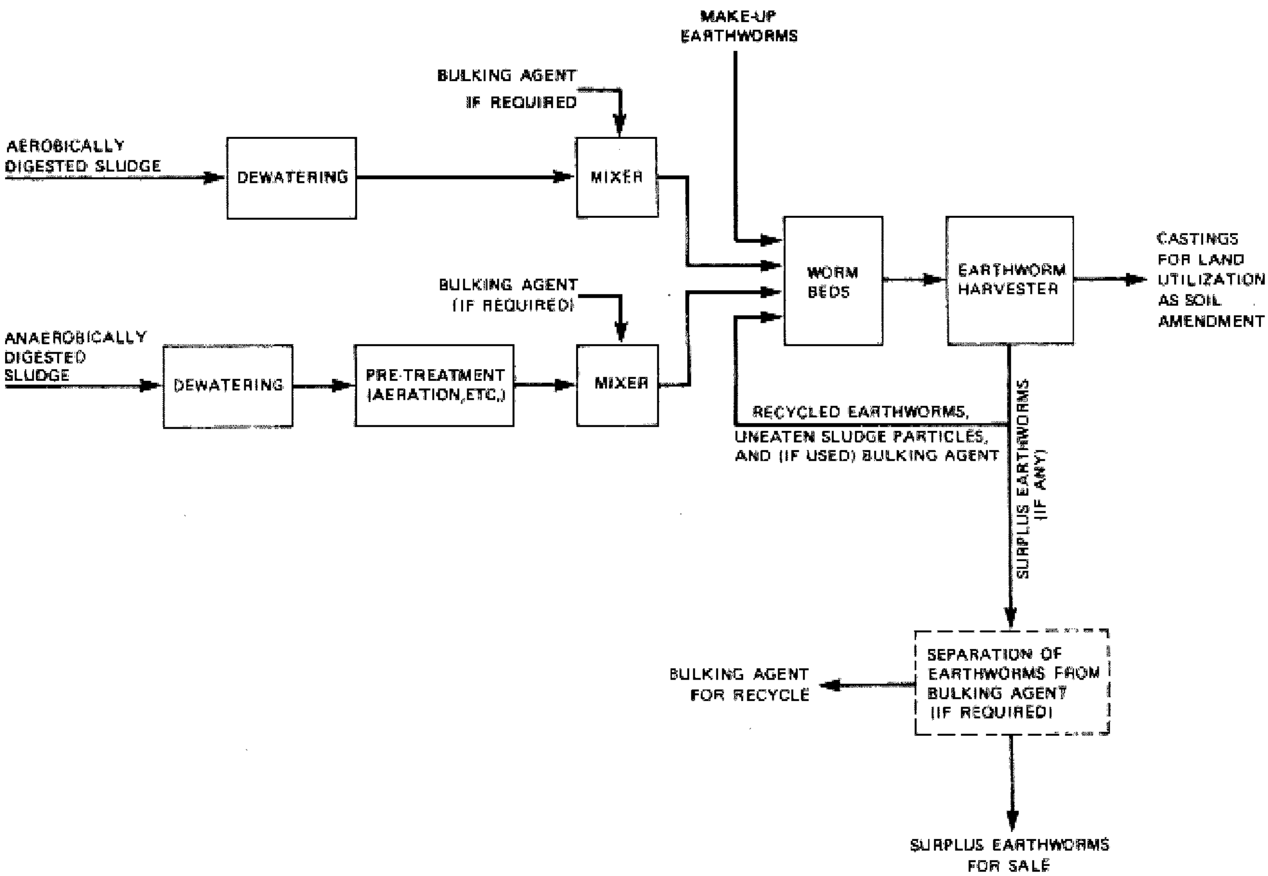

FIGURE 13-1

DIAGRAM OF AN EARTHWORM CONVERSION PROCESS

The main product of the earthworm conversion process is the worm's castings. In some process arrangements there may be a net earthworm production. The excess earthworms may then be sold for fish bait or animal protein supplement. Earthworm marketing is a complex problem. For municipal sludge applications, surplus earthworms may be considered a by-product; the principal product is the castings, which can be a resource.

TABLE 13-2

PARAMETERS FOR EARTHWORM CONVERSION

Parameter	Values
Detention time of sludge in worm beds	2 days (19) 32 days (18)
Worm reproductive cycle	1 to 2 months
Rate of worm feeding (15°C)	0.17 to 1.7 grams dry sludge per gram dry worm weight per day (17)
Optimum temperature	15°C to 20°C (17)
Dry matter content of worms	20 to 25 percent (*Eisenia foetida*) (20)
Minimum solids content of the worm bed mixture	20 percent solids[b]

[a]Species of worm being tested: *Eisenia foetida* (redworm, hybrid redworm, tiger worm, dung worm) (17), *Lumbricus rubellus* (red manure worm, red wiggler worm) (18), and *Lumbricus terrestris* (nightcrawler) (17).

[b]Actual minimum solids content depends on such factors as porosity, type of sludge, ability to keep aerobic. Experiments are being conducted to better define these parameters.

1°F = 32 + 1.8°C

13.4.2 Advantages of the Earthworm Conversion Process

When dry, earthworm castings are essentially odorless; when damp, they have a mild odor like a good quality topsoil. Also, the castings have a favorable appearance. When sifted and dry, they are granular, about 0.02 to 0.1 inches (0.5 to 3 mm) in maximum dimension (with some fines); color is brownish gray. In a study where municipal sludge was applied to a wheat crop, it was found that when earthworms were added to the sludge, the germination rate of the wheat was improved (21). The odor, appearance, and soil supplementation advantages of the earthworm conversion process may help in the acceptance of sludge by farmers and householders.

Earthworm conversion affects several other sludge characteristics. The oxygen uptake rate increases (17); the acid-extractable fraction of various nutrients increases (21). The volatile content of the solids drops slightly and humic acid concentrations fluctuate (17). While these effects may be beneficial, there are no data to show how the results affect design or operation of earthworm conversion installations.

The earthworm conversion process would appear to be low in cost, although this cannot be said with certainty, since no cost data are available for full-scale operations on sludge. The process does not require chemicals, high temperatures, or large amounts of electricity. Only a small amount of low-speed mechanical equipment is needed. Significant expenditures may be required to offset the potential operating difficulties discussed below.

13.4.3 Possible Operating Difficulties

A number of potential operating difficulties and their solutions are listed in Table 13-3. None of these difficulties are insurmountable. Probably it is most difficult to economically pretreat anaerobically digested sludge so that it is nontoxic to the worms.

13.4.4 Limitations

Limitations are:

- Earthworm conversion decreases the total nitrogen values in the sludge because ammonia nitrogen will be lost to the atmosphere.

- Published information to date (1979) is almost nonexistent on full-scale municipal wastewater treatment plant sludge operations. Consequently, costs are unpredictable.

- Two common ions in municipal wastewater sludge, ammonium and copper, may be toxic to worms. Studies have found that these ions were lethal at additions equivalent to 180 mg NH_4-N and 2,500 mg Cu per kilogram of wet substrate (26,27). Safe limits for these elements are not known.

- Cadmium accumulates in the worm Eisenia foetida. Zinc apparently does not accumulate in Eisenia foetida but does accumulate in other species (27,28). If the worms are to be used as animal feed, the system must be operated such that cadmium and zinc concentrations in the worms do not exceed recommended levels for animal consumption.

- Space requirements may rule out earthworm conversion at some treatment plants.

- The earthworm business has been afflicted with unsound investments and excessive claims. For example, it has been claimed that earthworm processing is able to reduce concentrations of heavy metals (29). Any such reduction could only be caused by simple dilution with uncontaminated waste or by concentration of the contaminants in the earthworms.

TABLE 13-3

POSSIBLE OPERATING DIFFICULTIES IN EARTHWORM CONVERSION

Possible difficulty	Comments
Worm drowning	Worms must be protected from flooding.
Predation by birds and animals	Not a problem at San Jose - Santa Clara, California experiments (22).
Worm loss due to migration from the process	Caused by flooding, toxic sludge, unpalatable sludge, adjoining areas attractive to worms, lack of artificial lighting on rainy nights.
Toxicity of sludge to worms	Significant for anaerobically digested sludge. However, toxicity is eliminated by exposing the sludge to air for two months (17) or wetting sun-dried sludge daily for 14 days (21). Stabilization by lime or chlorine is not recommended for sludge that will be fed to earthworms. Toxicants such as copper salts might also cause problems. Aerobic digestion is best suited for sludge to be converted by earthworms.
Toxicity or unpalatable nature of dewatering chemicals	Avoided at Hagerstown, Md., by use of food-grade polymer (19). Drying beds may be used; drying beds do not usually require chemicals.
Worm shortage in the process, so that worm additions are required	Worms reproduce via egg capsules. These capsules may be lost from the process in the castings. Also, toxic conditions, drowning, and other problems will cause worm populations to drop. At Hagerstown, Md., a worm raising operation has been proposed to supply the necessary make-up worms to the sludge conversion process (19).
Shortage of worms for initial inventory or restart	To begin operation, a large worm inventory may be needed, so large that local worm suppliers may be unable to fill it. Gradual start-up is therefore desirable, especially for large plants. Also, earthworm exchanges may become available nationwide so that sludge operations can draw on larger numbers of earthworm suppliers.
Temperature extremes	Worm feed most rapidly at 15 to 20 degrees C; about 5 degrees C, feeding is quite slow (17). Freezing will kill worms. High temperatures can also cause problems. It may be necessary to stockpile sludge during the winter or provide a heated building for the conversion process.
Shortage of enzymes	Not a problem, despite claims by marketers of enzyme preparations that these preparations are valuable to the process (23).

TABLE 13-3

POSSIBLE OPERATING DIFFICULTIES IN EARTHWORM CONVERSION (CONTINUED)

Possible difficulty	Comments
Exposure to light	Worms avoid bright light. Some sort of cover or shade should be provided so that worms will convert the top layer of the sludge.
Dehydration	There is a minimum moisture content for the worm bed (23).
Salinity in castings	Under some conditions, castings may have sufficient dissolved salts to inhibit plant growth. This problem may be eliminated by leaching or by mixing the castings with other materials with lower dissolved salts (24, 25).
Contamination of castings by heavy metals, motor oil, rags, and similar materials	Source control may be used, where feasible, as for other processes aimed at reuse of sludge as a soil conditioner. See Chapter 2 for regulations on sludge products.
Odors	The most likely source is raw or aerobically digested sludge, which has been stockpiled to await earthworm conversion.

$^{o}C = 0.555\ (^{o}F - 32)$.

- If a particular sludge is suitable for earthworm conversion, that sludge should also be suitable for reuse as a soil conditioner without being processed by earthworms. However, earthworm conversion reduces odor, improves texture, and may increase germination rate.

These limitations may be significant but not overwhelming. There is considerable research and development underway. It appears that earthworm conversion may have a role in municipal wastewater treatment plant sludge processing.

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EPA 625/1-79-011

PROCESS DESIGN MANUAL FOR SLUDGE TREATMENT AND DISPOSAL

Chapter 14. Transportation

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 14

TRANSPORTATION

The fundamental objective of all wastewater treatment operations is to remove undesirable constituents present in wastewater and consolidate these materials for further processing and disposal. Solids removed by wastewater treatment processes include screenings and grit, naturally floating materials called scum, and the remainder of the removed solids called sludge. This chapter discusses the transportation of solids, or the movement of sludge, scum, or other miscellaneous solids from point to point for treatment, storage, or disposal. Transportation includes movement of solids by pumping, conveyors, or hauling equipment.

14.1 Pumping and Pipelines

Unless a sludge has been dewatered, it can be transported most efficiently and economically by pumping through pipelines. Sludge is subject to the same physical laws as other fluids. Simply stated, work put into a fluid by a pump alters velocity, elevation, and pressure, and overcomes friction loss. The unique flow characteristics of sludge create special problems and constraints. Nevertheless, sludge has been successfully pumped through short pipelines at up to 20 percent solids by weight, as well as in pipelines of over 10 miles (16 km) long at up to 8 percent solids concentrations.

Most of the following information is related to sludge, although screenings, grit, and scum may also be transported by pipeline. Mention is made of these miscellaneous solids when special considerations are involved.

14.1.1 Simplified Head Loss Calculations

Head losses must be estimated for sludge pumping; they are not available in standard tables. Head requirements for elevation change and velocity are the same as for water. However, friction losses may be much higher than friction losses in water pipelines. Relatively simple procedures are often used in design work; such a procedure is described below. The accuracy of these procedures is often adequate, especially at solids contents below 3 percent by weight. However, as the pipe length, percent total solids, and percent volatile solids increase, these simple procedures may give imprecise or misleading results. A more elaborate method for situations demanding greater accuracy is given in Section 14.1.2.

In water piping, flow is almost always turbulent. Formulas for friction loss with water, such as Hazen-Williams and Darcy-Weisbach, are based on turbulent flow. Sludge also may flow turbulently, in which case the friction loss may be roughly that of water. Sludge, however, is unlike water in that laminar flow also is common. When laminar flow occurs, the friction loss may be much greater than for water. Furthermore, laminar flow laws for ordinary "Newtonian" fluids, such as water, cannot be used for laminar flow of sludge because sludge is not a Newtonian fluid; it follows different flow laws.

Figure 14-1 may be used to provide rough estimates of friction loss under laminar flow conditions. This figure should be used when:

- Velocities are at least 2.5 feet per second (0.8 m/s). At lower velocities, the difference between sludge and water may greatly increase.

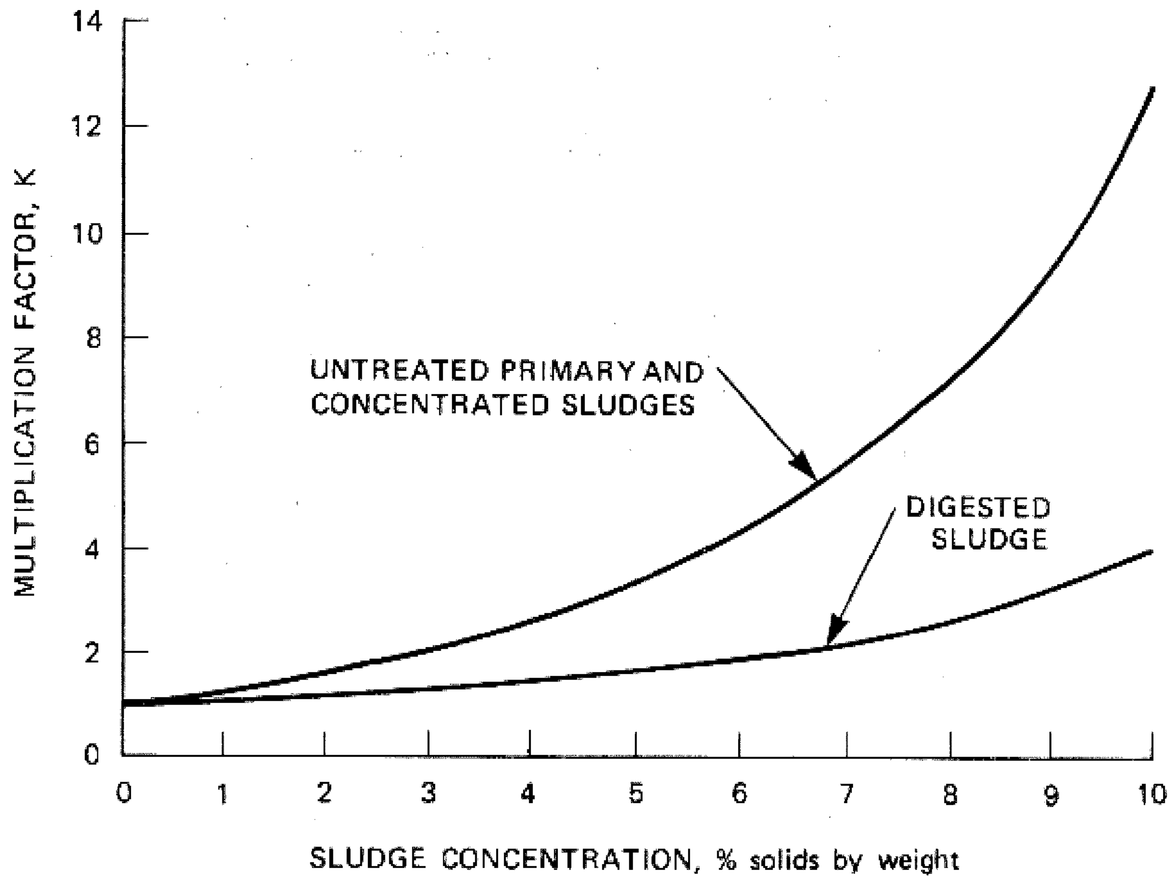
- Velocities do not exceed 8 feet per second (2.4 m/s). Higher velocities are not commonly used because of high friction loss and abrasion problems.

- Thixotropic behavior is not considered. Friction losses may be much higher in suction piping. Also, when starting a pipeline that has been shut down for over a day, unusually high pressures may be needed.

- The pipe is not seriously obstructed by grease or other materials.

As an example, consider a pipe carrying unstabilized primary sludge. The pipe is 500 feet (152 m) long and 6 inches (150 mm) in diameter; flow rate is 300 gallons per minute (19 l/s). Assume that the sludge solids concentration may be up to 7 percent solids on occasion. Using the Hazen-Williams formula with a "C" of 100, a friction loss of 6.5 feet (2.0 m) would apply. If laminar sludge flow occurs, Figure 14-1 gives a multiplication factor of 5.8, so a friction loss of 38 feet (12 m) might occur. The friction loss could easily vary from 6.5 to 38 feet (2.0 to 12 m) in actual operation due to changes in sludge properties and factors not considered on Figure 14-1.

Grit slurries are usually dilute; also, grit particles do not stick to each other. Therefore, ordinary friction formulas for water are usually adequate. A velocity of about 5 feet per second (1.5 m/s) is typically used. Low velocities may cause deposition of grit within the pipe; high velocities may cause erosion.



NOTE: MULTIPLY LOSS WITH CLEAN WATER BY K TO ESTIMATE FRICTION LOSS UNDER LAMINAR CONDITIONS (SEE TEXT).

FIGURE 14-1

APPROXIMATE FRICTION HEAD-LOSS FOR LAMINAR FLOW OF SLUDGE

14.1.2 Application of Rheology to Sludge Pumping Problems

Water, oil, and most other common fluids are "Newtonian." This means that the pressure drop is directly proportional to the velocity and viscosity under laminar flow conditions. As the velocity increases past a critical value, the flow becomes turbulent. The transition from laminar to turbulent flow depends on the Reynolds number, which is inversely proportional to the fluid's viscosity. The viscosity is a constant for the fluid at any given temperature. Formulas for Newtonian fluids are available in fluid mechanics textbooks.

Wastewater sludge, however, is a non-Newtonian fluid. The pressure drop under laminar conditions is not simply proportional to flow, so the viscosity is not a constant. Special procedures may be used, however, to determine head loss under laminar flow conditions, and the velocity at which turbulent flow begins. These procedures use at least two constants to describe the fluid instead of a single constant (the viscosity) which is used for Newtonian fluids.

The behavior of wastewater sludge is compared with the behavior of water on Figure 14-2. This figure is based on steady state behavior, after thixotropic breakdown. (Thixotropic breakdown will be discussed in a subsequent paragraph.) The following features are notable concerning the behavior of wastewater sludge:

- Essentially no flow occurs unless the pressure is high enough to exceed a yield stress τ_O.
- Turbulent flow may occur, but a much higher velocity is needed for sludge than for water.
- In fully developed turbulent flow, the pressure drop is roughly that of water.
- For the laminar plastic flow region, sludge approximately obeys the laws of a "Bingham plastic." A Bingham plastic is described by two constants, which are the yield stress τ_O and the coefficient of rigidity, η.
- It is also possible to consider sludge to be a "pseudoplastic" material. In that case, two other constants are used, and the formulas are different. The following discussion uses the Bingham plastic approach.

14.1.2.1 Solution of Pressure Drop Equation

If the two constants τ_O and η can be determined, it is quite easy to determine pressure drop over the entire range of velocities with the aid of Figure 14-3 and ordinary equations for water. To use this figure, calculate the two dimensionless numbers (Reynolds and Hedstrom) by reading the graph. The only real difficulty is in obtaining the two constants; see Section 14.1.2.4.

The two dimensionless numbers are a Reynolds number, given by:

$$Re = \frac{\rho VD}{\eta} \qquad (14\text{-}1)$$

where:

Re = Reynolds number, dimensionless

ρ = density of sludge, lb (mass)/ft^3, (g/cm^3)

V = average velocity, ft (cm/s)

D = diameter of pipe, ft (cm)

η = coefficient of rigidity, lb (mass)/ft-sec, poise (same as dyne-s/cm^2 and g/cm-s);

and the Hedstrom number, given by:

$$He = \frac{D^2 \tau_o \, g_c \rho}{\eta^2} \qquad (14\text{-}2)$$

where:

He = Hedstrom number, dimensionless

τ_o = yield stress, lb(force)/ft^2

g_c = units conversion factor:
32.2 lb(mass)-ft/lb(force)-sec^2 for English units
1.0 for metric units

$$\Delta p g_c = \frac{2 f \rho L V^2}{D} \qquad (14\text{-}3)$$

where:

Δp = pressure drop due to friction, lb(force)/ft^2, (dyne/cm^2)

f = Fanning friction factor from Figure 14-3, dimensionless

L = length of pipeline, ft (cm)

There are a few subtleties in the correct use of these equations. First, the Reynolds number in Equation 14-1 is not the same as a Reynolds number based on viscosity. In plastic flow, an effective viscosity may be defined, but it is variable and it can be much greater than the coefficient of rigidity. Consequently, the two Reynolds numbers can differ by factors of more than ten under some conditions. Second, many textbooks use a somewhat different definition of f, which is four times the value as used in Equation 14-3 and Figure 14-3. Third, care is required with units. For English units, it is not possible to use pounds (mass) in density at the same time as pounds (force) in stress without introducing the conversion factor (g_c) into Equations 14-2 and 14-3. Alternatively, the "slug," English mass unit could be used.

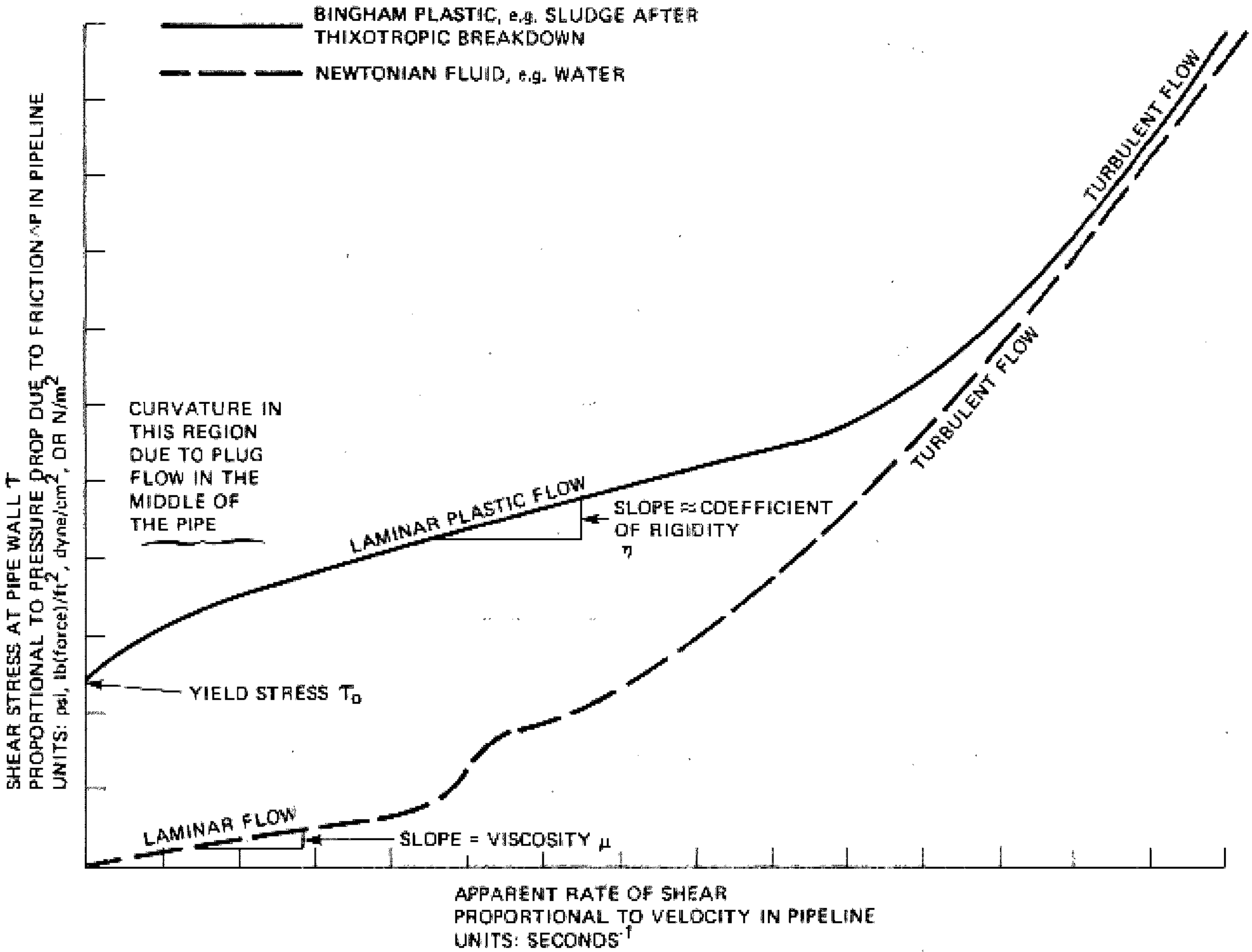


FIGURE 14-2

COMPARISON OF BEHAVIORS OF WASTEWATER SLUDGE AND WATER FLOWING IN CIRCULAR PIPELINES

These equations apply to the entire range from virtually zero velocity to the fully turbulent range, except that Figure 14-3 does not allow for pipe roughness. To allow for pipe roughness, ordinary water formulas may be used. If, for example, the Hazen-Williams formula gives a higher pressure drop than Equation 14-3, then pipe roughness is dominant, the flow is fully turbulent, and the pressure drop will be given by the ordinary water formula to a sufficiently good approximation for engineering purposes (3).

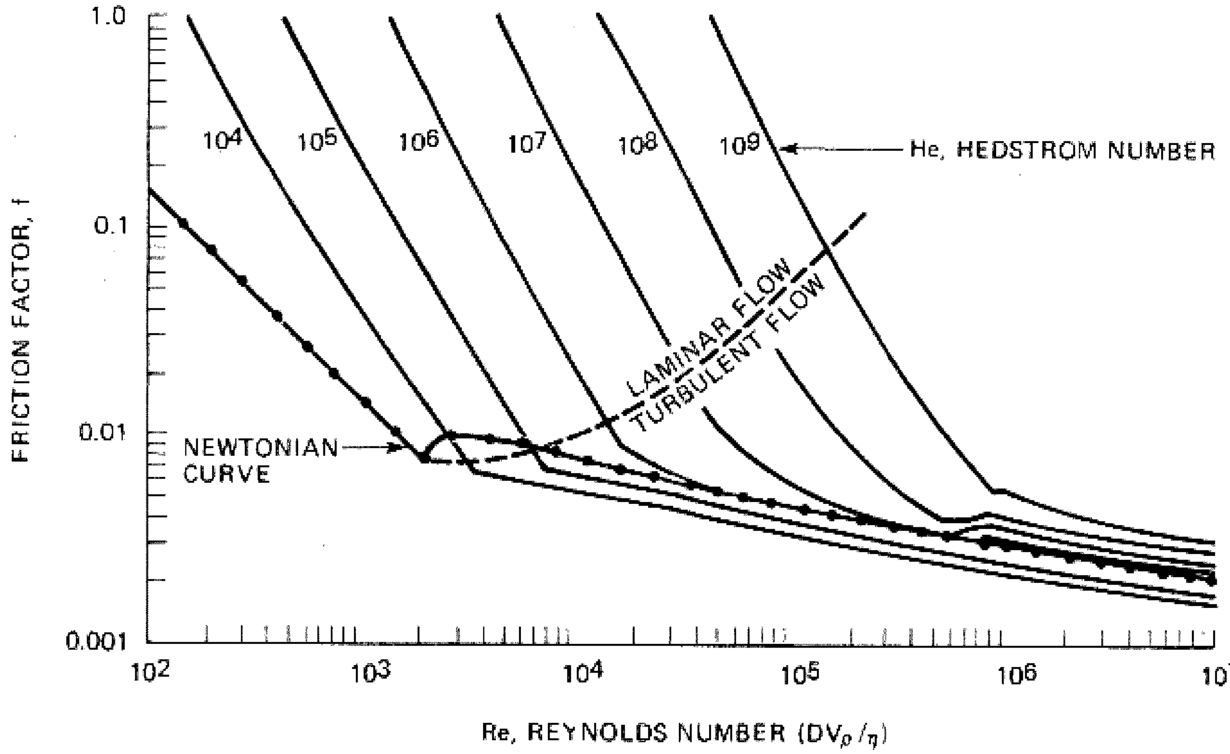


FIGURE 14-3

FRICTION FACTOR FOR SLUDGE, ANALYZED AS A BINGHAM PLASTIC

Figure 14-3 also shows whether flow is laminar or tubulent. The friction factor f is located by the intersection of the Reynolds and Hedstrom numbers (Re and He). If this point is above the dashed line on Figure 14-3, or if the Reynolds number Re is less than 2,000, the flow is laminar; otherwise it is turbulent. For example, at Re = 10^4, a Hedstrom number of 10^4 gives turbulent flow, while a Hedstrom number of 10^6 gives laminar flow.

Interpolation on logarithmic graphs such as Figure 14-3 is somewhat difficult. This is particularly true for the Hedstrom number curves on Figure 14-3. If the logarithm (base 10) of He is calculated, interpolation between lines will be linear. Alternatively, if flow is laminar, the Buckingham equation (3,4) may be used. Figure 14-3 incorporates the Buckingham equation in the laminar region. The Bingham pressure loss equation is an approximate solution of the Buckingham equation (5,3).

14.1.2.2 Design Example

The designer wishes to transport anaerobically digested sludge 6 miles from one plant to another plant where there are dewatering facilities. If transported at 5 percent solids, the sludge quantity is 100,000 gallons per day (378 m^3/day). The sludge may be diluted or thickened, if desired, to improve economics. All of the sludge must be pumped in a 4-hour period each day to accommodate dewatering schedules at the receiving plant.

It is assumed that the sludge can be considered as a Bingham plastic using the following data from Canton, Ohio (2):

Case	Solids concentration, percent	Yield stress τ_o, dyne/cm^2	Coefficient of rigidity η, g/cm-s
1	7.12	100	0.40
2	5.34	30.5	0.24
3	3.56	5.8	0.13

For a comparison, water has a yield stress of zero and a coefficient of rigidity of about 0.01 g/cm-s. The pipe is assumed to be unlined steel pipe, schedule 40; nominal pipe sizes of 4 to 10 inches (100 to 250 mm) in diameter will be considered.

The calculation is illustrated in detail for the 8-inch (200-mm) pipe and 7.12 percent sludge. First, the flow rate is needed. If the sludge were at 5 percent solids, 100,000 gallons (378 m^3) of sludge would be transported daily. Since the sludge is at 7.12 percent, the volume is:

$$100{,}000 \times \frac{5}{7.12} = 70{,}224 \text{ gallons } (266 \text{ m}^3)$$

and the flow rate is:

$$\frac{70{,}224 \text{ gallons/day}}{4 \text{ hours flow/day} \times 60 \text{ min/hr}} = 292.6 \text{ gpm } (18.46 \text{ l/s})$$

Calculations of Reynolds and Hedstrom numbers will be carried out in the centimeter-gram-second (cgs) system because τ_o and η are given in cgs units. The flow rate in cgs units is:

$$\frac{292.6 \text{ gpm} \times 3.785 \text{ l/gal} \times 1{,}000 \text{ cm}^3\text{/l}}{60 \text{ sec/min}} = 18{,}460 \text{ cm}^3\text{/sec}$$

The internal diameter of an 8-inch (200 mm) Schedule 40 pipe is 7.981 inches (20.27 cm) and the cross sectional area is 322.7 cm^2. The velocity V is the flow rate divided by the area:

$$V = \frac{18{,}460\ cm^3/sec}{322.7\ cm^2} = 57.2\ cm/sec$$

The Reynolds number is obtained from Equation 14-1:

$$Re = \rho\frac{VD}{\eta} = 1.0 \times \frac{57.2 \times 20.27}{0.40} = 2898\ \text{(dimensionless)}$$

The Hedstrom number is obtained from Equation 14-2:

$$He = \frac{D^2\tau_o\rho g_c}{\eta^2} = \frac{(20.27)^2 \times 100 \times 1.0 \times 1.0}{(0.40)^2} = 256{,}800\ \text{(dimensionless)}$$

Refering to Figure 14-3, **f** is about 0.08. The flow is laminar, not turbulent.

The length L is needed in cgs **units**:

$$L = 6\ \text{miles} \times 5{,}280\ \text{ft/mile} \times 30.48\ \text{cm/ft} = 965{,}600\ \text{cm}$$

Now Equation 14-3 is used to calculate pressure drop due to friction:

$$\Delta p = \frac{2f\rho LV^2}{Dg_c} = \frac{2 \times 0.08 \times 1.0 \times 965{,}600 \times (57.2)^2}{20.27 \times 1.0} = 24{,}940{,}000\ \text{dyne/cm}^2$$

Convert this **value** to pounds per square inch:

$$24{,}940{,}000\ \text{dyne/cm}^2 = \frac{24.94 \times 10^6\ \text{dyne} \times 2.248 \times 10^{-6}\ \frac{\text{pounds (force)}}{\text{dyne}}}{\text{cm}^2 \times 0.1550\ \text{in.}^2/\text{cm}^2}$$

$$= 362\ \text{psi}\ (2.49\ \text{MN/m}^2)$$

This value may be compared to the value for water for the same conditions, calculated from the Hazen-Williams equation:

$$V = 1.318\ C\ R^{0.63}\ S^{0.54} \tag{14-4}$$

where:

- V = average velocity, ft/sec,
- C = friction coefficient,
- R = hydraulic radius = $\frac{1}{4}$ of diameter, ft,
- S = hydraulic gradient, ft/ft.

This equation may be rearranged and solved on a calculator, or tables or nomographs may be used. In the present case, V = 57.2 cm/sec = 1.88 ft/sec and R = 0.166 ft. With a C of 100, S is 0.00310, indicating a pressure drop of 98.2 ft or 42 psi. The drop with this sludge is 362 psi or about 9 times higher than the drop for water.

For the various cases, calculations are summarized in Table 14-1. Friction factor plots from Figure 14-3 are shown on Figure 14-4.

A precaution that is useful for detection of computational error is to check to see whether the pressure drop across the pipe calculated by the above procedure produces a sufficient shear stress at the pipe wall to exceed the yield stress of the sludge. If the yield stress is not exceeded, the sludge will not flow. The pressure drop needed is calculated by setting the calculated shear stress at the wall equal to yield stress:

$$\frac{\Delta p_o g_c D}{4L} = \tau_o g_c \tag{14-5}$$

where:

Δp_o = pressure drop needed to exceed yield stress.

Results of the calculation are shown for Case 1 and Case 2 in Table 14-2. Equation 14-5 is also useful as a screening test. If τ_o, D, and L are known, it is possible to quickly calculate the minimum pressure drop that could occur, regardless of velocity or flow rate. If Δp_o is excessive, the diameter D should be increased. Impractical pipe sizes could be quickly eliminated as requiring too high a pressure drop for consideration.

Values from Table 14-1 and 14-2 are plotted on Figure 14-5. Selection of the optimum pipe diameter and solids content requires an economic analysis. However, it is evident that at the more reasonable pressure drops (below 200 psi or 1400 kN/m^2), the 7.12 percent solids has a much higher pressure drop at a given pipe diameter even though the volumetric flow rate is much lower than for the other two cases. At 8 inches (200 mm), the pressure drops are about the same for the 5.34 percent and the 3.56 percent sludges. However, as noted in Table 14-1, the flow is not in the turbulent regime for the 5.34 percent sludge. This is a disadvantage because small changes in the rheological constants τ_o and η could cause changes in f. The 3.56 percent solids content is probably a better selection based on the likelihood of more stable operation. At 10 inches (250 mm), the value of f is considerably higher for the 5.34 percent sludge than for the 3.56 percent sludge. The choices between 8-inch and 10-inch (200 and 250 mm) diameter and 3.56 percent and 5.34 percent sludge would have to be made on the basis of minimum overall cost. The 5.34 percent sludge will be more expensive to transport, but this cost increase may be offset by more economical dewatering at the plant receiving the sludge.

TABLE 14-1

SUMMARIZED CALCULATIONS FOR NON-NEWTONIAN FLOW EXAMPLE PROBLEM

Case	Diameter		Average velocity, cm/sec	Reynolds number, Re	Hedstrom number, He	Fanning friction factor, f	Pressure drop, psi	
	in.	cm					sludge	water[a]
1	4.03	10.2	225	5,750	65,000	.010[b]	1,380	1,190
	5.05	12.8	143	4,580	103,000	.019[b]	775	394
	6.06	15.4	99.1	3,820	148,000	.03[b]	534	162
	7.98	20.3	57.2	2,900	257,000	.08[b]	362	42
	10.02	26.4	36.3	2,310	405,000	.20[b]	290	14
2	4.03	10.2	300	12,780	55,300	.0083	2,038	2,020
	5.05	12.8	190	10,150	87,000	.0085	673	667
	6.06	15.4	132	8,480	126,000	.0090	285	275
	7.98	20.3	76.3	6,440	218,000	.019[b]	152	72
	10.02	25.4	48.4	5,130	343,000	.035[b]	90[c]	24
3	4.03	10.2	450	35,400	36,000	.0066	3,650[c]	4,280
	5.05	12.8	286	28,200	56,000	.0070	1,250[c]	1,423
	6.06	15.4	198	23,500	82,000	.0072	513[c]	582
	7.98	20.3	114	17,800	141,000	.0075	135[c]	152
	10.2	25.4	72.6	14,200	222,000	.0080	46[c]	50

[a]Calculated from Hazen-Williams equation with a friction coefficient (C) of 100.

[b]Flow is not in the turbulent region.

[c]Note that pressure drop for sludge, by equation 14-3, is less than the pressure drop for water if C = 100. The pressure drops would be about the same if C=110.

1 psi = 6.9 kN/m^2 = 69,000 $dyne/cm^2$

Note that the pressure drop for Cases 1 and 2 is greater in all cases than the minimum drop Δp_o (see Figure 14-5).

FIGURE 14-4

FRICTION FACTORS FOR EXAMPLE PROBLEM

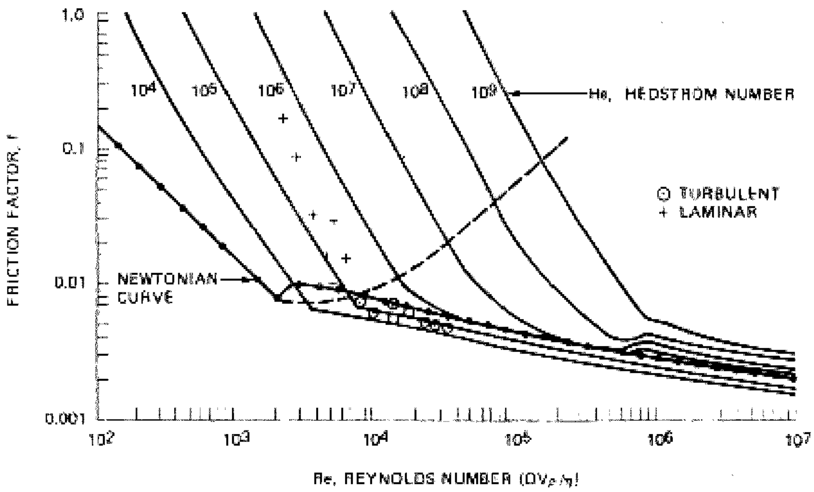


TABLE 14-2

PRESSURE REQUIRED TO EXCEED YIELD STRESS - EXAMPLE PROBLEM

Diameter, in.	Pressure drop Δp_o, psi[a] Case 1 τ_o = 100 dyne/cm^2	Case 2 τ_o = 30.5 dyne/cm^2
4.03	548	167
5.05	437	133
6.06	363	111
7.98	276	84
10.02	220	67

[a]Pressure drop to cause the shear stress at pipe wall to exceed the yield stress τ_o. Higher pressures may be needed to start the pipeline due to thixotropic effects not considered in Figure 14-3.

1 in. = 2.54 cm
1 psi = 6.9 kN/m^2 = 69,000 dyne/cm^2

14.1.2.3 Thixotropy and Other Time-Dependent Effects

Besides possibly being dependent on the shearing rate, the flow resistance of liquids can depend on the length of time of shearing or on some function of both the time and intensity of shearing. The most commonly encountered time-dependent change in viscosity is a drop which occurs with time of shearing, followed by a gradual recovery when shearing is stopped. This behavior is called thixotropy. A familiar example is an ice cream milkshake, which "sets up" in its container and will only flow out when the container is rapped or jarred several times. The structure rebuilds when the rapping is stopped. Paints typically not only are Bingham plastics but are thixotropic as well. They will flow for a short time after being "worked" by the paint brush so brush lines tend to disappear. Their "plastic" characteristics rebuild quickly after shearing stops so the paint does not flow downwards on vertical surfaces.

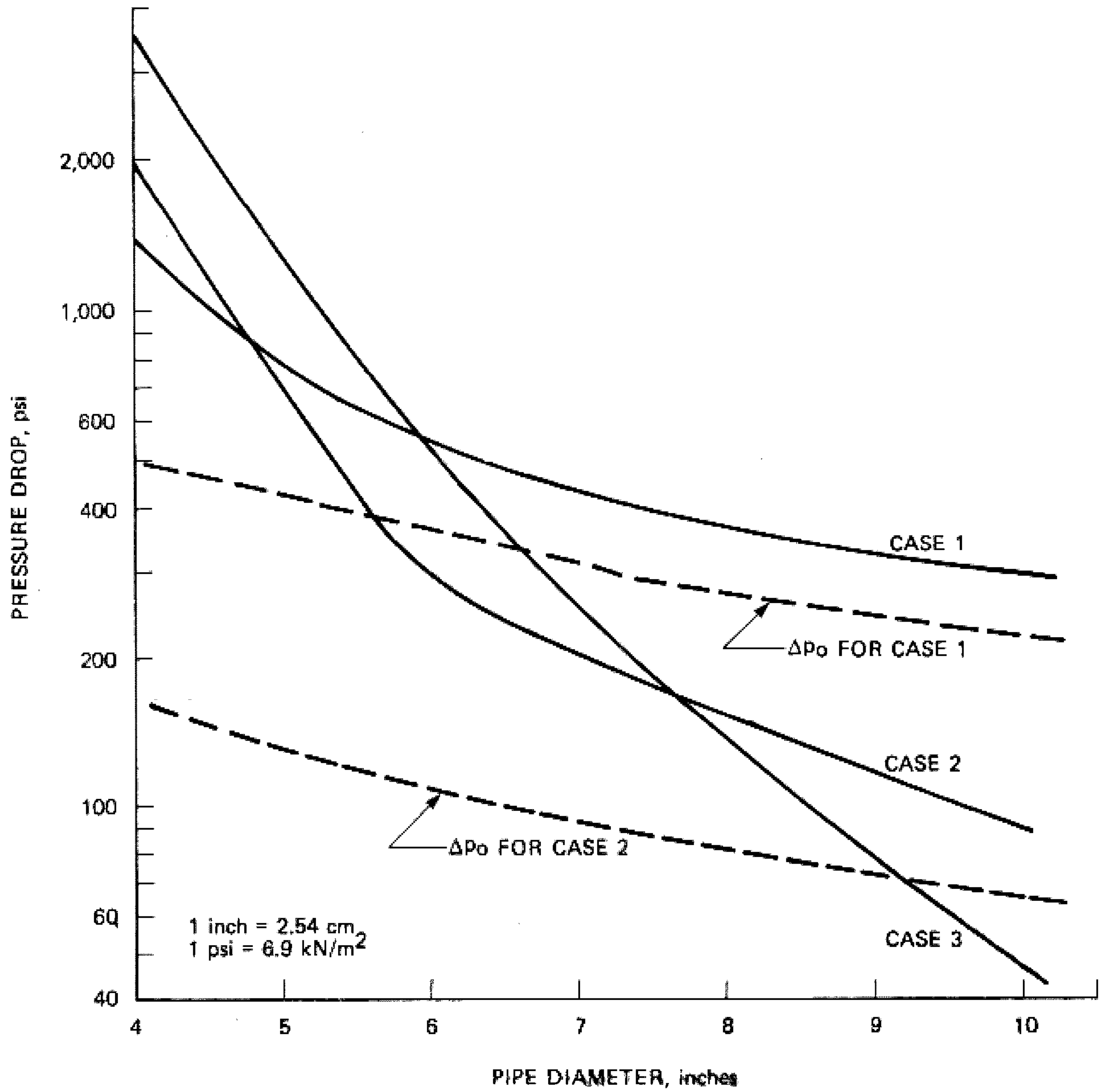


FIGURE 14-5

PRESSURE DROPS FOR EXAMPLE PROBLEM

Wastewater sludge is also thixotropic. The effect is increasingly important as the percent solids and percent volatile solids increase. Thixotropy has three major effects:

- It complicates the measurement of constants such as the yield stress τ_o.
- It makes pump suction conditions very important. In one case, a centrifugal pump produced ample pressure to move the sludge through a hose. The pump was suspended in a lagoon but the sludge would not flow into the pump suction. It was found that mixers next to the pump caused thixotropic breakdown sufficient for satisfactory pumping (5,6).
- It raises the pressure needed to start a pipeline that has been shut down. At one installation, this effect was found to be significant for shutdowns exceeding one day. An operating procedure is used to prevent this problem; that is, if shutdowns over 8 hours are expected, the line is purged of sludge (5,6).

Permanent degradation of yield stress can occur with time of shearing. Intense shearing produces this result in high polymers. This phenomena can be expected in wastewater sludges, when shear levels are sufficiently high to physically disrupt a portion of the particles making up the sludge. If this occurs, it may be difficult to later thicken or dewater the sludge.

Sometimes the reduction in viscosity that occurs with time of shearing is actually the effect of a temperature increase produced by the energy delivered to the liquid. The general effect of an increase in temperature with both Newtonian and non-Newtonian liquids is a reduction in viscosity. However, for sludge, the main effect of temperature is that low temperatures may cause the grease fraction of the sludge to harden. Other temperature effects appear to be unimportant, at least up to 160°F (70°C) (5,7).

There is another unusual effect that occurs in wastewater sludge pipelines: slippage and seepage (6). Essentially, the sludge is riding on a thin film of water next to the wall of the pipe. This effect is noticeable at very low velocities when starting a sludge pipeline; it partially offsets the thixotropic effect. Seepage and slippage are hard to calculate but are useful when starting pipelines flows (6).

14.1.2.4 Obtaining the Coefficients

Figure 14-3 cannot be used unless the yield stress $_o$ and the coefficient of rigidity can be obtained. There is a reasonable amount of data on anaerobically digested sludges (3,5,7,8) but very little data on sludge that has not been digested.

Several types of instruments are available for viscosity measurements. However, only two of these types are suitable for sludge: test pipes and rotational viscometers. Some instruments, such as capillary viscometers, are unable to handle the relatively large particles in sludge; other instruments, such as ball-drop viscometers, are not suited to strongly non-Newtonian fluids such as sludge.

Flow curves from test pipes are directly scalable to full-scale pipes provided flow is laminar. However, the onset of turbulence in a large pipe cannot be predicted directly from small pipe tests. It is necessary to use the yield stress and coefficient of rigidity, compute Reynolds and Hedstrom numbers, and use Figure 14-3 to predict the onset of turbulence. The flow curves obtained with test pipes do not provide fundamental rheological data, because at a given flow rate, shear stress and rate of shear vary across the radius of the pipe. By using the Rabinowitsch equation, the flow curve can be transformed into a rheologically correct shear stress versus rate of shear curve (9). An offsetting disadvantage of test pipes is that a high degree of experimental skill is required to get reliable data. Also these installations are relatively expensive and cumbersome and require large sample volumes.

For sludge, the best instrument appears to be a rotational viscometer. In this type of machine, the test liquid is placed between two concentric cylinders, one of which rotates. The torque on a cylinder is measured as a function of rotational speed. Such machines can produce approximately uniform shear rates at given shear stresses, provided the space between the bob (inner cylinder) and cup (outer cylinder) is small compared to the bob radius. Viscometers in which the bob rotates and the twisting force on the cup is measured are relatively easy to design mechanically but turbulence occurs at low shear rates for low viscosity materials. Turbulence onset does not occur until much higher shear rates for viscometers in which the cup rotates and the twisting force on the bob is measured. In both types of viscometers, end effects become substantial if the bob and cup are not long relative to the clearance.

There are a number of viscometers which feature rotational movement, but either do not have constant clearances between an inner and an outer cylinder, or do not control or measure shearing rate or shear stress. These devices are of little value for obtaining consistency curves for non-Newtonian liquids.

The nearly uniform shear rate achievable in rotational viscometers allows direct measurement of the fundamental shear stress-rate of shear curve, which is a major advantage when it comes to application to complex flow relationships. Rotational viscometers are simple to operate. Their primary disadvantage is that close clearances between outer and inner cylinders are needed to give uniform shear rates across the gap between cylinders. Obviously too small a clearance will give erroneous results for sewage sludges. Gap size should not be reduced below

1.0 mm (0.025 inch). Sludge must be screened to remove large particles. This creates no substantial error because a few large particles do not strongly affect the coefficients.

A representative test curve adapted from Rimkus and Heil (5) is shown on Figure 14-6. In this test, the viscometer speed was gradually increased from zero to 100 rpm and then decreased. Torque was measured and converted to shear stress, providing "consistency curves." The upper curve (increasing speed) shows thixotropy; the lower curve (decreasing speed) shows behavior of the fluidized sample. The lower curve is appropriate for pipeline design because the sludge is fluidized by passing through a pump. In this case, the shear stress projected to zero rpm (232 dynes/cm^2) is the yield stress τ_o; the coefficient of rigidity η is the slope of the straight part of the lower curve. Even when fluidized, sludge is not exactly a Bingham plastic, as shown by curvature in the lower curve at low rpm. This departure from Bingham plastic conditions can be used to refine the pressure drop calculations. The viscometer for this test was a Haake Model RV-3 Rotoviso with sensor head MV-1.

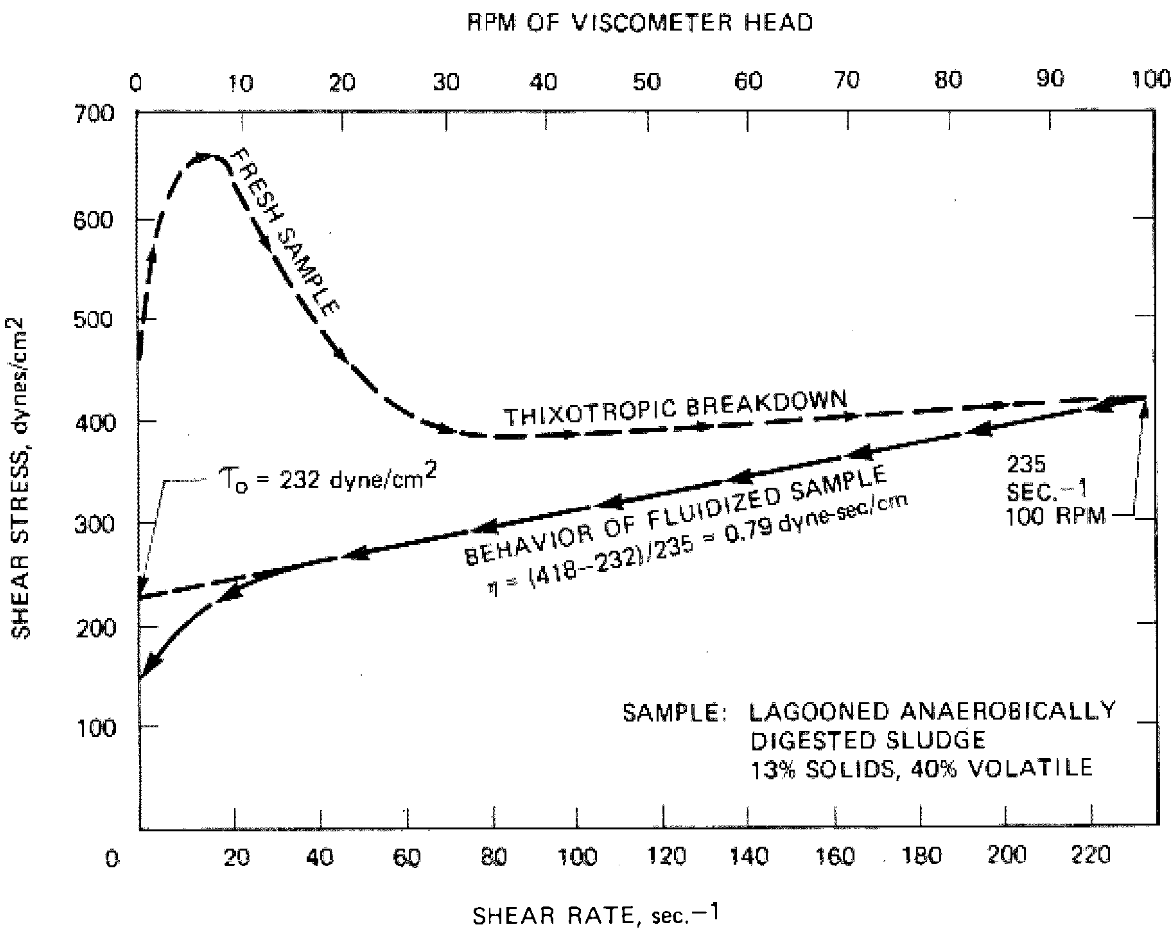


FIGURE 14-6

VISCOMETER TEST OF SEWAGE SLUDGE (5)

14.1.2.5 Additional Information

Sludge has been successfully and reliably pumped in the laminar flow range. Some of the installations describedin Section 14.1.6, Long Distance Pumping, operate in this range. That section also contains several design recommendations.

Several researchers have investigated sludge pumping, rheology, and related subjects (10 through 24).

14.1.3 Types of Sludge Pumps

Sewage sludges can range in consistency from a watery scum to a thick paste-like slurry. A different type of pump may be required for each type of sludge. Pumps which are currently utilized for sludge transport include centrifugal, torque flow, plunger, piston, piston/hydraulic diaphragm, progressive cavity, rotary, diaphragm, ejector and air lift pumps. Water eductor pumps are sometimes used to pump grit from aerated grit removal tanks.

14.1.3.1 Centrifugal Pumps

A centrifugal pump (Figure 14-7) consists of a set of rotating vanes in a housing or casing. The vanes may be either open or enclosed. The vanes impart energy to a fluid through centrifugal force. The non-clog centrifugal pump for sewage or sludges, in comparison to a centrifugal pump designed to handle clean water, has fewer but larger and less obstructed vane passageways in the impeller; has greater clearances between impeller and casing; and has sturdier bearings, shafts, and seals. Such non-clog centrifugal pumps may be used to circulate digester contents and transfer sludges with lower solids concentrations, such as waste activated sludge. The larger passageways and greater clearances result in increased reliability at a cost of lower efficiency.

The basic problem with using any form of centrifugal pump on sludges is choosing the correct size. At any given speed, centrifugal pumps operate well only if pumping head is within a relatively narrow range; the variable nature of sludge, however, causes pumping heads to vary. The selected pumps must be large enough to pass solids without clogging of the impellers and yet small enough to avoid the problem of diluting the sludge by drawing in large quantities of overlying sewage. Throttling the discharge to reduce the capacity of a centrifugal pump is impractical both because of energy inefficiency and because frequent clogging of the throttling valve will occur. It is recommended that centrifugal pumps requiring capacity adjustment be equipped with variable-speed drives. Fixed capacity in multiple pump applications is achieved by equipping each pump with a discharge flow meter and using the flow meter signal in conjunction with the variable speed drive to control the speed of the pump. Seals last longer if back suction pumps are used. Utilizing the back of the impeller for suction removes areas of high pressure inside the pump casing from the location of the seal and prolongs seal life.

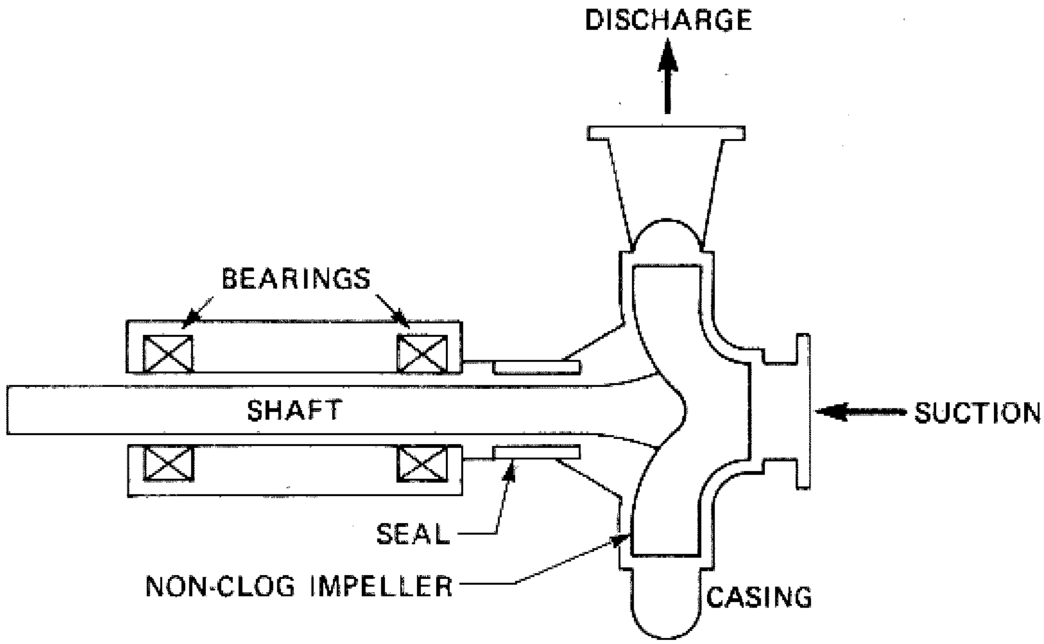


FIGURE 14-7

CENTRIFUGAL PUMP

Propeller or mixed flow centrifugal pumps are sometimes used for low head applications because of higher efficiencies, a typical application is return activated sludge pumping. When being considered for this type of application, such pumps must be of sufficient size (usually at least 12 inch [300 mm] in suction diameter) to provide internal clearances capable of passing the type of debris normally found within the activated sludge system. Such pumps should not be used in activated sludge systems which are not preceded with primary sedimentation facilities.

14.1.3.2 Torque Flow Pumps

A torque flow pump (Figure 14-8), also known as a recessed impeller or vortex pump, is a centrifugal pump in which the impeller is open faced and recessed well back into the pump casing. The size of particles that can be handled by this type of pump is limited only by the diameter of the suction or discharge openings. The rotating impeller imparts a spiralling motion to the fluid passing through the pump. Most of the fluid does not actually pass through the vanes of the impeller, thereby minimizing abrasive contact with it and reducing the chance of clogging. Because there are no close tolerances between the impeller and casing, the chances for abrasive wear within the pump are further reduced. The price paid for increased pump longevity and reliability is that the pumps are relatively inefficient compared with other non-clog centrifugals; 45 versus 65 percent efficiency is typical. Torque flow pumps for sludge service should always have nickel or chrome abrasion resistant volute and impellers. The pumps must be sized accurately so that excessive recirculation does not occur at any condition at operating head. Capacity adjustment and control is achieved in the same manner as for other centrifugal pumps.

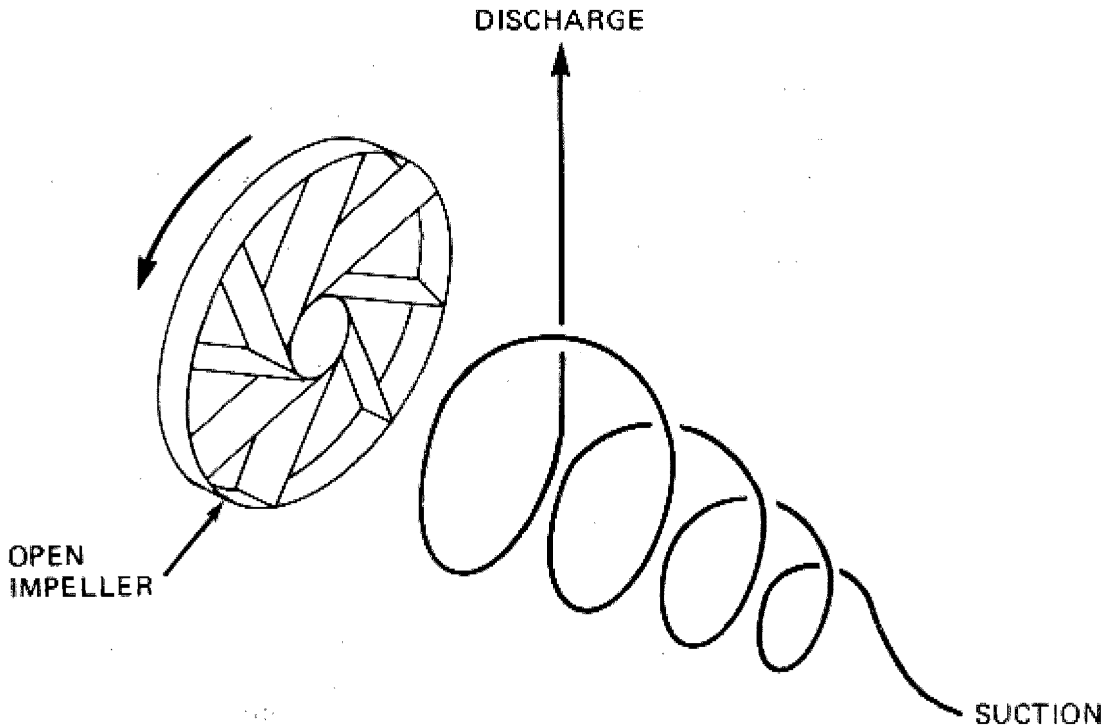


FIGURE 14-8

TORQUE FLOW PUMP

14.1.3.3 Plunger Pumps

Plunger pumps (Figure 14-9) consist of pistons driven by an exposed drive crank. The eccentricity of the drive crank is adjustable, offering a variable stroke length and hence a variable positive displacement pumping action. The check valves, ball or flap, are usually paired in tandem before and after the pump. Plunger pumps have constant capacity regardless of large variations in pumping head, and can handle sludges up to 15 percent solids if designed specifically for such service. Plunger pumps are cost-effective where the installation requirements do not exceed 500 gpm (32 l/s), a 200 feet (61 m) discharge head, or 15 percent sludge solids. Plunger pumps require daily routine servicing by the operator, but overhaul maintenance effort and cost are low.

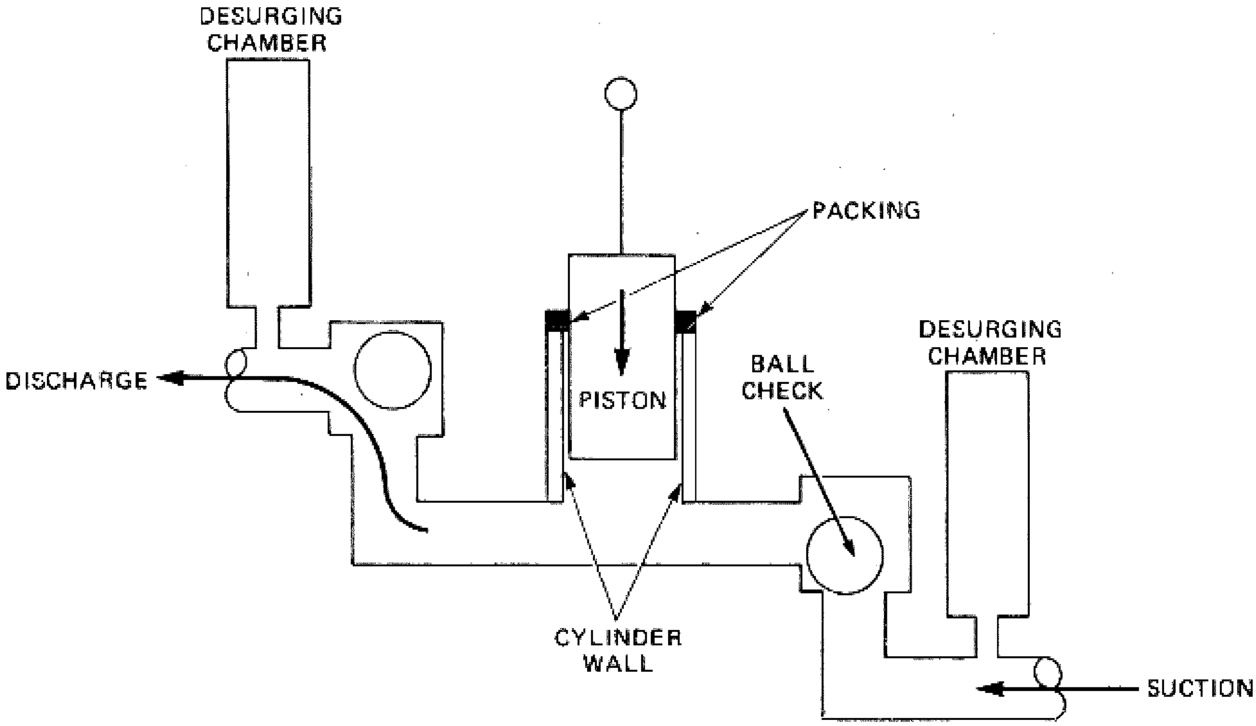


FIGURE 14-9

PLUNGER PUMP

The plunger pump's internal mechanism is visible. The pump's connecting rod attaches to the piston inside its hollow interior and this "bowl" is filled with oil for lubrication of the journal bearing. Either the piston exterior or the cylinder interior houses the packing, which must be kept moist at all times. Water for this purpose is usually supplied from an annular pool located above the packing; the pool receives a constant trickle of clean water. If the packing fails, sludge may be sprayed over the surrounding area.

Plunger pumps may operate with up to 10 feet (3 m) of suction lift; however, suction lifts may reduce the solids concentration that can be pumped. The use of the pump with the suction pressure higher than the discharge is not practical because flow will be forced past the check valves. The use of special intake and discharge air chambers will reduce noise and vibration. These chambers also smooth out pulsations of intermittent flow. Pulsation dampening air chambers, if used, should be glass lined to avoid destruction by hydrogen sulfide corrosion. If the pump is operated when the discharge pipeline is obstructed, serious damage may occur to the pump, motor, or pipeline; this problem can be avoided by a simple shear pin arrangement.

14.1.3.4 Piston Pumps

Piston pumps are similar in action to the plunger pumps, but consist of a guide piston and a fluid power piston. (See Figure 14-10). Piston pumps are capable of generating high pressures at low flows. These pumps are more expensive than other types of positive displacement sludge pumps and are usually used in special applications such as feed pumps for heat treatment systems. As for other types of positive displacement pumps, shear pins or other devices must be used to prevent damage due to obstructed pipelines.

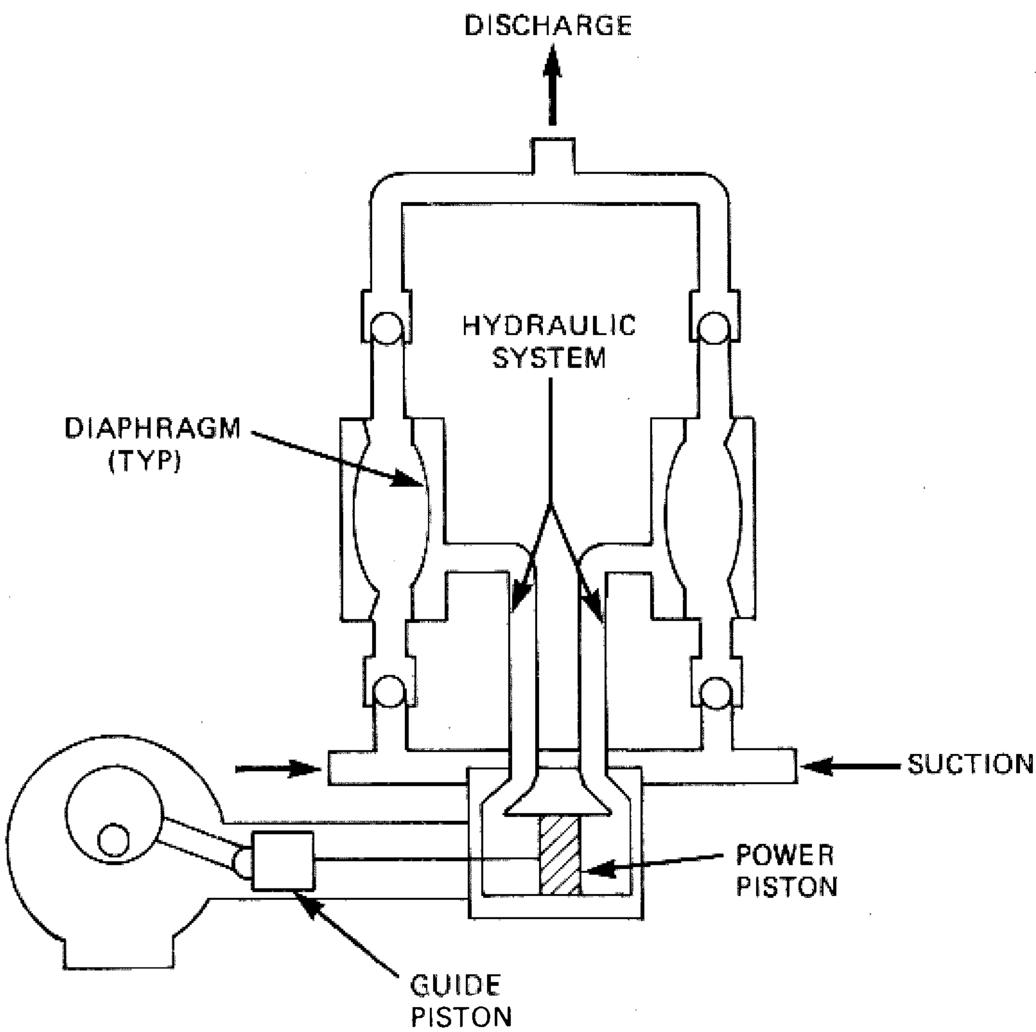


FIGURE 14-10

PISTON PUMP

A variation of the piston pump has been developed for use where reliability and close control are needed. The pump utilizes a fluid power piston driving an intermediate hydraulic fluid (clean water), which in turn pumps the sludge in a diaphragm chamber (Figure 14-11). The speed of the hydraulic fluid drive piston can be controlled to provide pump discharge conditions ranging from constant flow rate to constant pressure. This pump is used primarily as a feed pump for filter presses. This special pump has the greatest initial cost of any piston pump, but the cost is usually offset by low maintenance and high reliability.

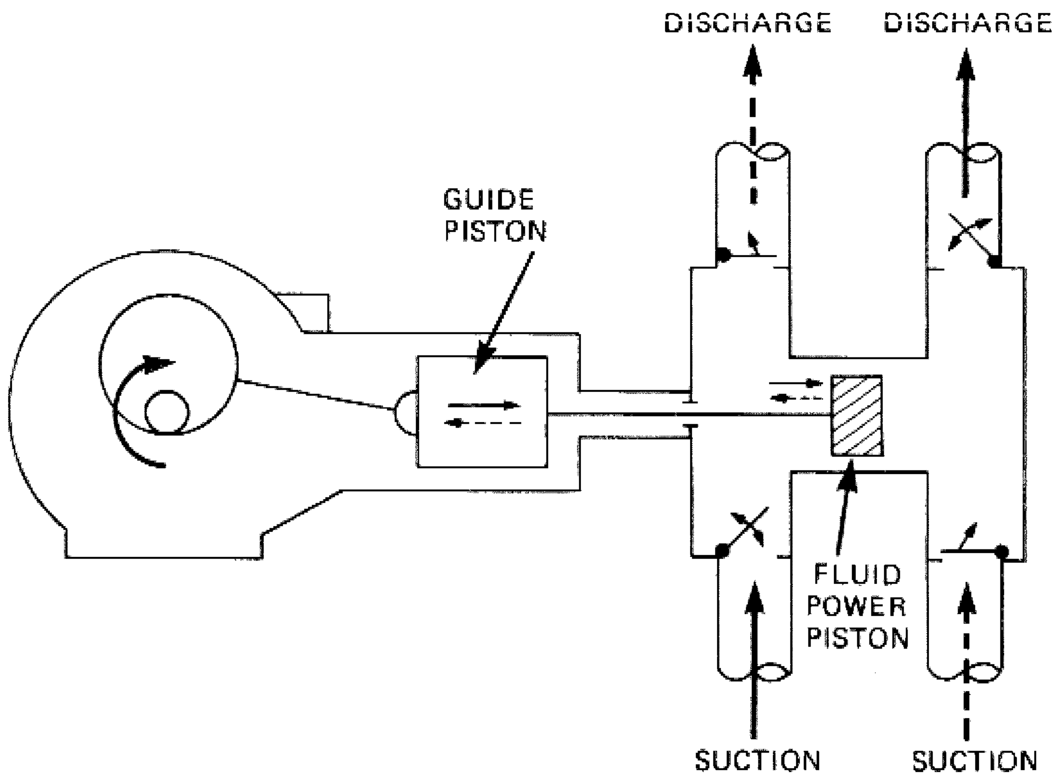


FIGURE 14-11

COMBINATION PISTON/HYDRAULIC DIAPHRAGM PUMP

14.1.3.5 Progressive Cavity Pumps

The progressive cavity pump (Figure 14-12) has been used successfully on almost all types of sludge. This pump comprises a single-threaded rotor that operates with an interference clearance in a double-threaded helix stator made of rubber. A volume or "cavity" moves "progressively" from suction to discharge when the rotor is rotating, hence the name "progressive cavity." The progressive cavity pump may be operated at discharge heads of 450 feet (137 m) on sludge. Capacities are available to 1,200 gpm (75 l/s). Some progressive cavity pumps will pass solids up to 1.125 inches (2.9 cm) in diameter.

Rags or stringy material should be ground up before entering this pump. The rotor is inherently self-locking in the stator housing when not in operation, and will act as a check valve for the sludge pumping line. An auxiliary motor brake may be specified to enhance this operational feature.

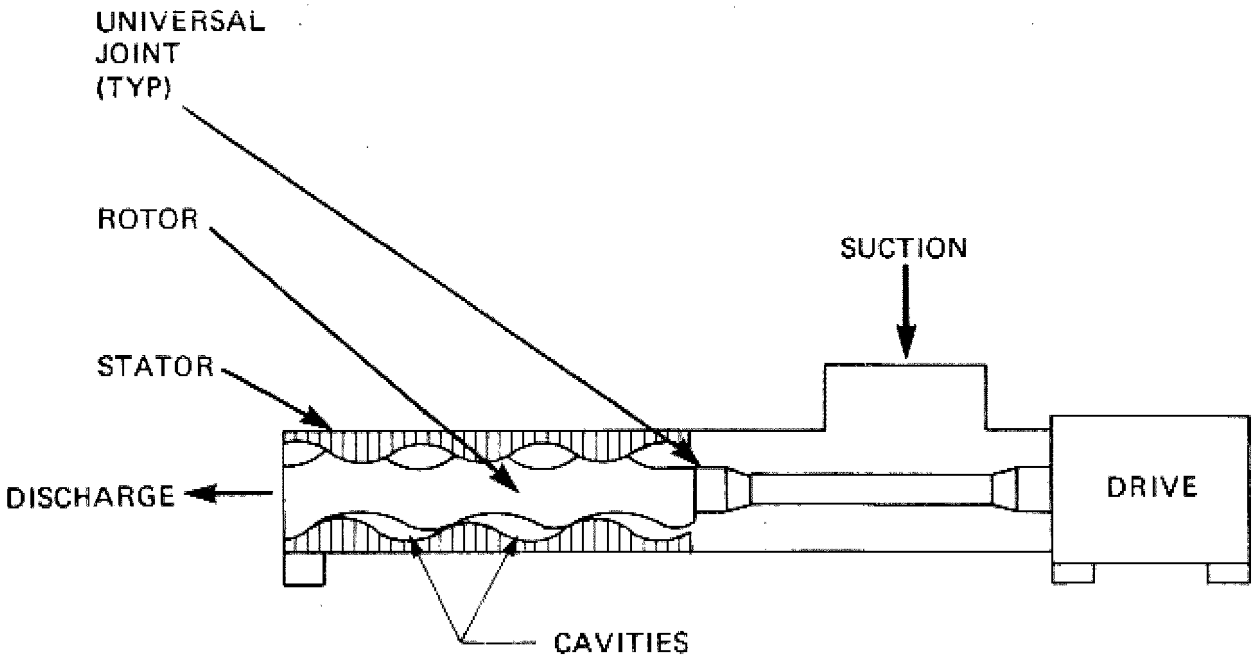


FIGURE 14-12

PROGRESSIVE CAVITY PUMP

The total head produced by the progressive cavity pump is divided equally between the number of cavities created by the threaded rotor and helix stator. The differential pressure between cavities directly relates to the wear of the rotor and stator because of the slight "blow by" caused by this pressure difference. Because wear on the rotor and stator is high, the maintenance cost for this type of pump is the highest of any sludge pump. Maintenance costs are reduced by specifying the pump for one class higher pressure service (one extra stage) than would be used for clean fluids. This creates many extra cavities, reduces the differential pressure between cavities, and consequently reduces rotor and stator wear. Also, speeds should not exceed 325 rpm in sludge service, and grit concentrations should be minimized.

Since the rotor shaft has an eccentric motion, universal joints are required between the motor shaft and the rotor. The design of the universal joint varies greatly among different manufacturers. Continuous duty, trouble-free operation of these universal joints is best achieved by using the best quality (and usually most expensive) universal gear joint design. Discharge pressure safety shutdown devices are required on the pump discharge to prevent rupture of blocked discharge lines. No-flow safety shutdown devices are often used to prevent the rotor and stator from becoming fused due to dry operation. As previously mentioned, these pumps are expensive to maintain. However, flow rates are easily controlled, pulsation is minimal, and operation is clean. Therefore, progressive cavity pumps are widely used for pumping sludge.

14.1.3.6 Diaphragm Pumps

Diaphragm pumps (Figure 14-13) utilize a flexible membrane that is pushed or pulled to contract or enlarge an enclosed cavity. Flow is directed through this cavity by check valves, which may be either ball or flap type. The capacity of a diaphragm pump is altered by changing either the length of the diaphragm stroke or the number of strokes per minute. Pump capacity can be increased and flow pulsations smoothed out by providing two pump chambers and utilizing both strokes of the diaphragm for pumping. Diaphragm pumps are relatively low head and low capacity units; the largest available air-operated diaphragm pump delivers 220 gpm (14 l/s) against 50 feet (15 m) of head. The distinct advantage of the diaphragm pumps is their simplicity. Their needs for operator attention and maintenance are minimal. There are no seals, shafts, rotors, stators, or packing in contact with the fluid; also, diaphragm pumps can run in a dry condition indefinitely.

Flexure of the diaphragm may be accomplished mechanically (push rod or spring) or hydraulically (air or water). Diaphragm life is more a function of the discharge head and the total number of flexures than the abrasiveness or viscosity of the pumped fluid. Power to drive air driven diaphragm pumps is typically double that required to operate a mechanically driven pump of similar capacity. However, hydraulically operated (air or water) diaphragms generally outwear mechanically driven diaphragms by a considerable amount. Hydraulically driven diaphragm pumps are suitable for operation in hazardous explosion-prone areas; also a pressure release means in the hydraulic system provides protection against obstructed pipelines. Typical repairs to a diaphragm pump usually cost less than $75 (1978 basis) for parts and require approximately two hours of labor. In some locations, high humidity intake air will cause icing problems to develop at the air release valve and muffler on an air driven diaphragm pump. A compressed air dryer should be used in the air supply system when such a condition exists.

The overall construction of some diaphragm pumps, the common "trash pump," is such that abrasion may cause the lightweight casings to fail before the diaphragms, since the pumps are not designed for continuous service. For wastewater treatment applications the mechanical diaphragm "walking beam" pumps are more appropriate. These pumps are dependable, have quick cleanout ball or flap check valves and are presently used to handle scum and sludge at numerous small plants throughout the country.

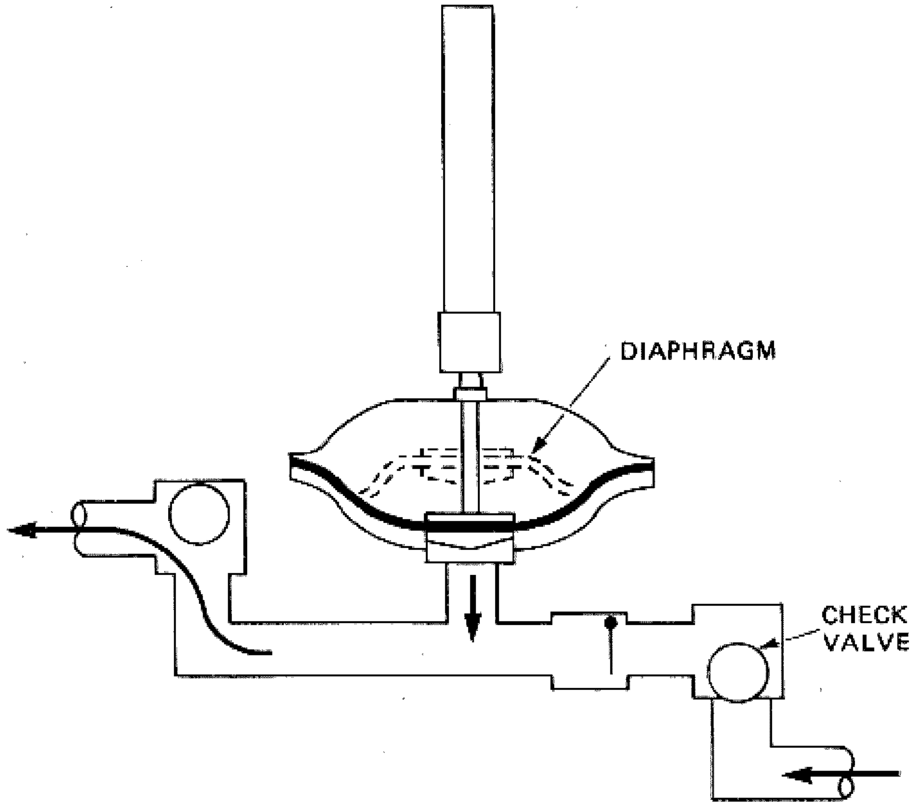


FIGURE 14-13

DIAPHRAGM PUMP

One air-driven diaphragm pump is sold in a package expressly intended for pumping sludge from primary sedimentation tanks and gravity thickeners. The basic pump package consists of a single-chambered, spring return diaphragm pump, an air pressure regulator, a solenoid valve, a gage, a muffler, and an electronic transistorized timer. This unit pumps a single 3.8 gallon (14.4 l) stroke after an interval of time. The interval is readily adjusted to match the pumping rate to the rate of formation of the sludge blanket in the sedimentation tank or thickener. The large single stroke capacity of this pump has several maintenance advantages. Not only is total flexure count reduced, but ball valve flushing is improved, so large particles cause less difficulty. The maximum recommended solids size is 7/8 inch (2.2 cm). Pump stroke speed is constant regardless of the selected pump flow so that minimum scouring velocities are always maintained in the discharge piping during the pumping surge.

The traditional sequence of intermittent pumping for primary sedimentation tanks has been to thicken for an interval without pumping and then draw the sludge blanket down. A relatively long interval is required by pump motors, since frequent motor starts can cause over heating. Theoretically if the sludge concentration is 10 percent on the bottom and decreases to 8 percent at the top of the pumped sludge zone, then the pumped average is 9 percent. However, by using air drive, a diaphragm pump can operate with starts every few seconds instead of every several minutes or longer. The manufacturer claims its system will draw single intermittent pulses from the 10 percent bottom layer since the sludge blanket depth is maintained at a virtually constant height. Downstream sludge treatment processes can have greater solids capacity because more concentrated sludges can be obtained.

The City of San Francisco ran independent pump evaluation tests in 1975 (25). They concluded that proper use of air-driven diaphragm pumps will increase the sedimentation tanks' ability to concentrate sludges. The sludge collection system in the sedimentation tanks and the sludge pumping equipment had to be controlled together to give optimum thickening. Savings in operations and maintenance as well as improved thickening were accomplished by lowering the overall average rate of sludge withdrawal and making the sludge collectors work continuously at a reduced rate instead of intermittently. When considering such a pump installation, the capacity requirement is based on the maximum rate at which the sludge blanket forms in the tank and not the capacity required to maintain minimum pipe velocities.

14.1.3.7 Rotary Pumps

Rotary pumps (Figure 14-14) are positive displacement pumps in which two rotating synchronous lobes essentially push the fluid through the pump. Because rotary pump lobe configurations can be designed for a specific application, rotary pumps are suitable for jobs ranging from air compressor duty to sewage sludge pumping. Rotational speed and shearing stresses are low. Sewage pumping lobes are noncontact and clearances are factory changed according to the abrasive content of the slurry. It is not recommended that the pumps be considered self-priming or suction lift pumps although they are advertised as such. Experience at one plant indicates that the pump operates best with a bottom suction and top discharge. Only very limited operational data are available for rotary pumps used on sludge. Two manufacturers now advertise hard metal two-lobed pumps for sludge usage. Lobe replacement for these pumps appears to be less costly than rotor and stator replacement on progressive cavity pumps. One manufacturer is offering hard rubber three-lobed rotary pumps, which are used successfully for sludge pumping in Europe. Test units of this pump are presently being evaluated in the United States. To date these tests have been unsuccessful due to the failure of the lobe liners. Rotary pumps, like other positive displacement pumps, must be protected against pipeline obstructions.

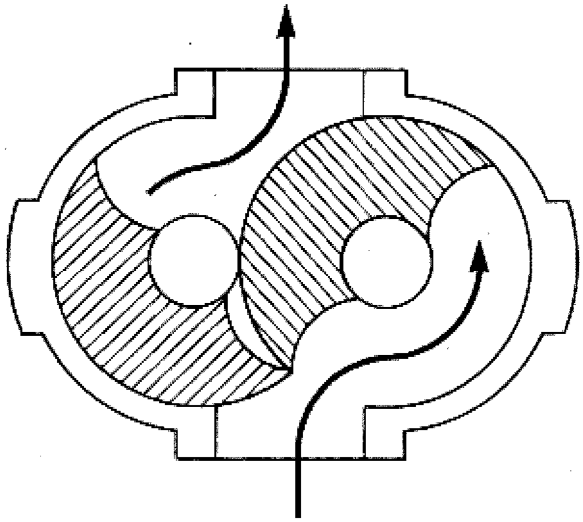


FIGURE 14-14

ROTARY PUMP

14.1.3.8 Ejector Pumps

Sewage ejectors use a charging pot which is intermittently discharged by a compressed air supply (See Figure 14-15). Ejectors are most applicable for incoming average flow rates less than 150 gpm (9 l/s). These pumps require a positive suction and usually discharge to a vented holding tank or basin. Scum and sludge can incapacitate the standard mechanical or electronic probe-type level sensors offered by most manufacturers to sequence pot discharge; custom instrumentation may be necessary. Large flushing and cleanout connections should be provided. If ejectors are to be used to discharge sludge to an anaerobic digester where the air could produce an explosive mixture, special precautions should be taken to see that the units cannot bleed excessive quantities of air into the digester. Ejector pumps have been used in some installations to pump thickened waste-activated sludge produced by the dissolved air flotation process.

14.1.3.9 Gas Lift Pumps

Gas lift pumps use low pressure gas released within a confined riser pipe with an open top and bottom. The released gas bubbles rise, dragging the liquid up and out of the riser pipe. Air is commonly used, in which case the pump is called an air lift pump.

Air lift pumps are used for return activated sludge and similar applications; gas lift pumps using digester gas are used to circulate the contents of anaerobic digesters. The main advantage of these relatively inefficient pumps is the complete absence of moving parts. Gas lift sludge pumps are usually limited to lifts of less than 10 feet. The capacity of a lift pump can be varied by changing its bouyant gas supply. Reliable gas lift pumping requires the gas supply to be completely independent of outside flow or pressure variables. Gas lift pumps with an external gas supply and circumferential diffuser can pass solids of a size equivalent to the internal diameter of the confining riser pipe without clogging. When the gas is supplied by a separate inserted pipe, the obstruction created negates this non-clog feature. Gas lift pumps, because of their low lifting capability, are very sensitive to suction and discharge head variations, and to variations in the depth of bouyant gas release. Special discharge heads are usually required to enhance the complete separation of diffused air once the discharge elevation has been reached.

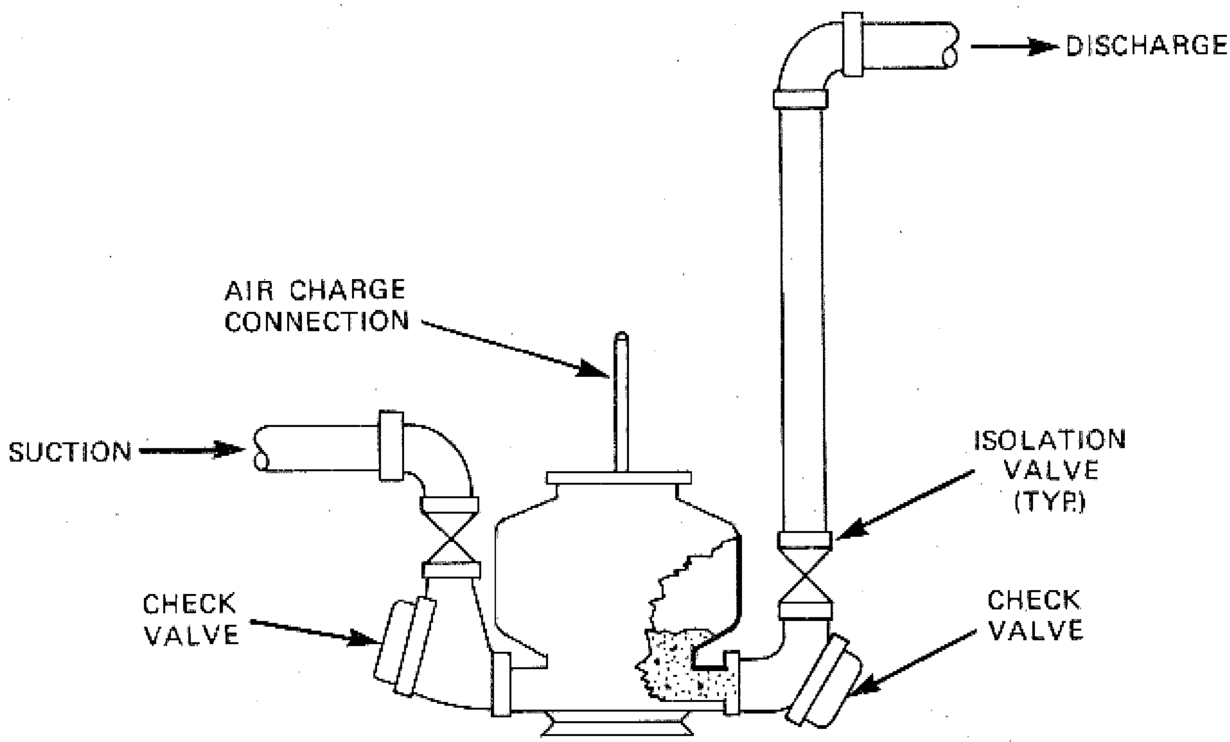


FIGURE 14-15

EJECTOR PUMP

14.1.3.10 Water Eductors

Water eductors use the suction force (vacuum) created when a high pressure water stream is passed through a streamlined confining tube (venturi). Like the air lift pump, water eductors have no moving parts. When water is required to transport a solid material, the water eductor becomes a very convenient pump. Most water eductors with reasonable water demands cannot pump solids of golf ball size. They have, however, been successfully used to remove grit from aerated grit removal tanks and discharge the grit into dewatering classifiers.

14.1.4 Application of Sludge Pumps

The previous section describes the types of pumps available for sludge pumping. This section describes appropriate applications for these pumps and identifies some limitations and constraints. This section covers screenings, grit, and scum as well as sludge.

Suction conditions require special attention when pumping sludge. When pumping water or other Newtonian fluids, calculations of net positive suction head (NPSH) can be used to determine permissible suction piping arrangements. However, sludge is a non-Newtonian fluid, especially at high solids concentrations. This behavior may drastically reduce the available NPSH. Consequently, long suction pipelines should be avoided and the sludge pump should be several feet below the liquid level in the tank from which the sludge is to be pumped. If these conditions are not met, a pump will not be able to handle sludge at high concentrations.

Special precautions are usually required to reliably pump screenings and grit. Screenings should be ground up and pumped by pumps with the ability to pass large material. Torque flow pumps are ideal for this application. Grit pumping requires special abrasion and non-clogging considerations. Both screenings and grit pumps should be easy to disassemble with quick access to the volute and impeller.

Table 14-3 presents an application matrix that identifies the various types of sludges or solids normally encountered in wastewater applications, and provides a guide for the suitability of each type of pump in that service.

14.1.5 Pipe, Fittings, and Valves

Materials for wastewater solids pipelines include steel; cast and ductile iron; pretensioned concrete cylinder pipe; thermoplastic; fiberglass reinforced plastic; and other materials. Steel and iron are most common. With steel or iron, external corrosion may occur in unprotected buried lines; corrosion may be adequately controlled under most conditions by coatings and, where needed, cathodic protection. Inside the pipe, a lining of cement, plastic, or glass may be used to protect the pipe from internal corrosion and abrasion. With raw sludges and scum, linings have an additional function: they provide a smooth surface that greatly retards accumulations of grease on the pipe wall (26, 27). With anaerobically digested sludge, linings may be useful to prevent crystals of struvite from growing on the pipe wall. (Refer to the anaerobic digestion portion of Chapter 6 for control of struvite). Smooth linings are especially valuable in pump suction piping and in key portions of piping (header pipes and the like) where maintenance shutdowns would cause process difficulties.

TABLE 14-3

APPLICATIONS FOR SLUDGE PUMPS

	Miscellaneous solids				Primary sludge		Secondary sludge				Digested sludge, percent		Lagooned sludge, percent		
									Thickened sludge						
Pump type	Ground screenings	Grit	Scum	Septage	Settled sludge	Thickened sludge	Trickling filter	Activated sludge	Float	Gravity	Mixed <6	Thickened >6	Wet <10	Dry >15	Comments
Centrifugal	0	0	0	0	3	2	4	4	0[a]	3	4	3	4	1	-[b]
Torque flow	5	4	3	5	4	3	4	4	0[a]	4	4	3	3	0	-[b]; low efficiency
Plunger	0	0	4	4	4	4	4	1	1[c]	4	4	4[d]	4	0	Daily attention required
Piston	0	0	0	3	3	3	3	3	3	3	3	3	3	0	High cost[e,f]
Progressive cavity	4[g]	1	5	4[g]	5	5	5	5	5	5	4	5	5	5	-[h]
Piston/hydraulic diaphragm	0	0	0	2	3	3	3	3	3	3	3	3	3	0	High cost[e,f]
Diaphragm	4	0	4	4	5	5	5	5	5	5	5	4	3	0	
Rotary	0	0	0	0	3	3	3	3	3	3	3	3	3	0	High maintenance cost
Pneumatic ejector	4[i]	4[i]	3	3	3	[illegible]	3	3	3	3	3	3	3	0	
Air lift	0	2[j]	0	0	4	0	4	4	0	0	0	0	0	0	Low lift
Water eductor	0	3[j]	0	0	0	0	0	0	0	0	0	0	0	0	Low lift

[a]Float may cause air binding.
[b]Varying quality and head conditions requires positive flow control.
[c]Restricted to low flows.
[d]Maximum 15 percent solids.
[e]High discharge pressure only.
[f]Should be preceded by grinding.
[g]Large bore pumps may be used with in-line grinding.
[h]Requires special mechanical conditioning on dry sludge feed.
[i]Batch Pneumatic Ejector type recommended.
[j]Short distance only.

Key:
0 - Unsuitable
1 - Use only under special circumstances
2 - Use with caution
3 - Suitable with limitations
4 - Suitable
5 - Best type to use

Fittings and appurtenances must be compatible with sludge and pipe. Long sweep elbows are preferred over short radius elbows. Grit piping may be provided with elbows and tees made of special erosion resistant materials.

Valves of the nonlubricated eccentric plug type have proven reliable in sludge pipeline service. Care must be taken if a cleaning tool is to pass through the valves. Grit pipelines are usually equipped with tapered lubricated plug valves.

Wastewater solids piping should be designed for reasonably convenient maintenance. Even under good conditions, pipe may occasionally have erosive wear, grease deposits, or other difficulties. Pipe in tunnels or galleries is more accessible than buried pipe. An adequate number of flanged joints, mechanical couplings, and take-down fittings should be provided. It is recommended that 4 to 6 inches (10 to 15 cm) be considered the minimum diameter for wastewater solids pipelines to minimize grease clogging or particle blockage and facilitate maintenance. Blind flanges and cleanouts should be provided for ease of line maintenance. Gas formation by wastewater solids left for long periods in confined pipe or equipment can create explosive pressures; therefore, provision should be made for flushing and draining all pipes, pumps, and equipment. The pressure rating of wastewater solids pipelines should be adequate for unusual as well as routine operating pressures. Unusual pressures will occasionally occur due to high solids concentrations, pipe obstructions, gas formation, water hammer, and cleaning operations.

Temperature changes may cause stress in the pipe. Temperatures are changed by heated material as it enters cold pipe; flushing; and the use of hot fluids during cleaning to remove grease. Pipe should be designed to accommodate such stresses.

14.1.6 Long Distance Pumping

Sludge may be pumped for miles. A pipeline is frequently less expensive than the alternatives of trucks, rail cars, or barging (see Section 14.1.3 and reference 28), especially if, by pipelining, mechanical dewatering can be avoided. Pipelines may have less environmental impact along their routes than trucks.

14.1.6.1 Experience

Tables 14-4 and 14-5 describe some typical pipelines for unstabilized and digested sludges. There is considerable additional U.S. experience; see Tables 14-6 and 14-7. An examination of these tables shows that:

- Centrifugal pumps are widely used, even on unstabilized sludge.
- Operating pressures are usually below 125 psig (860 kN/m^2 gage).
- Velocities are usually below 3.5 ft/sec (1.1 m/s).
- If the volatile solids content of the sludge is low, the sludge can be pumped at a high total solids concentration. This is well illustrated by the lagoon sludge pipelines, which have operated at up to 18 percent solids; lagooned sludge has a very low volatile content.

In some cases, sludge thickening at the receiving location was adversely affected by the shearing or the septicity that occurred in the pipelines. Special flushing practices after pipeline use or use of a pipe cleaning device were not used in several cases. Need for these techniques seem to depend on the nature of the sludge being pumped, although experience is not conclusive on this point.

TABLE 14-4

TYPICAL LONG PIPELINES CARRYING UNSTABILIZED SLUDGE

Characteristics	Cleveland, OH Easterly to Southerly	Indianapolis, IN Southport to Belmont	Jacksonville, FL District II to Buckman	Kansas City, MO West Side to Big Blue River	Philadelphia, PA Southeast to Southwest
Length, mi	13.2	7.5	7	6.6	5
Diameter, in.	12	Twin 14	8	12	8[a]
Pipe material	Cast iron, unlined	Ductile iron	-	Ductile iron	Ductile iron[a]
Sludge type	Primary, waste-activated[b]	Primary, waste-activated	Primary, waste-activated	Primary	Primary, excluding scum
Percent solids	3 - 3.5[c]	0.75 - 1.75	3	0.4 - 1.0	2.5 - 5
Percent volatile	65[c]	68	80	50 - 70	50
Flow rate, gpm	350[c]	1,000 minimum	500 normal	1,000	500
Velocity, ft/sec	1.0[c]	2 minimum	3	2.8	3
Total pressure, psig	150 - 175[c]	90 normal	90 normal	65	90 normal
Pump type	Centrifugal, three in series	Centrifugal	Centrifugal, two in series	Centrifugal	Centrifugal
Operating schedule	Continuous	Continuous	30 - 60 minutes every two hours	Continuous	Continuous
Use of cleaning tool	Every 4-6 weeks	None	Possible, not needed	Weekly	Every 1 to 2 weeks[d]
Septicity of sludge	-	Yes	Yes	Some; chlorine used	Not much odor
Comments	Difficulty with solids accumulation at receiving plant	Thickeners do not work as well on sludge that has been pumped from Southport	Heat treatment dewatering less	Good thickening at receiving plant	Good thickening at receiving plant

[a] Two ductile iron lines will replace a single line. The old lines is subject to external corrosion and will be abandoned over most of its length. The new lines have polyethylene wrap and cathodic protection.

[b] Pickle liquor is added to primary treatment for phosphorus removal. Skimmings are handled separately.

[c] Data from Reference 10. Later, sludge thickness was decreased to 1-2 percent solids to reduce operating pressures and line breaks.

[d] There is a heavy grease buildup in the pipe, especially in winter.

1 mi = 1.6 km
1 in. = 25.4 mm
1 gpm = 0.063 l/s
1 ft/sec = 0.30 m/s
1 psig = 6.9 kN/m^2 gage

14.1.6.2 Design Guidance

Proper pre-planning of a pipeline installation is of great importance. For example, a pump breakdown or a plugged pipeline has a great impact on plant operation, and its likelihood can be greatly minimized by good initial design and equipment selection.

If digestion is to be part of the system, the digesters may be located either before or after the long sludge pipeline. However, sludge is much easier to pump after it has been digested. In addition, raw sludges may cause problems related to thickening, odors, and corrosion at the receiving point, since septic conditions may develop in the pipeline. If raw sludge is to be pumped long distances, the least environmental impact will result if the pipeline contents are discharged directly into anaerobic digesters.

TABLE 14-5

TYPICAL LONG PIPELINES CARRYING DIGESTED SLUDGE

Characteristics	Chicago, IL lagoon no. 28[a]	Denver, CO Northside to Metro[b]	Fort Wayne, IN	Rahway Valley Sanitary Authority, NJ	San Diego, CA Point Loma
Length, mi	1.7	2	3	3	7.5
Diameter, in.	16	Twin 8	12, some 10	8	8
Material	Steel	Cast iron	Unlined cast iron	-	Fiber reinforced plastic[c]
Sludge type	Lagooned	Anaerobically-digested primary	Digested[d]	Anaerobically digested primary and waste-activated	Anaerobically digested primary
Percent solids	13 average 15 maximum	4 - 7	5 maximum	3 - 4	Up to 7.5[e]
Percent volatile	40	49	35 - 40	-	57
Flow rate, gpm	1,300	700	600	500	550 - 600
Velocity, ft/sec	2.1	2	1.6	3	3.5
Total pressure, psig	87	40 - 60	20 - 30	80	155
Pumps	Centrifugal with mixers	Centrifugal	Centrifugal[f]	Two-stage centrifugal, formerly reciprocating	Torque flow[g]
Operating schedule	Intermittent	1 - 2 hr/day, not flushed	3 hr/day, can flush but not needed	4 hr/day, not flushed	5 times/week, flushed before and after use
Use of cleaning tool	None	None	None	Not needed[h]	None

[a]Temporary pipeline to clean Lawndale lagoon no. 28 (5,6). No longer in service.

[b]Also, a 25-mi pipeline has been designed but not yet constructed, as of early 1979.

[c]Fiber reinforced plastic replaced a lined and coated steel pipe that corroded.

[d]Anaerobically digested primary and waste-activated sludges with phosphorus-precipitating chemicals.

[e]Dilution water is needed sometimes to get the sludge started. Once it is moving, the dilution water may be shut off, depending on pressure.

[f]Non-clog centrifugal pumps are suitable for ordinary digested sludge. A nickel-alloy torque flow pump is being added for digester cleaning and septic tank waste.

[g]Three pumps in series, two of which have variable speed drives.

[h]In the past, a novel ice bag tool was used (26).

1 mi = 1.6 km
1 in. = 25.4 mm
1 gpm = 0.063 l/s
1 ft/sec = 0.30 m/s
1 psig = 6.9 kN/m^2 gage

Sludge that has been piped for a long distance may experience floc breakdown. If this occurs, thickening and dewatering may be impaired. Chemical conditioning may require a higher chemical dose; thermal conditioning may produce a sludge with poorer dewatering properties.

The following special design features should be considered for long distance pipelines:

1. Provide two pipes unless a single pipe can be shut down for several days without causing problems in wastewater treatment system.

2. Consider external corrosion and pipe loads just as for any other utility pipeline, for example, water or natural gas. External corrosion has been a problem on some long sludge pipelines. Electrical return currents,

TABLE 14-6

LONG PIPELINES FOR UNSTABILIZED SLUDGE ADDITIONAL LOCATIONS

City	Treatment plants	Length, mi	Diameter of pipe, in.	Sludge type	Percent solids	Pump type
Austin, TX	Walnut Creek	7	12	Primary, waste-activated	1-1.2	Positive displacement
Chicago, IL	Northside to West-Southwest	18	14	Primary, waste-activated	1	Torque flow
Houston, TX	Simms Bayou to Northside[a]	6.8	8	Waste-activated	0.5-1	Centrifugal, 2 in series
Jersey City, NJ	Eastside to Westside	2.5	[illegible]	Primary	4 (maximum)	Plunger, 3 speed
Knoxville, TN	Loves Creek to Third Creek system	3.2	6	Primary, trickling filter	1-3	Centrifugal
Linden-Roselle, NJ	Linden-Roselle Sewerage Authority	1	24	Primary	2-4	Centrifugal
Miami, FL	Interama to Virginia Key	14	16[b]	Primary, waste-activated	1-3	Progressive cavity
San Francisco, CA	North Point to Southeast	6	10	Primary with ferric chloride	1	Centrifugal, 2-speed
Seattle, WA	Renton to West Point system	3.7	12[c]	Primary, waste-activated	0.5-1	Progressive cavity, variable speed

[a] There are additional pipelines in Houston (26).
[b] Two 16-in. pipes over most of the route.
[c] Two pipes.

1 mi = 1.6 km
1 in. = 25.4 mm

TABLE 14-7

LONG PIPELINES FOR DIGESTED SLUDGE ADDITIONAL LOCATIONS

Location	Length, mi	Diameter of pipe, in.	Type of digestion	Percent solids	Pump type
Austin, TX - Govalle plant	7	10	Aerobic	0.8	Positive displacement
Boston, MA - Nut Island plant	4.5	12	Anaerobic	3	Centrifugal, reciprocating
Chicago, IL - West-Southwest plant to Lawndale lagoons	5.5	16	Anaerobic	3.5 - 4.5	Centrifugal
Chicago, IL - 1970 rail loading[a]	3.5	12	Anaerobic, lagoon	4 - 15 9.2 average	-
Chicago, IL - barge loading	1.0	16	Anaerobic, lagoon	8 - 18	Centrifugal with mixers
Chicago, IL - Calumet lagoons[a]	1	18	Anaerobic, lagoon	12	Centrifugal
East Rockaway, NY - Bay Park plant	1.5	16	Anaerobic	3.7	Variable speed
Evansville, IN	3.5	8	Anaerobic	1 - 9	Torque flow, plunger
Fulton County, IL	10.8	20	Anaerobic, lagoon	4 - 8	Centrifugal
Los Angeles, CA - Hyperion	7	20	Anaerobic, aerobic, diluted	0.9	-
Morgantown, WV[a]	4.5	2	Anaerobic	-	Reciprocating
Philadelphia, PA - Southwest	1	-	Anaerobic, lagoon	10-12 normal 15 average	-
Wantagh, NY - Cedar Creek	11	10	-	2.5	Centrifugal, 3 stage

[a] Temporary pipeline, now out of service.

1 mi = 1.6 km
1 in. = 25.4 mm

acid soils, saline groundwater, and other factors may cause serious difficulty unless special corrosion control measures are used. Advice of specialists on the need for cathodic protection is advised.

3. Provide for adding controlled amounts of water to dilute the sludge or flush the line. Primary effluent may be used in raw sludge pipelines; disinfected final effluent may be preferred for digested sludge pipelines. The water connection should have a flow rate indicator. The flushing water should flow at about 3 fps (0.9 m/s).

4. Provide for inserting and removing a cleaning tool ("pig," "go-devil") which can be sent through the line if needed (10, 28a, 28b). Such cleaning may be frequently required if unstabilized sludge is pumped, even if scum is handled separately. If tool cleaning is to be used, some additional recommendations apply:

   a. Valves must provide an unobstructed waterway to pass the tool.

   b. Flushing water pressure should be sufficient to push the tool through the full length of pipeline.

   c. Pipe bend fittings should be 45-degree or, if possible, 22-1/2-degree. Some cleaning tools will pass 90-degree bends, but such bends are likely to be trouble spots. Length/radius of bends should be checked with the tool supplier.

   d. A recording or totalizing flowmeter should be provided. (See Chapter 17, Instrumentation.) If the tool gets stuck in the line, the flow record can be used to compute the number of gallons pumped since the tool was inserted. Thus, the tool can be located and retrieved.

5. The pipeline route should be selected for ease of maintenance.

6. At high points, air or gas relief valves should be provided. With care, automatic relief valves can be made reliable on digested sludge lines; however, in unstabilized sludge lines, grease and debris generally cause automatic valves to be unreliable. Simple manual blowoff valves are generally better for unstabilized sludge. Air and gases from sludge pipelines may be odorous. In confined spaces, the air or gas may also be toxic, flammable, explosive, and corrosive.

7. If sludge is to be pumped at more than about 3 percent solids, the pumps and pipeline should be designed for high and variable friction head losses. Sludge may flow

more like a Bingham plastic than an ordinary Newtonian fluid. A multiplication factor, such as those on Figure 14-1, should not be used. A more accurate design method, such as the one in Section 14.1.2, should be used.

8. If centrifugal pumps are used, flow rates will be somewhat unpredictable because of the varying flow resistance properties of the sludge. Storage provisions should be made for these variations. Pumps should be capable of operating at shutoff head with very low flow during pipeline startup.

9. Positive displacement pumps may experience difficulty when starting a long sludge pipeline. The thixotropic nature of sludge may cause very high resistance to flow during start-up. Consequently excessive pressures may be generated by positive displacement pumps. To avoid this problem, variable speed drives should be provided and the pumps should be started at low speeds. An air chamber (see Section 14.1.3.3) may be installed on the discharge side of the pumps; the chamber will assist in start-up, as well as dampen pulsations. With digested sludge, a relief valve piped back to the digesters may be used near the pumps.

10. For very long lines, a booster pumping station may be required. If positive displacement booster pumps are used, a holding tank should be provided. It is practically impossible to match booster pumping rates to the sludge flow reaching the booster station unless centrifugal pumps are used.

11. Waterhammer is best controlled by limiting velocity. Unless a special evaluation is made, velocities should not exceed about 3 fps (0.9 m/s). Even lower velocities may be required in some cases.

14.1.7 In-Line Grinding

In-line grinders are used to reduce the size of sludge solids to prevent problems with the operation of downstream processes. Grinders require high maintenance; therefore they should not be installed unless shown to be absolutely necessary. For locations where a grinder may be installed in the future, removable spool pieces should be inserted into the pipeline to facilitate the later installation of a grinder. Grinders may be applicable to streams carrying debris, rags or stringy materials, but are usually not needed for streams carrying only secondary (biological) sludge. Grinders have often been installed preceding equipment with ball or flapper check valves. However, utilizing dual check valving, proper stroke seating can be obtained and the grinders can often be eliminated. Grinders remain a necessity upstream from small diameter, high pressure positive displacement pumps.

Sophisticated, slow speed, hydraulic or electric grinders that can sense blockages and clear themselves by reverse operation are now available. Special combination centrifugal pump-grinders are available for use as digester circulation pumps, and are effective in preventing rag balls. Experience indicates such pumps require as much maintenance as grinders.

14.2 Dewatered Wastewater Solids Conveyance

Dewatered or dried sludges, screenings, ash, and grit can be conveyed by most forms of industrial materials handling equipment, including belt, tubular, and screw conveyors; slides and inclines; elevators; and pneumatic systems. Each may be used to advantage in certain applications. Because the consistency of wastewater solids is highly variable, and because the solids are often difficult to move and may tend to flow, the design of this equipment must consider the most severe conditions that may be expected.

14.2.1 Manual Transport of Screenings and Grit

A common method of handling screenings or grit is simply to place a mobile container (29) beneath the discharge point and to periodically empty the mobile container into a larger container to be hauled away to a landfill. The mobile container may have wheels for ease of movement or it may be maneuvered by an overhead crane. The principal disadvantage of this approach is the amount of manual labor required. However, for small or isolated operations this may be the most appropriate method.

14.2.2 Belt Conveyors

Troughed belt conveyors are simple and reliable (Figure 14-16). They may be equipped with load-cell weigh-bridge sections for totalization of conveyed solids weight. (See Chapter 17, Instrumentation). Totalization is useful when an accurate solids balance must be calculated for a dewatering facility or treatment plant. Sludge concentrated enough to maintain a semi-solid shape (15 percent) can be conveyed at about 18 degrees maximum inclination on troughed belt conveyors. Sludges with a higher solids content can be moved up steeper slopes. Where wash sprays are utilized, splash pans should be provided on the underside of belts to direct the used washwater to a proper disposal point. Such splash protection will assist in keeping the area dry and preventing head and tail pulley slippage. Head and tail pulley lagging (grooving), crowning, and other auxiliary ways of maintaining belt guidance should be thoroughly reviewed with conveyor manufacturers before specifying a troughed belt installation. Most troughed belt installations for sludge currently utilize steel idlers and pulleys with lubricated anti-friction bearings. The fisheries industry, which also uses conveyors in constantly wet applications, is successfully using lubricated thermoplastic (TFE, Delrin) idler bearings with Schedule 80 PVC pipe rollers; these provide longer service life than is achieved with all steel construction.

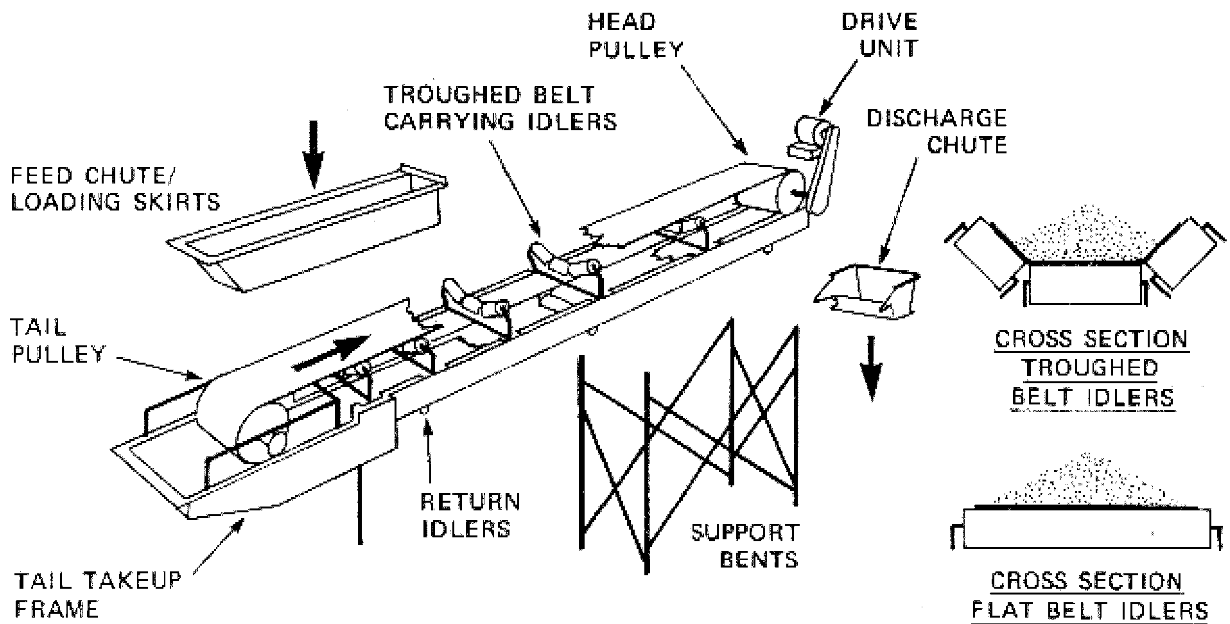


FIGURE 14-16

BELT CONVEYOR

In sludge applications, belt failures usually occur first at the zipper-like mechanical belt seams. Endless belts with field vulcanized seams may be specified to eliminate this mode of failure. Belt material must be resistant to dilute sulfuric acid, formed by the reaction of hydrogen sulfide and moisture. Material selection must also consider oil, grease and a multitude of other elements found in sludge.

Belt conveyors have been successfully used to transport coarse solids removed from mechanically cleaned bar racks, and can be used to transport grit. Special consideration should be given to the type of belt design, construction materials, bearings, type of drive and controls. Since screenings are heavily laden with water, the belt must be designed to contain and direct draining water to a point of disposal. A means of changing belt speeds should be provided so that a range of loads can be accommodated.

The handbook on belt conveyors for bulk materials by the Conveyor Equipment Manufacturers Association (30) is a good reference for general design of belt conveyors. However, there is little specific information available relating to the special problems associated with the cohesive, non-uniform properties of dewatered sludge. Experience at existing facilities using this type of conveying equipment and transporting sludge with similar characteristics provides the most useful design information.

The experience of the County Sanitation Districts of Los Angeles County in the first three years of operation of a two-stage digested sludge dewatering station provides useful guidance for conveying centrifuge-dewatered digested sludge (31). The facility includes solid bowl centrifuges as a first stage, after which the centrate is screened and then dewatered using basket centrifuges. The system uses belt conveyors to transport dewatered sludge between production, storage, and truck loading.

The system has 44 belt conveyors totaling approximately one-half mile in length. Troughed conveyor belts carry both first stage centrifuge cake at 32 percent solids and second stage centrifuge cake at 17 percent solids. Dewatered sludge is usually stored in the twelve storage bins at 22 to 24 percent solids and then transported to trucks by additional belt conveyors.

Helpful guidelines resulting from start-up of this facility include the following:

1. Reduction of splashing at transfer points: The dump point should be enclosed and the drop distance minimized. Skirtboards (stationary sidewalls at edges of belts) should be used at critical areas and covered if necessary. Rubber gaskets from hoppers to skirtboards and on the bottom of skirtboards may be required to reduce splashing or spillage. Where long drops cannot be avoided transfer chutes should have interior impact baffles to dissipate the momentum of falling sludge.

2. Removal of sludge from returning belts: Counter-weighted rubber-bladed scrapers at head pulleys are not effective in scraping sludge off return belts and are a maintenance problem. The use of adjustable tension finger-type scrapers is recommended. To avoid problems with idler roller vibration and irregularities, and to ensure continuous contact, scrapers should be installed beyond the idler on the flattened portion of the belt.

3. Assuring minimum pulley slippage: Appurtenances that contact the dirty side of the belt should be avoided. Figure 14-17 illustrates both the undesirable and the recommended design features of inclined belt conveyors. Snubber pulleys and trippers (devices that remove the moving material from the belt) cannot be successfully used for sludges. Gravity counterweight take-ups should be avoided, and screw take-ups should be used instead. Where long lifts are required, multiple short belts should be used instead of one long belt to avoid the need for gravity take-ups.

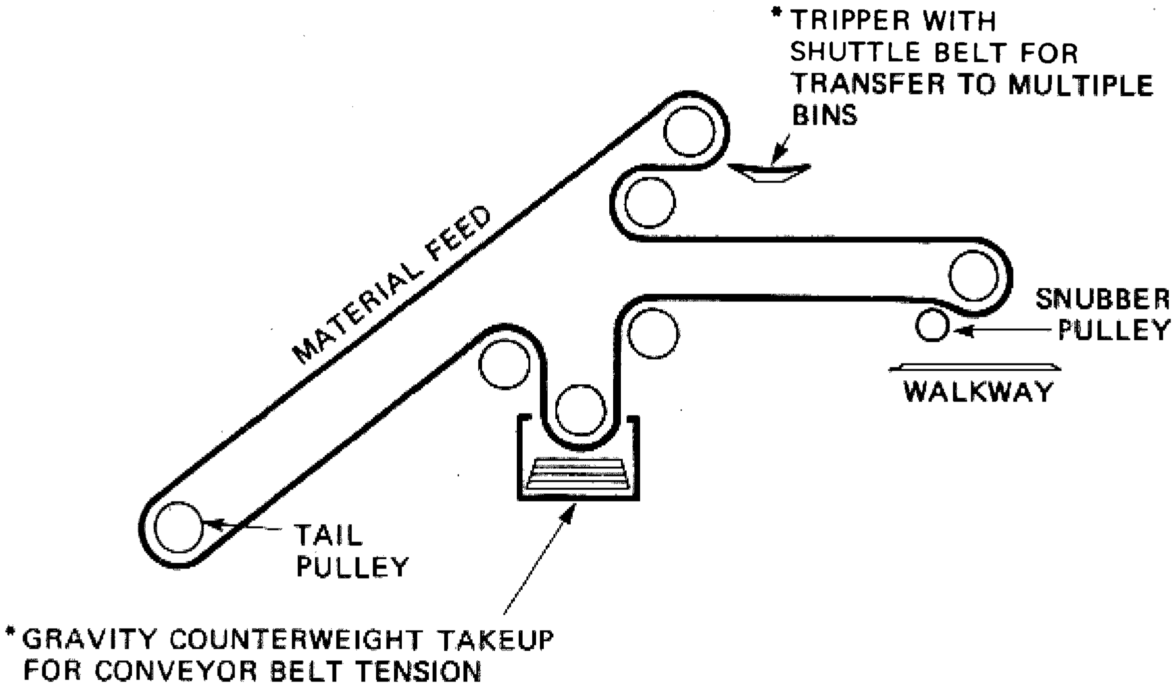
4. Importance of housekeeping facilities: Notwithstanding the care taken to avoid spillage or splashing, sludge handling facilities are dirty, and must be designed to facilitate cleanup. Non-skid cover plates, rather than grating, should be used for all access areas except those immediately over storage hoppers. Convenient hose stations should be located to serve all areas. Floors and slabs should be provided with exaggerated drainage slopes (up to one inch per foot [8 cm/m]) and should drain to liberally distributed drain sumps. Special care should be used at all transfer points, take-up pulleys, and dump points to minimize sludge spillage or splashing, or to provide surroundings that are easily cleaned.

Flexible conveyors are now available in styles with integral pockets, sidewalls and cleats that allow steep, high capacity operations on almost all materials (Figure 14-18). The belts may change inclination at several points in their run. They are best cleaned by a combination brush and spray cleaner. Except for belt pockets, sidewalls, and cleats, their mechanical components are similar to those on troughed belts; maintenance costs for mechanical drives and rollers are also similar.

There are patented flexible conveyors that can not only change inclination but also change direction or even spiral vertically upwards. One unit may replace several straight line belts. These units are not actually belts but segmental chain and sprocket-driven mechanisms with interlocked, pleated rubber trough sections. Drive mechanism wear and corrosion is high in comparison with flat belt conveyors. These conveyors are not recommended where there is sufficient room to allow installation of multiple conventional troughed or pocketed conveyors.

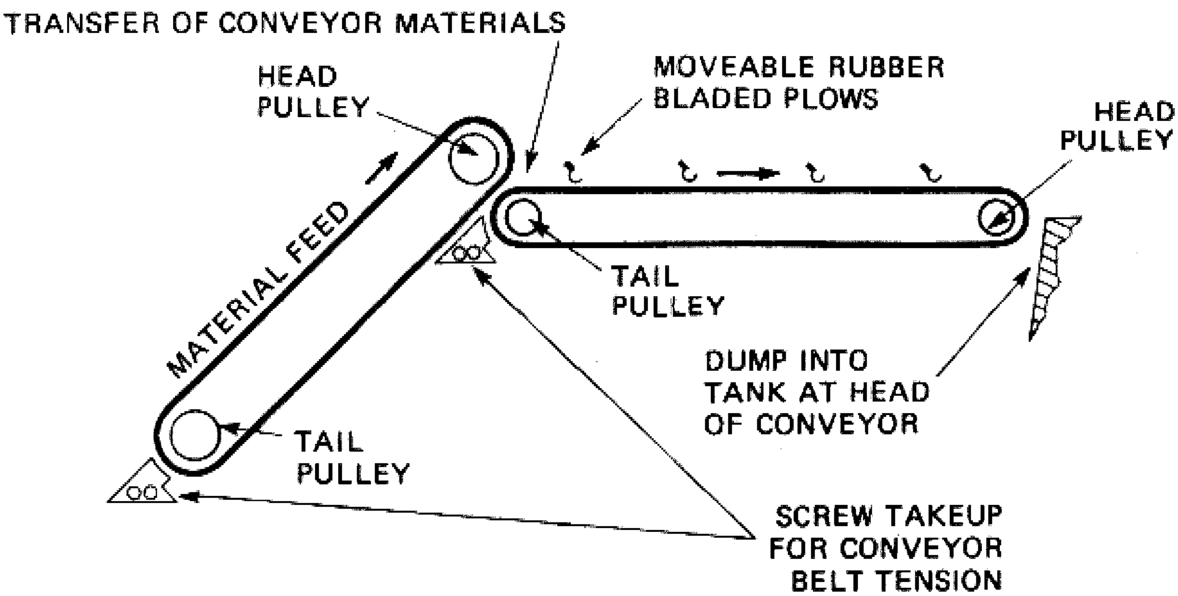
14.2.3 Screw Conveyors

Screw conveyors (Figure 14-19) are silent, reliable, and economical (32). They are used for horizontal movement of grit or sludge, or may be used to convey dewatered sludge up inclines. (The degree of incline depends upon sludge moisture content and consistency). Conservative sizing, abrasion resistant construction materials, and integral wash down systems within enclosed housings are recommended for solids handling facilities. All enclosed housings should have numerous quick opening access plates for maintenance and observation. Screw conveyors for dewatered sludge should not have internal intermediate bearings because sludge can pile up on the bearing and restrict or prevent flow. For this reason, screw conveyor lengths should be limited to 20 feet. Screw conveyors with reversible direction, or with several slide gate controlled discharge openings in the bottom of the conveyor housing, allow the point of conveyor discharge to be changed as appropriate, providing flexibility of operation.



UNDESIRABLE LAYOUT

*NOT RECOMMENDED FOR USE WITH SLUDGE



RECOMMENDED LAYOUT

FIGURE 14-17

INCLINED BELT CONVEYOR FEATURES (31)

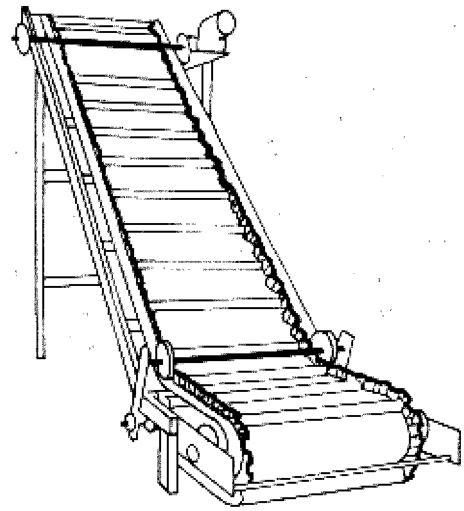


FIGURE 14-18

FLEXIBLE FLAT BELT CONVEYOR

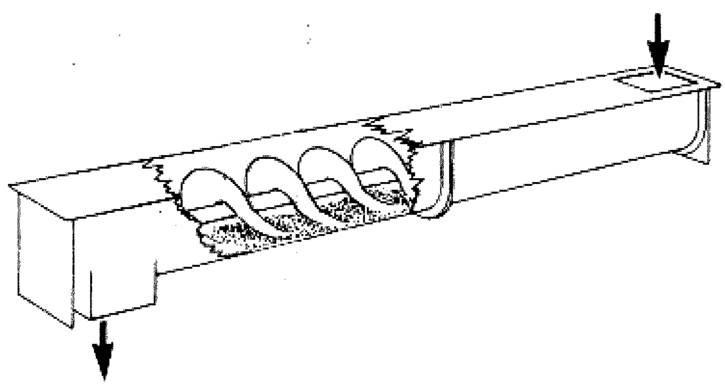


FIGURE 14-19

SCREW CONVEYOR

Screw conveyors have been successfully used for transporting grit but their application to screenings is questionable because rags may become entangled on the conveyor shaft. Oversized objects, such as sticks, can jam the screw or fall out of the conveyor, creating housekeeping problems. To reduce wear, open or ribbon type screw conveyors are sometimes used for grit.

14.2.4 Positive Displacement Type Conveyors

Positive displacement type conveyors include tubular conveyors and bucket elevators. Tubular conveyors (Figure 14-20) are tubular conduits through which circular flights are pulled by chains. They may be used for the horizontal transportation of dry solids such as incinerator ash or semi-dry grit. They are several times as expensive as flat belts per linear foot, but require much less room, are fully enclosed and air tight, and can be routed anywhere a conduit will fit. Maintenance is high. Most plants utilizing these conveyors routinely replace the chain elements at least once per month.

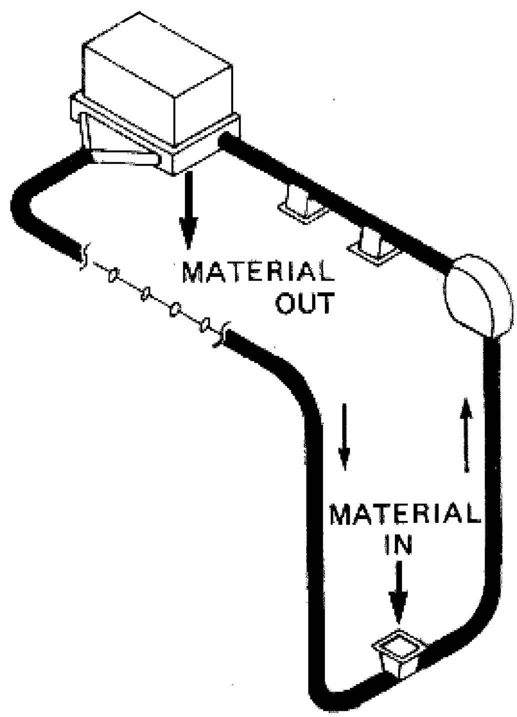


FIGURE 14-20

TUBULAR CONVEYOR

Bucket elevators (Figure 14-21) incorporate chain and sprocket driven buckets in a manner similar to the tubular conveyors except that the chain flights are not in continual contact with the product. As a result, mechanical longevity is greatly increased. They are usually restricted to vertical lifts with limited horizontal displacement.

14.2.5 Pneumatic Conveyors

Pneumatic conveyors are usually not appropriate for dewatered sludge, but can effectively handle screenings, grit, and dry finely divided materials such as incinerator ash. Screenings and grit can be easily transported, even over long distances, through the use of a batch pneumatic ejector system (Figure 14-22). Such pneumatic ejector systems have provided good service for distances up to one-half mile and up to 100 feet of lift. The transport system between the points of loading and discharge is a totally enclosed pipe, which is clean and odor-free and can be easily routed along available passages. The entire system utilizes a minimum of moving parts. Consideration must be given to the use of abrasion resistant materials, especially at pipe bends, and an air pressure system consistent with the distance and lift to be traversed.

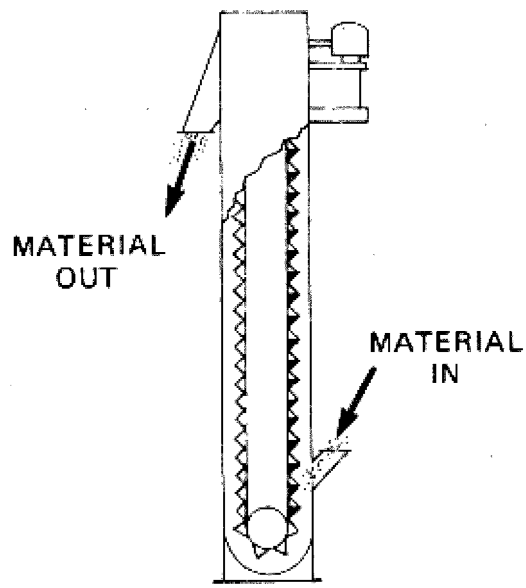


FIGURE 14-21

BUCKET ELEVATOR

Continuous pneumatic conveying systems (Figure 14-23), either pressure or vacuum type, are widely used where dry, particulate materials are to be transported. Their use in sludge transport is limited to materials such as incinerator ash. Where long distances or complex routings are involved pneumatic conveyor systems are especially well suited to ash transport.

Ash is an extremely abrasive material and rotary valves and elbow segments in particular must be carefully specified to provide maximum abrasion resistance. The blowers may require noise shielding.

14.2.6 Chutes and Inclined Planes

Chutes and inclined planes for sludge, screenings, ash, and grit should be tested for minimum inclination on the specific transported product whenever possible. In general, inclinations for dewatered sludge should be greater than 60 degrees from the horizontal. For dry bulk materials, such as ash, the inclinations should at least be greater than the material's natural angle of repose.

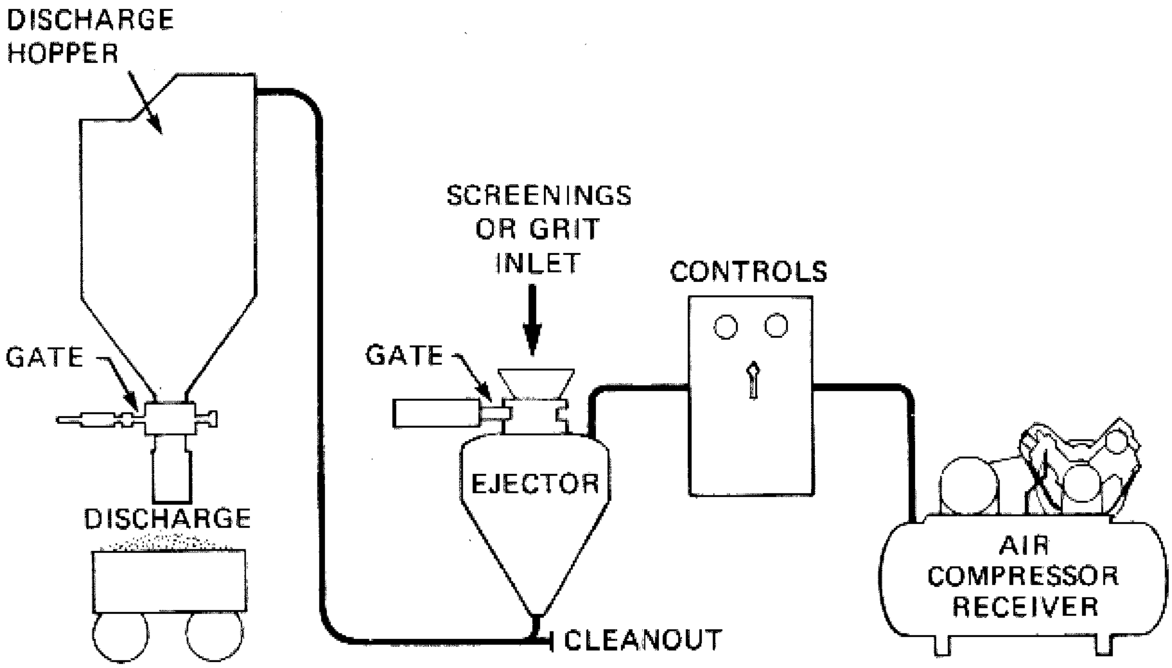


FIGURE 14-22

PNEUMATIC EJECTOR

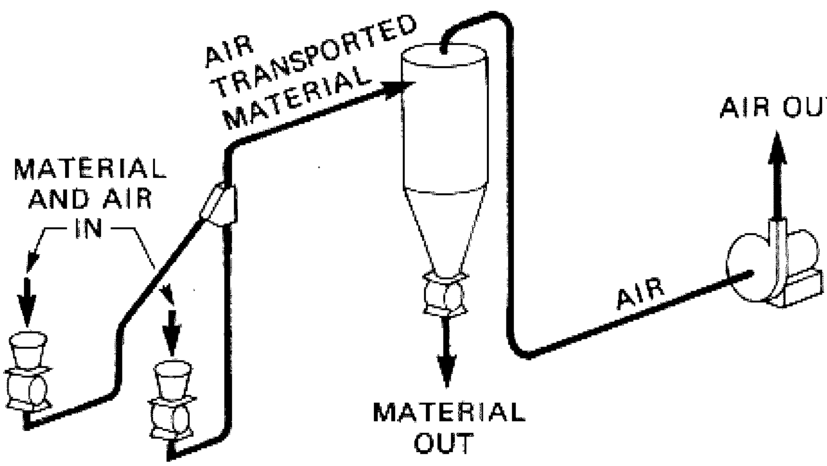


FIGURE 14-23

PNEUMATIC CONVEYOR

14.2.7 Odors

Open sludge conveyance can be a source of odors. All solids transporting facilities should be well ventilated and, if necessary, provided with odor control for the vented air. Even with stabilized sludges, if large holding or equalization tanks are required for the pumping system, floating covers or special odor control facilities for venting tank air should be provided when the detention time is greater than several hours. See Chapter 15 for more detailed information on sludge storage.

14.3 Long Distance Wastewater Solids Hauling

It is often necessary to transport the wastewater solids for long distances, that is, beyond the boundaries of the wastewater treatment plant site. This may be done by pumping if the material is sludge or scum (covered in Section 14.1.6) or by other methods, which shall be termed long distance hauling. For this chapter, long distance hauling is limited to trucking, rail transport, and barging.

Ettlich (28), in developing cost formulas for transport of wastewater sludge, makes the following general observations about the comparative economics of the long distance sludge hauling methods:

1. Transportation of dewatered sludge

    - Total annual cost for railroad is less than truck for all annual sludge volumes (7,500 to 750,000 cu yd [5730 to 573,450 m^3] and distances (20 to 320 miles [32 to 515 km]) studied with and without terminal facilities for loading and unloading sludge to the transport vehicle.

    - Railroad facilities are more capital intensive than truck facilities.

    - Transport equipment can be leased for both truck and railroad transport.

2. Transportation of liquid sludge

    - Truck is the least expensive mode for one way distances of 20 miles (30 km) or less and sludge volumes less than 10 to 15 million gallons (38,000 to 57,000 m^3) per year.

    - Pipeline is the least expensive mode for all cases when the annual sludge volume is greater than approximately 30 to 70 million gallons (110,000 to 260,000 m^3).

- Pipeline is not economically attractive for annual sludge volumes of 10 million gallons (38,000 m^3) or less because of the high capital investment.

- Pipeline is capital intensive and the terminal points are not easily changed. Pipeline is ideal for large volumes of sludge transported between two fixed points.

- Rail and barge are comparable over the 7 to 700 million gallons (30,000 to 2,600,000 m^3) volume range for long haul distances.

- Barge is more economical than rail for short to medium distances for annual sludge volumes greater than 30 million gallons (110,000 m^3).

While much information is available on costs of transporting sludge in specific situations (33, 34, 35, 36) there is a wide disparity in reported costs since there are so many variables in each situation. Consequently it is much more accurate to utilize an approach such as Ettlich's, than to rely upon cost estimates from other treatment plants where conditions may be quite different (28).

14.3.1 Truck Transportation

For most small plants and some large plants, the use of trucks is the best approach. Trucking provides a viable option for transport of both liquid and dewatered sludge. Trucking provides flexibility not found in other modes of transport since terminal points and route can be changed readily at low cost (35). Provided trucks are leased rather than purchased, a truck hauling option is not capital intensive and allows more flexibility than pumping or other transport modes. This flexibility is valuable since locations of reuse or disposal may change.

14.3.1.1 Types of Trucks

Sludge hauling trucks are similar to standard highway trucks because both types of trucks must use public roads and comply with their overall vehicle width, height and gross weight restrictions. Most of the variability can be seen in sludge containment body configuration. For the majority of cases, which involve comparatively short distances with one-way travel times less than one hour, ease and speed of loading and unloading are of paramount importance. The larger trucks are the most economical except for one-way haul distances less than ten miles and annual sludge volumes less than 3,000 cubic yards for dewatered sludge and for less than one million gallons per year for liquid sludge. Generally, diesel engines are used in the larger trucks and are the economical choice for small trucks that are operated at high annual mileage (35).

Where it is determined that economic, environmental, and institutional considerations allow direct land application of liquid digested sludge, special tank trucks are available equipped with specially designed spreaders, auger beaters, and/or special application apparatus. Some manufacturers equip their trucks with subsoil injectors for sub-surface treatment. Use of such dual purpose trucks allows transport and ultimate disposal without an intermediate storage/pumping step. Specialized tanks or trucking equipment can be custom built for specific applications. One company produces flexible tanks designed to fit on a flatbed truck (37).

Spillage or leakage from sludge hauling operations are unacceptable because of aesthetic and health considerations. This has meant a shift away from belly-dump vehicles, even for a very well dewatered sludge cake. There is increased concern for covering the top of the sludge to minimize both odor release during transit and the chance of spillage due to sudden stops or accidents. Consequently, tank-type bodies are gradually becoming the most common, even for mechanically dewatered sludges. These vehicles require unusually large hatch openings for loading purposes, and well designed water-tight hatches or tailgates for unloading. Tanks for liquid sludge transport are of more standard design, but the provision of internal baffles to minimize load shifting is recommended for highway transport.

14.3.1.2 Owned Equipment vs. Contract Hauling

The foregoing concerns apply equally whether or not the wastewater treatment management agency contracts out its sludge hauling or uses its own vehicles. The choice between utilizing agency personnel or contracting for private companies to drive sludge trucks is often decided not on the basis of cost, but on the size of the plant. Smaller plants favor the use of both their own vehicles and staff.

The choice of contract hauling can be limited to the provision of tractor units and driver services, with the trailers owned by the agency. This has two major benefits. First, treatment plant staff, assigned to sludge handling and/or dewatering operations are working in the immediate vicinity of the trailers, and can therefore re-spot the trailers under a conveyor belt at the best times. Second, with most contracts awarded for only one to three year terms, the contractor would otherwise need to figure in his bid price a very rapid amortization of custom trailers, which may be of no further use to him if he is not re-awarded the contract at a later date, even though they may have a useful life far in excess of the contract period. Since it is economically sensible to operate with more trailers than tractor units, trailer cost depreciation can be a significant overall cost factor.

14.3.1.3 Haul Scheduling

A common problem, usually not recognized, is the need to properly schedule trucking operations. In general, the total cost of truck transport will be decreased (per unit of material hauled) if the daily period of truck operation is increased, because capital intensive equipment is better utilized. However, restrictions may be placed on any significant truck operations, such as requiring specific routes or limiting operations to daylight hours (35). Such haul scheduling may require the provision of some form of temporary sludge storage at the plant. See Chapter 15 for sludge storage information. Whenever intermittent operations are possible, however, mechanically dewatered sludge is usually loaded directly from a conveyor belt. Using trucks or trailer bodies as temporary storage may not be the most economical method when drivers' work hours, overtime pay, and the cost of re-spotting trailers under a belt are considered.

In designing sludge handling facilities, it is desirable to provide several dump points with the capability to quickly shift from one to another. If trailers are used, the ability to fill several units before the tractor unit returns adds flexibility to scheduling and reduces storage requirements. If the receiving vessel for dewatered sludge is not self-powered (such as a trailer), consideration should be given to movable dump conveyors to allow the load to be distributed uniformly within the vessel. Dewatered sludge will mound when loaded from a single point. This may prevent effective utilization of the transport vessel.

14.3.1.4 Trucking Costs

When considering sludge trucking, it is worthwhile to remember that pumping equipment can handle digested sludge at least up to 20 percent solids concentration, and to note that the layout and design of loading and unloading facilities can contribute markedly to cost savings. A more detailed breakdown of relative costs associated with truck transportation is available (28).

14.3.2 Rail Transport

Rail transport is suitable for transporting sludges of any solids concentration. It is, however, not a common method of transporting sludge in the United States.

14.3.2.1 Advantages and Disadvantages of Rail Transport

Rail transport has a lower energy cost per unit volume of sludge than pipelining and truck hauling, and once found to be feasible has a right-of-way already established, which is not usually the case with a pipeline. Rail transport can suffer from many of the same problems as pipelines, such as large unrecoverable capital expenditures and fixed terminal points. In addition, it has some of the same problems associated with trucking, such as an ongoing administrative burden, vulnerability to labor disputes and strikes, risk of spills, and because of the labor requirements, an operational cost that will rise continually. However, special circumstances may favor rail hauling. For example, if sludge is to be used to rehabilitate strip-mined lands, a rail line may have been built for hauling out the coal. That line would still be available for the transport of sludge.

14.3.2.2 Routes

The construction of a new railroad line may not be cost-effective or even possible for the sole purpose of transporting wastewater sludge. New construction is normally limited to a short spur from a mainline railroad or the provision and/or expansion of small switching yards on a large treatment plant site in conjunction with chemical delivery facilities. Any attempt at longer new lines is impractical. This limits the overall route selection, generally between the treatment plant site and the final sludge disposal point, to railroad lines already in existence. In turn, this will limit either the selection of rail for sludge transport or severely limit the choice of or subsequent change in disposal site location.

14.3.2.3 Haul Contracts

Railroad cars must be hauled by a railroad company, except possibly for switching. Therefore a contract must be obtained with the railroad. Since this contract hauling is a major cost element, and since the railroad often cannot provide rapid and realistic cost estimates, some time and consideration will be required.

Railroads are a regulated utility; this complicates the rate quotation process. Rates are of two general types: a "class rate" and a "special commodity rate." The class rates are readily obtained, but are usually prohibitively expensive for sludge. To obtain a special commodity rate, the following procedure is necessary:

1. An application is submitted to the railroad, including a complete description of what is to be shipped; how it is to be shipped (type of material, liquid or solid); precisely where it is to be shipped; the frequency of shipping (how much per day, per week); the approximate loading and unloading time; what other types of materials are similar in form, concentration, and makeup to the material being shipped (for example, Code 5630, North Coast Freight Bureau, "tankage"--a commodity used

in production of fertilizers); and a statement of the price the shipper would be willing to pay in cents per 100 pounds net weight (45.4 kg).

2. The local railroad--the carrier--reviews the load, distance, terrain, switching requirements, and competition and calculates a rate.

3. The rate is published by the local freight bureau (for example, for Seattle, Washington, the North Coast Freight Bureau) for a notice period of 30 days for review by other, possibly competing, carriers, and by one of the five regional freight bureaus: Western, Southwest, Central, Southern, or Northeastern. The regional freight bureaus are conglomerations of the local ones and they regulate and control prices between bureau jurisdictions.

4. Comments and appeals of rates can be made to the Interstate Commerce Commission (ICC). An appeal of a proposed rate will cause that rate to be suspended for a seven-month period for the case to be heard by the suspension board of ICC and for the carrier to justify that rate. Historically, appeals have caused proposed rates to be eliminated from the carriers' tariffs. This effectively eliminates the option of rail transport of sludge for this locality.

Generally speaking, railroads are interested in providing sludge transportation. However, many railroads are unfamiliar with sludge hauling; similarly, many environmental engineers are unfamiliar with railroad procedures (38).

14.3.2.4 Railcar Supply

There are three methods of ensuring railcar equipment adequacy: by leasing, by outright purchase, or through placement of the required number of cars in "assigned service" by the carrier under the terms of the haul contract. Generally, an assigned service option is only available for a solid (dry) or semi-solid (mechanically dewatered) sludge which can be transported in hopper cars. A liquid sludge must be carried in tank cars which are not normally available "free" from the railroad. As a generalization, the amortization of the purchase of either type of car (at approximately $90,000 to $120,000 new) will be at considerably higher cost than the rental or lease fee. Consequently, it is expected that the assigned service option would be selected for hopper cars, and a lease arrangement negotiated with a private tank car rental company for tank cars.

Railroad hopper car use is subject to minimum shipment fees per car and certain demurrage criteria. For example, a single hopper car minimum shipment is 180,000 pounds (82,000 kg) and demurrage criteria are that the car must be loaded within 48 hours and unloaded within 24 hours. Reference time is 7 a.m. If a car is delivered between midnight and 8 a.m., the time begins at 7 a.m. the same day. If a car is delivered between 8 a.m. and midnight, the time begins at 7 a.m. the following day. Typical hopper car capacities are 2,600, 3,215, and 4,000 cubic feet (75, 91, and 113 m^3), with the smallest size being typically the most readily available.

Tank cars are normally rented by the month from private tank car rental companies with a minimum five-year commitment. A large non-insulated coiled car (coiled to prevent freezing during the winter months) will rent for approximately $450 per month (1978 prices). Tank car capacities are typically 10,000 to 20,000 gallons (37,850 to 75,700 l). The selection of rail transport, with its high transit times, for more putrescible sludges without special gas venting and control equipment, should be avoided. Typical minimum tank and hopper car requirements are shown in Table 14-8.

TABLE 14-8

TYPICAL MINIMUM TANK CAR REQUIREMENTS (28)

Approximate secondary treatment plant size, MGD	Annual sludge volume, MG	One-way distance, mi	Car loads[a] Per year	Car loads[a] Per day	Cars required[b]
5	7.5	20	375	1	5
		40	375	1	5
		80	375	1	7
		160	375	1	8
		320	375	1	9
10	15	20	750	2	9
		40	750	2	9
		80	750	2	13
		160	750	2	15
		320	750	2	17
50	75	20	3,750	10	47
		40	3,750	10	47
		80	3,750	10	68
		160	3,750	10	78
		320	3,750	10	89
100	150	20	7,500	21	97
		40	7,500	21	97
		80	7,500	21	139
		160	7,500	21	160
		320	7,500	21	181

[a]Car size 20,000 gal (76 m^3).

[b]Estimate assumes that ample storage is available so that extra cars are not required for peak sludge production or scheduling problems.

1 MGD = 0.044 m^3/s
1 MG = 3,785 m^3
1 mi = 1.6 km
1 gal = 3.8 l

The exact calculation of car requirements is very site- and area-specific and should be checked directly for any given situation. It should be recognized that the speed of railroad transport will depend in part on the track conditions and on the railroad's normal traffic schedule; the track conditions may also limit the loads carried per car, and hence the size and number of cars required. As a guide only, typical transit times are shown in Table 14-9.

TABLE 14-9

TYPICAL TRANSIT TIMES FOR RAILROAD TRANSPORTATION

One-way distance, miles	Round-trip transit time,[a] days
20	4
40	4
80	6
160	7
320	8

[a]For estimating rail car demand, an allowance of 25 to 50 percent should be added to accommodate scheduling and car holdup problems. Also, the transit time does not include time for loading and unloading, which must be estimated separately.

14.3.2.5 Ancillary Facilities

Railroad transport of sludge requires loading storage and equipment (tanks, pumps, and piping for liquid sludge and hoppers and conveyors for dewatered sludge), railroad sidings, and unloading equipment. Unloading is ordinarily accomplished by gravity. Car maintenance and storage will be undertaken by the owner of the cars--not normally the wastewater treatment authority--but car cleaning and washdown facilities may be required.

14.3.2.6 Manpower and Energy Requirements

The wastewater authority will have labor requirements for loading and unloading railroad cars and for associated maintenance;

estimates are given in Table 14-10. Data on energy demands associated with railroad transport are not readily available, but energy demands are relatively low compared with other transportation modes. The fuel consumed in transporting the sludge should nevertheless be estimated for inclusion in the sludge management program's energy effectiveness analysis.

TABLE 14-10

MANPOWER REQUIREMENTS FOR RAILROAD TRANSPORT (28)

Liquid sludge			Dewatered sludge		
	Labor, manhours/yr			Labor, manhours/yr	
Annual volume, mil gal	Operation	Maintenance	Annual volume, thousand cu yd	Operation	Maintenance
7.5	4,124	130	7.5	1,650	130
15	4,124	260	15	3,300	260
150	10,500	500	150	4,125	500
750	28,500	1,200	750	10,000	1,200

1 cu yd = 0.76 m^3
1 mil gal = 3,785 m^3

14.3.3 Barge Transportation

Barge transport for the ocean dumping of sludge has been practiced for many decades around the world. Recent decisions to limit ocean dumping, combined with rapidly escalating costs for dewatering or drying sludges, have led to more consideration of barge transport of liquid sludges between the wastewater treatment plant or plants and land disposal sites many miles distant. Barge transportation of sludges is generally only feasible for liquid sludges (to the solids concentration limit at which it may be pumped) and over longer distances, generally over 30 miles. Additional information is available (28,36,39).

14.3.3.1 Routes and Transit Times

It is evident that the key feature in consideration of barge transportation is the proximity to a suitable waterway. However, in planning a barge transport system, the transit time also plays a critical role. The traffic on the waterway; physical features such as drawbridges, locks, and height limitations,and natural characteristics such as currents, tides, and even wave heights will all affect the transit time. Local operators familiar with the waterway should be contacted for information and a conservative safety factor should be applied. Loading and unloading times then must be added to estimate the overall turnaround time--the key feature when contracting for towing service. Towing speeds and cost estimates are given in Table 14-11.

TABLE 14-11

TUG COSTS FOR VARIOUS BARGE CAPACITIES[a]

Barge Capacity, barrels	Average velocity, knots[b]		Tug costs,[c] dollars/hour
	Loaded	Unloaded	
25,000	6	7	120
50,000	7	8	150
100,000	8	10	195

[a]Source: Foss Tug, Seattle, Washington, a division of Dillingham Corporation, various personal interviews with Metropolitan Engineers/Brown and Caldwell staff members, 1975 through 1976.

[b]Velocities in open water. Waterway restrictions reduce average speeds.

[c]Costs are for late 1975 and early 1976. Inflation has been at about 15 percent per annum compounded since 1976.

1 barrel = 159 l
1 knot = 0.51 m/s = 1.85 km/hr

14.3.3.2 Haul or System Contracting

Only for very large plants should ownership of the motive power unit(s) (tug or powered barge) be considered. Self-propelled barges are no longer generally considered cost-effective when initiating a new system, although the specifics of any particular case could modify this conclusion. This means the choice for most wastewater treatment authorities narrows down to contracting for either complete barge transport services or for tug service alone. Full service contracts may prove the best for small operations with intermittent transport requirements. Moderate to large plants will generally favor contract towing only, with the barge(s) owned by the authority (although Chicago's barging system is a full service contract). Contractual agreements should clearly define in detail all services to be provided and include a barging schedule. In certain cases it may be possible for two or more wastewater treatment authorities to join in a common contractual agreement whereby sludge from two or more plants is picked up in tandem by the one haul contractor.

14.3.3.3 Barge Selection and Acquisition

Both the useful life and salvage value of barges tend to be high. This will often lead to a decision to purchase rather than lease equipment. Size and number of barges will depend on plant size and the specific sludge processing system.

Some data on typical barge sizes and costs are given in Table 14-12. Physical dimensions of barges are not standardized, since they are usually custom built within certain dimensions set by some waterway constriction, such as lockage limitations. Lead times on construction are about two years. Barge proportions are commonly length to breadth 4 or 5 to 1, and breadth to depth 3 or 4 to 1. For inland waterways, about two feet (0.6 m) of freeboard under the maximum loaded condition is usually adequate. Barges are very common in the 20,000 to 25,000 barrel (3,200 to 4,000 m^3) capacity range. Construction costs in 1976 were about $6 per cubic foot ($212/m^3) for a 25,000 barrel (4,000 m^3) barge, with only a slight reduction in unit costs as size increases, to about $5.50 per cubic foot ($194/m^3) at the 100,000 barrel (16,000 m^3) size. Greater flexibility in operations will usually dictate the choice of smaller barges, unless distances are about 200 miles (330 km) or more and number of waterway restrictions low. Then the increased speed offered by a larger tug/barge combination will substantially cut transit time and thus reduce towing fees.

TABLE 14-12

TYPICAL BARGE SIZES AND COSTS[a]

Capacity,[b] barrels	Dimensions, ft				Cost,[c] thousand dollars	
	Length	Breadth	Depth	Draft	New[d,e]	Used[f]
14,000	-	-	-	-	-	225
20,000	240	52	15	13.5	1,100	-
23,000	240	60	13.5	-	-	-
27,000	-	-	-	-	-	650
33,000	-	-	-	-	-	625
35,000	286	62	18	16	1,750	-
50,000	320	70	20	18	2,300	-

[a]Examples are for barges custom built for liquid sludges but do not include pumps necessary for unloading.

[b]One barrel equals 42 gallons (159 l).

[c]Costs are for 1976. Inflation in new and used barges has been about 15 percent per annum compounded 1976 through 1979.

[d]Source: L. R. Gloston and Associates, Naval Architects, Seattle, Washington.

[e]Construction costs were approximately 50 cents/lb of steel in the barge ($1.10/kg) in 1976 and are about 80 cents/lb ($1.80/kg) in 1979.

[f]Source: William Drury Company, Seattle, Washington, communication to Metropolitan Engineers/Brown and Caldwell, September 30, 1976.

1 barrel = 0.16 m^3
1 ft = 0.30 m
1 cent/lb = $0.022/kg

14.3.3.4 Ancillary Facilities

A critical factor in determining the feasibility of barging sludge lies in the cost of facilities for loading and offloading, and receiving the sludge. If the treatment plant is not close to the waterway, it may be desirable to locate a sludge storage tank or lagooon near the barge loading dock. For a tank, design would need to be similar to an unheated digester because of continued anaerobic decomposition. Lagoons should be operated as facultative sludge lagoons. In either case, costs of the tank or lagoon should be included in the barge system costs.

In most cases, it is desirable to load and meter the flow from a fixed pumping station located on a fixed wharf. Offloading is often accomplished by a pump mounted on the barge itself. The disposal site should be located near a dock capable of mooring a suitably sized barge. Floating docks are usually more expensive in both marine and freshwater environments than fixed wharfs, due to the complexity of anchoring devices capable of sustaining the loads imposed by a large barge. In certain instances, however, a floating dock may be more acceptable from an environmental standpoint.

Unloading to a land pipeline typically takes about 6 hours. If a tug must remain with the barge during the unloading period, rapid unloading becomes economically important.

14.3.3.5 Spill Prevention and Cleanup

One important element of a barge transportation system is a well developed spill prevention and cleanup program. Spills resulting from accidents during transport can result in serious water pollution and associated health problems. Sludge spills should be contained immediately and transferred to storage tanks or another barge as quickly as possible to reduce risks. The risk of spills during loading and unloading can be minimized by careful attention to design and operator training.

14.4 References

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PROCESS DESIGN MANUAL FOR SLUDGE TREATMENT AND DISPOSAL

Chapter 15. Storage

U.S. ENVIRONMENTAL PROTECTION AGENCY

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CHAPTER 15

STORAGE

15.1 Introduction

Storage is an integral part of every wastewater solids treatment and disposal system, since it is necessary to the assurance that the system will be used to full capacity. Recent emphasis on the control of wastewater solids treatment and disposal mandates that effective storage be provided. Storage that is compatible with the objectives of a system must be incorporated into its design to enhance both the system's reliability and its efficiency.

15.1.1 Need for Storage

Storage allows different processes to operate on schedules which best fit overall system objectives and precludes the need to force all processes to operate on the same schedule. For example, solids are generated from the wastewater treatment system 24 hours per day, but it may be most convenient to operate the solids processing system only on the day shift. Solids must therefore be stored during off-hours. Storage must also be provided between adjacent treatment or disposal processes which operate at different rates--for example, between centrifuges (which discharge solids at 100 tons per hour [91 t/hr]) and incinerators (which must be fed at 50 tons per hour [45 t/hr]). In addition, it must be provided upstream from virtually any land disposal system, since sludge can usually be applied to land only part of the year, whereas the waste treatment plant generates solids all year around.

15.1.2 Risks and Benefits of Solids Storage Within Wastewater Treatment System

Stored solids can be washed from the wastewater treatment system, thereby degrading effluent quality. They may also become septic, with the same effect. As a general rule, solids should not be stored in wastewater treatment systems unless storage provides benefits that clearly outweigh the risks involved. For many small plants, if sludge processing units are operated only on the day shift, the benefits do outweigh the risks. These plants frequently store solids within the wastewater treatment process for periods as long as 24 hours. Large plants, which typically process sludge around-the-clock, make less frequent use of storage within the wastewater treatment system. The main exception to this rule is the storage of solids within wastewater stabilization ponds, where solids and dead algae settle to the bottom of the ponds and anaerobically decompose. These solids are seldom removed and often accumulate for many years with no deleterious effect.

15.1.3 Storage Within Wastewater Sludge Treatment Processes

Solids can be stored within sludge treatment processes with fewer adverse effects than if they were stored within the wastewater treatment system. Whereas the processes of disinfection, conditioning, mechanical dewatering, high-temperature conversion, and heat-drying do not provide storage, those of gravity thickening, anaerobic and aerobic digestion, air drying, and composting do. Used judiciously, these processes can store enough solids to enable necessary adjustments to be made in rates of flow between processes. One or two of these processes can provide cost-effective storage for periods exceeding one month. However, because of process limitations, some cannot provide storage for minimum periods of three to four days even though they can store for periods of three to four weeks and longer.

15.1.4 Effects of Storage on Wastewater Solids

If wastewater solids are to be stored for any extended period of time, they must be stable. Stable liquid sludge with less than ten percent solids can be stored in facultative sludge lagoons, anaerobic sludge lagoons, or aerated basins. When it is air dried to greater than 30 to 40 percent solids, stable sludge can be stored safely and without odors in relatively small, confined structures or in unconfined stockpiles. It is impractical to store unstabilized dewatered or partially dried sludge (sludge containing more than 10 percent and less than 30 percent solids) for much longer than three to four days because septic conditions and problems associated with septicity (odors, poor solids transport properties) can develop.

Wastewater solids are usually stored in concentrated form. If these solids are biodegradable, indigenous oxygen supplies can rapidly be depleted and anaerobic decomposition begins. Anaerobic decomposition is often, but not always ,accompanied by the production of undesirable odors. However, anaerobic decomposition will not occur if:

- Biodegradable materials present are insufficient to support biological activity. For example, screenings and grit are relatively non-odorous, provided they have been processed and transported hydraulically prior to final dewaterings. The washing action which occurs during these operations reduces the concentration of putrescible organic material. Conversely, if processed and transported mechanically (that is, without washing), they may be the source of strong odors when subsequently stored.

- Oxidizing conditions can be maintained. Agents such as oxygen, chlorine, and hydrogen peroxide can be used to this end if the sludge is in liquid form. Forced aeration or physical manipulation can be used to maintain the aerobic condition if solids are dewatered and managed, as is done in composting.

- Moisture is reduced to discourage biological activity. For example, air dried stabilized sludge with a solids content greater than 40 to 50 percent and unstabilized heat-dried sludges can be stored indefinitely without nuisance, provided rewetting does not occur.

- pH is adjusted to values above approximately 12 and below approximately 4 by adding chemicals like lime or chlorine. Note that pH extremes must be maintained. These treatments do not destroy putrescible materials, and the biocidal effects caused by extreme pH are lost as the pH drifts toward neutral values as the result of interaction with atmospheric carbon dioxide.

The fact that anaerobic digesters and facultative sludge lagoons have operated without nuisance odors clearly indicates that storage can be accomplished under anaerobic conditions without adverse effects. Work on facultative sludge lagoons in Sacramento documents these conclusions (1).

Nuisance odors will not develop in anaerobic storage when sufficient methane bacteria are present. If the methane bacteria are destroyed, however, serious odor problems may result. As an example, consider anaerobically digested sludge which is placed on a drying bed or in a drying lagoon. The top layer of sludge is dewatered, and methane bacteria die as the sludge aerates and dries. Odor levels are extremely low, since the sludge is too dry to support anaerobic biological activity. Should the surface of the sludge be re-wetted (for example, by rainfall or surface flooding), however, anaerobic activity would resume, the organic acid concentration would rapidly increase, and odors would increase to nuisance levels. Odor problems experienced with approximately 580 acres (235 ha) of drying lagoons at San Jose, California, immediately following a rainstorm, is an example of this type of problem (2).

Not all the effects of solids storage are negative. Storage of anaerobically digested sludge in the liquid state can be beneficial for its ultimate disposal. If such sludge is stored for several years without being contaminated by freshly digested sludge, its organics content (40 to 50 percent) and its content of pathogenic bacteria, viruses, and parasites will be greatly reduced (1,3).

15.1.5 Types of Storage

Wastewater solids may be stored in facilities within the treatment system, within the sludge treatment and disposal system, and within tanks, lagoons, bins, or stockpiles provided primarily for storage. This latter group is divided into two divisions, those provided for either liquid or dewatered sludge. The use of wastewater and sludge treatment facilities for solids storage must not adversely affect their treatment capability. If this potential exists, then facilities dedicated primarily to storage must be provided.

Three methods of storage are described as follows:

- Single-Phase Concentration. Solids accumulate in a completely-mixed vessel as a result of increasing concentration. The solids concentration is uniform throughout and vessel volume is constant. For example, solids buildup within the aeration reactor of an activated sludge system if solids are not wasted.

- Two-Phase Concentration. Storage is within the solids layer of a liquid/solids separation device. Volume of the solids layer increases; however, total system volume remains constant. For example, solids are accumulated in a gravity thickener by terminating sludge withdrawal from the thickener and allowing the sludge blanket to build up.

- Displacement. Solids are stored as a result of changing total system volume. For example, solids can accumulate within digesters with floating covers by displacement storage, since the covers can rise to accommodate greater volumes of sludge.

Storage may be accomplished by two or three methods operating in concert. For example, solids can accumulate in a floating cover equipped secondary digester by simultaneous two-phase concentration and displacement.

Storage may be further categorized as follows by detention time:

- Equalization Storage — Solids detention time should not exceed three to four days.

- Short-Term Storage — Solids detention time should not exceed three to four weeks.

- <u>Long-Term Storage</u> Solids detention time is greater than one month.

Table 15-1 lists wastewater solids storage by type, facility, method, and detention time category.

TABLE 15-1

WASTEWATER SOLIDS STORAGE APPLICABILITY

Type	Method	Detention time: Equalizing (3 to 4 days)	Detention time: Short term (3-4 weeks)	Detention time: Long term (Greater than 1 month)	Comments
Storage within wastewater treatment processes					Use of wastewater treatment processes for storage must not adversely affect treatment efficiency.
Grit removal	Two-phase concentration	X	X	-	Storage time depends on sewer system grit loading to plant.
Primary sedimentation	Two-phase concentration	X	-	-	Temperature sensitive. Storage for over 24 hours.
Aeration reactors	Single-phase concentration	X	X	-	Storage within extended aeration systems, for example, oxidation ditches, can exceed 3 weeks if accomplished in conjunction with secondary sedimentation concentration.
Secondary sedimentation	Two-phase concentration	X	-	-	Highly temperature sensitive. Storage for over 8 hours requires chemicals.
Imhoff tanks	Two-phase concentration	-	X	X	Lightly loaded systems can store for over 6 months. Most systems will require solids removal every 4 to 6 weeks.
Community septic tanks	Two-phase concentration	-	-	X	Sludge from many septic tanks is removed only once in several years.
Wastewater stabilization ponds	Single and two-phase concentration	-	-	X	Aerated ponds operate like aeration reactors. Other ponds use two-phase concentration and can store solids for many years.
Storage within sludge treatment processes					Use of sludge treatment processes for storage must not adversely affect sludge treatment efficiency.
Gravity thickeners	Two-phase concentration	X	-	-	Temperature sensitive. Usually not used with WAS. Storage for over 24 hours requires chemicals.
Anaerobic digesters	Single and two-phase concentration and displacement	X	X	-	Floating covers allow for displacement storage. Two-phase concentration storage impracticable if WAS present. Single-phase concentration storage possible if digesters operated in conjunction with primary sedimentation concentration changes.

15.2 Wastewater Treatment Storage

Influent variability and fixed effluent requirements make operational flexibility a necessity for every wastewater treatment plant. One of the most cost-effective means of providing flexibility for small plants is to assure that treatment processes contain storage within themselves.

15.2.1 Storage Within Wastewater Treatment Processes

Listed in Table 15-1 are several wastewater treatment processes that can provide solids storage. The following sections describe ways in which this storage can be used effectively.

TABLE 15-1

WASTEWATER SOLIDS STORAGE APPLICABILITY (Continued)

Type	Method	Detention time: Equalizing (3 to 4 days)	Short term (3-4 weeks)	Long term (Greater than 1 month)	Comments
Storage within sludge treatment processes (continued)					
Aerobic digesters	Single and two-phase concentration and displacement	X	X	-	Decanting can be limiting. Short-term storage possible if digesters operated in conjunction with sedimentation concentration. Displacement storage requires aeration systems which will operate with variable level.
Composting	Two-phase concentration and displacement	-	X	X	Evaporation with process accomplishes two-phase concentration. Processed solids not removable for 3 to 4 weeks.
Drying beds	Two-phase concentration and displacement	-	X	X	Initial settling accomplishes two-phase concentration. Processed solids not normally removable for 3 to 4 weeks.
Facilities provided primarily for storage of liquid sludge					
Holding tanks	Single and two-phase concentration and displacement	X	-		Storage limited to equalizing by high costs of detention and continuous mixing.
Facultative sludge lagoons	Two-phase concentration	-	X	X	Time required for initial settling limits storage to short or long term. Mechanics of sludge removal makes short-term storage very expensive. Odor free operation requires anaerobically digested solids. Organic loadings must be restricted and surface agitation provided. Odor mitigation required when surface area exceeds 30 to 40 acres.
Anaerobic liquid sludge lagoons	Two-phase concentration	-	X	X	Time required for initial settling limits storage to short or long term. Mechanics of sludge removal makes short-term storage very expensive. Odor minimization requires anaerobic digested solids. Usually operated without organic loading restriction. No surface agitation provided. Potential odor risk high, although no quantifying data available.

15.2.1.1 Grit Removal

Grit removal basins and channels may be used to store unusually heavy grit loadings which, when combined sewer systems are involved, generally arrive at the treatment plant after a dry spell and during the first flush of a storm. Storage must be provided to contain all of the grit which could accumulate during the storm. The required storage volume is a function of grit loading and the rate at which the grit can be transferred out of the basin or channel. Where grit is transferred manually (for example, in small plants with duplicate channels), the designer may wish to provide storage sufficient to hold grit during periods when the plant may be unattended (long weekends). Grit production figures are shown in Chapter 4.

TABLE 15-1

WASTEWATER SOLIDS STORAGE APPLICABILITY (Continued)

Type	Method	Detention time: Equalizing (3 to 4 days)	Short term (3-4 weeks)	Long term (Greater than 1 month)	Comments
Facilities provided primarily for storage of liquid sludge (continued)					
Aerated storage	Single and two-phase concentration and displacement	X	X	-	High energy demand usually restricts detention time. Same limits as aerobic digesters.
Facilities provided primarily for storage of dewatered sludge					
Sludge drying lagoons	Two-phase concentration and displacement	-	-	X	Initial settling accomplishes two-phase concentration. Process solids not normally removable for one to two months. Odor minimization requires anaerobically digested solids. Can be odorous if aerobically stabilized surface layers begin to decompose anaerobically when rewetted.
Confined hoppers or bins	Displacement	X	X	-	Moist (15 to 30 percent solids) dewatered sludge can present major material management and odor production problems if storage time exceeds 3 to 4 days. Structures usually too expensive for long-term storage. Short-term storage can be successful with dry (greater than 30 to 40 percent solids) stabilized sludges.
Unconfined stockpiles	Displacement	X	X	X	Requires stabilized dry (greater than 30 to 40 percent solids) sludge. Stockpiles are usually covered in very wet climates. Natural freeze drying is possible.

Special techniques or equipment may be needed to transfer heavy grit accumulations. If grit is transferred mechanically (by flight, bucket, and screw conveyors), the equipment must be able to start while the entire basin or channel is filled with grit. If grit is transferred hydraulically, air agitation should be used to loosen up the accumulated solids during the removal operation. Hydraulic removal can be accomplished by eductors, air-lift pumps, or special centrifugal pumps. When special centrifugal (torque-flow or vortex) pumps are used, the grit should be loosened up in the immediate vicinity of the pump suction by a high-velocity water jet. More design information on grit removal facilities is available (4,5).

15.2.1.2 Primary Sedimentation

If storage is provided in primary sedimentation, solids processing systems can operate at rates independent of the rate at which solids are removed from the wastewater. This is especially useful for small plants which are not manned continuously and for any size plant that experiences large diurnal or seasonal fluctuations in settleable solids.

Concentration of sludge removed from the primary sedimentation tank may be controlled to some degree if the depth of the sludge layer in the sludge removal hoppers is controlled. Hopper sides should be sloped at least 60 degrees off the horizontal so that solids can flow by gravity to the pump suction. Primary sedimentation tank storage capacity should be sufficient to allow suitably sized primary sludge pumps to remove the peak sludge loadings. Otherwise the solids may interfere with the gathering function of the longitudinal sludge collectors in rectangular tanks or the main collector in circular clarifiers.

Efficient use of primary sedimentation storage requires the use of a control timer, density, and blanket level instrumentation. Ideally, all three devices can control primary sludge pump operations. Blanket level sets the time when the pump starts; control timers set the cyclical period when the pumps can share the discharge piping (if necessary) and the minimum pump operating period if the density of the pumped sludge is below the required concentration; and density sets the time when the pump shuts down. Chapter 17 provides more information on this instrumentation.

More design information on primary sedimentation tank design is available (4,5).

Design Example

The designer of a 7.5-MGD (0.33-m^3/s) average design flow wastewater treatment plant wishes to determine the available sludge storage volume in three rectangular primary sedimentation tanks, the tanks are designed to treat a peak wet weather flow of 20 MGD (0.88 m^3/s). Available storage will determine the maximum time allowed between sludge pumping cycles and the maximum capacity of the sludge pumps.

Tank design is based on conservative experience involving overflow rates and mean velocities at average design flows. Each tank is 110 feet (33.5 m) long and 19 feet (5.8 m) wide, with an average sidewater depth of ten feet (3.05 m). Longitudinal collectors operating continuously bring the settled sludge to the head end of the tank, where it is conveyed to the sludge removal hopper by cross-collectors. The sludge is then pumped from the removal hopper on a timed cycle with density and blanket level instrumentation. Cross collection channels and sludge removal hoppers have been laid out to aid in the concentration, storage, and removal of the collected sludge by providing steep side slopes, ample depths, and short suction pipelines. Combined storage volume of the cross collector channel and removal hopper of the selected tank design is approximately 350 cubic feet (9.9 m^3) for each tank.

It is assumed that peak and wet weather flows will be of at least eight hours duration and will have an average suspended solids content of 200 mg/l. Primary sedimentation tank removal efficiency is assumed to be only 50 percent at peak wet weather flow, down from 60 percent at average design flow, because of higher overflow rate and higher mean velocity. Using these assumptions, the solids collected in each primary sedimentation tank during the storm can be calculated as follows:

$$\frac{(20 \text{ MGD})\ (200 \text{ mg/l})\ (0.50)\ (8.33 \text{ lb/gal})}{(3 \text{ tanks})\ (24 \text{ hr/day})} = 231 \text{ lb/hr} (105 \text{ kg/hr})$$

Primary sludge solids concentration and wet bulk specific gravity are assumed to be six percent and 1.07, respectively. Using these assumptions, the volume produced in each tank can be calculated as follows:

$$\frac{231 \text{ lbs/hr}}{(0.06)\ (1.07)\ (62.4 \text{ lbs/ft}^3)} = 58 \text{ ft}^3\text{/hr } (1.6 \text{ m}^3\text{/hr})$$

By dividing this production into the storage volume available, the designer finds the maximum period of time between pump cycles to be slightly greater than six hours.

The primary sludge piping to the digester is arranged so that only one primary sludge pump can operate at a time. To assure sufficient pumping capacity to handle the peak wet weather sludge, it is necessary that each pump operate only one-third of the time. Each pump, therefore, must have the capacity to remove all of the sludge stored during the six-hour cycle in two hours. This capacity is calculated as follows:

$$\frac{(231 \text{ lbs/hr})\ (6 \text{ hr/2hr})}{(0.06)\ (8.92 \text{ lb/gal})\ (60 \text{ min/hr})} = 21.6 \text{ gpm } (1.36 \text{ l/s})$$

As an additional safety factor, to assure maximum reliability and operational flexibility, this pumping rate is doubled and rounded off to 50 gallons per minute (3.2 l/s). The pump selected (a diaphragm pump, see Chapter 14) can be adjusted down to 25 gpm (1.6 l/s) if higher flow rates are found to pull liquid instead of concentrating solids.

15.2.1.3 Aeration Reactors and Secondary Sedimentation

Solids are stored in aeration reactors and secondary sedimentation tanks whenever there is an increase in the solids concentration of the mixed liquor. This solids increase requires the two processes to be operated as one, with the sedimentation tank providing the two-phase concentration necessary to fully utilize the single-phase concentration storage capabilities of the reactors. Reactors should be designed with the flexibility to operate either in the plug flow, step feed, reaeration or contact stabilization modes or any combination of these. Given a fixed reactor size, maximum solids storage capability is provided when the process operates in a combination of the reaeration and contact stabilization modes. Often the ability to switch between complete plug flow and partial reaeration modes allows the solids to be removed from the hydraulic flow stream and prevents their loss when that stream receives a shock loading. Operation in the step feed mode also minimizes the solid loading rates to the secondary sedimentation tanks. This solids storage flexibility should be provided regardless of whether the source of aeration comes from dissolved air or pure oxygen. Plug flow nitrifying aeration systems, which are often required to retain solids for two to three weeks, operate at maximum efficiency when the hydraulic and organic loadings have the least diurnal fluctuation. This uniformity is often achieved in smaller plants through upstream flow equalization. Oxidation ditches are a simple type of aeration reactor found in many small treatment plants. More design information on aeration reactors and flow equalization is available (4-8).

Secondary sedimentation tank two-phase concentration storage is vital to the successful operation of an aeration system. Design of secondary sedimentation facilities usually involves the use of the solids flux theory, which is discussed briefly in Chapter 5 and in detail in references 9 and 10. To take maximum advantage of the concentration capabilities, secondary sedimentation tanks are usually from 150 to 200 percent deeper than primary sedimentation tanks (14 to 20 feet [4.3 to 6.1 m]). Blanket level instrumentation is commonly used to keep track of sludge storage levels within the secondary sedimentation tanks. Instrumentation for this determination is discussed in Chapter 17. More design information on secondary sedimentation tanks is available (4,5,7).

15.2.1.4 Imhoff and Community Septic Tanks

Both the Imhoff and the community septic tank were in use long before most of the sludge treatment processes discussed in this manual. For this reason, it is not surprising that their design includes significant sludge storage capabilities. Imhoff tanks are still in use in many of the older treatment plants, and therefore, still provide those plants with extensive solids storage capacity in what are essentially unheated low rate anaerobic digesters (see Chapter 6). The storage capacity of Imhoff and septic tanks is part of the empirical design criteria for these facilities. While their future use may be limited because of today's secondary treatment mandate, both processes offer low cost primary treatment for upgrading small community wastewater stabilization pond facilities. In Newman, California, existing community septic tanks are being upgraded to provide primary treatment for a 0.76-MGD (33.3-l/s) complete treatment plant with pond stabilization for secondary treatment and overland flow for tertiary treatment (11). More information on Imhoff and community septic tank design is available (4,12,13).

15.2.1.5 Wastewater Stabilization Ponds

Wastewater stabilization ponds are cost-effective because of their ability to store solids. Pure aerobic wastewater stabilization ponds provide only single-phase concentration type storage, whereas the more commonly used anaerobic and facultative ponds, can provide for long-term, two-phase concentration type storage of removed settleable and created biological solids. When debris is thoroughly removed from their influent, secondary facultative ponds can store most of the wastewater solids from a large secondary treatment plant for many years. In Sunnyvale, California, secondary treatment facultative stabilization ponds covering 425 acres (172 ha) have been receiving the majority of sewage solids from a 15-MGD (657-l/s) plant for the past ten years with no ill effects. Sunnyvale's tertiary treatment facilities for algae and nitrogen removal return all solids removed by dissolved air flotation and gravity filtration to the ponds (13). Primary sludge is removed from the plant before the primary effluent is discharged into the pond and anaerobically stabilized in complete-mix digesters. Supernatant from these digesters is discharged daily into the plant's influent. Most of the solids eventually find their way to the facultative pond. Bottom sludge is withdrawn every week or ten days from the complete-mix digesters and discharged to anaerobic sludge lagoons. The primary sedimentation effluent, and the uncaptured and unrecycled contents of the supernatant merge with the anaerobic bottom layers in the secondary treatment facultative stabilization ponds.

Primary wastewater (usually anaerobic stabilization) ponds that receive raw sewage must be drained and cleaned approximately every five to ten years, depending on loadings. Secondary wastewater (usually facultative stabilization) ponds that are sufficiently deep (6 to 8 feet [1.8 - 2.4 m]) and that receive only those solids generated by biological activity probably never require cleaning. More design information on wastewater stabilization ponds is available (14).

15.2.2 Storage Within Wastewater Sludge Treatment Processes

Table 15-1 lists wastewater sludge treatment processes that provide some degree of solids storage. The following paragraphs discuss how much of this storage capability can be used and how its use can be made as effective as possible.

15.2.2.1 Gravity Thickeners

Gravity thickeners separate liquid from primary and fixed-growth biological secondary solids. In this sense, they function like primary and secondary sedimentation facilities. Cool temperatures and chemicals which retard septicity enable gravity thickeners to store sludge for several days. Equipment precautions recommended for primary sedimentation facilities apply to gravity thickeners. Using the same type of calculation indicated in the primary sedimentation design examples, storage capacity can be increased by providing extra depth. For more design information on gravity thickeners see Chapter 5.

15.2.2.2 Anaerobic Digesters

Anaerobic digesters provide all three types of storage. Those with floating covers have the flexibility to store about 20 to 25 percent of the digester's volume. The cover movement is used to provide displacement storage. Fixed cover digesters must be protected from excessive vacuum or pressure conditions whenever an attempt is made to achieve displacement storage.

Secondary digesters can be used for two-phase concentration storage by means of liquid-solids separation as long as they are not treating stabilized biological suspended growth (waste-activated) secondary sludge. Biological fixed growth secondary sludge normally does not use secondary digester, two-phase concentration storage. More and more treatment plants are finding that the stabilization of waste-activated sludge has a major impact on digester operation. Without waste-activated sludge, the liquid-solids separation process in secondary digesters can concentrate and store solids for considerable periods of time. These time periods usually equal the time required to fill the secondary digester at design flow rates and, depending on the quality of acceptable supernatant, can often be extended.

All digesters can be used to provide equalization storage. Digesters may be used to equalize peak loadings and thereby make downstream dewatering more cost-effective as the following example illustrates.

<u>Design Example</u>

This example illustrates how the digester storage can be used to "damp-out" solids surges and thus prevent overloading of downstream dewatering units.

Consider a primary wastewater treatment plant with the flow scheme and average loads depicted on Figure 15-1. Average loading to the dewatering units is 103,313 pounds per day (46,904 kg/d). Dewatering unit capacity is 200,000 pounds

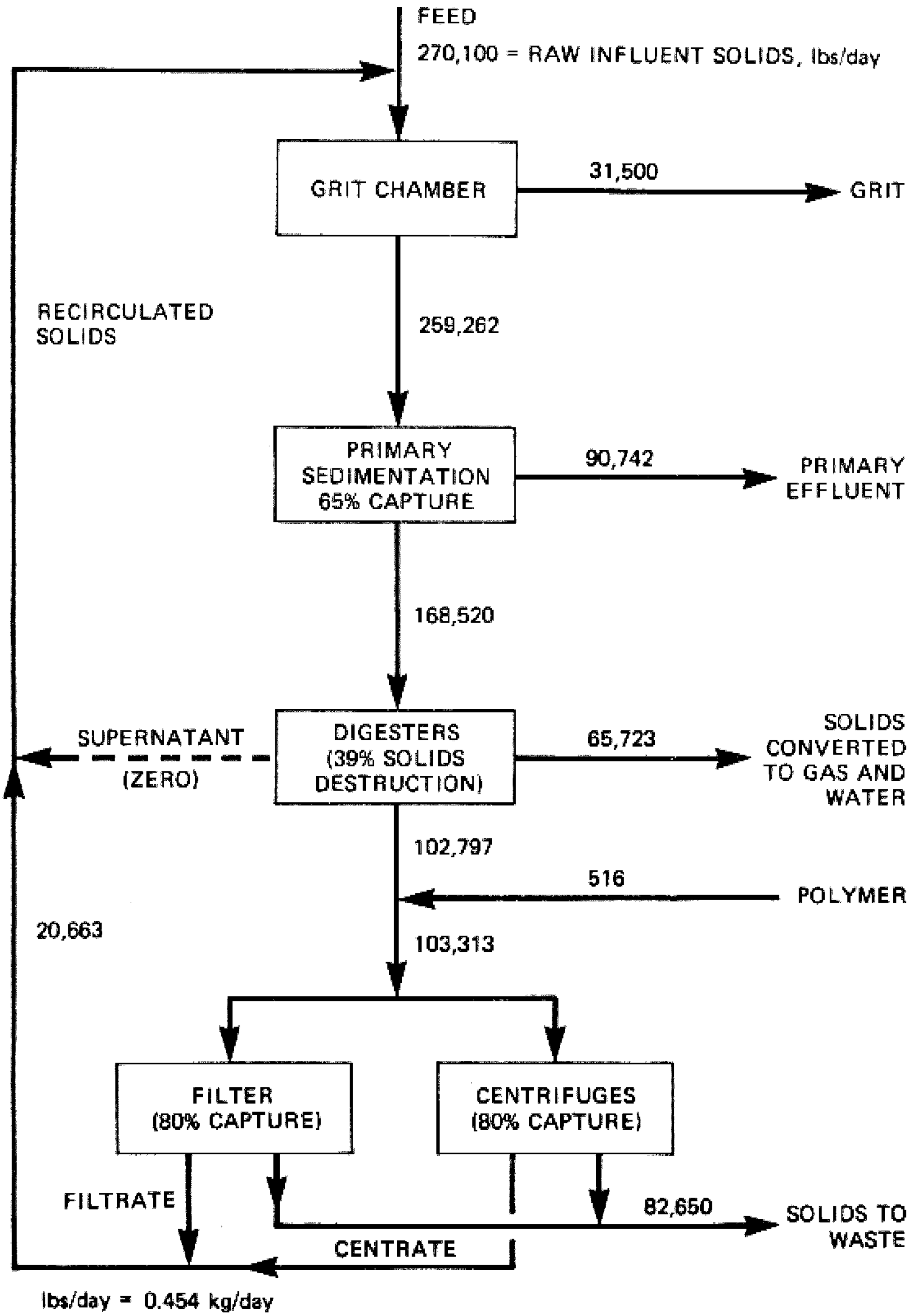

FIGURE 15-1

SOLIDS BALANCE AND FLOW DIAGRAM-DESIGN EXAMPLE
SINGLE-PHASE CONCENTRATION AND DISPLACEMENT STORAGE

per day (90,800 kg/d); under average loading conditions, the dewatering units are clearly not stressed. The treatment plant, however, receives flow from a combined sanitary/storm sewer network. During storms, hydraulic loadings increase dramatically as a result of infiltration and inflow to the sewer system. Plant solids loadings also increase sharply as the result of solids being carried into the sewer by run-off and the scouring of previously accumulated materials from the sewer system.

From historical records, the peak 5-day solids loading (average load for the most heavily loaded five consecutive days) is 433,000 pounds per day (196,582 kg/d). This is 2.57 times greater than the average digester load. If the storage available upstream of the dewatering units is not utilized, dewatering unit loading would also be 2.57 times the average value or 265,000 pounds per day (120,310 kg/d). The dewatering units would therefore be overloaded. Overload can be prevented, however, if digester storage is properly utilized. Solids can be stored within the digester so that, during peak loading periods, dewatering capacity is not exceeded. The accumulated solids can be released after the storm has passed and the dewatering units are no longer stressed.

Solids may be stored in the digesters by either of two mechanisms, acting either singly or in concert.

- The digester working volume is increased by allowing the floating covers to rise (displacement storage).

- The digester feed is thickened to a greater degree than previously. As a result, the solids concentration of the digested material increases (single-phase concentration).

The following analysis examines how one of several possible operating strategies can be implemented. It is assumed that the system is at average conditions (see Figure 15-1) when a large storm occurs and for the next five days average digester loadings increase to 433,000 pounds per day (196,582 kg/d). At the onset of the storm, the plant operator decides to ease a potentially serious dewatering overload situation by (1) allowing the floating covers to rise at the rate of one foot per day (0.305 m/d) and (2) by thickening the raw sludge withdrawn from the primary sedimentation basin from the normal five percent concentration to seven percent concentration. The additional thickening is accomplished by allowing sludge to accumulate to greater depths in the primary sedimentation tanks cross-collection trough and sludge hoppers. The intent of these two operations is to maintain digested solids mass flow rates below 200,000 pounds per day (90,800 kd/d) to prevent dewatering unit overload.

The effects of these operations can be estimated from an unsteady state analysis of digester operations. The basic predictive equation is derived by an unsteady state mass balance:

1. Solids in - solids out - solids destroyed = solids accumulated.

   a. Solids in = QC_i

   b. Solids out = $(Q-k)C$

   c. Solids destroyed = $QC_i\ X$

   d. Solids accumulated = $\frac{d(VC)}{dt}$

   Where:

   Q = digester feed rate, volume per time;

   C_i = digester feed solids concentration, mass per volume;

   C = digester sludge solids concentration, mass per volume;

   k = rate of liquid accumulation in the digesters due to rise of floating covers, volume per time;

   X = fraction of digester feed destroyed by digestion, dimensionless;

   V = digester liquid volume;

   t = time.

2. Summing the terms:

$$QC_i - (Q-k)C - QC_iX = \frac{d(VC)}{dt}$$

3. The right-hand side of the above equation can be further developed:

$$\frac{d(VC)}{dt} = V\frac{dc}{dt} + C\frac{dV}{dt} = V\frac{dc}{dt} + Ck$$

4. Simplifying:

$$QC_i\ (1-X) - QC = V\frac{dc}{dt}$$

5. Make the simplifying assumptions that digester feed flow, feed concentration, and liquid volume are constant for the period t. The above equation is integrated and solved for C.

$$C = C_i(1-X) - [C_i(1-X)-C_o] \exp -\left(\frac{Q}{V}t\right) \qquad 15\text{-}1$$

Equation 15-1 predicts digested sludge solids concentration at any time beyond initiation of the operating strategy. C_o is defined as digested sludge concentration at the time the operating strategy is put into operation. Note that the product of digested sludge concentration (C) and digester effluent liquid flow (Q-k) is the load which the dewatering units must process.

TABLE 15-2

CALCULATIONS FOR DIGESTER EFFLUENT MASS FLOW RATE FROM EQUATION 15-1

Operating strategy	Time after start of storm, days	Digester loading, lb/day	Digester feed solids concentration, percent	Digester feed rate, gpd	Digester volume increase/day due to rise of floating covers, gpd	Digester volume, gal	Fractional solids destruction	Digester effluent flow, gpd	Digested sludge solids concentration, percent	Dewatering unit feed rate, lb/day
A. Floating cover rise = 1 ft/day; digester feed thickened to 7 percent	0^-	168,520	5	396,051	0	5.97×10^6	0.39	396,051	3.05	102,797
	0^+	433,000	7	726,875	0	5.97×10^6	0.20	550,632	3.05	142,919
	1	433,000	7	726,875	176,243	6.05×10^6	0.20	550,632	3.38	156,429
	2	433,000	7	726,875	176,243	6.23×10^6	0.20	550,632	3.58	167,772
	3	433,000	7	726,875	176,243	6.41×10^6	0.20	590,632	3.78	177,373
	4	433,000	7	726,875	176,243	6.58×10^6	0.20	590,632	3.96	185,561
	5	433,000	7	726,875	176,243	6.76×10^6	0.20	550,632	4.11	192,594
B. Floating cover rise = 1 ft/day; digester feed remains at 5 percent	0^-	168,520	5	396,051	0	5.97×10^6	0.39	396,051	3.05	102,797
	0^+	433,000	5	1,017,626	0	5.97×10^6	0.20	841,383	3.05	218,385
	1	433,000	5	1,017,626	176,243	6.05×10^6	0.20	841,383	3.20	228,903
	2	433,000	5	1,017,626	176,243	6.23×10^6	0.20	841,383	3.31	237,330
	3	433,000	5	1,017,626	176,243	6.41×10^6	0.20	841,383	3.41	244,156
	4	433,000	5	1,017,626	176,243	6.58×10^6	0.20	841,383	3.49	249,740
	5	433,	5	1,017,626	176,243	6.76×10^6	0.20	841,383	3.56	254,989
C. Floating covers are not allowed to rise; digester feed thickened to 7 percent	0^-	168,520	5	396,051	0	5.97×10^6	0.39	396,051	3.05	102,797
	0^+	433,000	7	726,875	0	5.97×10^6	0.20	726,875	3.05	188,664
	1	433,000	7	726,875	0	5.97×10^6	0.20	726,875	3.34	206,745
	2	433,000	7	726,875	0	5.97×10^6	0.20	726,875	3.60	222,755
	3	433,000	7	726,875	0	5.97×10^6	0.20	726,875	3.83	236,928
	4	433,000	7	726,875	0	5.97×10^6	0.20	726,875	4.03	249,478
	5	433,000	7	726,875	0	5.97×10^6	0.20	726,875	4.21	260,588

1 lb/day = 0.454 kg/d
1 gpd = 0.00378 m^3/d
1 gal = 0.00378 m^3

Calculations related to the operating strategy just described are summarized in Table 15-2 part A. The digested solids mass flow rates are calculated just before the storm ($t = 0^-$), immediately after the storm begins ($t = 0^+$) and for each of the next five consecutive days. It is assumed digester loading increases in one step from 168,520 pounds per day (76,508 kg/d) to 433,000 pounds per day (196,582 kg/d) at t = 0. Digested sludge liquid volume at the beginning of the storm is 5.97×10^6 gallons (22,600 m^3). Each 1 foot (0.305 m) of cover rise increases tank volume by 176,243 gallons (667 m^3). Solids destruction within the digesters is assumed to be 39 percent (X = 0.39) during average conditions, dropping to 20 percent (X = 0.20) during the storm due to decreased digester retention time. The calculation shows that dewatering capacity (200,000 pounds per day [90,800 kg/d]) is not exceeded during the storm, thus the operating strategy has been successful. Calculations for two other strategies which were not successful are also included. The results are shown graphically on Figure 15-2.

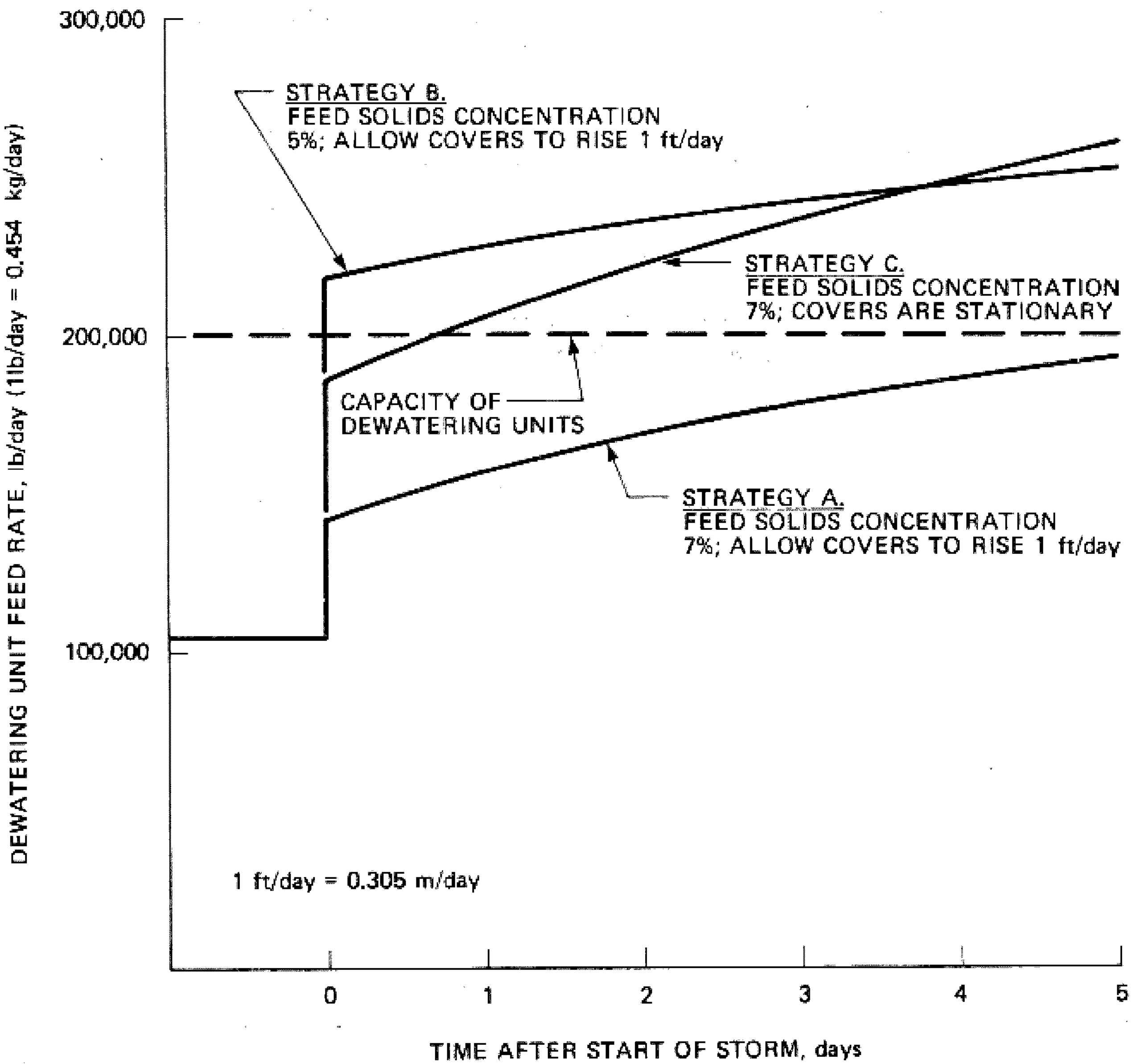

FIGURE 15-2

EFFECT OF VARIOUS OPERATING STRATEGIES ON DEWATERING UNIT FEED RATES

15.2.2.3 Aerobic Digesters

To use an aerobic digester for two-phase concentration type storage, the normally highly agitated contents must be made quiescent and the solids made to settle from the liquor before the whole mass becomes anaerobic and starts to decompose and create nuisance odors. Chemical treatment can facilitate solids settling. Without successful decanting, only single-phase concentration type storage and displacement type storage can be used by aerobic digesters. When displacement type storage is used with a fixed surface area, the liquid surface must rise or fall. Under such conditions, the aeration and mixing source must automatically adjust to such changes. Floating mechanical units and fixed-bottom mounted diffusers are both adaptable to these requirements; fixed mechanical aerators are not. Long-term storage in aerobic digesters will have a relatively low capital cost and a very high operating (energy) cost. Often, evaporation can account for significant concentration of the stored solids. As long as the solids remain aerobic throughout the digester, the odor impact of such storage is very minimal. For more information on aerobic digesters, see Chapter 6.

15.2.2.4 Composting

Composting is one of the two wastewater solids processes with storage capabilities that are effective for long-term storage. Once the wastewater solids have been stabilized by composting, the curing step can be extended as long as storage is required. This curing step usually involves nothing more than the placing of the composted material in unconfined stockpiles exposed to the atmosphere. As long as there are no site restrictions, this method of storage can be very economical, for it is actually just another use of time needed for curing and removing the material to its point of final disposal. For more design information on composting, see Chapter 12.

15.2.2.5 Drying Beds

Drying beds are used extensively by many smaller plants in conjunction with anaerobic and aerobic digestion. They are operated on a fill and draw basis and are often used to provide two-phase concentration and displacement type storage between production and disposal. To assure adequate storage capability, the designer should allow for up to 50 percent excess drying bed area. More design information on sludge drying beds can be found in Chapter 9.

15.3 Dedicated Storage Facilities

When solids storage within wastewater treatment processes and sludge solids treatment processes cannot provide the operational flexibility necessary to maintain cost-effective solids treatment and disposal, these within-process storage capabilities must be augmented with special dedicated storage facilities. These dedicated storage facilities can provide storage for sludge in either the liquid or dewatered state, and may, depending on design considerations and upstream treatment, be utilized for any of the three detention times listed in Table 15-1.

15.3.1 Facilities Provided Primarily for Storage of Liquid Sludge

Usually, dedicated liquid storage facilities consist of one of the three types listed in Table 15-1. Although listed as primarily for storage of liquid sludge, any of these facilities that are used for anything other than equalizing storage (3 to 4 days) will also provide some degree of solids treatment. Holding tanks, without air agitation, and facultative sludge lagoons usually continue anaerobic stabilization. Holding tanks, with air agitation, and aeration basins continue aerobic stabilization. As these are side benefits to the main design functions of these facilities, they have been ignored for the purpose of these classifications. However, if the storage is for a long term, then the additional treatment afforded certainly must be taken into account in setting final disposal criteria.

15.3.1.1 Holding Tanks

Holding tanks are commonly provided as an integral part of most conditioning processes and many stabilization processes. Holding tanks may be used for blending different materials as well as for equalizing storage, thereby assuring that the downstream sludge treatment process is uniformly loaded, both in quality and quantity. Holding tanks also often provide the decanting facilities for sludge treatment processes, such as thermal conditioning, which create products that support two-phase concentration.

Holding tanks that are to be used for blending must be maintained in a homogeneous condition. Such tanks can thus provide only single-phase concentration type storage or displacement type storage. Usually such tanks are relatively small, with detention times measured in hours instead of days. Most of the storage, therefore, is provided by volume adjustments. Holding tanks that involve blending and provide equalizing storage are usually limited to a batch, or a near-batch, type of operation or continuous level adjustments. Tank contents can be mixed by mechanical impellers, hydraulic recirculation, or gas agitation. Each method's applicability may be restricted by the type of material requiring the blending. For example, mechanical impellers are not applicable when unground sludge is being stored. The use of gas agitation and recirculation mixing is normally only limited by the volume which must be blended.

If the holding tank is located downstream from a sludge treatment process, special precautions may be required. For example, if downstream from anaerobic digestion and planned for more than a few hours of storage, the blending tank should be designed with a cover and be equipped to collect and remove combustible digester gas. If downstream from chlorine stabilization, it should be designed to function in a very low pH (acid) environment. Whatever its function, however, the holding tank must be designed to eliminate the production of malodorous gaseous discharges. This elimination is made especially difficult when the holding tank must provide equalizing storage and operate on a batch basis. Unless the solids supplied to the holding tank are completely stabilized (a condition seldom encountered with wastewater sludge), the tank's use for extended periods of storage will result in the creation of nuisance odors.

Even short periods of storage of unstabilized primary and secondary sludges in a holding tank can produce nuisance odors if no form of temporary inhibiting treatment has been applied. Decant tanks following thermal conditioning often create major odor problems. There are many ways of dealing with the odorous gases created by these holding tanks--for example, by passing the gases back through the aeration system, activated carbon filters, chemical scrubbers, and incinerators. The best design solution, however, is to minimize their creation.

Design Examples

The Sacramento California Regional Wastewater Treatment Plant, now under construction, is to be provided with a holding and/or blending tank that will be capable of receiving the daily anaerobically digested sludge discharged from nine complete-mix digesters (15). This digested sludge discharge will vary from 0.56 to 0.94 MGD per day (24.5 to 41.2 l/s) over the next 20 years. The blending tank will be 110 feet (33.5 m) in diameter and will have a 38.5-foot (11.7 m) sidewater depth. It will be provided with a Downes type floating cover that will have a vertical movement of at least 14 feet (4.3 m). This floating cover movement will allow the blending tank to mix the entire daily discharge from all the nine digesters prior to discharging its daily accumulation to downstream facultative sludge lagoons. This blending tank will provide a complete separation between the operational control of the complete-mix tank and the controlled feeding of the 20 lagoons. Total solids retention time of the blended sludges will be at least three days, and approximately one-third of the liquid contents of the blending tank will be displaced each day. Except for the provision for the extra floating cover travel and the use of bottom mounted gas diffusers, the blending tank will have the same design as the four complete-mix tanks now under construction. This method of blending and containment will minimize the release of odorous gases and maintain a safe control on the production and use of the digester gas during the blending operation. Figure 15-3 shows a sectional sketch of this proposed blending digester. In

Aliso, California, two 26,000-gallon blending tanks are being proposed to blend and equalize unstabilized sludge flows from several sources at the Aliso Regional Solids Stabilization Facility (16). These tanks are being provided with hydraulic mixing and fixed covers. The gas cap above the varying liquid level within the fixed covered tanks will be maintained at a constant pressure by an intertie with the low pressure digester gas system. This intertie will eliminate the need for special odor control equipment, minimize the danger from the possible production of an explosive gas-air mixture, and negate the need for some highly complicated pressure control system to protect against a rapid drawdown that might pull a vacuum or air into the blending tank. Figure 15-4 shows a sectional elevation of this raw sludge blending tank.

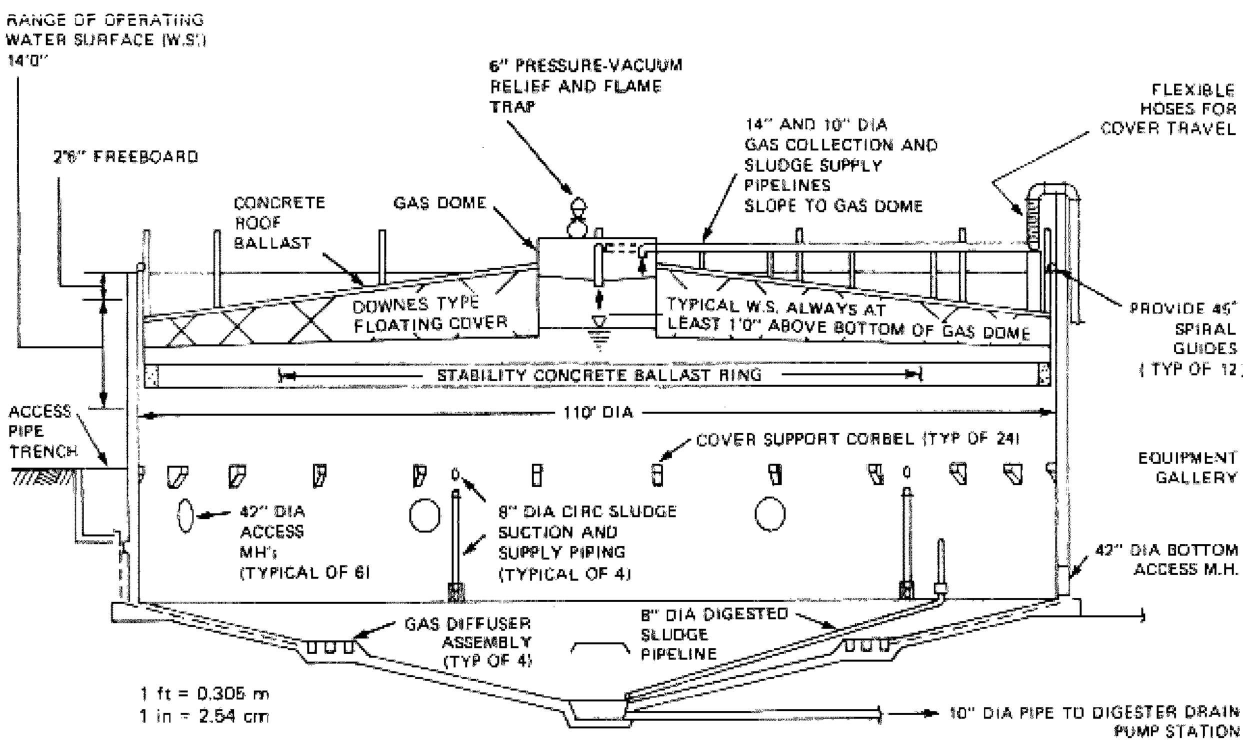

FIGURE 15-3

PROPOSED DESIGN FOR BLENDING DIGESTER--SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT

General Comments

While very little specific design guidance is provided in the literature for sludge holding tanks, the major issue that must be dealt with is the same as for most sludge treatment processes--material management. Wastewater sludge can contain almost anything. If a holding tank design is to incorporate mechanical mixing, which can be incapacitated by stringy material, the designer must make sure that material is either removed or cut up before reaching the blending tank. Likewise, hydraulic mixing pumps must be of the non-clog type or the material reduced in particle size by grinding so that it can pass through the minimum clearances of the type of pump used.

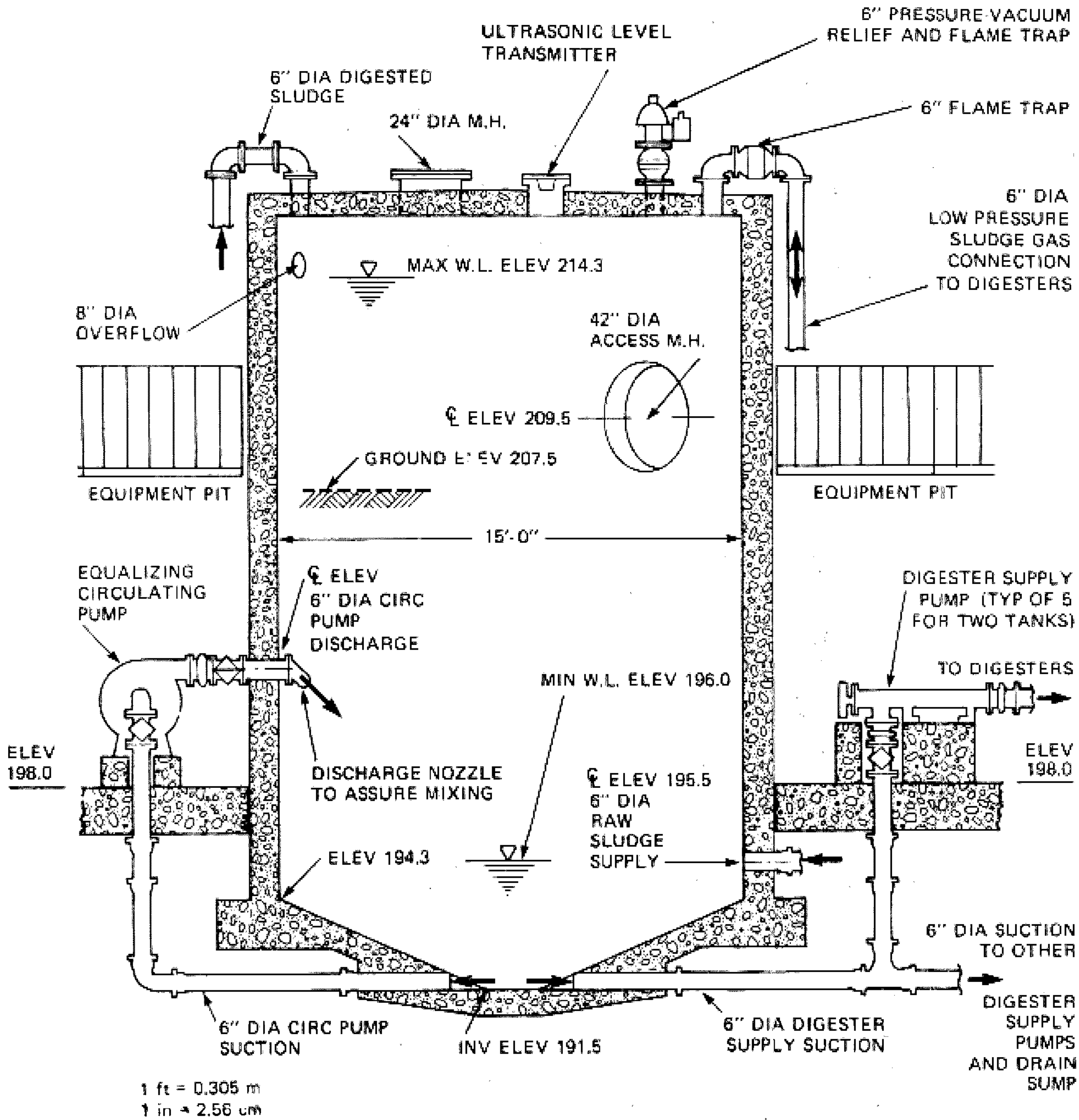

TABLE 15-4

26,000 GALLON SLUDGE EQUALIZATION TANK (TYPICAL OF TWO)
ALISO SOLIDS STABILIZATION FACILITY

The other major design problem involves the control of odors that are so often an integral part of any type of sludge holding tank. The Sacramento and Aliso holding tank design examples indicate two very successful means of dealing with such odors (that is, containing and incorporating them with the low pressure digester gas system). In many locations stabilized material is held within the holding tank only a few hours. Under these circumstances, their design depends on minimum odor generation, a reasonable assumption given the short retention period. Often decant tanks and conditioning blending tanks cannot depend on either of these methods of odor control. The designer should be very aware that when such a situation exists it will be expected that odors will be confined and treated to the point where their discharge ceases to create a nuisance. Odor control is a very complicated subject. Designers are referred to a Manual of Practice soon to be released by a Joint Committee of the ASCE and Water Pollution Control Federation.

15.3.1.2 Facultative Sludge Lagoons

Introduction

Sludge lagoons have been used for years to store wastewater solids. Unfortunately, most of this use has been with complete disregard to the aesthetic impact on the surrounding environment. Such misuse has become so widespread that just the use of the term "sludge lagoon" is often enough to eliminate their consideration in present-day alternatives analyses.

Recent studies in Sacramento, California, based on the successful operation of facultative sludge lagoons in Auckland, New Zealand, indicate that sludge lagoons can be designed to be environmentally acceptable and still remain extremely cost-effective (17,18). The facility studied in Sacramento provides storage for at least five years of sludge production. The sludge stored in the facultative sludge lagoon continues to stabilize without creating an odor level unacceptable to the surrounding neighborhood. Table 15-3 lists the advantages and limitations of using facultative sludge lagoons for long-term storage.

Theory

Facultative sludge lagoons (FSLs) are designed to maintain an aerobic surface layer free of scum or membrane-type film build-up. The aerobic layer is maintained by keeping the annual organic loading to the lagoon at or below a critical area loading rate and by using surface mixers to provide agitation and mixing of the aerobic surface layer. The aerobic surface layer of the FSLs is usually from one to three feet (0.30 to 0.91 m) in depth and supports a very dense population of between 50×10^3 and 6×10^6 organisms/ml of algae (usually Chorella). Dissolved oxygen is supplied to this layer by algal photosynthesis, by direct surface transfer from the atmosphere, and by the surface mixers. The oxygen is used by the bacteria in the aerobic degradation of colloidal and soluble organic matter in the digested sludge liquor, while the digested sludge solids settle to the bottom of the basins and continue their anaerobic decomposition. Sludge liquor or supernatant is periodically returned to the plant's liquid process stream.

TABLE 15-3

ADVANTAGES AND LIMITATIONS OF USING FACULTATIVE SLUDGE LAGOONS FOR LONG-TERM STORAGE

Advantages	Limitations
Provides long-term storage with acceptable environmental impacts (odor and groundwater contamination risks are minimized).	1. Can only be used following anaerobic stabilization. If acid phase of digestion takes place in lagoons they will stink.
Continues anaerobic stabilization, with up to 45 percent VS reduction in first year.	2. Large acreages require special odor mitigation measures.
Decanting ability assures minimum solids recycle with supernatant (usually less than 500 mg/l) and maximum concentration for storage and efficient harvesting (>6 percent solids) starting with digested sludge of <2 percent solids.	3. Requires large areas of land, for example, 15 to 20 gross acres (6 to 8 ha) for 10 MGD, (438 l/s) 200 gross acres (80 ha) for 136 MGD (6,000 l) carbonaceous activated sludge plants.
Long-term liquid storage is one of few natural (no external energy input) means of reducing pathogen content of sludges.	4. Must be protected from flooding.
	5. Supernatant will contain 300-600 mg/l of TKN, mostly ammonia.
Energy and operational effort requirements are very minimum.	6. Magnesium ammonia phosphate (struvite) deposition requires special supernatant design.
Once established, buffering capacity is almost impossible to upset.	
Allows for all tributary digesters to operate as primary complete-mix units (one blending unit may be required for large installations).	
Provides environmentally acceptable place for disposal of digester contents during periodic cleaning operations.	
Sludge harvesting is completely independent from sludge production.	

The nutrient and carbon dioxide released in both the aerobic and anaerobic degradation of the remaining organic matter within the digested sludge are, in turn, used by the algae in the cyclic-symbiotic relationship. This vigorous relationship maintains the pH of the FSL surface layer between 7.5 and 8.5, which effectively minimizes any hydrogen sulfide (H_2S) release and is believed to be one of the major keys to the successful operation of this sludge storage process.

Facultative sludge lagoons must operate in conjunction with anaerobic digesters. They cannot function properly (without major environmental impacts) when supplied with either unstabilized or aerobically digested sludge. If the acid phase of anaerobic stabilization becomes predominant, the lagoons will stink. Figure 15-5 provides a schematic representation of the reactions in a typical FSL.

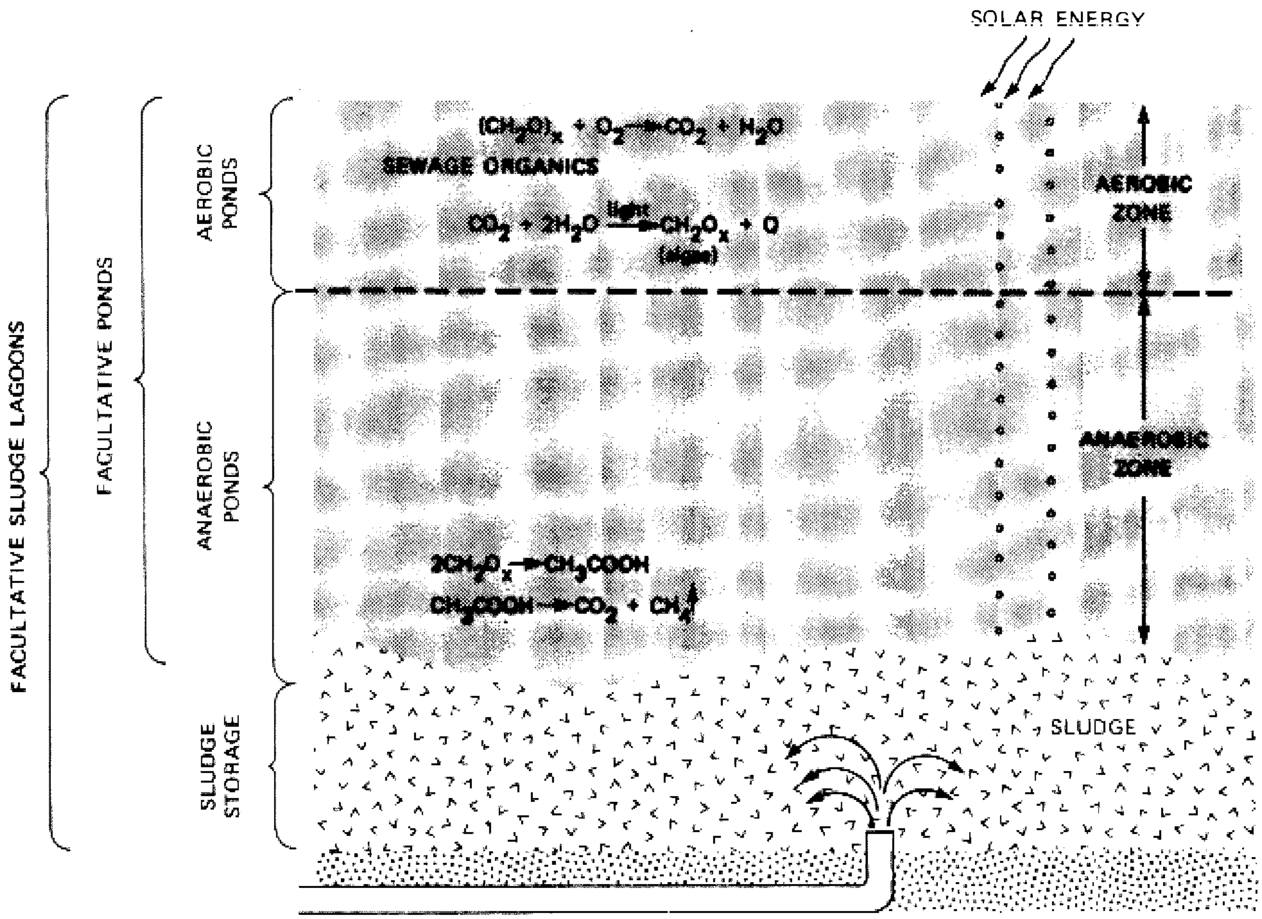

FIGURE 15-5

SCHEMATIC REPRESENTATION OF A FACULTATIVE SLUDGE LAGOON (FSL)

Current Status

Facultative sludge lagoons were installed initially in 1960 in the Auckland, New Zealand, Manukau sewage treatment plant to provide for the storage and disposal of that plant's anaerobically digested primary sludge. Although lagoons were installed at Dublin-San Ramon, California in 1965, Medford, Oregon in 1971, and other sites in the United States since 1960 in an attempt to duplicate the successful Auckland installation, it was not until 1974 that the area loading became the critical criterion for their success. Studies at Sacramento since 1974, with approximately 40 acres (16.2 ha) of FSLs, have determined that the standard annual loading rate can be doubled during the warm, long, sunny days of July, August, and September. Reduced algae activity during the colder winter months indicates that the standard loading rate should not be exceeded.

Since 1974, additional FSLs have been placed in service at Corvallis, Oregon - 4.5 acres (1.82 ha) and Salinas, California - 6.0 acres (2.43 ha). Other FSLs are being built or are under design for Eugene-Springfield, Oregon - 25 acres, (10.1 ha); Red Bluff, California - 0.93 acres (0.38 ha); Sacramento, California - 84 acres (34 ha); Flagstaff, Arizona 7.3 acres (2.95 ha); and Colorado Springs, Colorado - 60 acres (24.3 ha). Successful operation was experienced this past winter under freezing conditions at Corvallis, Oregon. Experience to date indicates the design criteria established at Sacramento are applicable under other climatic conditions.

Design Criteria

Design considerations for the FSLs include the area loading rate, surface agitation requirements, dimensional and layout limitations, and physical factors. All have been developed during the studies conducted over the past five years at the Sacramento lagoons.

Area Loading Rate. To maintain an aerobic top layer, the annual organic loading rate to that FSL must be at or below 20 pounds of volatile solids (VS) per 1,000 square feet per day (1.0 t VS/ha-d). Lagoons have been found to be capable of receiving the equivalent of the daily organic loading rate every second, third, or fourth day without experiencing any upset. That is, lagoons have assimilated up to four times normal daily loadings as long as they have had three days of rest between loadings. Loadings as high as 40 pounds VS per 1,000 square feet per day (1.0 t VS/ha-d) have been successfully assimilated for several months during the warm summer and fall. Experiments on small basins loaded to failure indicate that peak loadings up to 90 pounds VS per 1,000 square feet per day (4.4 t VS/ha-d) can be tolerated during the summer and fall as long as they do not occur for more than one week.

Surface Agitation Requirements. Experiments on FSLs that were continuously loaded at the standard rate indicate FSLs cannot function in an environmentally acceptable manner without daily operation of surface agitation equipment. Observations indicate the brush-type mixer is required to breakup the surface film that forms during the feeding of the lagoon. If this film is not dissipated, a major source of oxygen transfer to the surface layer is eliminated. FSLs with surface areas of from 4 to 7 acres (1.6 to 2.8 ha) require the operation of two surface mixers from 6 to 12 hours per day to successfully maintain scum-free surface conditions. All of the successful installations to date have used brush-type floating surface mixers to achieve the necessary surface agitation. Figure 15-6 shows a typical brush-type surface mixer. Recent experiments indicate that two brush-type mixers with 8-foot-long (2.4-m) rotors turning at approximately 70 rpm and driven by 15 horsepower (11.2 kW) motors are required for a 4 to 7 acre (1.6 to 2.8 ha) lagoon. The mixers need to operate 12 hours per day. Lagoons of much less than 4 acres (1.62 ha) should be able to achieve the same results with two mixers with 6-foot (1.8-m) long rotors and 5-horsepower (3.7 kW) motors. Operation time is expected to be about the same number of hours per day. FSLs of larger than 7 acres (2.8 ha) have not been found to be cost-effective because of the need to take the lagoons out of service during sludge removal operations.

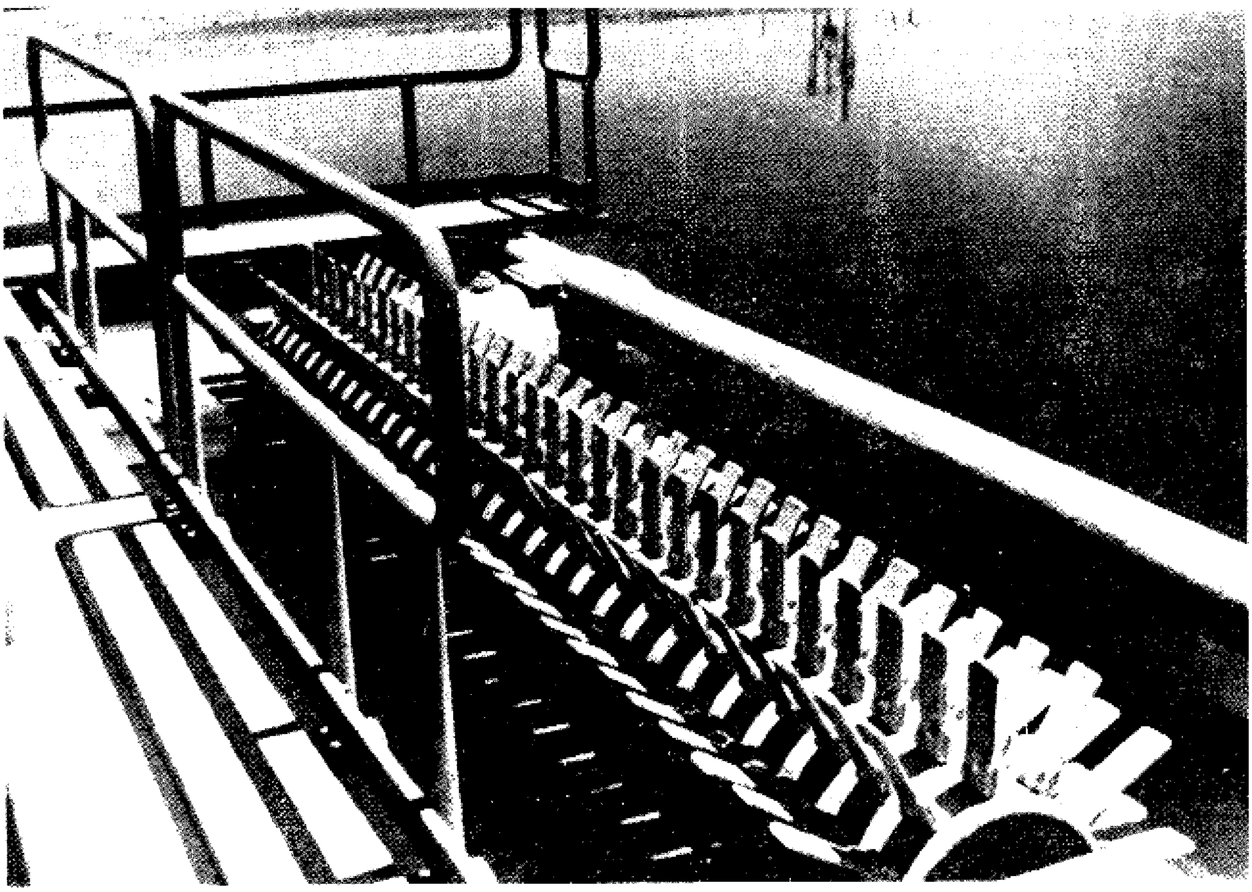

FIGURE 15-6

TYPICAL BRUSH-TYPE SURFACE MIXER, SACRAMENTO, CALIFORNIA

Brush type mixers have been used to limit the agitation to the surface layer of the FSLs. So far this has been an acceptable application; however, there is some question as to their applicability for very cold climates. Several submerged pump-type floating aerators have been reviewed, and they could be adapted to provide the necessary surface agitation if the brush-type could not function under severe freezing conditions. Two mixers are used per FSL to assure maximum scum break-up in those areas of the lagoon where the prevailing wind deposits the daily loading of scum. The agitation and mixing action of the two mixers located at opposite ends or sides of the lagoon also act to maintain equal distribution of the anaerobic solids.

Dimensional and Layout Limitations. FSL size is usually determined by the number of lagoons required to assure adequate surface area, while sludge is removed from a lagoon. If the removed sludge is to be reused, several spare lagoons are required to keep full lagoons out of service for the 2- to 3-year pathogen die-off period (3). The maximum area for a single lagoon area is somewhat arbitrary but is based on the most practical size for loading, surface agitation, mixing, and removal requirements. Large, 4 to 7 acre (1.6-2.8 ha) individual lagoons would be applicable only to plants with over 70 acres (28 ha) of FSLs. FSLs as small as 150 feet (45.7 m) on a side have been operated successfully.

Lagoon depth was established by the practical limitation of commercially available dredges with a proven capability of removing wastewater solids from beneath liquid surfaces. Equipment that meets this requirement is available to extract sludge from FSLs up to 11-1/2 and 15 feet (3.5 and 4.7 m) of depth. For plants ≤10 MGD (440 l/s), the 11-1/2 foot (3.5 m) depth dredge should be adequate. For plants >10 MGD (440 l/s) the 15-foot (4.7-m) depth should be used to provide additional storage flexibility. If surface agitation must be maintained by submerged pump type aerators, it may be necessary to employ the deepest lagoon possible to assure adequate separation between the aerobic zone and the anaerobic settling zone of the FSL. Contractors can supply dredge equipment for a lagoon, either with or without the manpower to operate it.

FSLs are usually best designed to have a long and a short dimension with the shortest dimension oriented parallel to the direction of the maximum prevailing wind. The longer side is made conducive to efficient dredge operation, while the short side's parallel orientation to the prevailing wind direction helps to minimize wave erosion on the surrounding levees. Figure 15-7 is a typical FSL layout, while Figure 15-8 is a typical FSL cross section.

When the area of FSLs exceeds 40 acres (16.2 ha), the potential cumulative effect of large odor emission areas to the vicinity must be considered. Figure 15-9 shows the layout for the 124 acres (50.2 ha) of Sacramento FSLs that were sited on the basis of the least odor risk to surrounding areas.

Work at Sacramento has also determined that batteries of FSLs totalling 50 to 60 acres (20 to 24 ha) are about the maximum size for most effectively reducing the transport of odors.

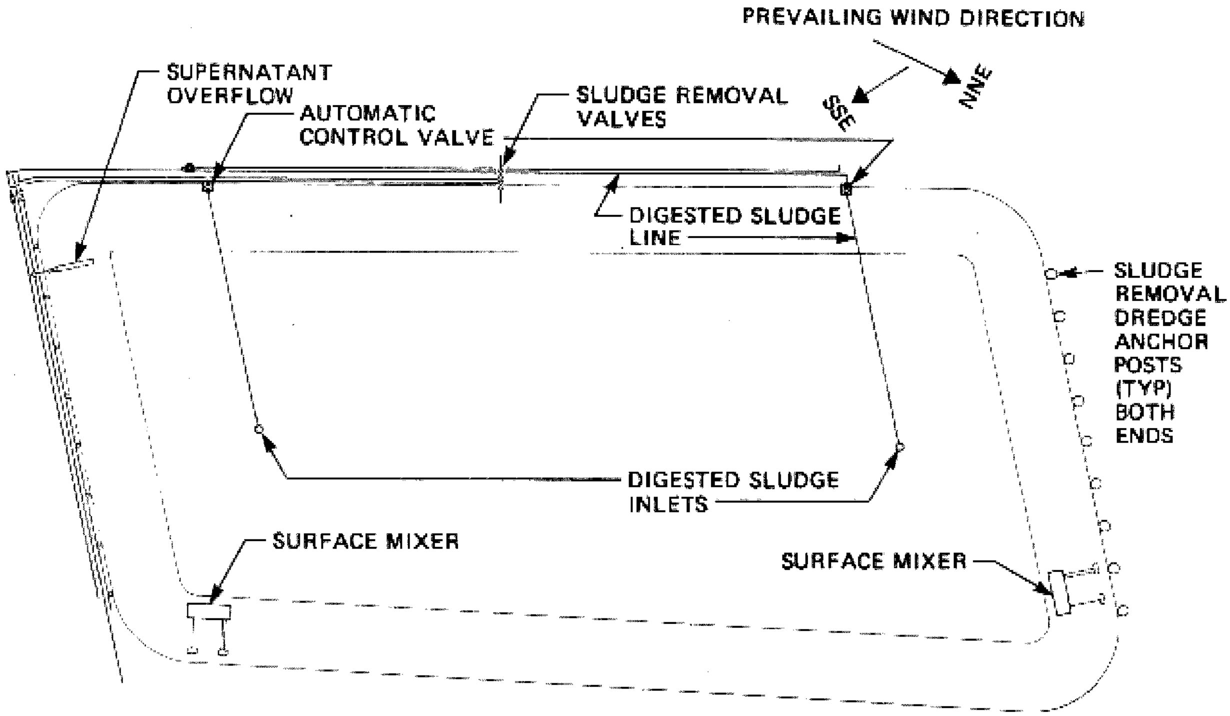

FIGURE 15-7

TYPICAL FSL LAYOUT

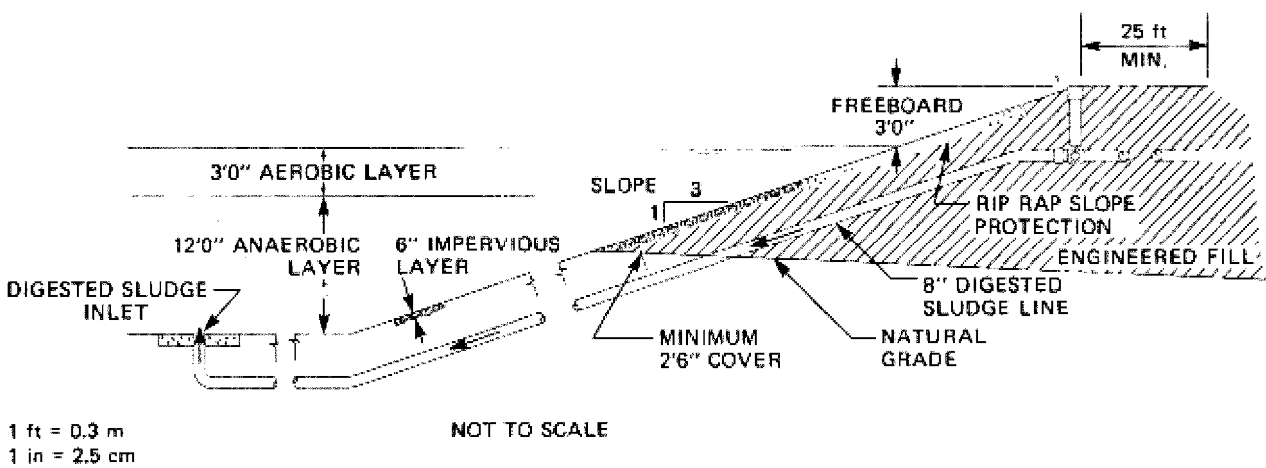

FIGURE 15-8

TYPICAL FSL CROSS SECTION

Physical Considerations. Many of the detailed physical considerations applied to the final design of the Sacramento FSLs are shown on Figures 15-8 and 15-9. Supernatant withdrawal is

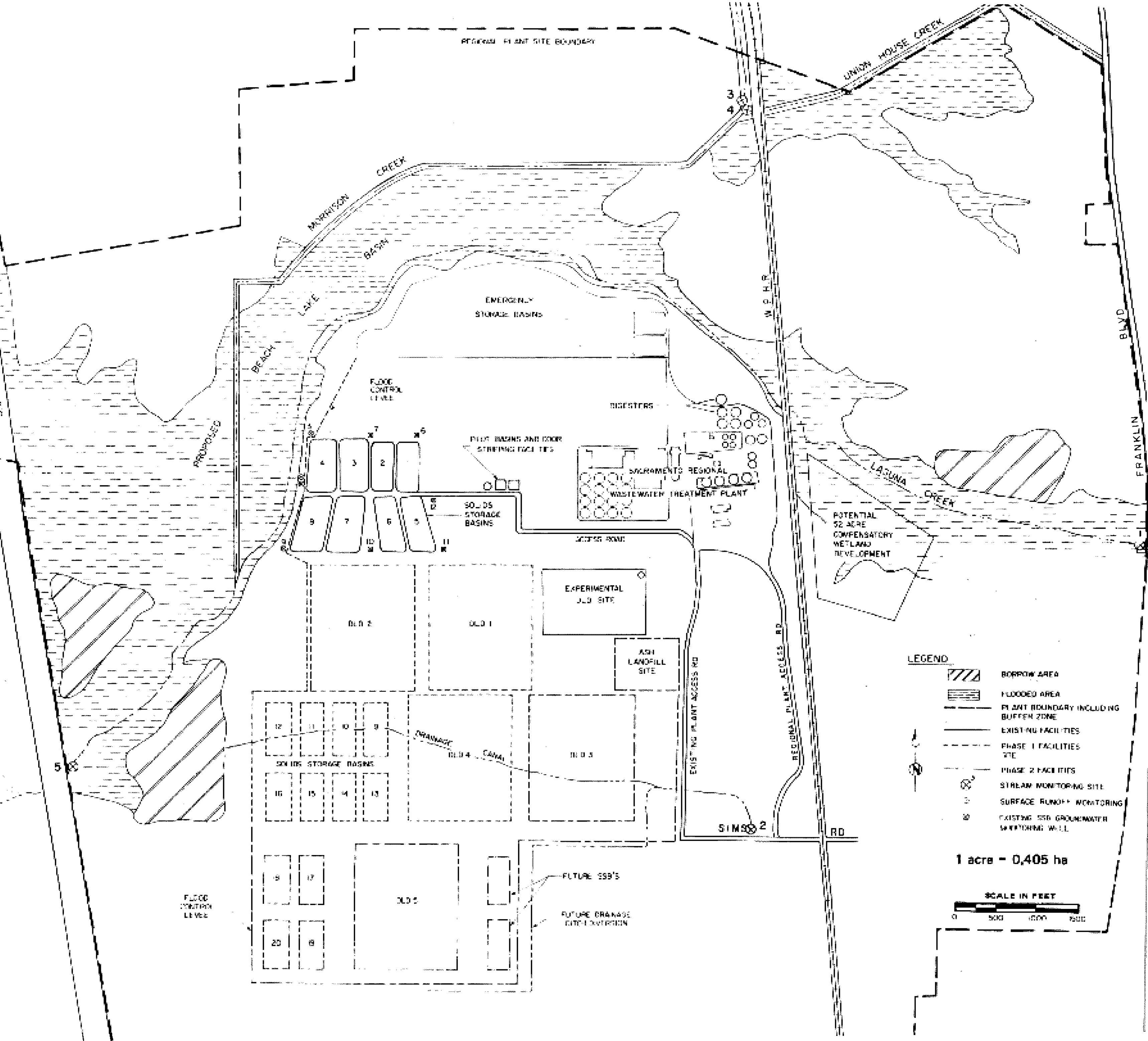

FIGURE 15-9
LAYOUT FOR 124 ACRES OF FSLs--SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT

located upstream from the prevailing winds to minimize scum build-up in its vicinity. FSL supernatant will precipitate magnesium ammonia phosphate (struvite) on any rough surface that is not completely submerged. It has also been found to precipitate inside cavitating pumps. This crystalline material can completely clog cast iron fittings and pump valves when the surface goes through a fill-and-draw cycle or when its operation results in the presence of diffused air. The most practical approach to successful elimination of this problem has been to use PVC piping throughout the FSL supernatant process and to design the process for gravity return to the plant influent, with a minimum of critical depth conditions. If pumping is required, submerged slow-speed non-clog centrifugal pumps with low suction and discharge velocities (to minimize cavitation) will be the most trouble-free. All equipment that cannot be PVC or other smooth non-metallic material should be coated with a smooth, impervious surface.

Two digested sludge feed lines are provided, each with its own automatic valve, to assure adequate distribution of solids over the whole volume of the FSL. Surface mixers are downstream of the prevailing winds. The harvested sludge dredge hookup is centrally located. Lagoon dike slopes are conservative--three horizontal to one vertical--with adequate rip-rap provided in the working zone of the surface level. Sufficient freeboard is provided to protect against any conceivable overtopping of the dikes. Digested sludge feed pipelines are located directly below the bottom of the lagoons, with the inlet surrounded by a protective concrete surface. All piping within the basin is out of the way of future dredging operations.

Many of the physical considerations for the basins have been required by the State Dam Safety Agency. Larger FSLs most probably will come under some regulatory agency whose responsibility involves seeing that earthen structures used to confine large quantities of liquid a significant height above the existing ground surface are safe. It is wise to check early to ascertain what, where, and how these agencies will be involved in FSL design.

Operational Considerations

Operational considerations can be divided into three categories: the loading or placement of sludge into the FSLs; their routine operation; and the removal of their solids. Considerations listed below were developed during the five years of study on the Sacramento lagoons.

Start-up and Loading. FSLs should be initially filled with effluent. Ideally, that effluent should then have about three to six weeks for development of an aerobic surface layer prior to the introduction of digested sludge. All FSLs should be loaded daily, with the loading distributed equally between FSLs. Loadings should be held below 20 pounds VS per 1,000 square feet per day (1.0 t VS/ha-d) on an average annual basis. As indicated earlier, considerable flexibility does exist. Loads can vary from day to day, and batch or intermittent loading of once every four days or less is acceptable. Shock loadings, such as with digester cleanings, should be distributed to all operating FSLs in proportion to the quantity of sludge inventory they possess. FSLs should be loaded during periods of favorable atmospheric conditions, particularly just above ground surface, to maximize odor dispersion. The fixed and volatile sludge solids loadings to the FSLs and their volatile contents should be monitored quarterly.

Daily Routine. Surface mixers should operate for a period of between 6 and 12 hours. Operation should not coincide with FSL loading and should always be during the hours of minimum human exposure (usually midnight to 5 a.m.) and during periods of favorable atmospheric conditions. FSL supernatant return to the wastewater treatment process should be regulated to minimize shock loadings of high ammonia. Supernatant return flows should be monitored so that their potential impact on the liquid treatment process can be discerned. The sludge blanket in a lagoon should not be allowed to rise higher than two feet below the operating water surface.

Sludge Removal. FSLs that are to be emptied of accumulated solids should be removed from routine operation at least 30 days prior to the removal of any solids. Pathogen safe reuse requires removal from operations for two to three years (3). Sludge removal should be limited to those FSLs that are concentrating the sludge solids to six to eight percent. During FSL sludge removal operations, the water surface level should not be allowed to drop more than 12 to 18 inches (30 to 46 cm) below its normal operating level.

Energy Impacts

Energy requirements of FSLs are relatively small because FSLs use solar energy. The sun supplies the needed energy for the algal photosynthesis. In turn, the algal cells supply the dissolved oxygen to support the aerobic bacterial action in the surface layer. The only outside power used in normal FSL operation is for surface agitation, supernatant pumping and treatment, and the supply and removal of the sludge. For the 124-acre (50.2 ha) Sacramento installation, it was recently calculated that these energy requirements could equal 31,700 x 10^6 Btu per year (33,400 GJ/yr) when the FSLs became fully loaded in 1990 (19). As loading is based on area, the energy impact of FSLs will be 255 x 10^6 Btu/yr/acre (670 GJ/yr/ha). With maximum odor source control and transport reduction measures, this energy use will increase to 294 x 10^6 Btu per year per acre (765 GJ/yr/ha). As no chemicals or major structures are involved, all FSL energy impacts are direct. There are no secondary impacts.

Actual Performance Data

The following figures and tables report the actual performance of the eight FSLs in operation at the Sacramento Central Wastewater Treatment Plant. Although the plant is designed as a 24-MGD (1.1-m^3/s) carbonaceous activated sludge secondary wastewater treatment plant with anaerobic digestion for solids stabilization, it treats the total solids from three upstream secondary treatment plants, the total annual flow of which is considerably greater than its own. Solids from those upstream plants are transported to the Central plant by its tributary sewer collection system. The Central plant also receives a substantial solids loading (up to 35 percent daily surcharge) from seasonal canning operations. Table 15-4 indicates the FSL loadings for the four years from 1975 through 1978.

TABLE 15-4

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT VOLATILE REDUCTIONS, DIGESTED SLUDGE QUANTITIES AND FSL AREA LOADINGS

		Digested solids to FSLs			FSL loading
Year	Digester volatile reduction, percent	Annual average total solids, 10^3 lb/day[a]	Percent volatile	Percent solids	Annual average lb volatile solids, 10^3 sq ft/day[a]
1975	52	44.1	63	1.7	22.5
1976	50	35.9	67	1.6	15.9
1977	51	44.0	68	1.6	17.1
1978	45	52.7	66	1.6	20.7

[a]Dry weight.

Source: Treatment plant records.

lb = 0.4536 kg.
sq ft = 0.0929 sq m.

Figure 15-10 summarizes typical surface layer data for four of the FSLs for July 1977 through June 1978. Unfortunately, some turbidity and algae count data are missing, but the seasonal trend is quite apparent. Table 15-5 summarizes the FSL's design data and provides the necessary background to understand the FSL solids inventory in Table 15-6. Data from Table 15-6 was used to calculate a volatile solids reduction of 42 percent. Solids profiles are taken quarterly in all FSLs.

Recycled FSL supernatant quality for 1978 is given in Table 15-7, and complete mineral, heavy metals, and chlorinated hydrocarbon data for digested, FSL, and harvested solids for 1977 is provided in Table 15-8. While the specific conductance in the supernatant remains high (2,500 to 4,300 mhos/cm), the supernatant contains very little of the heavy metals. Rainfall increases the quantity of supernatant and decreases its strength. Winter-specific conductivity always dropped in Sacramento following significant rainfall. The only solution to this problem would seem to be to reduce the heavy metals concentrations in the unstabilized sludge.

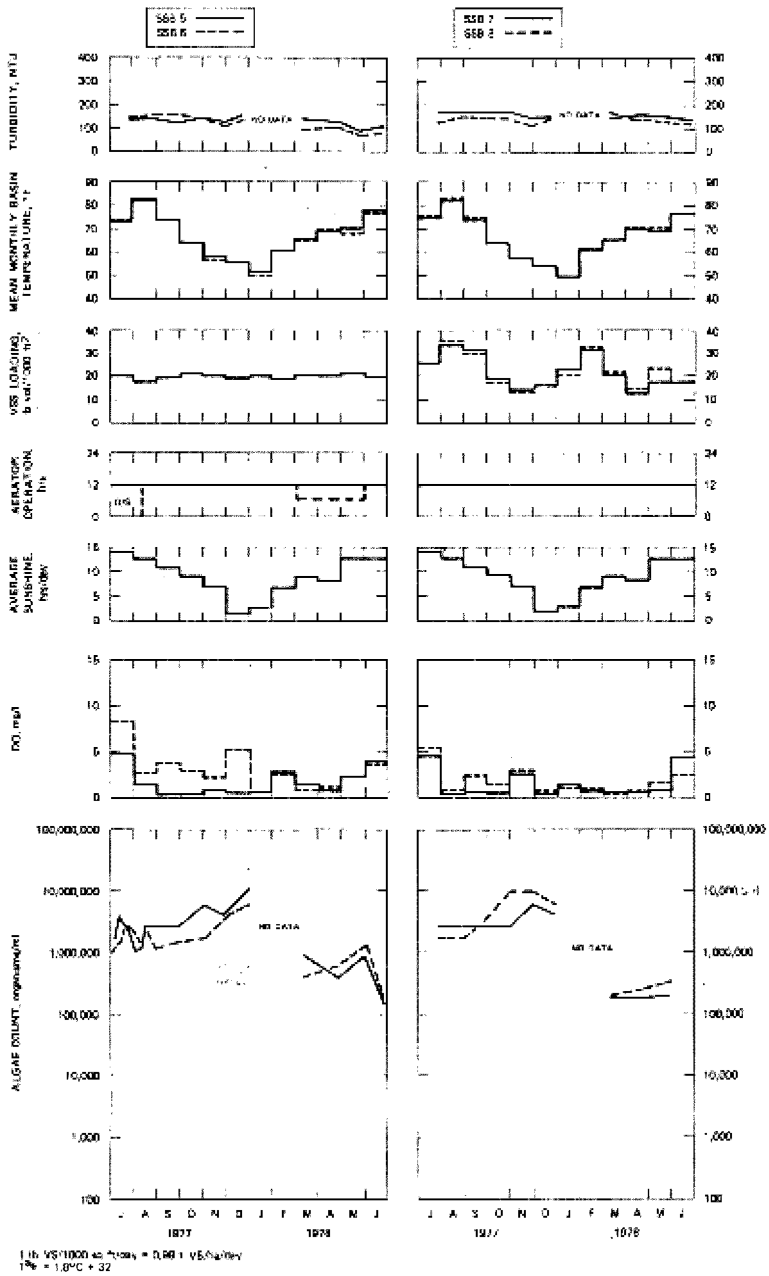

FIGURE 15-10

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT SURFACE LAYER MONITORING DATA FOR FSLs 5 TO 8

Public Health and Environmental Impact

FSLs have been found to have the following insignificant environmental impacts at Sacramento during five years of study:

- No vector impacts
- No groundwater impacts
- Controlled pathogen impacts
- Acceptable odor impacts

TABLE 15-5

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT FSL DESIGN DATA

FSL	Date placed in operation	Depth from water surface to bottom, ft	Area at water surface 1,000 ft^2 (acres)	Volume below sludge blanket, 1,000 cu ft	Loading capacity of basin,[a] 1,000 lb VS/day
1	7/73	11	164.0 (3.8)	1,030.4	3.28
2	8/73	11	164.0 (3.8)	1,030.4	3.28
3	9/74	14	244.2 (5.6)	2,137.0	4.88
4	11/74	14	229.0 (5.3)	1,983.0	4.58
5	8/76	15	204.2 (4.7)	1,851.0	4.08
6	8/76	15	204.2 (4.7)	1,850.0	4.08
7	11/75	15	270.0 (6.2)	2,689.0	5.40
8	11/75	15	270.0 (6.2)	2,689.0	5.40
		Total	1,749.6 (40.1)	15,259.8	31.80

[a]Capacity of lagoon based on a design volatile solid (VS) loading of 20 lb/1,000 ft^2 of water surface area per day.

1 ft = .3048 m
1 ft^2 = .0929 m^2.
1 lb = 0.4536 kg.
1 cu ft = 28.32 l.

TABLE 15-6

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT FSL SLUDGE INVENTORY, DRY TONS

	FSL 1		FSL 2		FSL 3		FSL 4		FSL 5		FSL 6		FSL 7		FSL 8		Total	
Parameter	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
Digested sludge added[a]	3,925	2,690	4,580	2,995	5,398	3,416	5,801	3,596	2,222	1,461	2,211	1,454	3,486	2,317	3,275	2,177	30,898	20,106
Stored sludge[b]	1,973	860	3,009	1,629	2,950	1,721	3,845	2,092	1,459	816	1,173	719	3,782	2,214	3,208	1,676	21,399	11,727

[a]Quantities account for sludge that has been (1) added to the SSBs, (2) applied to land (1,256 dry tons in 1974, 1,688 in 1975, 976 in 1976 and 1,930 in 1977) and (3) transferred between basins since beginning of operations.

[b]Quantities calculated based on data obtained from sludge samples collected July 12, 1978.

TABLE 15-7

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT RECYCLED FSL SUPERNATANT QUALITY

Constituent[a]	10/5/78	10/6/78	10/7/78	10/11/78	10/30/78	12/20/78	Average
BOD	140	140	140	96	200	110	143
TPO_4	51	50	66	120	110	80	79
Sulfides	0	0	0	0	0	0	-
COD	-	-	-	910	960	874	935
TKN	-	-	-	220	360	394	290
pH	-	-	-	7.7	7.7	7.8	7.7
SS	-	-	-	470	420	728	445
NH_3-N	-	-	-	-	300	335	300

[a]In mg/l except for pH.

Vector Impacts. Rodents and flies have apparently not bred around the FSLs for the last five years. Scum control is obviously the key to elimination of this problem.

Groundwater Impacts. Groundwater contamination is nonexistent. Monitoring wells surrounding the 40 acres (16.2 ha) of existing FSLs in Sacramento have been sampled monthly and have never shown any indication of groundwater contamination traceable to the lagoons. Tests show that sludge which settles to the bottom quickly and effectively seals off the lagoon contents from the surrounding soils. Undisturbed soil samples taken directly from the bottom of a lagoon with a limited history (one to two years) and a lagoon with a long history (four to five years) confirm that the FSL contents have a limited penetration into the surrounding soils. These studies indicate that the sealing of FSLs is a combination of soil pore plugging by suspended and colloidal materials within the sludge and the formation of mucus-like materials that create an impermeable membrane between the stored sludge and the underlying soil. Sandy soils take longer to seal than silty clay soils, but both achieve complete sealing in two to three months.

The two- to six-inch (5.08 to 15.24 cm) engineered fill seal provided over the natural bottom and side slopes of the typical FSL cross-section on Figure 15-8 assures that none of the FSL start-up sewage or diluted sludge content escapes during the natural sealing process.

Pathogen Impacts. It has been recognized for many years that long-term liquid storage significantly reduces the pathogenic microorganism content in sludge (3). Studies at Sacramento confirm this for the most common bacteria. Figure 15-11 indicates that the fecal coliform population decreases as the sludge passes through the sludge management system. Studies of parasitic protozoans and their cysts, helminths and their eggs (ova), and virus were inconclusive either because insufficient numbers were found or the techniques required for reasonable reproducibility were unavailable to the project. The system of disposal selected, that of dedicated land disposal, made further investigatory work unnecessary.

TABLE 15-8

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT COMPARISON OF DIGESTED FSL AND REMOVED SLUDGE ANALYTICAL DATA

Constituent	Digested sludge[a]	Stored sludge[a] FSL 1	FSL 2	FSL 3	FSL 4	FSL 5	FSL 6	FSL 7	FSL 8	Removed sludge[a]
mg/l										
Alkalinity[b]	2,556	2,653	2,676	2,638	2,348	1,940	1,687	2,239	2,175	2,069
Chloride[c]	143	178	225	204	209	169	166	171	186	171
Ammonia[c]	444	685	765	751	649	502	452	613	600	573
Soluble phosphorus (P)[c]	65	44	38	49	33	28	50	51	49	45
Sulfate[c]	38	87	97	91	113	73	77	68	49	151
Percent dry weight										
Total phosphorus (P)	1.8	2.0	1.9	1.7	1.8	1.4	1.6	1.6	1.4	1.9
Total nitrogen (N)	8.7	5.1	5.2	5.2	4.1	5.4	6.2	5.8	5.1	5.9
ppm, dry weight										
Calcium	21,000	27,000	25,000	21,000	28,000	28,000	24,000	26,000	21,000	24,000
Magnesium	5,800	8,200	7,900	7,900	6,300	5,500	5,300	6,300	3,500	8,600
Potassium	5,500	3,200	3,900	3,800	2,900	2,600	3,000	3,100	3,200	4,500
Sodium	9,200	3,100	3,450	3,500	3,300	4,100	5,600	4,600	4,200	5,400
Arsenic	47	75	72	89	101	22	28	82	62	15.4
Beryllium	<2.2	<1.1	<1.1	<1.0	<1.1	<1.4	<1.5	<1.0	<1.2	<1.3
Cadmium	12	24	26	19	16	14	18	21	17	19
Chromium	165	218	245	224	243	173	220	278	188	181
Copper	340	410	398	385	721	400	477	456	353	384
Lead	185	134	123	96	134	116	183	153	121	159
Mercury	3.7	5.3	5.1	5.3	5.2	5.0	5.8	5.8	4.2	5.6
Molybdenum	<22	<13.4	<16	<14	<12.5	<13.7	<15.4	<12.2	<11.8	<13
Nickel	63	58	72	70	115	46	48	60	53	77
Selenium	1.6	1.7	1.4	1.6	1.4	4.1	3.2	2.6	1.4	5.6
Silver	28	26	26	26	23	34	38	35	27	28
Zinc	930	1,700	1,500	1,300	1,325	1,207	1,400	1,400	1,090	1,200
PCB 1242	e	<2.8	<3.1	<2.9	<2.6	<2.3	<2.6	<3.0	<3.0	<2.1
PCB 1254	e	5.5	5.3	4.0	4.8	4.7	3.8	6.6	3.3	4.6
Tech chlordane	e	3.8	4.0	3.6	4.0	3.9	4.2	5.9	3.8	5.0
Other pesticidals[d]	e	0.30	0.27	0.25	0.22	0.25	0.25	0.27	0.23	<0.7
Units as noted										
Cd/Zn ratio, percent	1.3	1.4	1.7	1.5	1.0	1.1	1.3	1.5	1.5	1.5
Total solids, percent	1.7	7.0	6.3	6.1	7.6	4.7	3.4	4.8	5.7	4.1
Volatile solids, percent of total	68	55	55	53	52	60	62	61	52	54
pH	7.5	7.3	7.3	7.3	7.3	7.2	7.4	7.3	7.3	7.4
Specific conductance[c], µmhos/cm	4,742	5,109	5,847	5,743	4,914	4,434	4,093	5,061	4,760	4,731

[a]Values are averages from samples collected during 1977.

[b]As $CaCO_3$, determined by potentiometric titration of supernatant.

[c]Determined on supernatant; other determinations run on solution resulting from acid digestion of whole sample.

[d]Other pesticidals include residues such as DDT, DDE, dieldrin, etc.

[e]Analysis not performed.

Odor Impacts. Odor impacts change in direct proportion to the FSL's surface area. In most small plants (those requiring <40 acres [16.2 ha] of FSLs), controlling the loading rate, using adequate surface agitation, providing sufficient buffering area and carefully selecting the best time periods for feeding and surface agitation operation are sufficient to achieve acceptable levels of odor risk. Table 15-9 shows the annual odor risk analysis developed for the existing 40 acres (16.2 ha) of FSLs at the Sacramento site before the installation of the barriers and wind machines (1). No high technology mitigation has been required to maintain this acceptable risk level. For larger areas of FSLs, additional odor control measures would probably be required. These might include the installation of a blender digester to keep raw sludge from short circuiting to the FSLs, vacuum vaporization to remove entrained odors from the digested sludge prior to its discharge into the FSLs, separation of batteries of FSLs, construction of special 12-foot (3.7 m) high barriers around the FSLs, to ensure maximum odor dispersion at low wind speeds, and the use of wind machines to aid odor dispersion when the atmosphere is calm. Figure 15-12 shows typical wind machines and barriers at the Sacramento FSLs.

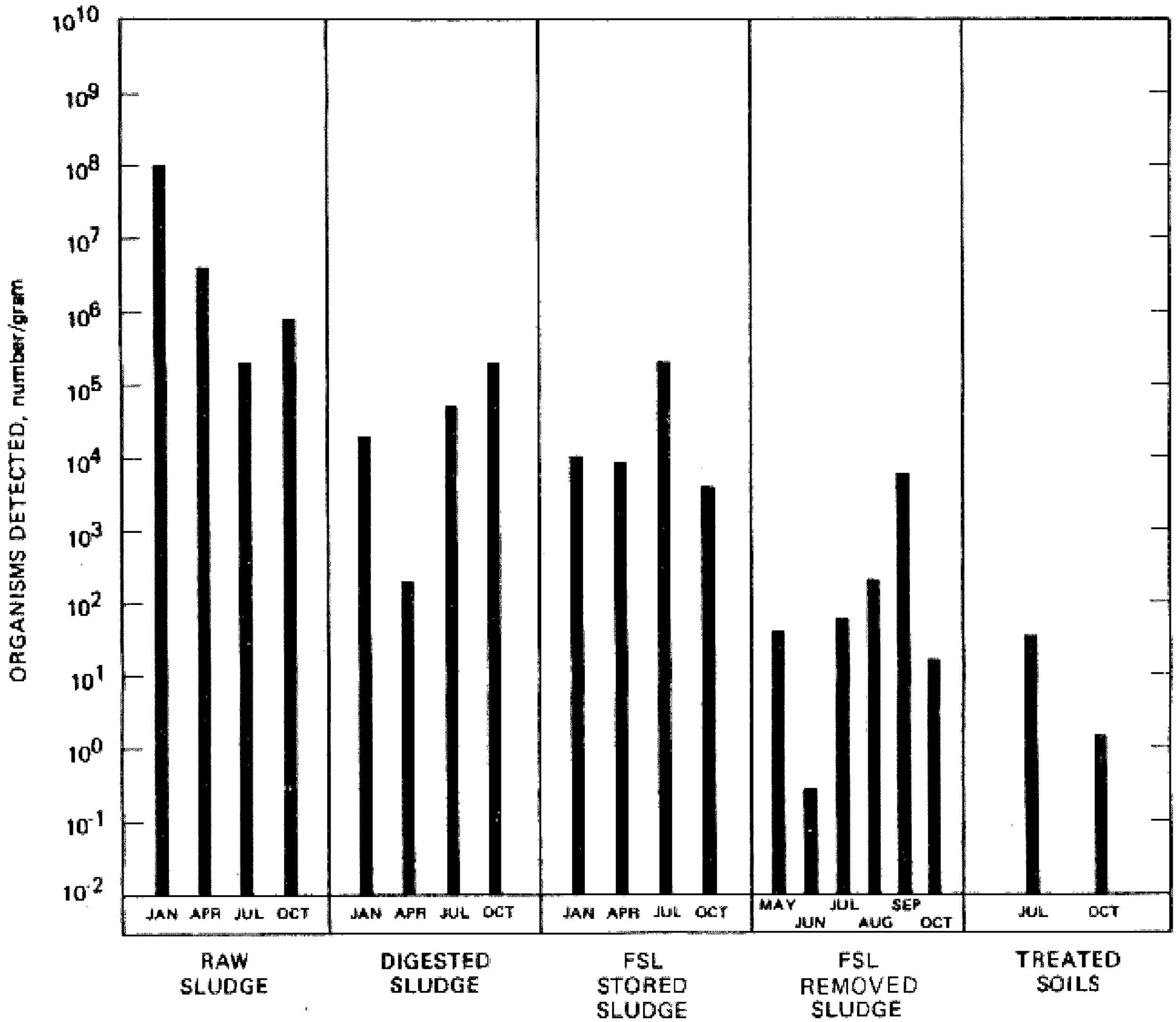

FIGURE 15-11

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT 1977 FECAL COLIFORM POPULATIONS FOR VARIOUS LOCATIONS IN THE SOLIDS TREATMENT-DISPOSAL PROCESS

TABLE 15-9

SACRAMENTO CENTRAL WASTEWATER TREATMENT PLANT ODOR RISK FOR 40 ACRES OF FSL[a], ANNUAL EVENTS (DAYS)

Downwind odor concentration, C	Direction towards which wind is blowing								
	N	NE	E	SE	S	SW	W	NW	Total
2[b]	2.8	2.1	3.2	7.3	11.5	6.7	4.1	3.1	38.9
5[c]	0.3	0.3	0.5	1.2	1.6	0.8	0.4	0.3	5.4
10[d]	0.08	0.06	0.10	0.20	0.3	0.2	0.1	0.1	1.1

[a]Includes source control mitigation - controlled organic surface loading rate, adequate surface mixers, and controlled feeding and mixer operating times - and odor transport mitigation - 2,000 to 5,000 feet of buffer.

[b]2 ou/cf barely detectable ambient odor criteria.

[c]5 ou/cf threshold complaint conditions.

[d]10 ou/cf consistent complaint conditions.

1 AC = .4047 ha.
foot = 0.3048 m.
1 cf = 0.02832 m^3.

The odors from 40 acres (16.2 ha) of FSLs at Sacramento have proven to be completely acceptable. An analysis of the expected annual odor risks for the 124 acres (50.2 ha) of FSLs to be constructed for the new regional treatment plant (see Figure 15-9) is shown in Table 15-10 (1). This analysis shows that with the installation of complete control measures, the incidence of threshold complaint odor levels at the plant boundary (2,000 to 5,000 feet [610 to 1,520 m] downwind) will be less than once every two years, regardless of wind direction, and once every seven years for the worst specific wind direction. This level of odor risk was found to be acceptable in the public environmental impact hearings.

Cost Information

The major elements involved in determining FSL costs are land and earth moving. Both are usually quite site specific. Normally, land costs vary less predictably than construction costs. A typical FSL storage facility for a 10-MGD (438-l/s) secondary carbonaceous activated sludge treatment plant with primary sedimentation, anaerobic digestion, and normal strength domestic and industrial sewage will cost about $1.5 million to construct and $25,000 per year to operate. Construction costs are based on a 3500 Engineering News Record Construction Cost Index and do not include the cost of land. Operation costs are based on 1978 wage rates and do not include dredge operators or any other removal costs.

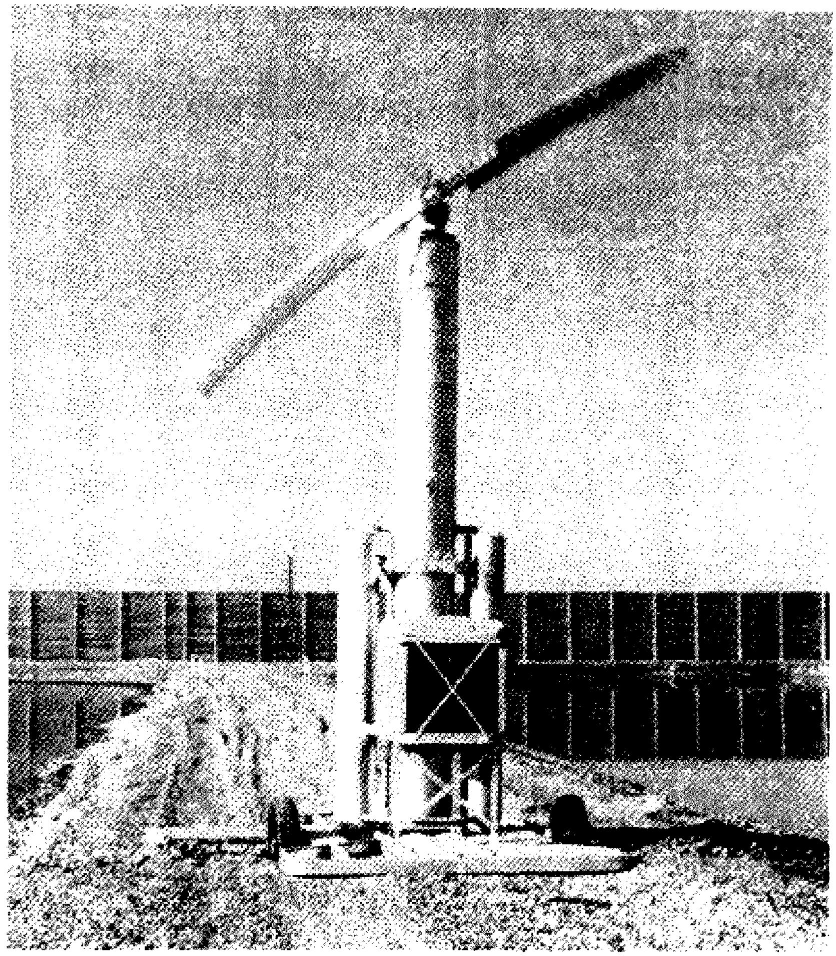

FIGURE 15-12

TYPICAL WIND MACHINES AND BARRIERS
SACRAMENTO, CALIFORNIA

Construction costs include the installation of three complete four-acre (1.62 ha) FSLs. This is assumed to be the capacity needed to meet the annual digested sludge loading rate criterion of 20 pounds VS per 1,000 square feet per day (1.0 t VS/ha-d). It is based on a conservative unstabilized sludge production rate and a nominal 50 percent volatile solids reduction in the anaerobic digesters. The three lagoons will provide capacity for daily loading, digester cleaning, and maintenance and storage for intermittent removal to dedicated land disposal. FSLs are assumed to be 15 feet (4.6 m) in depth and have 3:1 dike side slopes. If they are required, purchase of the dredge and booster pump would add another $150,000 to $180,000 to the construction costs.

Odor control costs, including blending digester, vacuum vaporizer, barriers, and wind machine could increase the construction costs another $250,000 and the operation costs another $25,000 per year. As indicated by the odor impact assessment, sufficient area to ensure maintenance of loading criteria, together with surface agitators and proper buffer, would make it possible to avoid the cost of the aforementioned more extensive odor mitigation facilities.

TABLE 15-10

SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT ULTIMATE ODOR RISK FOR 124 ACRES OF FSL[a], ANNUAL EVENTS (DAYS)

Downwind odor concentration, C	Direction towards which wind is blowing								
	N	NE	E	SE	S	SW	W	NW	Total
2[b]	0.44	0.15	0.18	0.41	0.85	0.31	0.22	0.33	2.9
5[c]	0.08	0.02	0.03	0.06	0.13	0.04	0.03	0.05	0.44
10[d]	0.02	<0.01	<0.01	0.01	0.02	0.01	0.00	0.01	<0.09

[a]Includes source control mitigation - controlled organic surface loading rate, adequate surface mixers, blending digester, vacuum vaporization and controlled feeding and mixer operation times, and odor transport mitigation - 2,000 to 5,000 feet of buffer and, separation of groups of FSLs, barriers and wind machines.

[b]2 ou/cf barely detectable ambient odor criteria.

[c]5 ou/cf threshold complaint conditions.

[d]10 ou/cf consistent complaint conditions.

1 AC = .40407 ha.
foot = 0.3048 m.
1 cf = 0.02832 m^3.

Construction costs for the 124 acres (50.2 ha) of FSLs with complete odor mitigation facilities for the Sacramento Regional Wastewater Treatment Plant are estimated to be $28.7 million. This includes almost $3.3 million for the existing 40 acres (16.2 ha) of FSLs with barrier wall and wind machines. This acreage will store the solids from a 136-MGD (5,960-l/s) secondary carbonaceous activated sludge treatment plant. Operation costs are estimated to be $650,000 per year.

15.3.1.3 Anaerobic Liquid Sludge Lagoons

Many such lagoons are being operated throughout the United States. One system that has collected some meaningful data is the 220.2 acres (89.1 ha) in operation at the Metropolitan Sanitary District of Greater Chicago (MSDGC) Prairie Plan land reclamation project in Fulton County, Illinois. In a personal communication R.R. Rimkus, Chief of Maintenance and Operations MSDGC provided the layout shown on Figure 15-13 of the four lagoons at this site. He reports that Lagoons 1 and 2 have been in service for eight and seven years, respectively, and Lagoons 3a and 3b for six years. Lagoons 1 and 2 have an average depth of 35 feet (10.7 m), plus or minus one foot (0.3 m), while Lagoons 3a and 3b are about 18 feet (5.5 m) deep. Lagoons 3a and 3b are utilized more for supernatant treatment and storage.

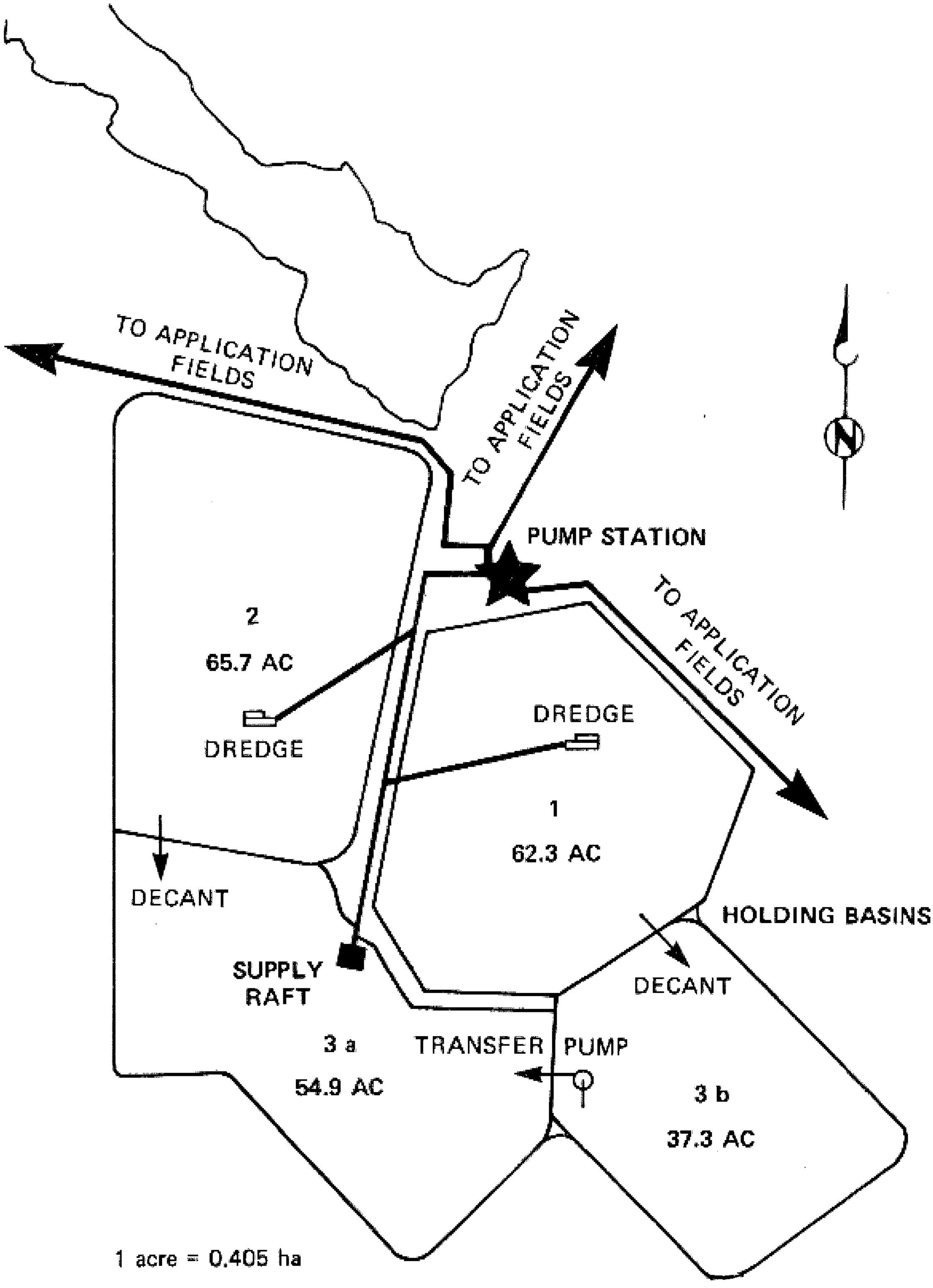

FIGURE 15-13

ANAEROBIC LIQUID SLUDGE LAGOONS, PRAIRIE PLAN LAND RECLAMATION PROJECT, THE METROPOLITAN SANITARY DISTRICT OF GREATER CHICAGO

Rimkus further indicates barged anaerobically digested waste-activated sludge from Chicago is discharged into Fulton County Lagoons 1 and 2 throughout the year, when river shipment conditions permit, at a frequency of about 20 days per month. Solids loading varies between 65,000 to 95,000 dry tons (59,000 to 86,200 t) per year. Based on the total loading received by Lagoons 1 and 2 and the volatile solids content of the digested sludge equaling 57 percent, the organic loading rate to the Fulton County Lagoons varies between 36 and 50 pounds VS per 1000 square feet per day (1.7 to 2.4 t/ha-d). This is considerably above the 20 pounds VS per 1000 square feet per day (1.0 t/ha-d) established at Sacramento to maintain facultative conditions within the lagoons. If the area of all four lagoons is considered, this organic loading rate drops to 21 to 29 pounds VS per 1,000 square feet per day (1.0 to 1.4 t/ha-d), which is close to the facultative sludge lagoon concept.

Rimkus reports that the solids concentration of sludge pumped from the barge to the lagoons varies from four to six percent by weight. Further, the sludge pumped from lagoons to fields in 1978 varied from 3.57 to 5.93 percent by weight. The average annual quantity of removed sludge is 60,000 dry tons (54,400 t). Mean value for volatile solids content of 1978 removed sludge was 47.5 percent. If the barged sludge volatile content is 57 percent, then the lagoons are reducing the volatile solids by 17 percent. Data for sludge removed in 1978 are given in Table 15-11. Sludge removal is usually accomplished in about 115 days, between May 1 and November 15.

According to Rimkus, Fulton County supernatant is disposed of on 1,320 acres (534.2 ha) of alfalfa-brome hay fields. Average annual quantity to dispose equals 700,000 wet tons (634,900 t) with an average ammonia content of 109.9 mg/l and an average TKN content of 156.4 mg/l. Table 15-12 provides other data on lagoon supernatant. Dissolved oxygen (D.O.) measurements taken in the summer and fall of 1977 in Lagoons 3a and 3b indicate the surface D.O. ranged between 0.9 and 8.5 mg/l,while the bottom D.O. ranged between 0.4 and 2.6 mg/l. The lowest lagoon temperature during this period was 40.6°F (15.5°C). The lagoon surface is frozen between 45 and 60 days per year, with scum build-up experienced only during periods of new sludge input. No surface agitation equipment is used on any of the lagoons. The nearest residence to the lagoon is approximately 6,000 feet (1,800 m) from the perimeter of the installation. No information is available regarding odors or odor complaints.

15.3.1.4 Aerated Storage Basins

To use aerated storage basins successfully for wastewater solids, a design must meet the following criteria:

- Basin contents must be sufficiently mixed to assure uniformity of solids concentration and complete dissemination of oxygen.

- Sufficient oxygen must be available to maintain aerobic conditions throughout the basin at maximum attainable solids concentration.

- Liquid level variation must be sufficient to accommodate maximum storage needs under anticipated rainfall.

TABLE 15-11

1978 REMOVED SLUDGE-PRAIRIE PLAN LAND RECLAMATION PROJECT, THE METROPOLITAN SANITARY DISTRICT OF GREATER CHICAGO[a]

Constituent	Minimum, mg/l[b]	Maximum, mg/l[b]	Mean, mg/l[b]	Mean content, lb/dry ton
pH, units	7.2	7.9	-	-
EC, umhos/cm	2,500	6,800	4,675	-
Total phosphorus	900	2,960	1,416	59.6
Kjeldahl nitrogen - N	1,276	2,905	2,329	98.1
Nitrogen as ammonia - $N\text{-}NH_3$	772	1,338	1,046	44.0
Alkalinity as $CaCO_3$	1,640	5,750	3,630	153
Cloride - Cl	228	752	388	16.3
Iron - Fe	1,000	2,900	1,938	81.6
Zinc - Zn	87	231	171	7.2
Copper - Cu	44.8	124	81.6	3.44
Nickel - Ni	9	28	18	0.76
Magnesium - Mn	8.5	28.3	18.0	0.758
Potassium - K	80	200	166	6.99
Sodium - Na	30	120	88	3.7
Manganese, Mg	80	810	450	18.9
Calcium - Ca	710	1,800	1,185	49.9
Lead - Pb	25.9	54.5	42.1	1.77
Chromium - Cr	90.6	513	175	7.37
Cadmium - Cd	7.5	20.2	13.2	0.556
Aluminum - Al	340	900	679	28.6
Mercury - Hg	0.132	1.920	0.417	0.018
Total solids, percent	3.57	5.93	4.75	2,000
Total volatile solids, percent	43.5	50.0	47.5	950

[a]Liquid fertilizer applied to fields from May 23, 1978 to November 18, 1978. Results are based on 24 weekly composite samples. Data supplied by Metropolitan Sanitary District of Greater Chicago.

[b]mg/l unless otherwise noted.

1 lb = 0.4536 kg
1 ton = .907 t

Mixing Requirements

Equipment required for aerated storage basins is similar to that for aerobic digestion (see Chapter 6). Unfortunately for the designer, mixing capability for various types of static or mechanical aeration devices varies greatly. Fixed or floating turbine or propeller-type aerators are often affected by very limited side boundaries, while brush-type aerators and aspirating pumps often have almost unlimited side boundaries but rather restricted vertical mixing capabilities. Submerged static aeration devices are excellent for vertical mixing but are always limited by very confined side boundaries. The designer should rely on a performance-type specification to achieve desired results. The equipment supplier should be given information about the configuration of the basin, its liquid level operating range, the maximum solids concentration expected, and the level of dissolved oxygen to be maintained. The designer is expected to have established the most cost-effective basin configuration based on loading, site-specific conditions and available aeration equipment requirements. A maximum horsepower limit should be established, and the specifications should include a bonus to be added to the bid price and a penalty to be subtracted from the bid price based on the energy costs involved when the equipment meets the required performance. A guarantee should be used to assure that the final installation will meet the performance requirement.

TABLE 15-12

1973/1974 SUPERNATANT-PRAIRIE PLAN RECLAMATION PROJECT, THE METROPOLITAN SANITARY DISTRICT OF GREATER CHICAGO[a]

Constituent	Mean value, mg/l	Range, mg/l
BOD - total	170	28 - 466
BOD - soluble	62	20 - 114
COD - total	951	325 - 2,120
COD - soluble	695	328 - 1,026
TSS	276	52 - 1,041

[a]Data supplied by The Metropolitan Sanitary District of Greater Chicago.

Oxygen Requirements

Oxygen requirements to maintain aerobic conditions within an aerobic storage basin will be considerably less than that required for aerobic digesters if the material being stored has been stabilized prior to its introduction to the basin. Minimum measurable dissolved oxygen levels of about 0.5 mg/l are quite adequate to maintain a basin free from anaerobic activity, as long as it is provided with adequate mixing. If the basin influent is not sufficiently stabilized to minimize oxygen requirements, then the aerobic storage basin must be designed for oxygen requirements similar to aerobic digesters (see Chapter 6). Oxygen transfer capabilities are similar to mixing capabilities for the various types of applicable equipment. The design should therefore include oxygen transfer requirements as part of the performance requirement indicated in the preceding section on mixing specifications.

Level Variability

Often, aerated storage basins cannot be decanted, because solids settle when the aerator is turned off, and anaerobic decomposition may also occur, resulting in odor production. Attempts at in-basin decanting without aeration and mixer shutdown will usually result in the recycling of the concentrated solids back to the liquid process. Separate continuous decanting is usually possible either by sedimentation or dissolved air flotation. Evaporation will also quite often result in significant liquid removal. Aerobic storage basins that do not have separate decanting facilities must be operated on single-phase concentration or displacement storage concepts.

The single-phase concentration concept will function as described for aerobic digesters. The displacement concept, however, will require liquid level variability and make aerated storage basin equipment installation quite complicated. Under such conditions, this equipment must be capable of maintaining adequate mixing and oxygen transfer over the complete range of liquid level variation. This requirement may cause this equipment to have varying mixing and aeration capabilities, depending on the basin depth. Variable speed drives, multi-speed drives, or variation in the quantity of diffused air should be investigated. At no time should the equipment be operated under conditions that will waste energy. Mixing and aeration design requirements and layout details can be found in Chapter 6.

15.3.2 Facilities Provided Primarily for Storage of Dewatered Sludge

Dedicated dewatered sludge storage of wastewater solids can include the storage of easily managed dry solids (>60 percent solids) or hard to manage wet solids (15 to 60 percent solids). Dry solids are usually the product of heat-drying, high temperature conversion, or air-drying processes and can be stored by standard dry material storage techniques. Descriptions of these techniques are readily available in materials processing textbooks, and, if desired, more detailed data is available (20,21). The storage of wet solids is another matter, however. The successful application of common storage techniques to this normally unstable organic material is practically impossible. The most commonly accepted methods of providing dedicated storage for wet organic material involves the use of drying sludge lagoons, placing the material in some type of confined structure or placing it in unconfined stockpiles. All three methods can involve special design considerations.

15.3.2.1 Drying Sludge Lagoons

Drying sludge lagoons are probably the most universally practiced method of storing of wet organic sludge. Actually, the material arrives at the lagoons in a liquid form, but as described under Chicago's actual performance data, most of the storage capability is derived while the material is in a partially dewatered state. Unfortunately, many existing applications of this method of storage are being operated with sludge that has not been anaerobically stabilized prior to its discharge to the lagoons. In some cases, drying sludge lagoons are used after aerobic digestion, and in other cases they have been used as digesters with no upstream stabilization. In these instances, odors that are quite unacceptable to the surrounding community are produced. When such lagoons are considered a means of ultimate disposal, they are called "permanent lagoons." Because permanent sludge lagoons have sometimes been the source of strong odors, they are often rejected as a means to store sludge, either in the liquid or semisolid state (22). A detailed discussion of design criteria for drying sludge lagoons can be found in Chapter 9.

Performance Data

Several reasonably successful drying sludge lagoon operations do exist. An investigation of their actual performance, however, indicates that these lagoons are acceptable because they receive adequately stabilized anaerobically digested sludge and do not normally generate the odors associated with the acid phase of anaerobic stabilization.

San Jose, California. The San Jose/Santa Clara Water Pollution Control Plant in San Jose, California, is a secondary treatment plant that operates on the Kraus modification of the activated sludge process during its seasonal canning loading period. The plant stores its anaerobically digested primary and waste-activated sludge in 73 sludge lagoons on 580 acres (235 ha) of land immediately adjacent to the plant (2). In 1978 the plant operated both anaerobic liquid sludge lagoons and drying sludge lagoons with 35 either filled or more than half filled with liquid sludge and 32 containing 2 feet (0.60 m) or less of dried sludge. Three lagoons have never been used, and three have been dredged and are now empty. The drying sludge lagoons were filled in layers of approximately one foot (0.3 m), and each layer was allowed to dry by evaporation prior to the addition of the next layer. The drying lagoon operation took place from 1974 until 1976, when operational limitations and odor production resulted in the return to anaerobic liquid sludge lagoon storage. Liquid sludge lagoon storage had been practiced prior to 1974.

As a result of existing operations, the present storage capacity of the lagoons will last until 1986. Because the plant does not have existing dewatering facilities, it will not be able to dispose of over 900,000 gallons per day (3,400 l/d) of liquid sludge without providing additional sludge treatment facilities by 1986. Studies are now under way evaluating alternative dewatering and drying processes and facilities for the disposal and use of dewatered and dried sludge.

Residents living in areas near the sludge lagoons have become increasingly concerned about odors produced by the lagoons. During 1976, several complaints were registered with the Air Pollution Control Board. The area most affected is a residential community just southeast of the plant. Correlation of complaints with atmospheric conditions indicates that the greatest odor risk occurs with a northwest wind and when dry weather is followed by heavy rain. This points to the danger of rewetting the dried surface layers and anerobically stabilized material and confirms that this can create strong odors.

Chicago, Illinois

The Metropolitan Sanitary District of Greater Chicago (MSDGC) operates 30 drying sludge lagoons, each with an average storage capacity of 200,000 cubic yards (153,000 m^3) and a storage depth of 16 feet (4.9 m) (23). Figure 15-14 provides a plan view of a typical lagoon. Anaerobically digested sludge is pumped to the MSDGC lagoons at a solids content of about 4 percent. Volatile content of this material is approximately 57 percent. Sludge is usually applied to each available lagoon in 6-inch (152-mm) layers in rotation. Rotations are repeated.

Supernatant appears on the lagoon surface approximately five to seven days after each fresh sludge application. It is then drained from the surface and returned to the West-Southwest Sewage Treatment Works by removing one or more stop logs from the draw-off box. Once the supernatant is decanted, the eight to ten percent solids sludge is further concentrated by evaporaion. Evaporation tapers off, however, as an aerobic sludge crust develops. Supply sludge concentration (4 percent solids) is beneficial, as it covers the entire lagoon surface with only a slight gradient from the point of application. Any higher concentration would inhibit this coverage and reduce the evaporative surface area per unit volume. Lagoons that have been filled to capacity by this method have an average solids content of 18 to 22 percent by weight. Volatile solids content of this material is in the range of 35 to 40 percent, indicating that the lagoons are producing about a 34 percent volatile solids reduction.

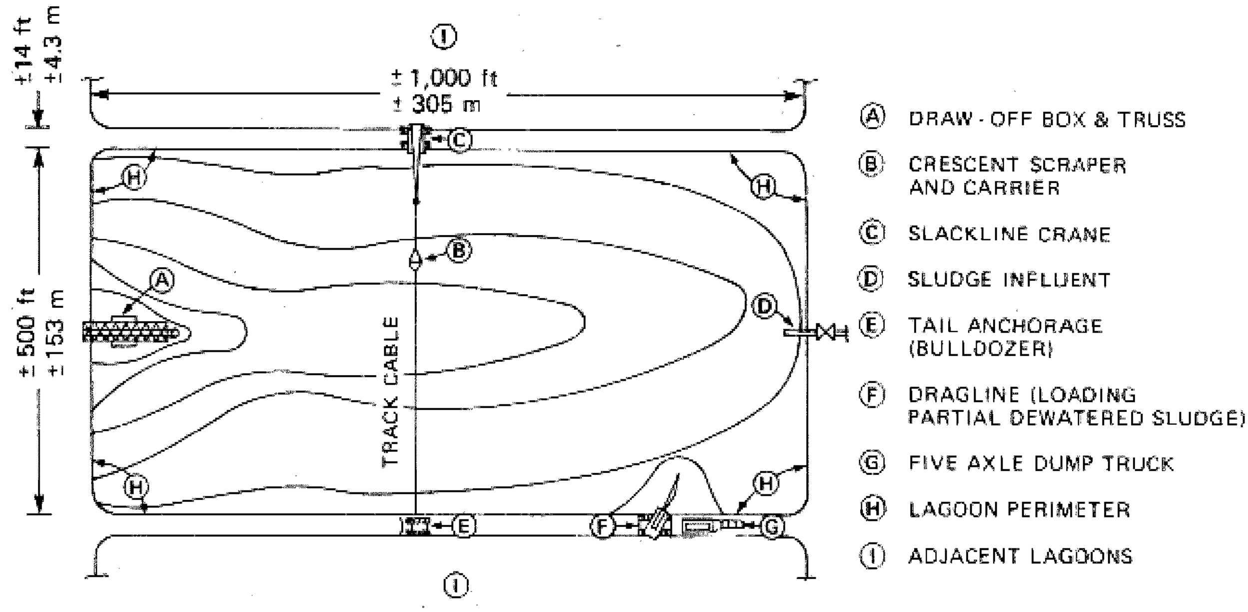

FIGURE 15-14

PLAN VIEW OF DRYING SLUDGE LAGOON NEAR WEST-SOUTHWEST SEWAGE TREATMENT WORKS, CHICAGO

Once the drying sludge lagoons are filled, they are taken out of service and preconditioned to provide an improved drainage gradient. For this purpose, the sludge is excavated from the area adjacent to the draw-off box and the slope within the lagoon is allowed to stabilize to the point at which the area remains reasonably free of solids. Excavation is by pump with nearby mixers and additional water, if necessary, to assure sludge fluidity. Figure 15-15 illustrates a cross section of this area after preconditioning is complete. When the sludge has stabilized, the lagoon is left dormant through the following winter and early spring. Trapped water and rainfall runoff are drained by gravity to the draw-off structure.

Once relatively dry weather returns, a slackline cable system is utilized with a dragline crane to further condition the sludge. The slackline system, which is shown on Figure 15-16, is used to improve the lagoon surface drainage and to scrape as much of the dried crust as possible to the side of the lagoon. This system provides the following four operational benefits:

- Drier sludge is scraped to the side, where it can be reached by portable dragline or clamshell and loaded onto dump trucks.

- Piling sludge along sides improves lagoon drainage pattern and profile.

- Removal of crust exposes wetter sludge to atmosphere for optimum evaporation.

- Some of dried crust mixes with wetter material during removal and increases the wet sludge solids content.

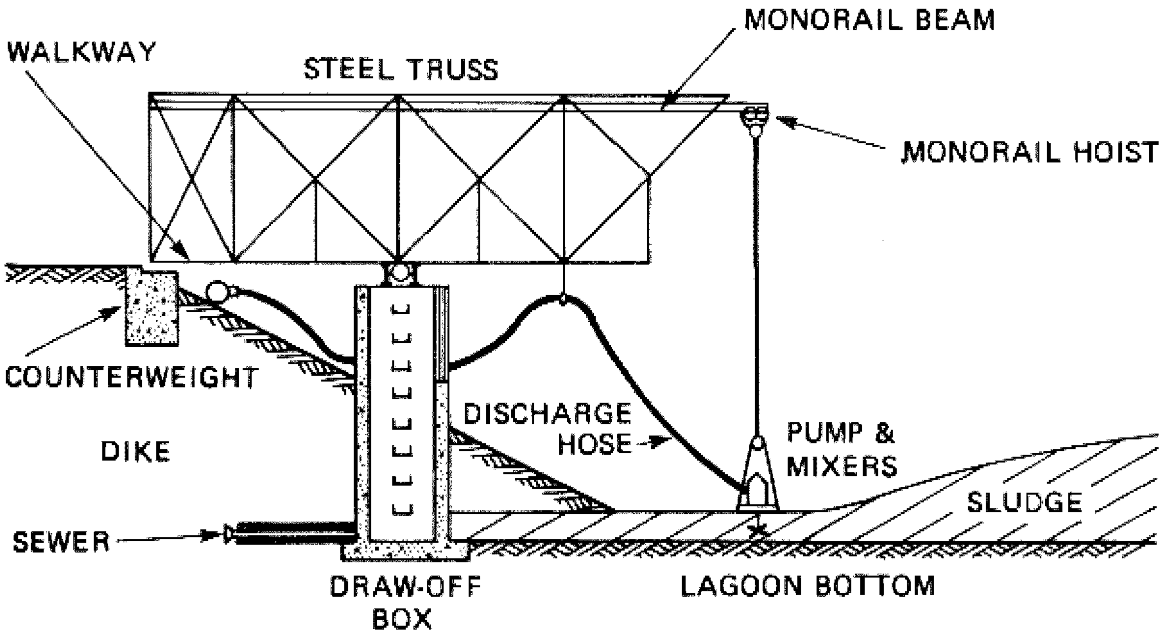

FIGURE 15-15

CROSS SECTION OF DRAW-OFF BOX AREA DRYING SLUDGE LAGOON NEAR WEST-SOUTHWEST SEWAGE TREATMENT WORKS, CHICAGO

Figure 15-16 shows the location of the equipment during lagoon partial dewatering and removal operation.

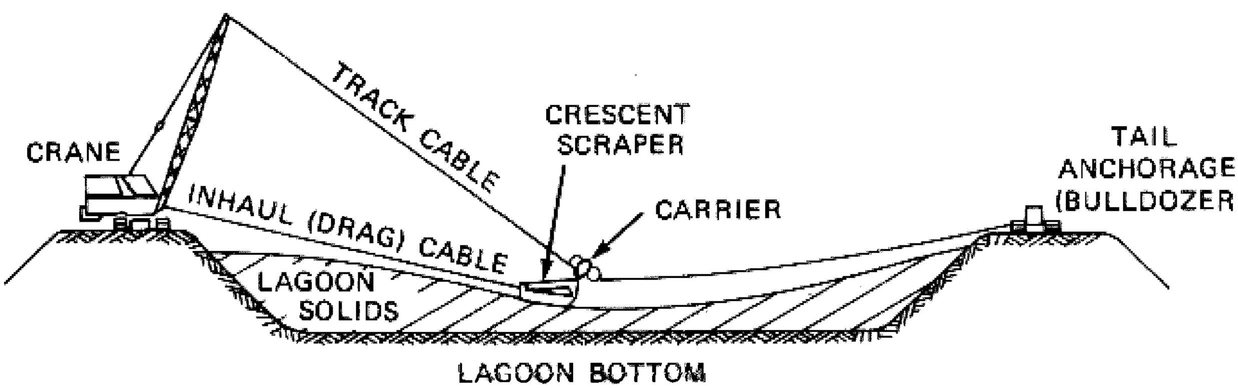

FIGURE 15-16

CROSS SECTION OF DRYING SLUDGE LAGOON WITH SLACKLINE CABLE NEAR WEST-SOUTHWEST TREATMENT WORKS, CHICAGO

Once the sludge crust is scraped to the side of the lagoon, it is removed by portable dragline or clamshell, loaded onto watertight five-axle dump trucks, and delivered to the general public for reuse. This lagoon sludge, at its time of delivery, usually has an average solids content of 30 to 35 percent by weight. Tree nurseries, sod farms, landfills, and stripped land are among the major users of this material. In 1977, the MSDGC disposed of 69,362 dry tons (62,925 t) of drying lagoon sludge at an average cost of $16.75 per dry ton ($18.47/t). In 1978, production was expected to exceed 100,000 dry tons (90,700 t) at a cost of $17.76 per dry ton ($19.58/t). Preconditioning costs are approximately $3.00 per dry ton ($3.31/t), which makes the cost for the whole operation about $21.00 per dry ton ($23.15/t). Preconditioning is accomplished by MSDGC manpower and equipment, and the services of the slackline, dragline, and trucks are contracted out. The overall operation requires little capital investment, minimal lead time, and limited effort. Natural processes are optimized and odors minimized. The level of odor involved has not been qualified.

15.3.2.2 Confined Hoppers or Bins

A designer is often tempted to take advantage of the volumetric reduction in material provided by the dewatering process and lay out his sludge disposal system based on short and long-term storage (3 weeks to >6 months) of the dewatered product. If the product is too wet (<30 percent solids), several problems may arise with this type of storage. These problems include continuing decomposition, liquefaction, and concentration and consolidation. Although each may have its own result, all three problems are interrelated and combine to limit the use of this type of storage to equalization storage and then only if special attention is given to controlling the difficulties. A brief description of some of these difficulties is given in the following paragraphs.

Continuing Decomposition

Unless it is stabilized to non-reactive levels (<50 percent by weight), the biodegradable volatile organic material of wastewater solids will continue to decompose if the moisture content is too high (solids content <30 percent). This decomposition will reduce organic material and generate gaseous byproducts. Depending on the stage and sometimes the type of stabilization employed prior to dewatering, the method of conditioning for dewatering, and the dewatering method itself, gaseous byproducts may or may not be odorous. For example, a biodegradable volatile content of <50 percent would result in strong odors; aerobically stabilized dewatered sludge would be more subject to strong odors than anaerobically stabilized dewatered sludge; polymer-conditioned dewatered sludge would be more subject to strong odors than lime and ferric conditioned dewatered sludge; and centrifuged dewatered sludge would be more subject to strong odors than vacuum filtered dewatered sludge.

Enclosed structures are often used in this type of storage to assure odor-free operation. Such structures may be extremely hazardous if the designer fails to recognize the potentially explosive nature of some of these gaseous byproducts and assure that they are never mixed with air within the combustible range. If such protection involves the replacement of the displaced volume, it may become the limiting feature of the storage structure's ability to manage the sludge.

One solution to this problem is to treat the volume above the solids as part of the digester gas storage system. However, this is only practical if the overall solids treatment system uses anaerobic digestion for stabilization and the gas collection system has sufficient capacity to fill the void created by storage discharge within the required period of time. Major problems of such a system are the sealing of sludge supply and discharge and the assurance of accessibility for maintenance.

To eliminate the discharge and supply problems and assure convenient access to the storage loading equipment, the enclosed area of the storage structures should be sufficiently ventilated. The area must be ventilated with about 20 to 30 air changes per hour. Air movement should be felt by the operators who work in the area. To assure ventilation of all areas, regardless of any continuously or intermittently operating openings, both supply and exhaust air should be managed by powered fans. All exhaust air should pass through an odor removal system. The quantity of exhaust ventilation air should be slightly greater than the quantity of supply ventilation air to assure a negative pressure within the area and minimize leakage that might bypass the odor removal system. The atmosphere of enclosed areas should be monitored with hydrocarbon detectors (see Chapter 17) to provide ample warning if the gas release begins to develop dangerous mixtures of methane and air.

Liquefaction

When the reduction of putrescible organic material is carried out within a confined structure used for short or long-range storage (three to four weeks to more than one month), the liquefaction of dewatered solids occurs. Liquefaction is negligible when the storage is limited to equalization (three to four days). The designer must be aware of the effects of this liquefaction and realize that as the liquid or moisture content of the sludge increases, the difficulties of transport also increase. An example of this liquefaction, in which no evaporation or additional moisture is assumed to be added during storage, can be seen in the following calculation:

Typical Liquefaction Calculation

Dewatered digested sludge (polymer conditioner used)

Solids to be stored, dry wt, tons	1,000	(907 t)

Total solids (TS) content, percent	20	
Volatile solids, percent	65	
Assumed reduction of VS during 6 months storage, percent	20	
Water content of dewatered sludge, tons	5,000	(4,535 t)
VS, dry tons at start of storage	650	(590 t)
VS, dry tons at end of storage	520	(472 t)
Fixed solids, dry tons (unchanged)	350	(317 t)
TS, dry tons at end of storage	870	(789 t)
Total solids content at end of storage, percent	14.8	

The example indicates how a reasonably dry, dewatered digested sludge (20 percent solids) can be liquefied to a fairly wet, digested sludge (14.8 percent solids) if the putrescible organic material continues to be reduced. The speed of this reduction is greatly affected by temperature and organic content in the dewatered sludge. Thus, liquefaction will be a greater problem in warm climates or during the hot summer seasons. If lime and ferric chemicals are used to condition the digested sludge for dewatering, liquefaction will be greatly reduced, both because of the lower overall organic content of the material and the inhibiting effects of the chemicals on the bacterial reduction of the putrescible organic matter.

Concentration and Consolidation

The material handling properties of the dewatered sludge entering the storage facilities often do not resemble those of the material discharged from the same facility. The method of controlling the discharge must be flexible enough to adapt to these changes in properties at any time. A live bottom discharge for variable positive control and back-up isolating valves for positive shut-off if the live bottom equipment fails or the material starts to run like water are mandatory when the volume of storage greatly exceeds the volumetric capacity of the transport system receiving the discharge. As long as the storage structure's volume does not exceed the capacity of the transport system receiving the discharge, and that transport system is of the bulk handling type (for example, truck, rail car, or barge) the discharge control can be a simple open-close valve. Water collecting, tracked, hopper valves with remote motor or air cylinder operation can be used for this control. Facilities whose storage volume exceeds the discharge transport system capacity or whose transport system is of the continuous rate type (for example, conveyor belts, screw conveyors, and pipelines) must be provided with a discharge system capable of infinite variability under all degrees of moisture content or concentration. Such systems must be provided with remote controls that are capable of detecting overloads prior to their overwhelming the transport system. The controls must be capable of automatically closing the discharge control system's back-up, open-close isolating valve. Sonic level detectors and capacitance probes can be used for this function. Chapter 17 provides additional information on this type of level detection instrumentation.

The use of polymers to condition the sludge prior to dewatering can have a major effect on its ability to be stored conveniently in the dewatered state. Hansen reports that high polymer doses used experimentally (testing a belt filter press) at the Los Angeles County plant created a dewatered sludge that was quite viscous. This material tended to act like glue and was extremely difficult to remove from conveyors especially at transfer points and the head point above the hoppers. The material could be stored, but required a positive type of unloading system at the storage discharge to assure that the lumps were pushed onto the discharge conveyor.

When exceptionally dry dewatered sludge (greater than 30 percent solids) is stored, bridging can be a very difficult problem. None of the facilities investigated had successfully solved this problem. It is suggested that any large system which anticipates storing dewatered sludge much dryer than 30 percent solids set up a test facility to develop a reliable system for overcoming this difficulty.

Performance Data

Probably one of the most successful confined bin dewatered sludge storage facilities is located at the County Sanitation Districts of Los Angeles County Joint Water Pollution Control Plant in Carson, California. The Joint Water Pollution Control Plant (JWPCP) provides advanced primary wastewater treatment for about 350 MGD (15.3 m^3/s) of wastewater. The JWPCP also receives the sludge from five tertiary treatment plants that employ activated sludge followed by multimedia filtration and have a combined capacity of 120 MGD (5.2 m^3/s). Sludge from all six plants is treated at the JWPCP using the anaerobic stabilization (digestion), dewatering (centrifugation), and composting (windrow) processes.

In June 1979, Mischeri reported the centrifuges were producing about 400 to 600 wet tons (360 to 540 t) of dewatered digested sludge each day with a 25 percent average solids content. Twelve storage bins, each capable of holding 550 wet tons (500 t) of dewatered sludge, are provided to equalize 24-hour-per-day centrifuge production with 10-hour-per-day windrow construction. The storage bins also provide the five-day storage needed to assure continuous dewatering when both the composting and backup sanitary fill disposal options are unavailable due to excessive rainfall. The facilities have been in service about three years, and according to Hansen, the maximum period of disposal unavailability has not exceeded two days to date, although there have been times when all twelve of the bins have been filled with dewatered sludge. An isometric sketch of the JWPCP storage and truck loading station is shown on Figure 15-17.

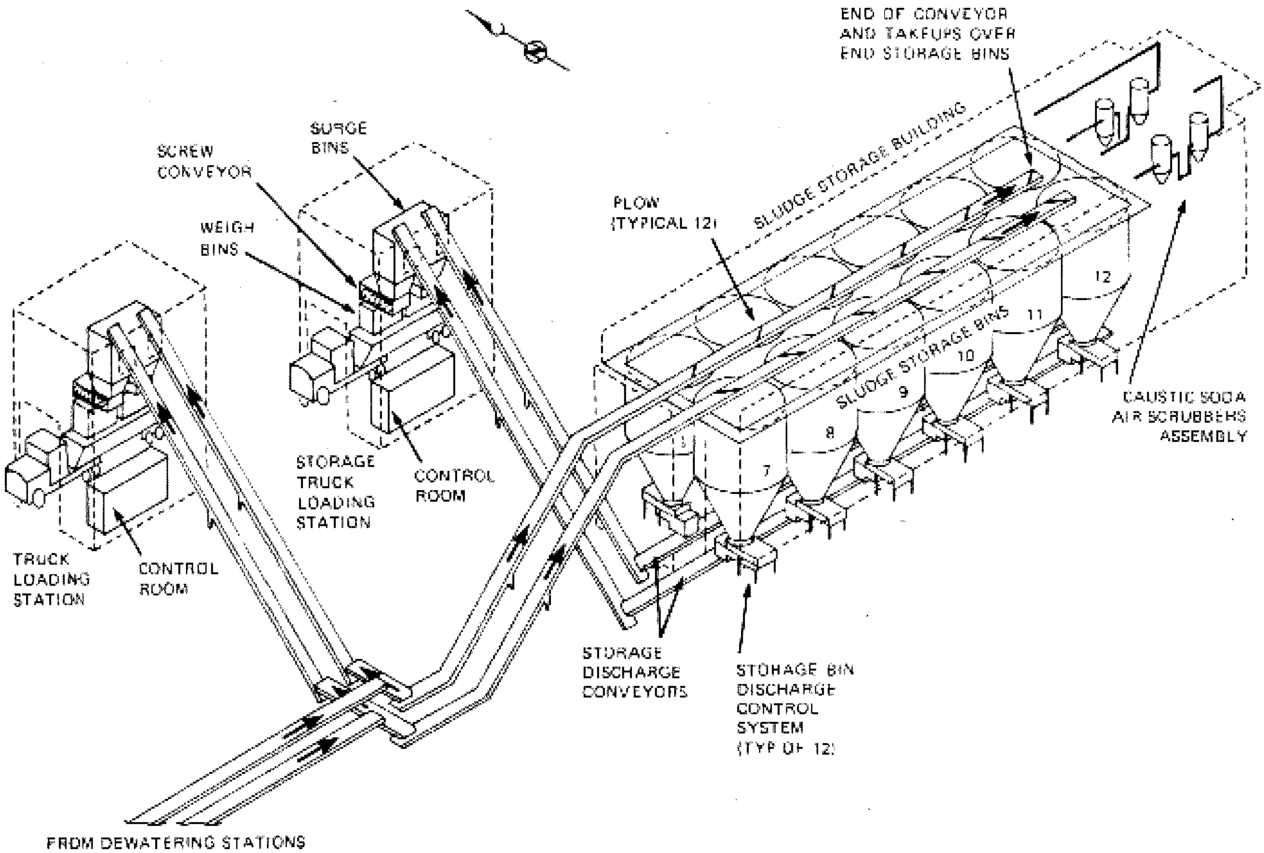

FIGURE 15-17

ISOMETRIC OF SLUDGE STORAGE AND TRUCK LOADING STATION, JOINT WATER POLLUTION CONTROL PLANT, LOS ANGELES COUNTY, CALIFORNIA

The upper and end areas of the JWPCP storage facilities are completely enclosed with metal cladding and equipped with positive supply and exhaust ventilation. The potentially most odorous ventilation air is passed through caustic wet scrubbers prior to discharge to the atmosphere. There is some indication that additional activated carbon scrubbing may be required to assure complete removal of all odors. Although the supply and discharge areas of the storage buildings are continuously monitored for explosive conditions, Hansen reports little methane gas seems to be generated as long as the dewatered sludge solids content is greater than 18 percent and the sludge is not left in storage more than a few days. Bubbles, which can be observed in the standing water on top of the stored sludge, attest to the fact that decomposition is continuing in the bins.

Each storage bin is fabricated of steel, is 30 feet in diameter, and tapers at the bottom to a five-foot-square discharge. The taper is at 30 degrees off the vertical. Hansen indicates this taper seems to eliminate bridging, except during the storage of extremely dry (greater than 30 percent solids) sludge. The five-foot-square (1.5-m square) discharge is equipped with five 12-inch (30.5 cm) diameter continuous screw conveyors (live-bottom system) that can be operated in any combination or number to positively control the stored sludge discharge to the discharge conveyor belt. Normal operation requires only the three middle screw conveyors to be in service. A cylinder-type plug valve with five ten-inch (25.4-cm) long by eight-inch (20.3-cm) wide openings has been provided to assure positive isolation between the live-bottom system and the discharge conveyor. The plug valve is fabricated of 0.406-inch (1.03 cm) steel wall, 12-inch (30.5 cm) O.D. steel pipe, approximately five feet (1.5 m) long and is actuated by a pneumatic cylinder that positively rotates the valve 90 degrees from a full open to a tight shut-off position. An isolating bull gate that can be hydraulically forced between the bottom of the storage bin and the top of the live-bottom assembly is also provided. It can be used to cut off sludge discharge should the live-bottom assembly fail with a load in the hopper. It has been suggested that a hydraulically operated gate valve or knife-gate valve could also be used to provide this isolation. An isometric view of this discharge control system is shown on Figure 15-18.

Hansen reports the storage facilities were built in 1973 at a cost of $3 million. Sludge variability during start-up created several problems that have now been successfully solved (24). Solutions included: simplifying the supply to the storage tanks by equipping each with a plow and moving the end of the supply belts over the end hoppers; providing the live-bottom discharge system with a positive discharge isolation valve; and increasing the ventilation level in the supply and storage areas to achieve the "breeze" atmosphere necessary to satisfy operator safety concerns.

15.3.2.3 Unconfined Stockpiles

Unconfined stockpiles are a major method of providing long-term storage for dewatered sludge. This method is used primarily for the storage of air-dried, anaerobic or aerobic stabilized sludge at thousands of small plants across the country. Probably the largest storage and weathering installation is operated by the Metropolitan Sanitary District of Greater Chicago (MSDGC) at their West-Southwest Sewage Treatment Works (WSW-STW). All of the air-dried Imhoff sludge at WSW-STW is stored and aged up to several years on between 50 and 100 acres (20 and 40 ha) of land and then made available for delivery to the public as "Nu-Earth" (23). The air-dried material weathers to less than 50 percent moisture after one to two years of aging.

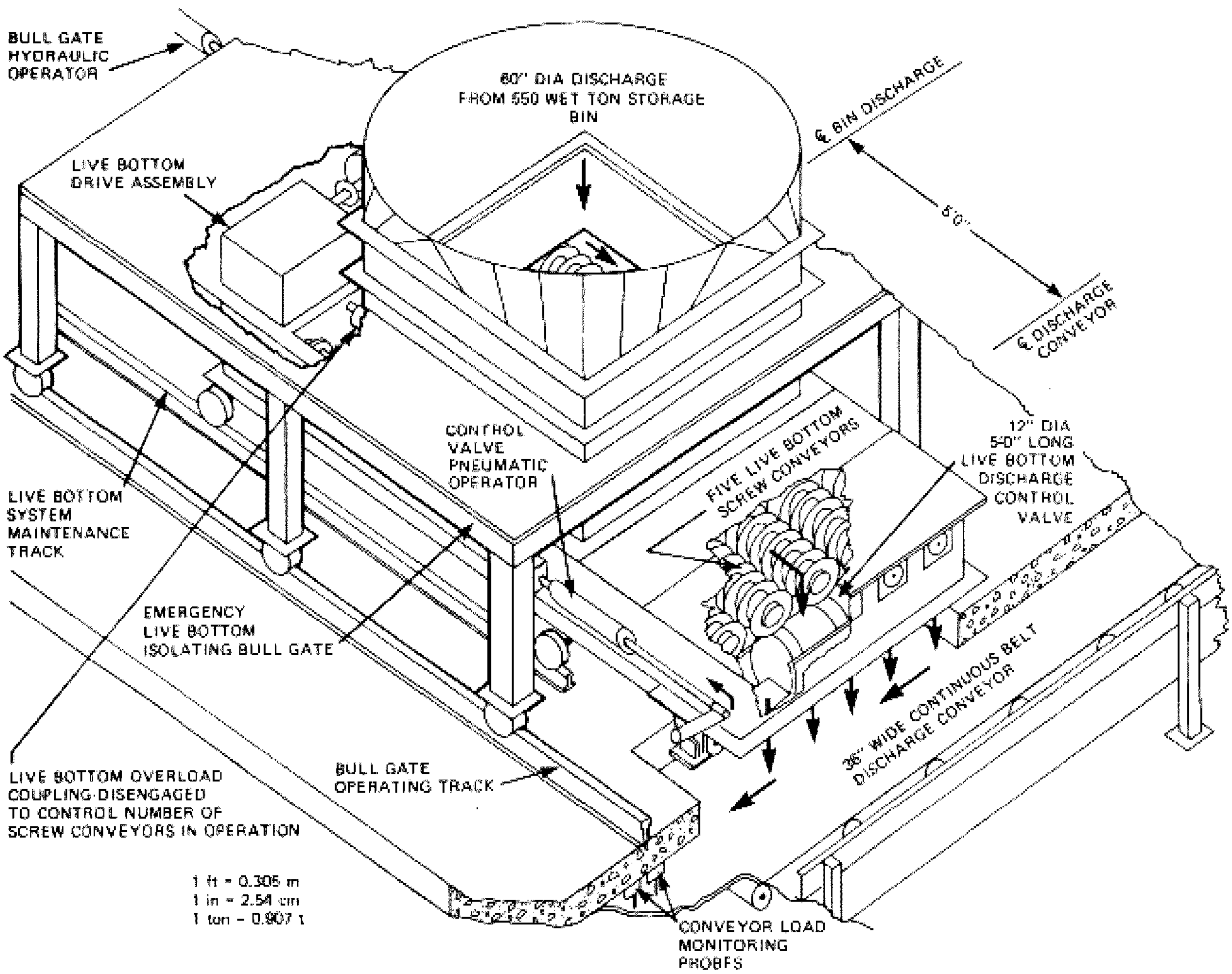

FIGURE 15-18

STORAGE BIN DISCHARGE CONTROL SYSTEM, JOINT WATER POLLUTION CONTROL PLANT, LOS ANGELES COUNTY, CALIFORNIA

Unconfined stockpiles of mechanically dewatered stabilized sludge, which has less than 25 percent solids, usually are destroyed (loose all semblance of stability) when exposed to extensive rainfall. While it is possible to maintain such a stockpile for equalizing or short-term storage, especially in very dry climates like the southwest, long-term storage is usually quite impossible. Stabilized sludges with a high chemical content (greater than 40 percent lime plus some ferric) or a very low organic content (less than 50 percent volatile solids) sometimes prove to be exceptions. Highly stabilized lagooned sludges can also be one of these exceptions. Such open stockpiles usually quickly absorb atmospheric moisture and rapidly deteriorate in climates with intense or frequent rainfall.

Covered stockpiles are often used in those areas where rainfall is intense or frequent to assure the dewatered sludge integrity during periods of equalizing storage. Such stockpiling is usually limited because of the expense of developing covered areas of sufficient size to provide adequate storage area and equipment accessibility. The North Shore Sanitary District (NSSD) (25), north of Chicago, Illinois, disposes of their anaerobically stabilized (digested) dewatered sludge in deep trenches on a 300 acre (121 ha) site. During 10 to 20 days per year, the NSSD disposal operation is abandoned due to wet conditions, and the dewatered sludge is stored in a covered and enclosed building for disposal within a few days. The building is enclosed to maintain odor control. The District also frequently liberally sprinkles the dewatered sludge with lime during transport and storage to maintain odor control.

Unfortunately, no quantitative work has been published regarding the odor risk of stockpiling dewatered sludge. Drying lagoons, like those operated at San Jose, California, do create malodorous conditions in surrounding urban areas during or immediately after being wetted by rainfall. Work in Sacramento, California, however, indicates that odors are generated cumulatively in direct relationship to the area covered by the odor producing sludge (1). Good housekeeping around such stockpiles is mandatory to assure proper rodent control.

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chater 16. Sidestreams from Solids Treatment Processes

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
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CHAPTER 16

SIDESTREAMS FROM SOLIDS TREATMENT PROCESSES

Sidestreams are a major reason why solids treatment and disposal facilities often become trouble spots at wastewater treatment plants. Failure to account for these sludge processing liquors in the wastewater treatment design can result in overloading of the treatment facility. It has been conventional practice to return sludge sidestreams to the treatment plant at a convenient point, usually at the headworks, with no pretreatment and with little concern for its pollutant loadings. These sidestreams can increase the organic loading by 5 to 50 percent, depending on the type and number of solids treatment processes used.

The major objectives of this chapter are to describe the sidestreams produced by sludge treatment processes, factors that affect sidestream quality, and options available to designers in managing the sidestreams. Information on the pollutant loads of the sidestream produced by a particular process is presented in the chapter dealing with that process.

16.1 Sidestream Production

Sidestreams are produced when wastewater solids are concentrated, and when water, usually plant effluent, is used to remove odors or particulate matter from flue gases, or to wash and transport debris from structures and equipment. Some sidestreams require special attention because of their impact on a wastewater treatment plant's efficiency.

Usually several sidestreams are produced at a particular plant. Figure 16-1 is a flow diagram showing eight wastewater solids sidestreams: (1) screenings centrate, (2) grit separator overflow, (3) gravity thickener supernatant, (4) dissolved air flotation subnatant, (5) decantate following heat treatment, (6) vacuum filter filtrate and washwater, (7) scrubber water from furnace flue gas cleanup, and (8) overflow from biological odor removal system.

This chapter devotes special attention to the most pronounced examples of the problem--anaerobic digester supernatant and thermal conditioning liquor. For additional information on production and treatment of wastewater solids sidestreams, several publications are available. Municipal Wastewater Treatment Plant Sludge and Liquid Sidestreams deals with sidestreams from several solids handling and treatment processes (1).

Effects of Thermal Treatment of Sludge on Municipal Wastewater Treatment Costs describes the increased wastewater treatment capacity required by use of thermal conditioning (2).

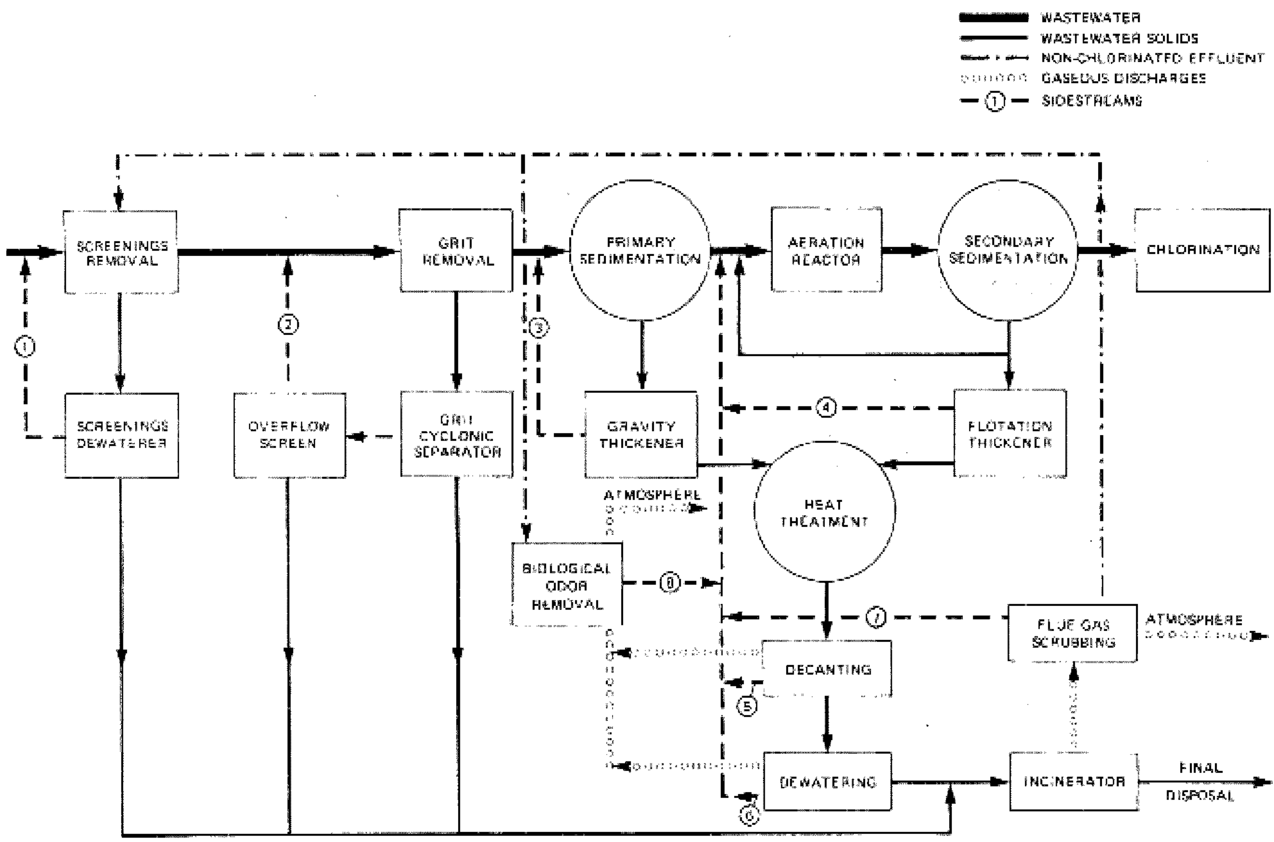


FIGURE 16-1

EXAMPLE OF SIDESTREAM PRODUCTION

16.2 Sidestream Quality and Potential Problems

The interrelationship between a wastewater treatment plant's effluent quality requirements and the processes used for solids treatment and disposal must be carefully scrutinized during planning and design to avoid problems caused by sidestreams. Generally, more sophisticated wastewater treatment plants produce greater quantities of more difficult-to-manage biological and chemical sludges. When processed, these sludges may indirectly cause the production of sidestreams containing large quantities of soluble and colloidal materials including nutrients.

Sidestream quality from a specific process is strongly affected by upstream solids handling processes. Vacuum filter filtrate and washwater quality, for example, are determined by the upstream conditioning or stabilization process.

Sidestreams should be returned to points in the wastewater treatment process which will result in treatment of the side-stream and prevent nuisances and operational problems. The return points shown on Figure 16-1 comply with this requirement.

Runoff from sludge composting areas and leachate from sludge landfilling areas may pose a unique problem, since it may be difficult and costly to return them to the treatment plant if the landfill or composting site is remote from the treatment facility. Chian and DeWalle extensively investigated the composition and treatment of sanitary landfill leachate, including anaerobic biological filtration, chemical precipitation, chemical oxidation, and activated carbon treatment (3). Data are also available on groundwater monitoring near sewage sludge or combined solid waste sewage sludge landfills (4,5,6). In addition, USEPA's Process Design Manual, Municipal Sludge Landfills, discusses methods of handling leachate (7). In dry climates, leachate can often be recycled to the landfill site.

At Beltsville, Maryland, runoff from a composting site is stored in a pond and periodically sprayed on a forest floor. Monitoring wells have been installed, and no groundwater contamination has been detected. At Durham, New Hampshire, and Bangor, Maine, runoff is recycled back to the treatment works without pretreatment. At Sacramento, California, runoff has been returned from a dedicated land disposal site to the plant headworks and has been monitored for several parameters (8). It was found that runoff is polluted with constituents, particularly the first runoff following the spreading of sludge. The concentrations of insoluble constituents such as heavy metals, however, were low.

16.3 General Approaches to Sidestream Problems

Several general approaches to preventing or solving problems that may result from sidestreams can be identified:

- Modification of solids treatment and disposal systems to eliminate particular sidestreams.
- Modification of previous solids processing steps to improve sidestream quality from a particular solids treatment process.
- Changing the timing, return rate, or return point for reintroducing sidestreams into the wastewater treatment process.
- Modification of wastewater treatment facilities to accommodate sidestream loadings.
- Provision of separate sidestream treatment prior to return.

Potential applications for each of these are described.

16.3.1 Elimination of Sidestream

Although not generally practical, specific situations arise in which it is possible to modify the solids treatment and disposal system and eliminate a troublesome sidestream. A particular case involves anaerobic digester supernatant, which has often been identified as a source of problems when a mixture of primary and waste-activated sludges is digested. Mignone has pointed out that where mechanical dewatering follows anaerobic digestion, it would be beneficial to eliminate the secondary (unmixed) digester by converting it to a primary mode (9,10,11). There would be no variable supernatant stream, only a predictable filtrate or centrate stream of low solids content which would be amenable to biological treatment.

16.3.2 Modification of Upstream Solids Processing Steps

Thickening of sludge prior to anaerobic digestion by the use of gravity, flotation, or centrifugal thickeners can improve the quality and reduce the quantity of digester supernatant (12). Residence time in the digesters is increased and/or smaller digesters can be constructed. Liquor that would otherwise be produced by the secondary digester as supernatant is produced instead in the thickening step. Its quality will be better, and it will have a lesser impact when returned to the wastewater treatment facility.

Other digester operating parameters such as organic loading and temperature also affect supernatant quality. An increase in organic loading will generally result in poorer supernatant quality (13). Thermophilic digestion produces poorer supernatant quality than mesophilic digestion.

Substitution of an equivalent solids treatment process for another may also reduce sidestream problems. For example, substitution of chemical conditioning for elutriation or heat treatment can reduce the level of contaminants in sidestreams from subsequent dewatering steps.

The high colloidal content of elutriate has been successfully reduced in several instances by addition of chemicals, particularly polymer, to the elutriation process. In 1973 the sludge treatment system at the District of Columbia's Blue Plains plant (a 253-MGD [11.1-m^3/sec] facility) consisted of gravity thickening, single-stage anaerobic digestion, elutriation of digested sludge, chemical sludge conditioning, and vacuum filtration. Large quantities of fines and activated sludge solids were recycled with the elutriate, and the primary clarifiers and aeration process could not accommodate them. Solids accumulated in the plant; upsets occurred in both the wastewater and sludge treatment systems; and it became necessary to temporarily discharge elutriate directly to the plant effluent. Eventually, addition of polyelectrolyte to the elutriation process, coupled with intensive effort on the part of plant staff to improve elutriation and vacuum filtration performance, resulted in a 90 percent solids capture through the two processes.

The Metropolitan Toronto main plant and the Richmond, California, facility experienced the same results as the Blue Plains plant. An example of successful use of polymer to improve elutriation is shown in Table 16-1 (14).

TABLE 16-1

EFFECT OF POLYMER ON ELUTRIATION (14)

Parameter	Before polymer use	After polymer use
Elutriate suspended solids, mg/l	3,385	365
Solids capture, percent	65.1	95.3
Underflow solids concentration, percent	3.5	4.3

16.3.3 Change in Timing, Return Rate, or Return Point

Sidestreams are normally returned to the wastewater treatment facilities at the plant headworks. In general, return of sidestreams to plant headworks should be at a low, steady rate rather than in slugs, since these are likely to cause upsets and overloads. In instances where there are high diurnal load fluctuations and the plant is approaching capacity, consideration should be given to returning sidestreams during off-peak hours, thus equalizing wastewater loadings. Adverse effects on primary treatment facilities, such as septicity, odors, and floating sludge can be avoided by returning sidestreams to the biological treatment process influent. Alternatively, mixing supernatant with waste-activated sludge before returning it to the headworks may also aid in reducing odors because of the adsorptive nature of the activated sludge particles.

16.3.4 Modification of Wastewater Treatment Facilities

Liquid treatment facilities should be designed with the capacity to treat recycled sidestreams whenever the sidestream will contain significant concentrations of pollutants or have a large hydraulic impact. Table 16-2 shows an example of the effect of supernatant return on suspended solids and phosphorus loadings at an activated sludge plant using two-stage anaerobic digestion (15). Table 16-3 shows estimated increases in BOD_5 treatment capacity required by sidestreams from several sludge treatment processes (16).

TABLE 16-2

EFFECT OF SUPERNATANT RETURN (15)

	Suspended solids, lb/day		Phosphorus, lb/day	
Point of measurement	With supernatant return[a]	Without supernatant return	With supernatant return[a]	Without supernatant return
Raw wastewater	10,520	16,035	756	857
To primary clarifiers	36,801	15,969	1,304	914
To secondary clarifiers	15,306	9,501	991	803
Final effluent	3,467	2,836	435	500
Primary sludge	19,626	13,249	299	156
Waste activated sludge	14,645	9,593	453	287

[a]Returned ahead of primary clarifiers.

The Central Contra Costa Sanitary District Water Reclamation Plant, an advanced waste treatment facility, removes nutrients through chemical-primary treatment and nitrification-denitrification. Recycled sidestreams were taken into account in plant design by allowing for additional loads of 12 percent for BOD_5 and 21 percent for suspended solids. Recycled streams include gravity thickener overflow, centrate from a two-stage dewatering centrifuge, and drainwater from a wet scrubber.

Sidestreams may contain compounds that are difficult to remove in wastewater treatment facilities. For example, the nonbiodegradable COD in heat treatment liquor will pass through normal secondary treatment unchanged. Digester and sludge lagoon supernatant may contain high concentrations of nutrients. In some instances separate treatment may be appropriate. The Metropolitan Sanitary District of Greater Chicago has conducted several investigations involving nitrification and nitrogen removal from sludge lagoon supernatant, using both attached growth and suspended growth biological processes (17,18,19).

In evaluating solids treatment and disposal processes, both the direct costs of the solids treatment and disposal systems and the indirect costs associated with return of sidestreams to the wastewater treatment facilities should be included in the cost-effectiveness analysis. The cost of handling the increased sidestream flows may or may not be negligible, but capital and operating expenses will surely increase as a result of the BOD_5 and suspended solids load of the returned stream. Major components of such indirect costs include increased aeration tank size and blower capacity (for diffused air-activated sludge systems), increased sludge treatment capacity, increased power requirements for blowers, and increased labor for operating and maintaining more heavily loaded secondary treatment facilities. Additional costs will also be incurred if odor control facilities are required.

TABLE 16-3

ESTIMATED INCREASE IN WASTEWATER STREAM BIOLOGICAL TREATMENT CAPACITY REQUIRED TO HANDLE SIDESTREAMS FROM VARIOUS SOLIDS TREATMENT PROCESSES (16)

Treatment process	Required capacity increase, percent
Liquid sludge to land	0
Raw sludge to drying beds	7
Chemical conditioning and filter pressing	6 - 11
Rotoplug dewaterer	10 - 30
Digestion and drying beds	0.6
Digestion, chemical conditioning, and filter pressing	5
Digestion, chemical conditioning, and vacuum filtration	4
Heat treatment of raw sludge	30
Heat treatment of digested sludge	7

Indirect solids treatment costs for handling sidestreams will vary significantly. The indirect costs associated with heat treatment have been estimated as 20 percent of the direct thermal treatment costs. A report has been prepared describing the effects of sludge heat treatment on overall wastewater treatment costs (2).

16.3.5 Separate Treatment of Sidestreams

Most sidestreams from properly operating solids treatment and disposal systems can be recycled to the wastewater treatment facilities without significant problems. In many cases two-stage, anaerobic digester supernatant return to the wastewater treatment facilities causes operating difficulties. Heat treatment is less widely used, but it results in conversion of some of the COD to the soluble form. Furthermore, a portion of the COD can be nonbiodegradable.

16.3.5.1 Anaerobic Digester Supernatant

In most cases, BOD_5 and suspended solids are of concern, although under certain circumstances, nitrogen and phosphorus removal may also be desirable. Anaerobic digester supernatant characteristics are summarized in Chapter 6, and typical values are given as a part of the example on Figure 16-2. Table 16-4 lists possible treatment processes for each major constituent (20). Chemical treatment of digester supernatant has been studied for many years (21,22,23). Rudolfs and Gehm studied coagulation using ferric chloride, lime, caustic soda, sulfuric acid, chlorine, bentonite clay, and zeolite (21). It was found that a lime/ferric chloride combination gave the best results and 150 mg/l ferric chloride and 1,200 mg/l lime reduced turbidity from 420 to 110 units.

The carbon dioxide in digester supernatant will react with the lime to form calcium carbonate precipitate. Lime requirements and the quantity of lime sludge produced can be reduced significantly by first air stripping carbon dioxide from the supernatant. This may also release odors, and for this reason, its use should be approached with caution. Because lime raises the pH of the supernatant and under high pH conditions the ammonia molecule tends to be in the nondissociated form, ammonia stripping can be affected after coagulation. The relatively high temperature of digester supernatant also aids ammonia stripping for the same reason.

Figure 16-2 shows a possible treatment scheme for digester supernatant based principally on chemical coagulation (20). Also shown are probable removals and common influent and expected effluent concentrations. Straight aeration of digester supernatant at plant scale has also been attempted (12,24,25). Even where the supernatant after aeration was not settled prior to return and no discernible improvement in quality resulted, it was found that wastewater treatment operation improved, probably as a result of better settling in the primary clarifiers.

Biological filters, either aerobic or anaerobic, appear to be feasible methods of biologically treating digester supernatant. The Greater London Council studied aerobic biofilter treatment of supernatant liquor using coke as the filter medium (26). At a 1:1 dilution with clarified plant effluent, 85 to 90 percent BOD_5 removal and 60 percent ammonia removal were obtained.

Howe suggested storage of digester supernatant in lagoons for long periods to reduce contaminant levels (22). In one experiment, a detention time of 60 days reduced BOD_5, suspended solids, color, and ammonia by about 85 percent; hydrogen sulfide was reduced by approximately 95 percent. Facultative sludge lagoons designed for long-term storage have been found to reduce levels of all contaminants except ammonia (see Chapter 15).

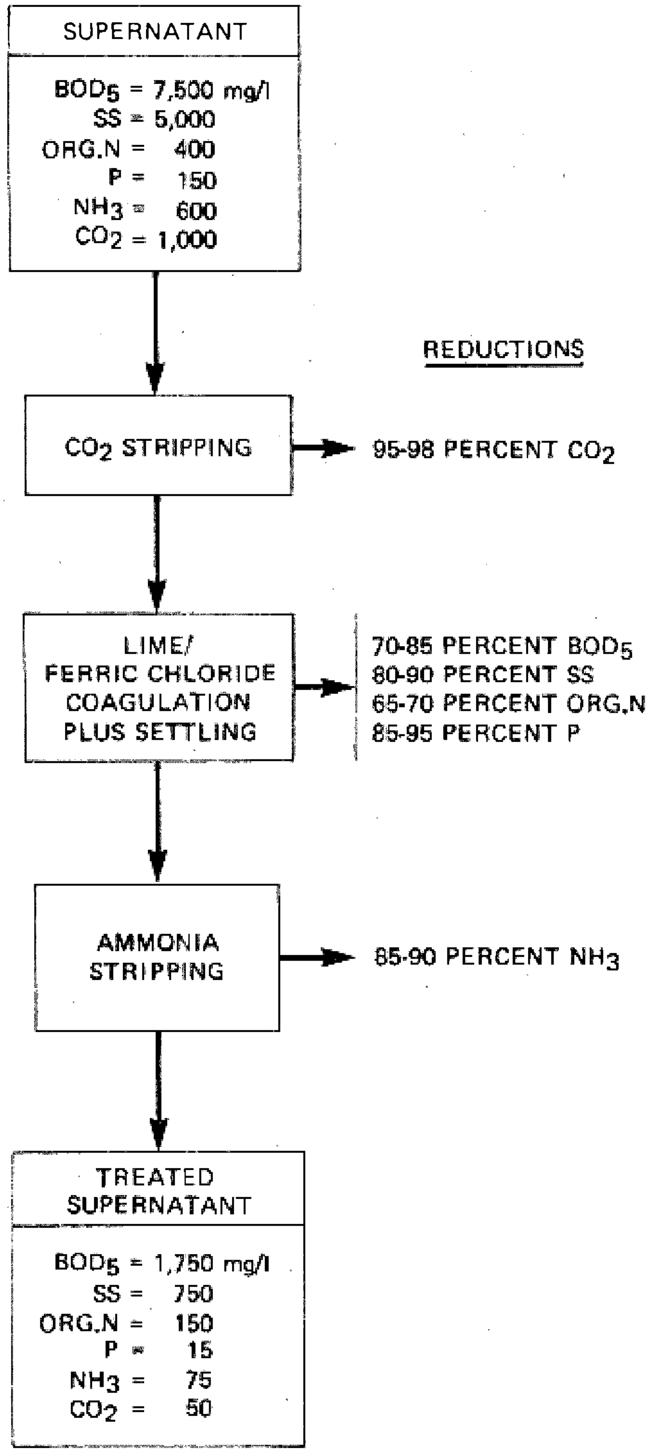


FIGURE 16-2

POSSIBLE TREATMENT SCHEME
FOR ANAEROBIC DIGESTER SUPERNATANT (20)

TABLE 16-4

POSSIBLE DIGESTER SUPERNATANT TREATMENT PROCESSES (20)

Constituent	Processes
Suspended solids	Coagulation, settling, microstraining
BOD_5	Removal with suspended solids, stripping of volatile acids, biological treatment, adsorption on activated carbon
Phosphorus	Removal with suspended solids, chemical precipitation, ion exchange
Nitrogen	Removal with suspended solids (limited), ammonia stripping, ion exchange
CO_2	Lime addition, air stripping

The chlorine stabilization process (see Chapter 6) has also been used to treat digester supernatant before it is returned to the treatment plant (Table 16-5). Low chlorine doses (100 to 300 mg/l) have little effect on BOD_5 and COD levels, but according to the manufacturer, they may be used to reduce odors and improve treatability of the supernatant. Very high dosages (1,500 to 2,000 mg/l) are required to appreciably reduce the levels of oxygen demanding materials in the supernatant liquor.

16.3.5.2 Thermal Conditioning Liquor

Heat treated sludge liquor, which is received as decantate and filtrate or centrate, contains high levels of soluble pollutants and a significant fraction of nonbiodegradable COD. The color level of the liquor may also be high, affecting the color of the final effluent (27). Furthermore, chlorination of effluent containing recycled heat treatment liquor may cause taste and odor problems if the receiving stream is used for drinking water supply (28).

Loll has cited average BOD_5 loading increases of 7 to 15 percent and COD increases of 10 to 20 percent at wastewater facilities recycling untreated liquor (29). Recycle of heat treatment liquor at Colorado Springs, Colorado, caused the BOD_5 loading to be increased by 20 percent and the suspended solids load by 30 percent (27).

TABLE 16-5

CHLORINE TREATMENT OF DIGESTER SUPERNATANT

Parameter	Value[a]					
	Untreated supernatant	Supernatant treated at indicated chlorine dose, mg/l				
		500	1,500	1,800	1,900	2,000
Suspended solids, percent	1.9	1.7	1.8	1.7	1.7	2.0
Chlorine residual, mg/l	0	0	0	10	80	190
pH	6.8	5.8	5.5	4.8	4.4	2.7
Specific conductance, micromhos	1,950	2,750	2,380	2,500	2,600	4,500
Alkalinity, mg/l	1,100	170	83	60	32	0
BOD_5, mg/l	2,600	2,600	2,600	2,200	2,000	1,500
COD, mg/l	43,900	43,100	40,800	32,000	31,200	20,200
Total nitrogen, mg/l	2,100	2,200	1,900	1,600	1,400	1,100
Total phosphate phosphorus, mg/l	510	430	440	400	380	260

[a]Based on results obtained with Purifax laboratory unit.

Trickling filters, the activated sludge process, anaerobic biological filtration, and aerobic digestion have been used to treat the liquor. To reduce the nonbiodegradable COD, activated carbon has been used. Ozonation or chlorination can also be used to reduce COD levels.

Loll has described experiments using autothermal thermophilic aerobic digestion of heat treatment liquors (29). Because the reactions are exothermic, the process is thermally self-supporting.

Presented on Figure 16-3 are the results of batch aerobic digestion tests. Note that the temperature rose during the period of most rapid degradation. The results of continuous flow tests are presented in Table 16-6 at residence times of five and ten days. The COD reduction is significantly less than the BOD_5 reduction, reflecting the nonbiodegradable character of a portion of the waste.

Erickson and Knopp used the activated sludge process for heat treatment liquor (30). They reported a COD reduction of 83 percent and a BOD_5 reduction of 98 percent with an aeration time of 41 hours. Results are shown in Table 16-7, (page 16-14).

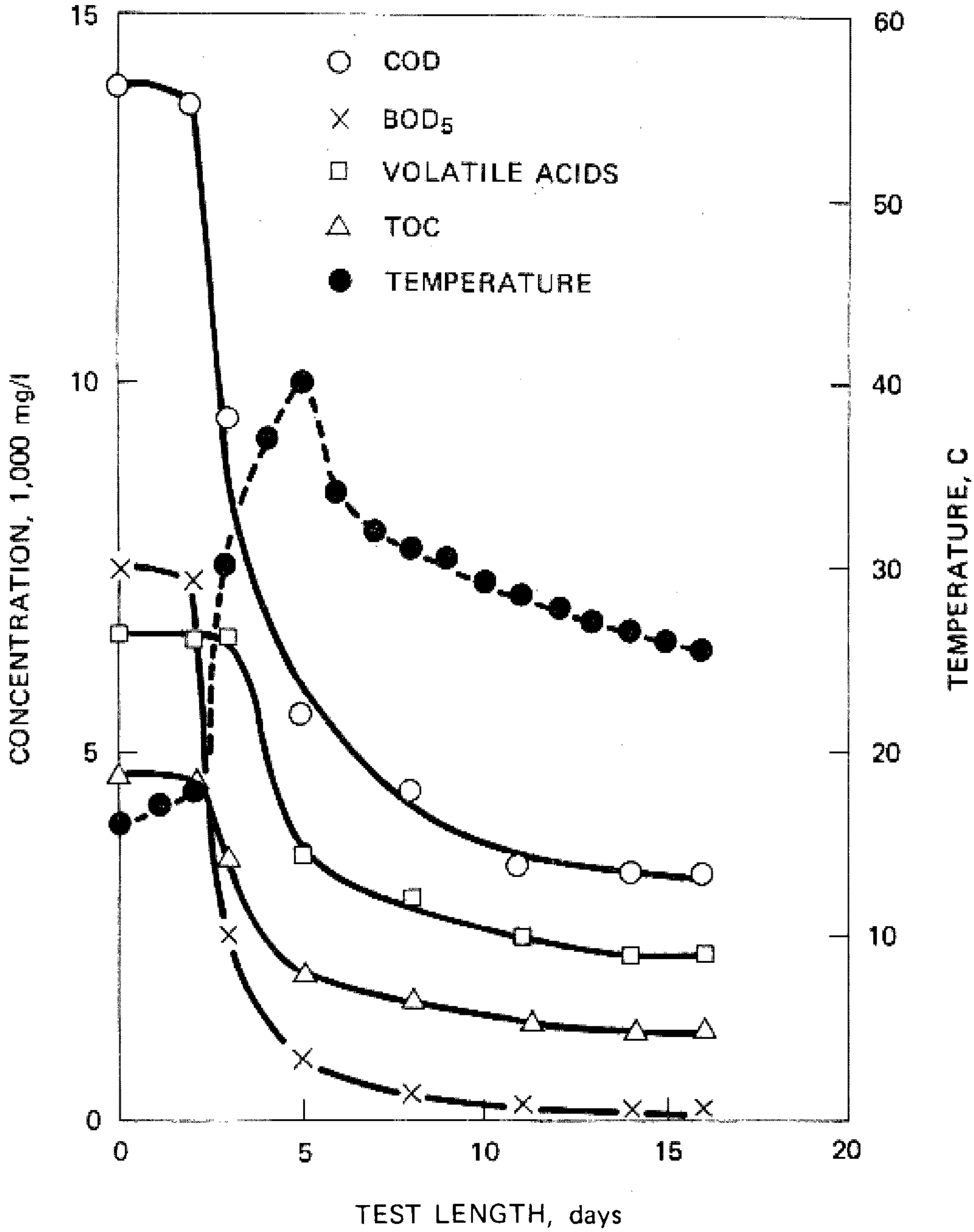


FIGURE 16-3

AEROBIC DIGESTION OF
HEAT TREATMENT, BATCH TESTS (29)

Anaerobic biological filtration of heat treatment liquor has been tested for use at the City of Los Angeles Hyperion treatment plant (31). The waste-activated sludge treatment scheme is shown on Figure 16-4. The anaerobic filter, originally developed by Young and McCarty is similar to the conventional aerobic trickling filter in that organisms are attached to the media surface and a short hydraulic detention time results (32). Advantages are that the production of methane can result in energy recovery and that no power is required for oxygen addition. Care must be taken, however, to avoid any plugging from periodic high suspended solids loadings. Results of a two-month test are shown in Table 16-8 (31). At a hydraulic detention time of two days, BOD_5 and COD removals averaged 85 and 76 percent, respectively. This study concluded that detention time could be reduced to about 0.5 to 1.0 days without significant deterioration in performance. Other pilot scale tests on anaerobic filtration of heat treatment liquor have been conducted. One study reported COD removals of approximately 65 percent at detention times of 3.5 days and organic loadings of 125 lb COD per 1,000 cubic feet per day (2.0 $kg/m^3/day$)(33).

TABLE 16-6

AEROBIC DIGESTION OF HEAT TREATMENT LIQUOR (29)

Parameter	Residence time, days	
	5	10
Temperature, °C	38	34
COD		
Influent, mg/l	13,500	12,400
Effluent, mg/l	4,100	3,800
Reduction, percent	66	71
BOD_5		
Influent, mg/l	6,900	6,100
Effluent, mg/l	510	250
Reduction, percent	94	96

Figure 16-5 illustrates the AS pilot treatment scheme used in a pilot study in Great Britain (28). The purpose of the study was to reduce the quantity of refractory organics entering the Thames River from treatment plants conditioning sludge with heat treatment. The study was prompted by the fact that the Thames is used for water supply, and possible taste and odor problems would result from chlorinating the water; in addition, there was uncertainity about the exact composition and effects of the organics in the liquor. The process can reduce COD from 20,000 mg/l to about 100 mg/l, or by approximately 99.5 percent.

The chlorine oxidation process can also be used for treating liquor from thermal sludge conditioning. BOD_5 and COD levels are reduced by approximately 25 to 35 percent. The odor is changed from noxious to chlorinous or medicinal. The color is changed from dark brown to yellow or tan which may allow the liquor to go undetected when diluted in the liquid stream. Results of a pilot test on Zimpro process liquor are shown in Table 16-9. A flow diagram indicating sampling point locations is shown on Figure 16-6.

TABLE 16-7

ACTIVATED SLUDGE TREATMENT OF THERMAL CONDITIONING LIQUOR (30)

Parameter	Aeration time, hours	
	21.8	40.9
Temperature, °C	33.4	31.7
COD		
Influent, mg/l	10,600	11,900
Effluent, mg/l	4,300	2,000
Reduction, percent	59	83
BOD_5		
Influent, mg/l	4,700	5,900
Effluent, mg/l	400	110
Reduction, percent	91	98

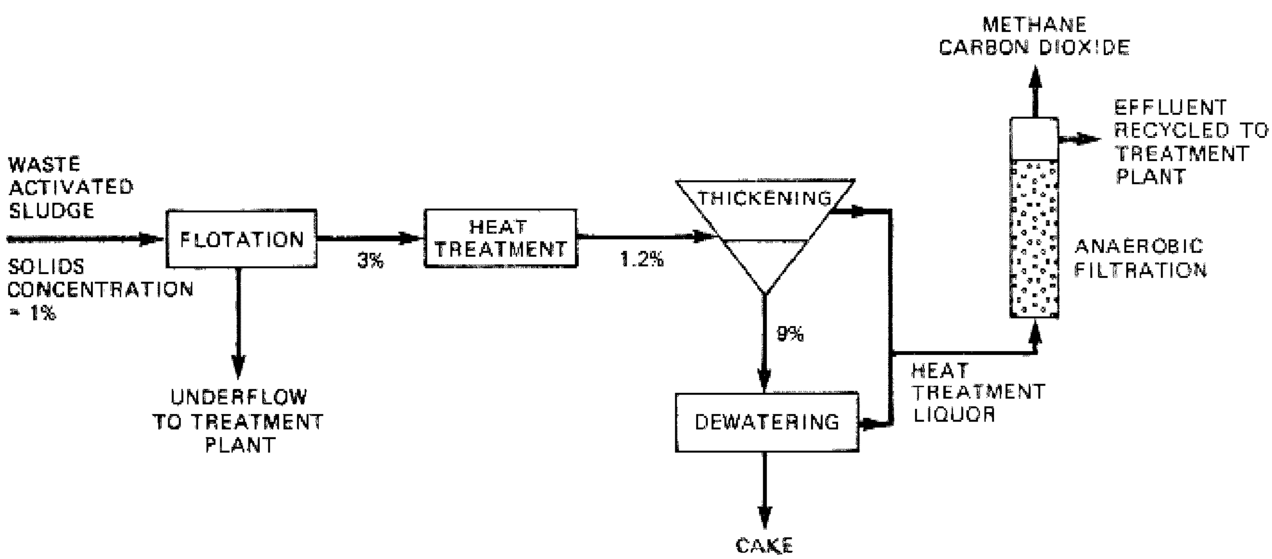


FIGURE 16-4

FLOW DIAGRAM, ANAEROBIC FILTRATION OF HEAT TREATMENT LIQUOR (31)

TABLE 16-8

AEROBIC BIOLOGICAL FILTRATION OF THERMAL CONDITION LIQUOR (31)

Parameter	Value
Hydraulic detention time, days	2.0
Temperature, °C	32
COD	
Influent, mg/l[a]	9,500
Effluent, mg/l	2,300
Reduction, percent	76
BOD_5	
Influent, mg/l[a]	3,000
Effluent, mg/l	450
Reduction, percent	85
Suspended solids	
Influent, mg/l[a]	110
Effluent, mg/l	100
Total solids	
Influent, mg/l[a]	8,800
Effluent, mg/l	4,900
Volatile acids	
Influent, mg/l[a]	520
Effluent, mg/l	300
Alkalinity, as $CaCO_3$	
Influent, mg/l[a]	2,200[b]
Effluent, mg/l	3,500
pH	
Influent[a]	7.1[b]
Effluent	7.1

[a]Decant liquor.

[b]pH following thermal conditioning was approximately 5.5; 1,600 mg/l alkalinity added to influent for pH adjustment.

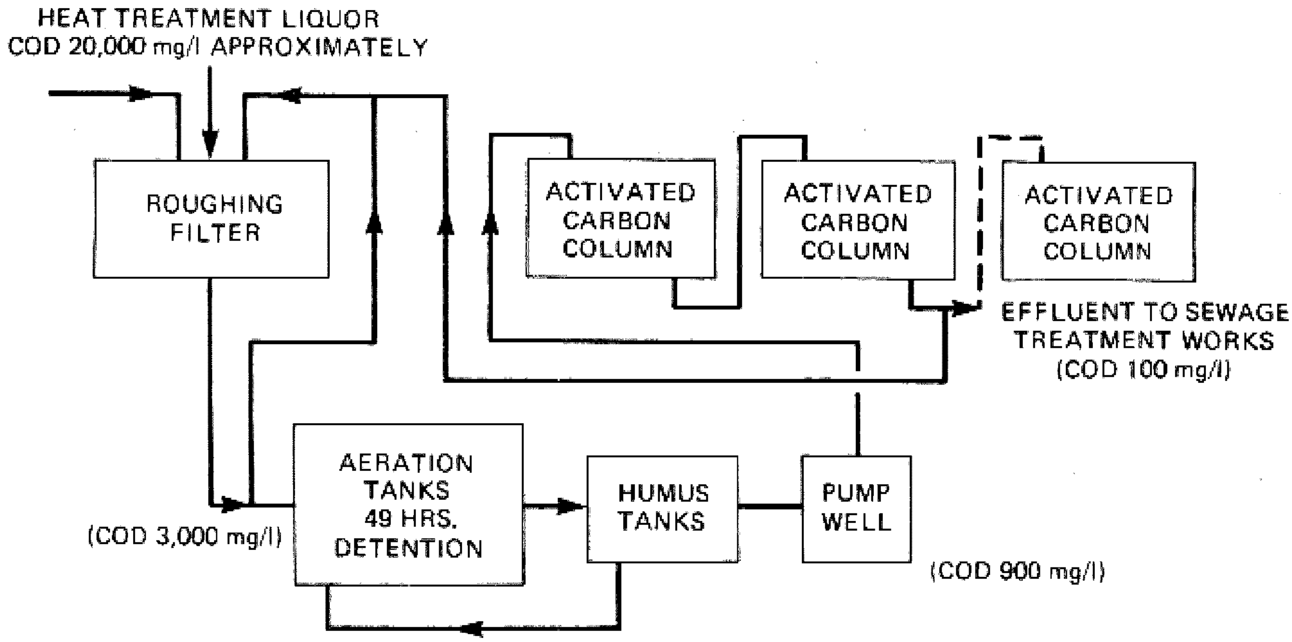


FIGURE 16-5

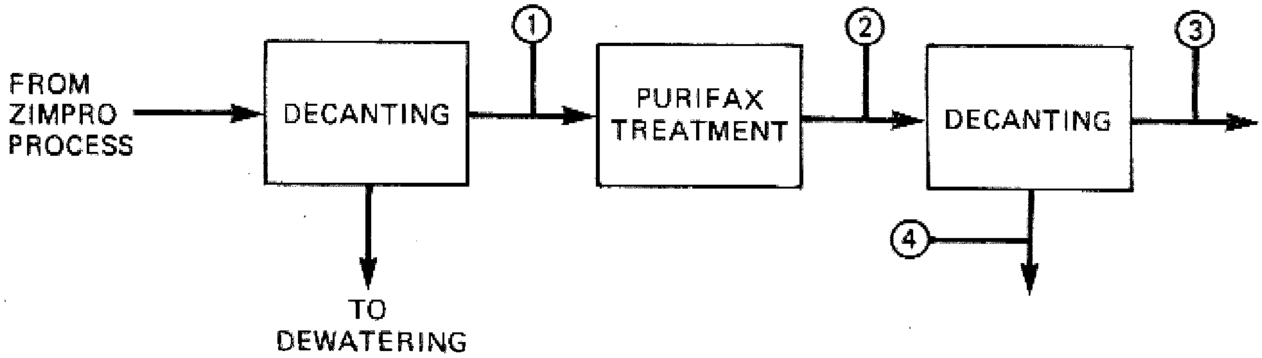
SCHEMATIC DIAGRAM OF PLANT FOR PROCESSING HEAT TREATMENT LIQUOR (2)

TABLE 16-9

CHLORINE OXIDATION TREATMENT OF THERMAL CONDITIONING LIQUOR

Parameter	Value[a,b] 1	2	3	4
COD, mg/l	40,664	31,280	3,910	70,380
Suspended solids, mg/l	19,300	15,400	172	51,600
Total solids, mg/l	24,500	16,800	5,700	52,000
Total volatile solids, percent	63.1	65.5	66.4	56.1
Ammonia, mg/l	225	209	209	269
Chlorine dose, mg/l	0	1,000	1,000	1,000
Chlorine residual after three hours, mg/l	0	0	0	0
pH	5.1	3.7	3.5	3.9

[a]For location of sampling point, see Figure 16-6.
[b]Data taken at Canton Water Pollution Control Center, May 10 and 11, 1977.



NOTE: CIRCLED NUMBERS DESIGNATE SAMPLING POINTS; SEE TABLE 16–9 FOR QUALITY DATA.

FIGURE 16-6

CHLORINE TREATMENT OF HEAT TREATMENT LIQUOR

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EPA 625/1-79-011

PROCESS DESIGN MANUAL FOR SLUDGE TREATMENT AND DISPOSAL

Chapter 17. Instrumentation

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 17

INSTRUMENTATION

17.1 Introduction

Wastewater solids treatment and disposal systems are generally under-instrumented in comparison to other treatment systems, such as those in water supply or chemical processing plants (1). While the economics and operating efficiencies of various measuring devices, control equipment, and operator interface displays should be carefully evaluated by the treatment system designer, increased use of instrumentation is recommended. This chapter examines instruments suitable for sludge treatment and disposal facilities.

17.1.1 Purposes of Instrumentation

Most of the measuring devices described in this chapter are "on-line" equipment designed for essentially unattended operation. However, some critical data can be obtained only by the use of portable test or laboratory equipment that requires manual operation or attention. On-line instrumentation serves the following purposes in a wastewater solids treatment system:

- Reduces labor
- Reduces chemical consumption
- Reduces energy consumption
- Improves treatment process efficiency and reliability
- Provides information for planning
- Verifies compliance with discharge requirements
- Assures personnel safety

17.1.2 Instrumentation Justification and Design Considerations

Some uses of instrumentation--for example, to reduce labor, chemical consumption, or energy consumption--will be justified primarily from an economics viewpoint. Economics may, however, be a secondary consideration in decisions to install instrumentation for any of the other purposes listed above. For instance, instrumentation for providing planning information and/or for verifying compliance with discharge requirements may be justified on non-economic grounds. The information provided may be essential for planning new facilities and/or improving existing facilities. Such information may also be required for monitoring treatment results for reports to various government agencies. Economic considerations will also be secondary for those systems requiring continuous monitoring to protect operating personnel.

Economic analyses of instrumentation, when required, must include both capital and operation and maintenance (O/M) costs. O/M costs can be high, especially in sludge management, where the materials being measured are usually debris-laden and sometimes corrosive. A 1976 USEPA study found that many wastewater treatment instruments are not properly operated or maintained and quickly fall into disuse (1). This is particularly true in small plants where the maintenance staff usually does not include full-time instrumentation specialists, and where contract instrumentation specialists are unavailable. The designer must consider whether proper operation and maintenance will be available before incorporating instrumentation into a plant's design. In larger plants (20 to 30 MGD [0.88 to 1.3 m^3/s]), O/M staffs should include full-time instrumentation specialists.

Aside from the cost evaluations and O/M requirements discussed above, several factors will influence the selection of instruments for a specific application. These include:

- Characteristics of the process fluid, particularly the water, grease, grit, and gas content and the degree of variability in the influent material from day to day.
- Configuration of process piping, channels, or vessels.
- Requirements relating to instrument measurement range and accuracy.
- Utility availability (instrument air, purge water, electricity, etc.).

The instrumentation information presented in Tables 17-1 through 17-12 is applicable to a wide variety of sludge treatment and disposal processes. The tables list the process and process variables, the measurements, and the suggested instruments for individual process steps in treatment and disposal. The specific instruments listed in these tables should be considered as candidates, not as specific recommendations.

More detailed information about the various instruments is available including illustrations, descriptions, and lists of manufacturers (2). Note, however, that although many specific instruments are used in both sludge processing and in conventional industrial processes, some manufacturers are not active in the wastewater field. The suitability of their instruments for sludge applications has not been established.

TABLE 17-1

THICKENING

Process and process variables	Measurements	Suggested instruments
Gravity Thickener		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Weir Pump displacement
Dilution water	Flow	Venturi Magnetic Ultrasonic Propeller Orifice
Tank sludge depth	Blanket level	Optical Ultrasonic
Supernatant	(See Table 17-12, Sidestreams)	
Collection equipment	Torque or power draw	Shearpin Ammeter
Thickened sludge	Flow	Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal Diaphragm
	Density	Nuclear Optical Ultrasonic
Polymer or chemicals	Level	Tape and float Capacitance Ultrasonic
	Flow	Magnetic Rotameter Pump displacement
	Weight	Static
Flotation Thickener		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler
	Pipe empty	Capacitance Nuclear
Thickened float or sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
Subnatant	(See Table 17-12, Sidestreams)	
Polymer or chemicals	Level	Capacitance Ultrasonic Tape and float
	Flow	Magnetic Rotameter Pump displacement
	Weight	Static

TABLE 17-1

THICKENING (Continued)

Process and process variables	Measurements	Suggested instruments
Flotation Thickener (continued)		
Dissolution system (assuming subnatant recycle or full make-up)	Flow	Venturi Magnetic Ultrasonic Propeller Orifice
	Pressure	Bourdon Diaphragm
Air supply	Flow	Rotameter Pitot tube
	Pressure	Bourdon Diaphragm
Centrifuge		
Feed sludge	Flow	Magnetic Pump displacement
	Pipe empty	Capacitance Nuclear
Centrate	(See Table 17-12, Sidestreams)	
Thickened sludge	Level	Ultrasonic
	Flow	Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Centrifuge operation	Vibration	Accelerometer Displacement probes
	Torque or power draw	Ammeter
Polymers or chemicals	Level	Capacitance Ultrasonic Tape and float
	Flow	Magnetic Rotameter Propeller Pump displacement
	Weight	Static

TABLE 17-2

STABILIZATION

Process and process variables	Measurements	Suggested instruments
Anaerobic Digesters		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Digester liquid surface		
Floating cover	Level	Tape (attach to cover)
Fixed cover	Level	Bubbler with nitrogen purge Diaphragm Capacitance Ultrasonic
Gas holding cover	Level	Diaphragm (differential pressure)
Digester contents	Temperature pH and ORP	RTD Portable selective-ion
Circulating sludge	Pressure Temperature pH and ORP	Bourdon with cylindrical seal RTD (pad type) Selective-ion (pipeline mtg)
Digested sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal RTD (pad type)
	Density	Nuclear Optical Ultrasonic
	pH and ORP	Portable selective-ion
Supernatant	(See Table 17-12, Sidestreams)	
Digester gas	Flow	Orifice Turbine Vortex
	Pressure	Diaphragm
	Composition	Chromatograph
	Heat value	Calorimeter
Hot water heating system	Pressure Temperature	Bourdon RTD
Atmospheric monitoring	Hydrocarbons Odors	Catalytic Portable olefactometer

TABLE 17-2

STABILIZATION (Continued)

Process and process variables	Measurements	Suggested instruments
Aerobic Digesters		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical
Digester liquid surface	Level	Bubbler Diaphragm Capacitance Ultrasonic
Digester contents	Temperature	RTD
	Suspended solids	Optical
	Dissolved oxygen	Polarographic Galvanic Thallium
	pH or ORP	Portable selective-ion
Sedimentation tank	Blanket level	Optical Ultrasonic
Supernatant	(See Table 17-12, Sidestreams)	
Recycled sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler
	Density	Nuclear
Digested sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
	pH and ORP	Selective-ion (pipeline mtg)
Lime Treatment		
Feed Sludge	Flow	Magnetic Doppler Venturi with diaphragm seal Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
	pH and ORP	Portable selective-ion
Treated sludge	Flow	Magnetic Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
	pH and ORP	Selective-ion (pipeline mtg)

TABLE 17-2

STABILIZATION (Continued)

Process and process variables	Measurements	Suggested instruments
Lime Treatment (continued)		
Chemicals	Level	Ultrasonic
	Flow	Magnetic Pump displacement
	Weight	Static
Chlorine Treatment		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Treated sludge	Flow	Magnetic Doppler
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD
	Density	Nuclear Optical
	pH	Selective-ion (pipeline mtg)
Chemicals	Flow	Rotameter Orifice
	Pressure	Bourdon with diaphragm seal
	Weight	Static

TABLE 17-3

DISINFECTION

Process and process variables	Measurements	Suggested instruments
Pasteurization		
Feed sludge	Level	Bubbler Diaphragm Capacitance Ultrasonic
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Pasteurization system	Pressure	Bourdon with flush diaphragm seal
	Temperature	RTD (pad type)
	Time	Digital Synchronous motor
Pasteurized sludge	Level	Ultrasonic
	Flow	Pump displacement
	Pressure	Bourdon with cylindrical seal
Steam supply	Flow	Nozzle Orifice
	Pressure	Bourdon with steam service siphon
	Temperature	RTD
Electron Irradiation		
Feed Sludge	Level	Bubbler Diaphragm Capacitance Ultrasonic
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
Irradiation system E-beam monitoring	Power draw	Ammeter
Irradiated sludge	Flow	Venturi with diaphragm seal Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)

TABLE 17-3

DISINFECTION (Continued)

Process and process variables	Measurements	Suggested instruments
Electron Irradiation (continued)		
Cooling air	Flow	Pitot tube
	Flow loss	Vane
		Differential pressure
		Thermal
Gamma Irradiation		
Feed sludge	Level	Bubbler
		Diaphragm
		Capacitance
		Ultrasonic
	Flow	Venturi with diaphragm sensors
		Magnetic
		Doppler
		Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear
		Optical
		Ultrasonic
Irradiation system	Dosage	Geiger counter
Radiation	Safety	Geiger counter
		Dosimeter
		Badge
Irradiated sludge	Flow	Venturi with diaphragm sensors
		Magnetic
		Doppler
		Pump displacement
		Transport displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Radiation	Geiger counter

TABLE 17-4

CONDITIONING

Process and process variables	Measurements	Suggested instruments
Inorganic Chemical Conditioning		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Chemicals (aluminum sulfate, aluminum chloride, lime ferric chloride, ferrous sulfate)	Level	Ultrasonic Tape and float
	Flow	Magnetic Doppler Pump displacement
	Pressure	Bourdon with chemical seal
	Weight	Static
Organic Chemical Conditioning		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Polymers	Level	Capacitance Ultrasonic Tape and float
	Flow	Magnetic Rotameter Pump displacement
	Pressure	Bourdon with cylindrical seal
	Weight	Static
Non-Chemical Additions		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Miscellaneous materials (ash, pulverized coal, sawdust, wastepaper	Level	Capacitance Ultrasonic
	Weight	Static Mass flow

TABLE 17-4

CONDITIONING (Continued)

Process and process variables	Measurements	Suggested instruments
Thermal Conditioning		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Sonic
	Pipe empty	Capacitance Nuclear
Conditioning	Pressure Temperature	Bourdon with cylindrical seal RTD (pad type) Thermocouple
Solids separation	Level	Ultrasonic
	Blanket level	Optical Ultrasonic
Atmospheric monitoring	Odors	Portable olefacttometer Panel
Decant liquor	(See Table 17-12, Sidestreams)	
Conditioned sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
Steam supply	Flow	Nozzle Orifice
	Pressure	Bourdon with steam siphon
	Temperature	RTD
Air supply	Flow	Venturi Rotometer Orifice
	Pressure	Bellows Diaphragm
Elutriation		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic

TABLE 17-4

CONDITIONING (Continued)

Process and process variables	Measurements	Suggested instruments
Elutriation (continued)		
Solids separation	Level	Bubbler Diaphragm Ultrasonic
	Blanket level	Optical Ultrasonic
Elutriate	(See Table 17-12, Sidestreams)	
Conditioned sludge		Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
Wash water	Flow	Venturi Magnetic Rotameter Propeller

TABLE 17-5

DEWATERING

Process and process variables	Measurements	Suggested instruments
Drying beds		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Bed contents	Moisture content	Portable ohmmeter Lab test
Dewatered sludge	Flow (volume)	Transport displacement
	Weight	Static
	Moisture content	Portable ohmmeter Lab test
Drainage and surface runoff	(See Table 17-12, Sidestreams)	
Weather	Wind speed (15 ft (4.6 m)) above ground	Anamometer
	Wind direction (15 ft (4.6 m)) above ground	Wind vane
	Temperature, dry bulb (5 and 25 ft (1.5 and and 7.6 m)) above ground	RTD with solar shield Thermistor with solar shield
	Relative humidity	RTD with lithium chloride cloth (wet bulb temperature)
	Rainfall	Tipping bucket
	Solar radiation	Thermopile
Atmospheric monitoring	Odors	Portable olefactometer
Drying Lagoons		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic

TABLE 17-5

DEWATERING (Continued)

Process and process variables	Measurements	Suggested instruments
Drying Lagoons (Continued)		
Lagoon contents	Moisture content	Portable ohmmeter Lab test
Harvested sludge	Flow (volume) Weight	Transport displacement Static
Supernatant and surface runoff	(See Table 17-12, Sidestreams)	
Weather	Wind speed (15 ft (4.6 m)) above ground	Anemometer
	Wind direction (15 ft (4.6 m above ground	Wind vane
	Temperature (5 and 25 ft ft (1.5 and 7.6 m)) above ground	RTD with solar shield Thermistor with solar shield
	Relative humidity	RTD with lithium chloride cloth (wet bulb temperature)
	Rainfall	Tipping bucket
	Solar radiation	Thermopile
Atmospheric monitoring	Odors	Portable olefactometer
Centrifugal Dewatering		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
	Pipe empty	Capacitance Nuclear
Centrate	(See Table 17-12, Sidestreams)	
Centrifuge operation	Torque of power draw Vibration	Ammeter Accelerometer Displacement probes
Dewatered sludge	Flow (volume)	Pump displacement Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Polymers or chemicals	Level	Capacitance Ultrasonic Tape and float
	Flow	Magnetic Rotameter Propeller Pump displacement
	Pressure	Bourdon with chemical seal
	Weight	Static

TABLE 17-5

DEWATERING (Continued)

Process and process variables	Measurements	Suggested instruments
Filtration Dewatering		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
	Pipe empty	Capacitance Nuclear
Vacuum filter		
Operation	Level	Capacitance Ultrasonic
	Pressure	Bourdon with chemical seal
	Speed	Reluctance pick-up
Filtrate	(See Table 17-12, Sidestreams)	
Spent wastewater and rejected feed sludge	(See Table 17-12, Sidestreams)	
Washwater	Flow	Venturi Rotameter Propeller Orifice
	Pressure	Bourdon
Belt filter presses		
Operation	Pressure	Bourdon or bellows with chemical seal Diaphragm
	Speed	Reluctance
Filtrate	(See Table 17-12, Sidestreams)	
Spent wastewater and rejected feed sludge	(See Table 17-12, Sidestreams)	
Washwater	Flow	Venturi Rotameter Propeller Orifice
	Pressure	Bourdon
Recessed plate filter presses		
Operation	Pressure	Bourdon with cylindrical seal
Filtrate	(See Table 17-12, Sidestreams)	
Spent washwater and reject feed sludge	(See Table 17-12, Sidestreams)	

TABLE 17-5

DEWATERING (Continued)

Process and process variables	Measurements	Suggested instruments
Filtration Dewatering (Continued)		
Dewatered sludge	Flow	Pump displacement Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmeter Lab test
Polymers or chemicals	Level	Capacitance Ultrasonic Tape and float
	Flow	Magnetic Rotameter Propeller Pump displacement
	Pressure	Bourdon with chemical seal
	Weight	Static
Cyclonic Separation		
Feed wastewater solids	Flow	Magnetic Doppler
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear (sludge system only) Ultrasonic
Overflow	(See Table 17-12, Sidestreams)	
Underflow	Flow (volume)	Transport displacement
Screening		
Feed wastewater	Level	Bubbler Diaphragm
	Flow	Venturi Magnetic Doppler Weirs and flumes
Feed wastewater solids	Level	Bubbler Diaphragm Ultrasonic
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pipe empty	Capacitance Nuclear
Automatic bar screens	Torque or power draw	Shear pin Ammeter
Hydraulic sieve bends	Level	Bubbler Diaphragm
Moving screens	Level	Bubbler Diaphragm
	Speed	Bubbler Diaphragm
Screened liquid	(See Table 17-12, Sidestreams)	

TABLE 17-6

HEAT DRYING

Process and process variables	Measurements	Suggested instruments
Flash drying		
Feed sludge	Flow, volume	Pump displacement Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
	Pipe empty	Capacitance Nuclear
Drying operation	Temperature	RTD (pad type)
Dried sludge	Flow, volume	Transport displacement
	Temperature	RTD (pad type)
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Hot air furnace		
Burner operation	Flame monitoring	Ultravilot scanner
Fuel	Flow	Pitot tube Orifice Positive displacement
Combustion air	Flow	Pitot tube Orifice plate
	Pressure	Diaphragm Bellows
	Temperature	RTD
Heated air	Temperature	Thermocouple
Fan monitoring	Flow loss	Vane Differential pressure Thermal
	Vibration	Accelerometer
Scrubber water	(See Table 17-12, Sidestreams)	
Direct rotary dryer		
Feed sludge	Flow, volume	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Drying operation	Temperature	RTD (pad type)
	Speed	Reluctance
	Torque or power draw	Shearpin Ammeter
Dried sludge	Flow, volume	Transport displacement
	Temperature	RTD (pad type)
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test

TABLE 17-6

HEAT DRYING (Continued)

Process and process variables	Measurements	Suggested instruments
Direct rotary dryer (continued)		
Hot air furnace		
Burner operation	Flame monitoring	Ultravilot scanner
Fuel	Flow	Pitot tube Orifice Vortex Positive displacement
Combustion air	Flow	Pitot tube Orifice
	Pressure	Diaphragm
	Temperature	RTD
Heated air	Temperature	Thermocouple
Fan monitoring	Flow loss	Vane Differential pressure Thermal
	Vibration	Accelerometer
Scrubber water	(See Table 17-12,	Sidestreams)
Indirect and direct-indirect rotary dryers		
Feed sludge	Flow, volume	Pump displacement Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Drying operation	Temperature	RTD (pad type)
	Speed	Reluctance
	Torque or power draw	Shearpin Ammeter
Dried sludge	Flow, volume	Transport displacement
	Temperature	RTD (pad type)
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter
Hot air furnace		
Burner operation	Flame monitoring	Ultraviolet scanner
Fuel	Flow	Pitot tube Orifice Vortex Positive displacement
Combustion air	Flow	Pitot tube Orifice
	Pressure	Bellows Diaphragm
	Temperature	RTD
Heated air	Temperature	Thermocouple
Fan monitoring	Flow loss	Vane Differential pressure Thermal
	Vibration	Accelerometer
Scrubber water	(See Table 17-12,	Sidestreams)

[a] See Table 17-12, Sidestreams.

TABLE 17-6

HEAT DRYING (Continued)

Process and process variables	Measurements	Suggested instruments
Incinerators	(See Table 17-7, High Temperature Processes)	
Torodial dryers		
Liquid or dewatered solids storage	(See Table 17-11, Storage)	
Dewatering	(See Table 17-5, Dewatering)	
Feed sludge	Flow, volume	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Drying operation	Temperature	RTD (pad type)
Dried sludge	Flow, volume	Transport displacement
	Temperature	RTD (pad type)
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Hot air furnace Burner operation	Flame monitoring	Ultraviolet scanner
Fuel	Flow	Pitot tube Orifice Vortex Positive displacement
Combustion air	Flow	Pitot tube Orifice
	Pressure	Bellows Diaphragm
	Temperature	RTD
Heated air	Temperature	Thermocouple
Fan monitoring	Vibration	Accelerometer
	Flow loss	Vane Differential pressure Thermal
Scrubber water	(See Table 17-12, Sidestreams)	
Spray drying		
Feed sludge	Flow	Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Drying operation	Temperature	RTD (pad type)
Dried sludge	Flow, volume	Transport displacement
	Temperature	RTD (pad type)
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter
Hot air supply	Temperature	Thermocouple

[a] See Table 17-12, Sidestreams.
[b] See Table 17-7, High Temperature Processes.
[c] See Table 17-11, Storage
[d] See Table 17-5, Dewatering.

TABLE 17-6

HEAT DRYING (Continued)

Process and process variables	Measurements	Suggested instruments
Solvent extraction		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
Cooled sludge	Temperature	RTD (pad type)
Extraction system	Pressure	Bourdon with chemical seal
	Temperature	RTD
Dried sludge	Flow, volume	Transport displacement
	Temperature	RTD (pad type)
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Product water	Flow	Venturi Magnetic Pump displacement
	Pressure	Bourdon with chemical seal
	Temperature	RTD
	Suspended solids	Optical
	Chemical oxygen demand	TOC analyzer
Hot air	Temperature	RTD Thermocouple
Chilled water	Flow	Rotameter Propeller Orifice
	Pressure	Bourdon
	Temperature	RTD
Multiple-effect evaporator		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
Fluidizing system Fluidizing tank	Level	Ultrasonic
	Temperature	RTD (pad type)

TABLE 17-6

HEAT DRYING (Continued)

Process and process variables	Measurements	Suggested instruments
Multiple-effect evaporator (continued)		
Fluidizing system (continued)		
Fluidizing pump	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
Feed tank	Level	Ultrasonic
	Temperature	RTD (pad type)
Feed pump	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
Evaporation system	Pressure	Bourdon with chemical seal
	Temperature	RTD (pad type)
Dried sludge	Flow, volume	Transport displacement
	Temperature	RTD (pad type)
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Condensate	Flow	Rotameter Orifice
	Pressure	Bourdon with chemical seal
	Temperature	RTD (pad type)
Recycled oil	Level	Ultrasonic
	Flow	Orifice Pump displacement
	Pressure	Bourdon with diaphragm seal
	Temperature	RTD
Steam supply	Flow	Nozzle Orifice
	Pressure	Bourdon with steam siphon
	Temperature	RTD

TABLE 17-7

HIGH TEMPERATURE PROCESS

Process and process variables	Measurements	Suggested instruments
Incineration		
Feed sludge	Flow (volume)	Pump displacement Transport displacement
	Temperature	RTD
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Furnace operation		
Multiple-hearth	Temperature	Thermocouple
	Speed	Reluctance
	Torque of power draw	Shear pin Ammeter
	Flame monitoring	Ultraviolet scanner
Fluid-bed	Pressure	Bourdon with diaphragm seal
	Temperature	Thermocouple
	Flame monitoring	Ultraviolet scanner
Electric	Temperature	Thermocouple
	Speed Power draw	Reluctance Ammeter
Single-hearth cyclonic	Temperature	Thermocouple
	Speed	Reluctance
	Torque or power draw	Shear pin Ammeter
	Flame monitoring	Ultraviolet scanner
Ash	Flow (volume)	Transport displacement
	Temperature	Thermocouple
	Weight	Static Mass flow
Combustion air	Flow loss	Vane Differential pressure Thermal
	Pressure	Diaphragm Bellows
Recycled flue gas	Temperature	Thermocouple
Afterburner	Temperature	Thermocouple
Multiple-hearth furnace	Temperature	Thermocouple
	Flame monitoring	Ultraviolet scanner
Electric furnace	Temperature	Thermocouple
	Power draw	Ammeter
Exhaust (stack gas)	Pressure	Bellows Diaphragm
	Temperature	Thermocouple
	Oxygen content	Paramagnetic Catalytic Ceramic
	Opacity	Optical
	Other measurements as required by local air quality management districts	As required

TABLE 17-7

HIGH TEMPERATURE PROCESS (Continued)

Process and process variables	Measurements	Suggested instruments
Incineration (continued)		
Heat recovery system		
Flue gas	Temperature	Thermocouple
Boiler	Level	Float (cage mounted)
	Pressure	Bourdon
	Temperature	Thermocouple
Steam produced	Flow	Nozzle
		Orifice
	Pressure	Bourdon with steam siphon
	Temperature	Thermocouple
Scrubbing water	(See Table 17-12, Sidestreams)	
Fuel		
Electric furnace	Power draw	Ammeter
Other furnaces	Level	Diaphragm
		Tape and float
	Flow	Positive displacement
		Orifice
	Pressure	Bourdon
		Bellows
		Diaphragm
Starved Air Combustion		
Feed sludge	Flow (volume)	Pump displacement
		Transport displacement
	Temperature	RTD
	Weight	Static
		Mass flow
	Moisture content	Portable ohmmeter
		Lab test
Furnace operation	Pressure	Bellows
		Diaphragm
	Temperature	Thermocouple
Ash	Flow (volume)	Transport displacement
	Temperature	Thermocouple
	Weight	Static
		Mass flow
Combustion air	Flow loss	Vane
		Differential pressure
		Thermal
	Pressure	Bellows
		Diaphragm
	Temperature	RTD
Afterburner	Temperature	Thermocouple
	Flame monitoring	Ultraviolet scanner

TABLE 17-7

HIGH TEMPERATURE PROCESS (Continued)

Process and process variables	Measurements	Suggested instruments
Starved Air Combustion (continued)		
Exhaust (stack gas)	Pressure	Bellows Diaphragm
	Temperature	Thermocouple
	Oxygen content	Paramagnetic Catalytic Ceramic
	Opacity	Optical
	Other measurements as rquired by local air quality management districts	As required
Heat recovery system		
Flue gas	Temperature	Thermocouple
Boiler	Level Pressure Temperature	Float (cage mounted) Bourdon Thermocouple
Steam produced	Flow	Nozzle Orifice
	Pressure Temperature	Bourdon RTD
Scrubbing water	(See Table 17-12, Sidestreams)	
Fuel		
Flue gas for after-burner	Pressure	Bellows Diaphragm
Supplemental fuel	Level	Diaphragm Tape and float
	Flow	Orifice Positive displacemeent
	Pressure	Bourdon Bellows Diaphragm
Watergate Furnace		
Feed scum	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Furnace operation	Level	Diaphragm Ultrasonic
	Temperature	Thermocouple
	Flame monitoring	Ultraviolet scanner
Exhaust (stack gas)	Pressure	Bellows Diaphragm
	Temperature	Thermocouple

TABLE 17-7

HIGH TEMPERATURE PROCESS (Continued)

Process and process variables	Measurements	Suggested instruments
Watergate Furnace (Continued)		
Exhaust (stack gas) (continued)	Oxygen content	Paramagnetic Catalytic Ceramic
	Opacity	Optical
	Other measurements as required by local air quality management districts	As required
Scrubbing water	(See Table 17-12, Sidestreams)	
Fuel	Level	Diaphragm Tape and float
	Flow	Orifice Positive displacement
	Pressure	Bellows Diaphragm
Co-Combustion with Municipal Refuse		
Feed sludge		
Liquid state	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Dewatered state	Flow (volume)	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Municipal refuse	Flow (volume)	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Furnace operation		
Grate fired	Temperature Flame monitoring	Thermocouple Ultraviolet scanner
Multiple-hearth	Temperature	Thermocouple
	Speed	Reluctance
	Torque or power draw	Shear pin Ammeter
	Flame monitoring	Ultraviolet scanner

TABLE 17-7

HIGH TEMPERATURE PROCESS (Continued)

Process and process variables	Measurements	Suggested instruments
Co-Combustion with Municipal Refuse (continued)		
Furnace operation (continued)		
Fluid-bed	Pressure	Bellows Diaphragm
	Temperature	Thermocouple
	Flame monitoring	Ultraviolet scanner
Ash	Flow (volume)	Transport displacement
	Temperature	Thermocouple
	Weight	Static Mass flow
Combustion air	Flow loss	Vane Differential pressure Thermal
	Pressure	Diaphragm Bellows
	Temperature	RTD
Recycled flue gas	Temperature	Thermocouple
Afterburner		
Multiple hearth	Temperature	Thermocouple
	Flame monitoring	Ultraviolet scanner
Exhaust (stack gas)	Pressure	Bellows Diaphragm
	Temperature	Thermocouple
	Oxygen content	Paramagnetic Catalytic Ceramic
	Opacity	Optical
	Other measurements as required by local air quality management districts	As required
Heat recovery system		
Flue gas	Temperature	Thermocouple
Boiler	Level	Float (cage mounted)
	Pressure	Bellows Diaphragm
	Temperature	Thermocouple
Steam produced	Flow	Nozzle Orifice
	Pressure	Bourdon with steam siphon
Scrubber water	(See Table 17-12, Sidestreams)	

TABLE 17-8

COMPOSTING

Process and process variables	Measurements	Suggested instruments
Unconfined		
Windrow		
Feed sludge	Level	Capacitance Ultrasonic
	Flow (volume)	Transport displacement
	Weight	Static
	Moisture content	Portable ohmmeter
Composting	Temperature	Portable thermometer
	Moisture content	Portable ohmmeter Lab test
	Aerobic condition	Portable galvanic cell Portable polarographic cell
Composted sludge	Flow (volume) Weight Moisture content	Truck displacement Static Portable ohmmeter Lab test
Amendment or bulking agent	Flow (volume)	Transport displacement
	Weight	Static
	Moisture content	Portable ohmmeter Lab test
Leachate and surface runoff	(See Table 17-12, Sidestreams)	
Weather	Wind speed (15 ft (4.6 m)) above ground	Anemometer
	Wind direction (15 ft (4.6 m)) above ground	Wind vane
	Temperature (5 and 25 ft (1.5 and 7.6 m)) above ground	RTD Thermistor with solar shield
	Relative humidity	RTD with lithium chloride cloth (wet bulb temperature)
	Solar radiation	Thermophile
Atmosperic monitoring	Odors	Portable olefactometer
Aerated pile		
Feed sludge	Level	Capacitance
	Flow (volume)	Ultrasonic
	Weight	Transport displacement
	Moisture content	Portable ohmmeter Lab test

TABLE 17-8

COMPOSTING (Continued)

Process and process variables	Measurements	Suggested instruments
Unconfined (continued)		
Aerated pile		
Feed sludge	Level	Capacitance Ultrasonic
	Flow (volume)	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Composting	Temperature	RTD Portable thermometer
	Moisture content	Portable ohmmeter Lab test
	Aerobic condition	Portable galvanic cell Portable polarographic cell
Composted sludge	Flow (volume)	Transport displacement
	Weight	Static
	Moisture content	Portable ohmmeter Lab test
Aeration air	Flow	Venturi Pitot tube Orifice
Amendment or bulking agent	Flow (volume)	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Leachate and surface runoff	(See Table 17-12, Sidestreams)	
Weather	Wind speed (15 ft (4.6 m)) above ground	Anemometer
	Wind direction (15 ft (4.6 m)) above ground	Wind vane
	Temperature (5 and 25 ft (1.5 and 7.6 m)) above ground	RTD) with solar shield Thermistor)
	Relative humidity	RTD with lithium chloride cloth (wet bulb temperature)
	Rainfall	Tipping bucket
	Solar radiation	Thermopile
Atmospheric monitoring	Odors	Portable olefactometer

TABLE 17-8

COMPOSTING (Continued)

Process and process variables	Measurements	Suggested instruments
Confined Systems		
Feed sludge	Level	Capacitance Ultrasonic
	Flow (volume)	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Composting	Temperature	RTD
	Moisture content	Portable ohmmeter
	Aerobic condition	Portable galvanic cell Portable polarographic cell
Composed sludge	Level	Capacitance Ultrasonic
	Flow (volume)	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Amendment or bulking agent	Level	Capacitance Ultrasonic
	Flow (volume)	Transport displacement
	Weight	Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Atmospheric monitoring	Odors	Portable olefactometer

TABLE 17-9

MISCELLANEOUS CONVERSION PROCESSES

Process and process variables	Measurements	Suggested instruments
<u>Fixation</u>		
Feed sludge	Flow (volume)	Transport displacement
	Moisture content	Portable ohmmeter Lab test
Fixed sludge	Moisture content	Portable ohmmeter Lab test
<u>Encapsulation</u>		
Feed sludge	Flow (volume) Moisture content	Transport displacement Portable ohmmeter Lab test
Polyethlene system	Pressure Temperature	Bellows with diaphragm seal RTD Thermocouple
Asphalt system	Temperature	RTD Thermocouple
Encapsulated sludge	Flow (volume)	Transport displacement
<u>Earthworm Conversion</u>		
Feed sludge	Flow (volume) Temperature Moisture content	Transport displacement Portable thermometer Portable ohmmeter Lab test
Castings (egesta)	Flow (volume) Moisture content	Transport displaceement Portable ohmmeter Lab test

TABLE 17-10

TRANSPORTATION

Process and process variables	Measurements	Suggested instruments
Pumping		
Centrifugal and torque flow pumps		
Variable speed drive	Speed	Tachometer generator Reluctance
	Vibration	Accelerometer
Pumped sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler
	Pressure	Bourdon with cylindrical seal
	Empty pipe	Capacitance Nuclear
Positive displacement pumps		
Variable speed drive	Speed	Reluctance
Pumped sludge	Flow Pressure Empty pipe	Reluctance (revolution counter) Bourdon with cylindrical seal Capacitance Nuclear
Pipelines		
Corrosion, electrolytic Pig location	Power draw Flow	Ammeter Venturi with diaphragm sensors Magnetic Pump displacement
Conveying		
Continuous belt	Underspeed Level (volume overload) Weight	Reluctance Capacitance Ultrasonic Mass flow
Positive displacement	Underspeed	Reluctance
Pneumatic ejection	Flow (volume)	Transport displacement
Open screw	Level (volume overload) Underspeed	Capacitance Ultrasonic Reluctance
Trucking	Flow (volume)	Transport displacement Vehicle detection
	Weight	Static
Barging	Level	Bubbler Diaphragm Ultrasonic
Railroad Cars	Flow (volume)	Transport displacement Vehicle detection
	Weight	Static

TABLE 17-11

STORAGE

Process and process variables	Measurements	Suggested instruments
Wastewater Treatment		
Sedimentation facilities	Density	Nuclear Optical
	Suspended solids	Optical
	Blanket level	Optical Ultrasonic
Aeration reactors	Suspended solids	Optical
Imhoff and septic tanks	Blanket level	Optical Ultrasonic
	Density	Nuclear Optical
Oxidation ditches	Suspended solids	Optical
Stabilization ponds	Suspended solids	Optical
Wastewater Solids Treatment	(See Individual Process Tables)	
Liquid Storage		
Holding Tanks		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
Tank liquid surface		
Fixed cover	Level	Bubbler Diaphragm Capacitance Ultrasonic
Floating cover	Level	Tape (attach to cover)
Tank contents	Temperature pH	RTD Portable selective-ion
Circulating sludge	Pressure Temperature pH	Bourdon with cylindrical seal RTD (pad type) Selective-ion (pipeline mtg)
Discharged sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic

TABLE 17-11

STORAGE (Continued)

Process and process variables	Measurements	Suggested instruments
Confined Hoppers or Bins		
Feed sludge	Flow (volume) Weight	Transport displacement Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Hopper or bin contents	Level	Capacitance Ultrasonic
	Weight	Static
Discharged sludge	Level (volume over load) Flow (volume) Weight	Capacitance Ultrasonic Transport displacement Static Mass flow
	Moisture content	Portable ohmmeter Lab test
Atmosperic monitoring	Hydrocarbons Odors	Catalytic Portable olefactometer
Unconfined Stockpiles		
Feed sludge	Flow (volume) Weight Moisture content	Transport displacement Static Portable ohmmeter Lab test
Stockpiled sludge	Moisture content	Portable ohmmeter Lab test
Harvested sludge	Flow (volume) Weight Moisture content	Transport displacement Static Portable ohmmeter Lab test
Weather	Wind speed (15 ft (4.6 m) above ground	Anemometer
	Wind direction (15 ft (4.6 m)) above ground	Wind vane
	Temperature (5 and 25 ft (1.5 and 7.6 m)) above ground	RTD) Thermistor) with solar shield
	Relative humidity	RTD with lithium chloride cloth (wet bulb temperature)
	Rainfall	Tipping bucket
	Solar radiation	Thermopile
Atmospheric monitoring	Odors	Portable olefactometer

TABLE 17-11

STORAGE (Continued)

Process and process variables	Measurements	Suggested instruments
Facultative Sludge Lagoons		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Lagoon contents	pH	Portable selective-ion
	Conductivity	Portable conductivity probe
	Blanket level	Portable optical Portable ultrasonic
	Dissolved oxygen	Portable galvanic Portable polarographic
Harvested sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Supernatant	(See Table 17-12, Sidestreams)	
Weather	Wind speed (15 ft (4.6 m)) above ground	Anemometer
	Wind direction (15 ft (4.6 m)) above ground	Wind vane
	Temperature (5 and 25 ft (1.5 and 7.6 m)) above ground	RTD) with solar shield Thermistor)
	Relative humidity	RTO with lithium chloride cloth (wet bulb temperature)
	Rainfall	Tipping bucket
	Solar radiation	Thermopile
Atmospheric monitoring	Odor	Portable olefactometer
Anaerobic Sludge Lagoons		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Lagoon contents	Sludge blanket	Portable optical Portable ultrasonic

TABLE 17-11

STORAGE (Continued)

Process and process variables	Measurements	Suggested instruments
Anaerobic Sludge Lagoons (Continued)		
Harvested sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler
	Pressure	Bourdon with cylindrical seal
Supernatant	(See Table 17-12, Sidestreams)	
Weather	Wind speed (15 ft (4.6 m)) above ground	Anemometer
	Wind direction (15 ft (4.6 m)) above ground	Wind vane
	Temperature (5 and 25 ft (1.5 and 7.6 m)) above ground	RTD) Thermistor) with solar shield
	Relative humidity	RTD with lithium chloride cloth (wet bulb temperature)
	Rainfall	Tipping bucket
	Solar radiation	Thermopile
Atmospheric monitoring	Odors	Portable olefactometer
Aerated Basin		
Feed sludge	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal Nuclear Optical Ultrasonic
Basin contents	Dissolved oxygen	Portable galvanic Portable polarographic
	Flow	Venturi with diaphragm sensors Magnetic Doppler
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
Supernatant	(See Table 17-12, Sidestreams)	
Solid State Storage		
Drying sludge lagoons	(See Table 17-5, Dewatering)	

TABLE 17-12

SIDESTREAMS

Process and process variables	Measurements	Suggested instruments
Thickening		
Gravity supernatant	Flow	Venturi with diaphragm sensors Magnetic Doppler Weirs and flumes Pump displacement
	Pressure	Bourdon with diaphragm sensors
	Suspended solids	Optical
Flotation subnatant	Flow	Venturi with diaphragm sensors Magnetic Doppler Weirs and flumes Pump displacement
	Pressure	Bourdon with diaphragm sensors
	Suspended solids	Optical
Centrifuge centrate	Flow	Venturi with diaphragm sensors Magnetic Doppler Weirs and flumes Pump displacement
	Pressure	Bourdon with diaphragm sensors
	Suspended solids	Optical
Stabilization		
Anaerobic digestion supernatant	Level	Bubbler Diaphragm Tape and float
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear
	Sludge blanket	Optical Sonic
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Chemical oxygen demand	TOC Analyzer
	Ammonia	Selective-ion analyzer
Aerobic digestion supernatant	Level	Bubbler Diaphragm Float and tape
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal

TABLE 17-12

SIDESTREAMS (Continued)

Process and process variables	Measurements	Suggested instruments
Stabilization (continued)		
Aerobic digestion supernatant (continued)	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Ammonia	Selective-ion analyzer
Atmospheric monitoring odors		Portable olefactometer
Conditioning		
Thermal liquor (decant and filtrate)	Level	Bubbler Diaphragm Float and tape
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Temperature	RTD (pad type)
	Density	Nuclear Optical Ultrasonic
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Chemical oxygen demand	TOC analyzer
	Ammonia	Selective-ion analyzer
Elutriation elutriate	Level	Bubbler Diaphragm Float and tape
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Ammonia	Selective-ion analyzer
	Blanket level	Optical Ultrasonic

TABLE 17-12

SIDESTREAMS (Continued)

Process and process variables	Measurements	Suggested instruments
Conditioning (continued)		
Atmospheric monitoring	Odors	Portable defactometer Panel
Dewatering		
Drying bed drainage and surface runoff	Level	Bubbler Diaphragm Float and tape
	Flow	Venturi with diaphragm sensors Magnetic Doppler Weirs and flumes Pump displacement
	Pressure	Bourdon with cylindrical seal
	Suspended solids	Portable optical
	pH	Portable selective-ion
	Ammonia	Lab test
Drying lagoons supernatant and surface runoff	Level	Bubbler Diaphragm Ultrasonic
	Flow	Magnetic Doppler Weirs and flumes Pump displacement
	Pressure	Bourdon with cylindrical seal
	Suspended solids	Portable optical
	pH	Portable selective-ion
Centrifuge centrate	Level	Bubbler Diaphragm
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Pressure	Bourdon with cylindrical seal
	Density	Nuclear Optical Ultrasonic
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Ammonia	Selective-ion analyzer
	Blanket level	Optical Ultrasonic
Vacuum, belt press, recessed plate and frame and screw and roll press filters		
Filtrate	Level	Bubbler Diaphragm Float and tape
	Flow	Venturi with diaphragm sensors Magnetic Doppler Weirs and flumes Pump displacement

TABLE 17-12

SIDESTREAMS (Continued)

Process and process variables	Measurements	Suggested instruments
Dewatering (Continued)		
Filtrate (continued)	Pressure	Bourdon with diaphragm seal
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Ammonia	Selective-ion analyzer
Spent washwater and rejected feed sludge	Level	Bubbler Diaphragm
	Flow	Venturi with diaphragm sensors Magnetic Doppler Pump displacement
	Density	Nuclear Optical Ultrasonic
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Ammonia	Selective-ion analyzer
Cyclonic separation		
Overflow	Level	Bubbler Diaphragm
	Flow	Magnetic Doppler Weirs and flumes
Screening		
Screening liquid	Level	Bubbler Diaphragm
	Flow	Venturi Magnetic Doppler Weirs and flumes
	Density	Nuclear Sonic
High Temperature Processes and Heat Drying		
Scrubber water supply	Level	Bubbler Diaphragm Float and tape
	Flow	Rotameter Propeller Orifice
	Pressure	Bourdon
	Temperature	RTD
Discharge	Flow	Venturi Magnetic Ultrasonic Orifice
	Temperature	RTD
	Suspended solids	Optical

TABLE 17-12

SIDESTREAMS (Continued)

Process and process variables	Measurements	Suggested instruments
Composting Leachate and Surface Runoff	Level	Bubbler Diaphragm Float and tape
	Flow	Venturi with diaphragm sensors Magnetic Doppler Weirs
	Pressure	Bourdon with cylindrical seal
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Chemical oxygen demand	Total organic carbon analyzer
Storage		
Facultative sludge lagoon supernatant	Level	Bubbler Diaphragm Ultrasonic
	Flow	Magnetic Doppler Weirs and flumes
	Pressure	Bourdon with cylindrical seal
	Suspended solids	Portable optical
	pH	Portable selective-ion
	Ammonia	Lab test
Anaerobic sludge lagoon supernatant	Level	Bubbler Diaphragm Ultrasonic
	Flow	Magnetic Doppler Weirs and flumes
	Pressure	Bourdon with cylindrical seal
	Suspended solids	Portable optical
	pH	Portable selective-ion
	Ammonia	Lab test
Landfilling Leachate and Surface Runoff	Level	Bubbler Diaphragm Ultrasonic Float and tape
	Flow	Venturi with diaphragm sensors Magnetic Doppler Weirs and flumes Pump displacement
	Pressure	Bourdon with cylindrical seal
	Suspended solids	Optical
	pH	Selective-ion (pipeline mtg)
	Chemical oxygen demand	Total organic carbon Analyzer
	Ammonia	Selective-ion analyzer

17.2 Measurements

This section briefly describes each of the instrumentation devices listed in Tables 17-1 through 17-12.

17.2.1 Level Measurements

Level measurements are required for both displacement volume and open channel flow instrumentation. Some instruments have almost unlimited applicability, while others are restricted because of material interferences. Sometimes these interferences can be minimized or eliminated with special purging; however, the designer must provide the support systems required if such instruments are to be reliable.

17.2.1.1 Bubblers

The pneumatic bubbler remains the most universally applicable liquid level measuring device in wastewater treatment facilities. In its simplest form, a bubbler consists of a dip tube through which a constant small flow of purge gas, usually air, is discharged. The gas flow prevents the liquid from rising in the dip tube; therefore, the pressure required to maintain the gas flow is directly proportional to the depth of a liquid above the dip tube outlet. This pressure can be measured by virtually any pressure measurement device, some of which are described in Section 17.2.3. The bubbler can be used with almost any liquid, but clogging may be a problem when solids are present. Clogging can be controlled by frequent purging with high pressure air. Where the use of an air purge is undesirable, such as in anaerobic digesters, nitrogen or natural gas can be used for purging the bubbler dip tube. Figure 17-1 shows a typical bubbler schematic with air purge capabilities.

17.2.1.2 Diaphragms

Bubbler dip tube clogging problems can be overcome by use of diaphragm level element. A diaphragm is usually 3 to 4 inches (7.6 to 10. cm) in diameter and serves as one wall of what is, essentially, a box. Inside the box, a pneumatic, hydraulic, or electric mechanism transmits any pressure exerted on the diaphragm. The entire box is submerged in a vessel, or the diaphragm may be inserted in the wall of the vessel by means of a standard pipe flange. In either case, the pressure exerted on the diaphragm is directly proportional to the depth of liquid above the diaphragm. The type of diaphragm shown on Figure 17-2 is air-purged and produces a back pressure similar to a bubbler. Thus, both the air supply and pressure measuring devices are similar to those used in bubbler systems. The air-purged diaphragm can, therefore, be used as a replacement for existing bubblers. The second type of diaphragm uses a filled

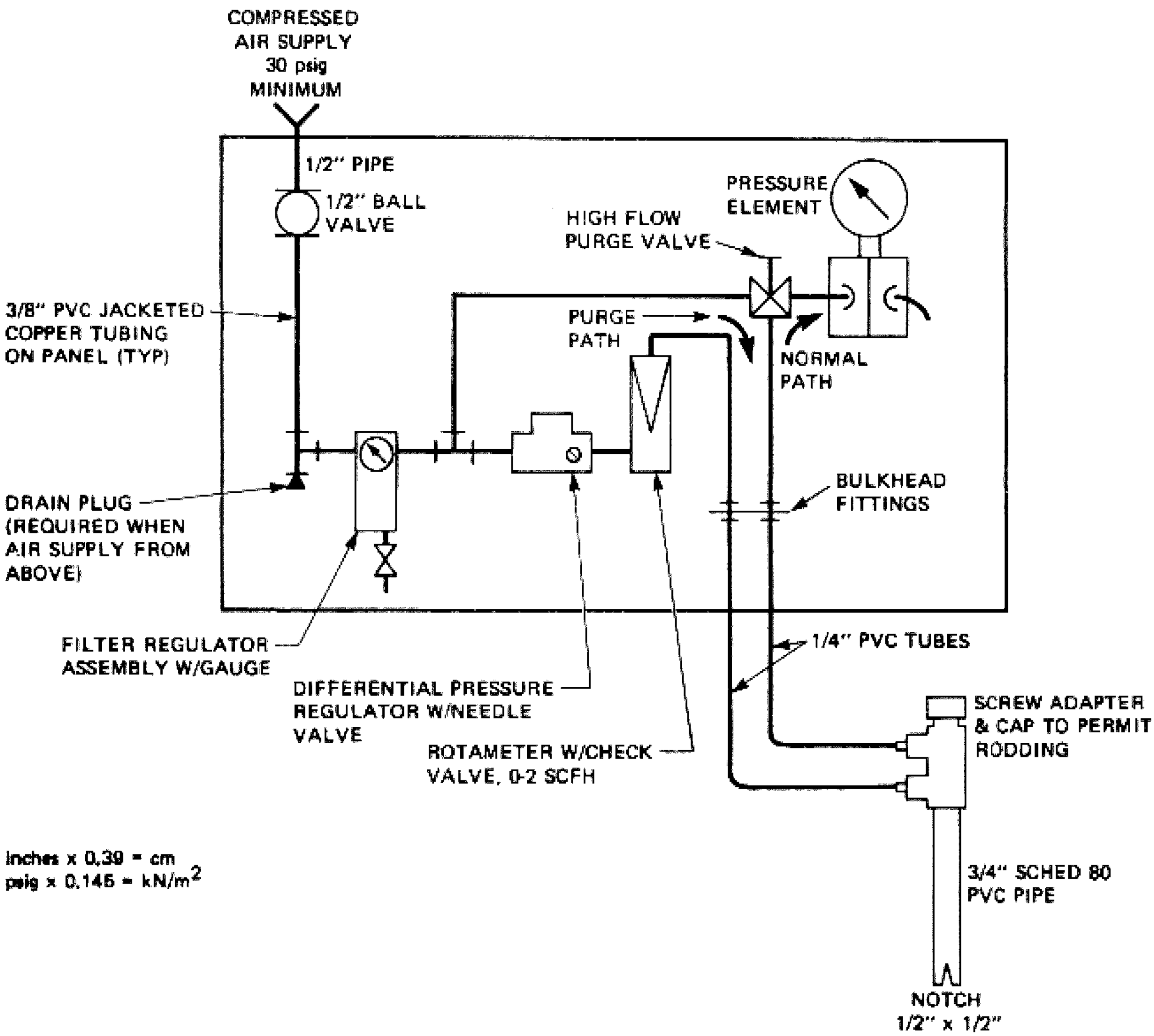


FIGURE 17-1

TYPICAL BUBBLER SCHEMATIC WITH
AIR PURGE CAPABILITIES

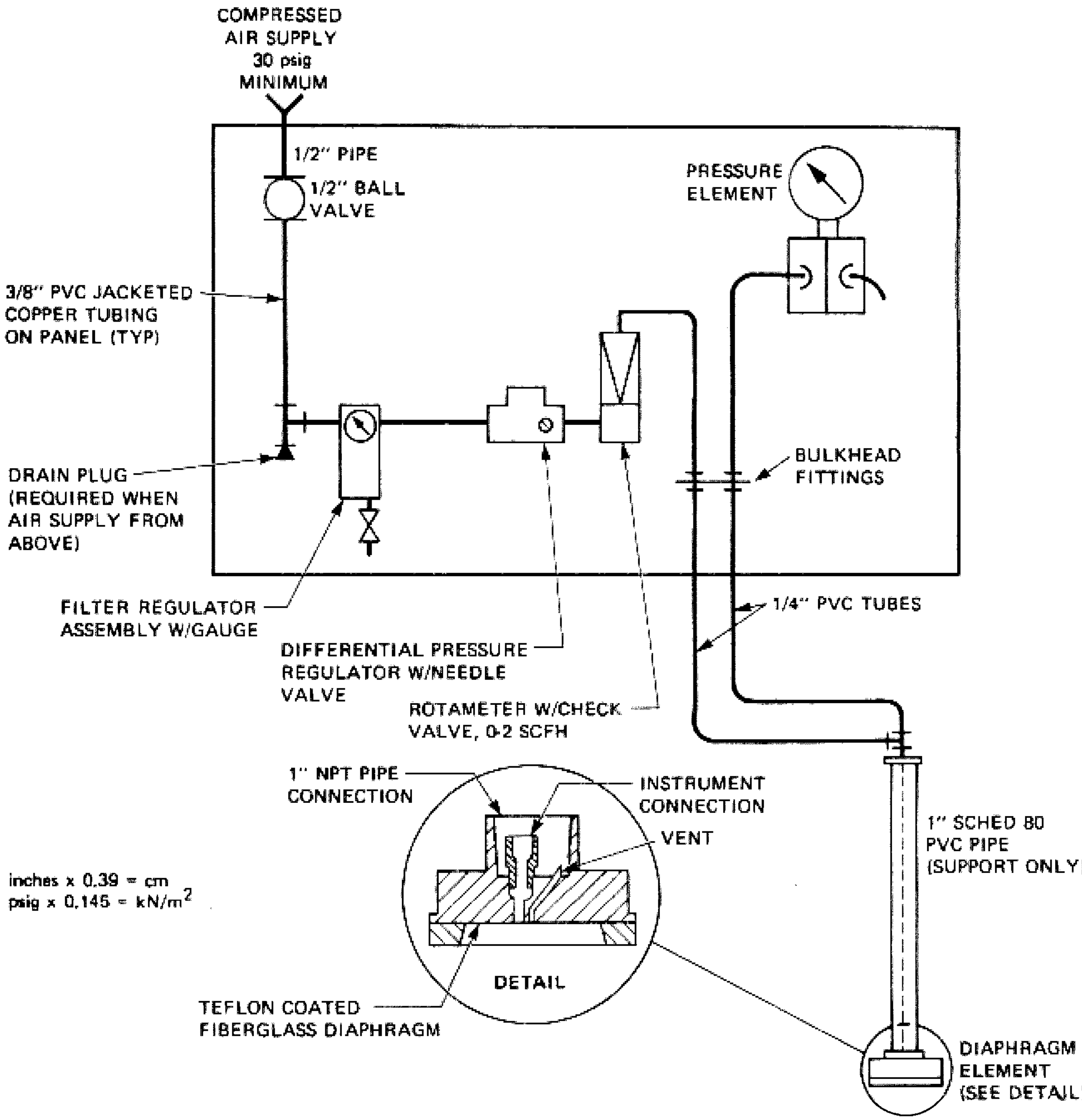


FIGURE 17-2

TYPICAL BUBBLER SCHEMATIC WITH DIAPHRAGM ELEMENT capillary tube between the diaphragm and a conventional pressure transmitter, thus eliminating the need for an air supply. When a filled capillary tube is employed, the volumetric displacement of the diaphragm is critical, and pressure indicators or transmitters should have as low a displacement as possible so that diaphragms with low movement can be used. Capillary filling fluid should have a low thermal expansion coefficient to limit errors resulting from temperature changes. Diaphragms are flush-mounted and have no crevices to accumulate solids. The almost insignificant movement required for accurate measurement is maintained even when the diaphragm is coated with grease.

17.2.1.3 Capacitance Transmitters

In recent years, several electronic level measuring devices have appeared. Capacitance and ultrasonic instruments are particularly applicable for sludge measurements. The capacitance liquid level transmitter consists of a steel rod or cable (probe), usually teflon-coated, which is installed in the tank. The probe forms one plate of a capacitor, and the liquid, which must be conductive and grounded, forms the second. The probe insulation forms a dielectric between these two plates. The electrical capacitance between the probe and the liquid is proportional to the axial length of probe immersed in liquid. An electrical instrument measures this capacitance and provides a signal proportional to level. This signal can be used to provide either on-off or continuous level measurement. Gross changes in fluid conductance can affect calibration of capacitance probes. This is not ordinarily a problem in sludge handling facilities. One disadvantage with capacitance instruments is that, even with teflon-coated probes, greasy material can adhere and cause errors. Improved electronics has reduced this problem on some units. Very successful level measurements have been made for all types of sludge, including the fluid level inside fixed cover digesters. Capacitance instruments are also used to measure the level of dry solids in bins or silos. In this application, a bare rod or cable (probe) is used, and the side of the tank serves as the ground plate. Where tanks are non-metallic, a metallic ground plate can be installed on the side of the tank. The material in the tank then serves as the dielectric and must have a stable dielectric constant significantly different from air. Since many solids contain large and varying amounts of air, the use of capacitance probes for solids level measurement is frequently unsuccessful.

17.2.1.4 Ultrasonic Transmitters

Ultrasonic level instruments operate with the level transmitter completely out of contact with the process material. This is a very appealing advantage for sludge treatment and disposal processes. A transducer suspended above the material emits an ultrasonic pulse toward the liquid. The pulse bounces off the material surface and the reflected pulse returns to the transducer. The time that elapses between the transmitted pulse and the received pulse is related to the distance between the transducer and the reflecting surface by the speed of sound in air. Unfortunately, the speed of sound in air is affected by both temperature and humidity, and the reflected signal is also scattered. These conditions substantially weaken the received pulse. All these problems can be overcome with more complex electronics and larger transducers, but experience to date (1979) with these units has been very poor. Their use cannot be recommended until their serviceability has been proved under treatment plant conditions.

17.2.1.5 Tape-Supported Floats

Tape-supported floats are suitable for level measurements of many liquids. Floats are suspended from a tape that winds on a drum. The drum is provided with either a counterweight or a "constant tension" spring to remove all the slack from the tape. The position of the drum is a very accurate measure of float position and, hence, liquid level. Standard units provide an accuracy of 0.01 feet (3.09 mm) for local readout and can be equipped with electric signal transmission for remote readout. In the case of floating cover digesters, the cover becomes the float, and the same drum assembly provides measurement of level in the digester. Tape-supported floats are often located within concentric wells to isolate them from the turbulence of the liquid surface being measured. To assure maximum reliability, these wells are usually purged with water at rates sufficient to keep a continuous flow from the well, even during periods of maximum rising levels. Such installation is usually not practical when the material being monitored contains significant amounts of debris and grease.

17.2.2 Flow Measurements

Flow is an important measurement for sludge treatment and disposal operations. Accuracy has been an ongoing problem with all types of flowmeters. Venturi-type flow tubes, orifice plates, and weirs are regarded as standard flow measuring devices providing proper approach conditions--the length of straight pipe upstream and downstream from the device--are maintained. This by itself is a strong argument in favor of their use. In many situations, proper approach conditions cannot be obtained or a wider range of operation is needed. Some in-plant method should be provided to "prove" the accuracy of non-standard meters. A liquid flowmeter can frequently be calibrated by discharging a flow into a tank of known dimensions and measuring the change in level. In other cases, meters may be compared with other meters of proven accuracy. For comparison, the meter under test must be left in the actual plant piping, or a test stand with an identical piping configuration must be provided. Flow measurements of wastewater sludge are difficult to take. The designer must select the instrument with care, recognizing that reliability may be a far more important criterion than accuracy.

17.2.2.1 Venturi Tubes

Venturi-type flow tubes have been successfully used for all sludges, including primary sludge. Venturi tubes are classical differential pressure producers that function according to Bernoulli's relationships. A Venturi tube has a restricted throat. A pressure drop is produced as the fluid accelerates through the throat. The pressure drop is proportional to the square of the liquid velocity and is measured by differential pressure instruments, as described in Section 17.2.3. Modern flow tubes operate on the same principles; they are improvements on early Venturi devices. However, they are less expensive and produce less residual head loss. When used for sludge flow measurement, the pressure taps must be protected from plugging. This can be done by water purge or by use of diaphragms similar to those described earlier and installed in the tube wall. The disadvantage of a Venturi tube is the narrow usable flow ranges available. Anything over 3 to 1 is usually accomplished at reduced accuracy. If air-purging is used, the Venturi tube static lines require careful sloping to eliminate errors caused by trapped bubbles. Water-purged systems require a source water free of both soluble and insoluble solids to avoid clogging of flow control needle valves. Consideration should be given to the potential impact of purging water on downstream sludge processes.

17.2.2.2 Nozzles

Flow nozzles are similar in operation to Venturi tubes but are substantially less expensive. Residual head loss is much greater than for Venturi tubes and approaches that of an orifice plate installation. Flow nozzles do not wear out as quickly as orifice plates and can handle fluids containing limited solids. The most common application of the flow nozzle is for steam flow measurement.

17.2.2.3 Magnetic Meters

The magnetic flowmeter functions according to Faraday's law which, in simple terms, states that when an electrical conductor (in this case water) passes through a magnetic field, an electrical voltage is developed at right angles to the direction of the field and to the direction of the movement. If the magnetic field is constant, the voltage is proportional to the conductor's velocity. Hence, a magnetic flowmeter is simply a tube with magnetic coils that uses electronics to measure the voltage produced. In the past, a number of poor applications has put magnetic flowmeters in disfavor. When they are properly applied with modern electronics, magnetic flowmeters are now as reliable as any other flow measuring devices.

Flow velocity of primary sludge through a magnetic flow tube should be in the range of 5 to 25 feet per second (1.5 to 7.6 m/s), providing a usable range of 5:1. The lower limit is established by the minimum scouring action required to keep electrodes free of grease. The upper limit is necessary to limit erosion of the tube's plastic liner. Flow velocity for secondary sludges may be extended down to 3 feet per second (0.9 m/s) because less grease is present. For intermittent flow, velocities may be extended up to 30 feet per second (9 m/s) because less grit is present. Combining these conditions provides a usable range for secondary sludges of 10:1. Magnetic flowmeter manufacturers generally recommend certain accessories, such as electrode cleaning devices, when metering sludge. Purchase specifications should clearly state the application and require provision of all recommended accessories. Properly applied and installed, modern magnetic flowmeters are giving excellent service in many installations.

17.2.2.4 Ultrasonic Meters

Ultrasonic meters are a fairly new development, and no two meters work exactly the same. There are two basic types. The first and most common one, which is listed as the ultrasonic device in this chapter, consists of a pair of transducers mounted on opposite sides of the pipe and displaced so that one transducer is one pipe diameter downstream from the other. The first transducer emits an ultrasonic pulse, and the time it takes this pulse to reach the second transducer is measured. The system is then reversed. The second transducer emits the pulse, and the time until the first transducer receives this pulse is measured. The travel time is known as propagation time. In one case, flow velocity decreases propagation time, and in the reverse case, increases the propagation time. The difference in time between the two measurements is directly proportional to flow velocity. The ultrasonic flow measuring system is relatively insensitive to factors that normally affect the speed of sound (for example, temperature). This is because the effects are cancelled as the signals reverse. However, some difficulties have been experienced with this technique. Most sludge is sonically opaque. The signal cannot travel between the transducers, even with a high power. Therefore, at this time, this type of meter is not considered reliable.

17.2.2.5 Doppler Meters

The second type of ultrasonic flowmeter depends on the Doppler effect. A continuous ultrasonic signal is emitted into the pipe by the transducer. This signal is reflected by solids or bubbles in the liquid stream and is returned to a second transducer at a frequency different from that transmitted. This difference is related to the velocity of the material that caused the reflection. Presently, difficulties prevent the practical application of this technique. The frequency change is affected by the velocity of sound, which in turn is affected by temperature in the fluid. Furthermore, in sludge applications, the particles or bubbles causing reflections will very probably be located close to the pipe walls, and their velocity may not be representative of average fluid velocity. Hence, the accuracy of this type of meter is questionable. Actual field experience with this type of meter is not extensive.

17.2.2.6 Rotameters

Rotameters are commonly used for both gas and liquid flow measurements of clear homogeneous fluids. Their use in sludge management is primarily for chemical feed systems, air flows, and purge systems. A rotameter consists of a "float" in a conically shaped tube. The "float" does not actually float, since it must sink into the fluid being measured. The size of the rotameter orifice increases as the "float" rises in the tube; therefore, the upward force on the "float" for any fluid velocity decreases as the float rises. The equilibrium point between "float" weight and upward force due to flow velocity is an indication of flow. Rotameters are constructed of a wide variety of materials, including metals and plastics. They can be constructed to measure almost any type of fluid. Rotameters are available up to 3-inch (8 cm) pipe size. Larger pipes are accommodated by installing an orifice plate parallel to the rotameter so that a known fraction of the flow passes through the rotameter. This is called a "by-pass" rotameter. If the float is made of magnetic material or contains an iron core, a magnet mounted on the outside of the tube can be made to follow it. This magnet can be attached to a transmitting mechanism to provide remote readout.

17.2.2.7 Propeller Meters

Relatively clean, non-corrosive fluids flowing through large pipes (2 inches [5 cm] or larger) can be readily measured with propeller meters. Propeller meters can provide local readout or can be equipped with transmitting mechanisms for remote readout or recording. They are not applicable for sludge flows, but can provide reliable, cost-effective service for support systems.

17.2.2.8 Pitot Tubes

Pitot tubes very economically measure flow in pipes of almost any size. The pitot tube produces a differential pressure proportional to the square of the fluid velocity, which may be measured by differential pressure transmitters described in Section 17.2.3. One commercial unit provides four ports spaced across the diameter of the pipe and averages the impact pressure of each to provide compensation for irregular flow profiles. The pitot tube produces a very small pressure differential for liquid flow velocities typically used in treatment plants and, therefore, is not particularly suitable for liquid service. It is frequently suitable for gas flows where wide flow ranges are not required. The small tube entrances make it completely unsuitable for use with sludge flows.

17.2.2.9 Weirs and Flumes

Weirs and flumes provide a simple, very accurate method of measuring liquid flows in open channels. They are not applicable to pressure systems. Any of the level measuring instruments described in Section 17.2.1 provide a means of measuring the liquid level behind the weir or at the critical point in a flume. Weirs are not suitable for flows with large amounts of settleable solids or debris. This material will collect behind the weir and change weir measuring characteristics.

17.2.2.10 Orifice Plates

Gas flow measurement is commonly required where anaerobic or aerobic digesters are used. Gas produced by anaerobic digesters is dirty and corrosive. Permissible head losses in anaerobic and aerobic digesters are often very low and the range of operating requirements extreme. An orifice plate can be used in this service. Orifice plates are similar in theory to Venturi tubes; that is, pressure drop through the device is proportional to the square of the liquid velocity. Orifice plates, however, lack a smooth recovery cone and, consequently, have a much greater residual head loss. The advantage of the orifice plate, other than lower cost, is the ease with which it can be changed. The optimum size of orifice plate can be readily installed for any flow. Quick change fittings permit changing of orifice plates without disturbance of a piping run.

17.2.2.11 Turbine Meters

Turbine meters, which provide good service in gas flow applications, consist of flow directing channels, a suitable turbine blade, gearing, shafting, and a readout device. In the simplest form, the output shaft directly drives the readout register. Where remote readout is desired, the shaft rotation actuates an electrical switch. Each switch closure represents a discrete quantity of gas. The meter must be specially designed for dirty and corrosive gas. Moderate maintenance is required to keep the meter clean. The turbine meter's ability to operate over wide ranges makes it attractive for the measurement of anaerobic digester gas.

17.2.2.12 Vortex Meters

The Vortex shedding flowmeter is a comparatively new meter that is also applicable to anaerobic digester gas flow measurement. The meter consists of an obstruction placed in the pipeline with sensors that detect the vortices caused by the obstruction. The flow is proportional to the number of vortices produced. These meters are suitable for Reynolds Numbers above 5,000 and readily provide a usable operating range of 100:1.

17.2.2.13 Positive Displacement Meters

Orifice plates, turbine meters, and Vortex meters have all provided adequate instrumentation for anaerobic digester gas flow. However, these instruments cannot provide the absolute accuracy of positive displacement meters at the very low flows encountered during digester operations. Positive displacement meters can be of the rotating cavity (lobe) or the diaphragm type. Positive displacement meters are probably the oldest meter used for digester gas measurements. In recent years, they have been almost completely replaced by the in-line meters described in the previous paragraphs. Positive displacement meters are frequently used for clean oil or clean gas flow measurements and are inherently useful over an extremely wide operating range. The meter's cavities, exposed bearings, and/or close clearances make them unsuited for dirty gas service.

17.2.2.14 Pump and Transport Displacement Systems

Sludge transport systems should not be overlooked as flow measurement devices. Progressive cavity and other positive displacement pumping equipment can be equipped with speed monitors or cycle counters that provide a fairly accurate flow indication. None of the problems usually associated with flowmeters operating on sludge are encountered. Where materials are trucked, the number of truck loads will provide a rough measure of quantities. If the trucks are also weighed-in and -out, accurate measurements can be obtained.

17.2.3 Pressure Measurement

Pressure measurement is basic to many level and flow measuring systems, as well as to the measurement of individual process pressures. As a result, pressure elements are without a doubt the most highly developed instruments used in industry.

17.2.3.1 Bourdons or Bellows

Pressure Elements

The bourdon tube is the most commonly used pressure element for pressure ranges of 15 pounds per square inch (103 kN/m^2) or greater. The bourdon tube is essentially a piece of tubing closed at one end and bent in an arc. When pressure is applied to the tube, it tends to straighten. The movement produced at the free or closed end is amplified by mechanical linkage to operate a pointer or transmitter mechanism. Bellows are frequently used when lower pressures must be measured or greater movement is required for direct actuation of control mechanisms. Bourdon tubes are rarely used in modern industrial process pressure transmitters. Bellows elements are frequently used in process pressure transmitters for pressure ranges from 10 inches water pressure (2.4 kN/m^2) to as high as 600 pounds per square inch (4.14 MN/m^2). Bellows elements are also readily adaptable to differential pressure measurements and absolute pressure measurements.

Chemical Seals

Both bourdon tubes and bellows are unsuitable for direct measurement of fluids containing solids. Collecting solids within the pressure element is the problem. Corrosive fluids also must be kept out of the pressure element. A "chemical seal" is used for these applications. The most common chemical seal consists of a small metal or elastomer diaphragm, one side of which is exposed to the process fluid. Sometimes this exposed side is purged with water or mounted flush with the fluid containment vessel. The other side of the seal is close-coupled or connected by a capillary tube to the measuring element and filled with a suitable fluid such as silicon oil. For very dirty, grease-laden process fluids such as wastewater sludge, an in-line tubular or cylindrical chemical seal, as shown on Figure 17-3, must be used to assure operational reliability. This seal is constructed as an elastomer tube of the same size as the process pipe line and mounted within a flanged steel pipe spool. The space between the elastomer and steel spool is sealed, filled with a suitable fluid (anti-freeze when necessary), and connected directly to the pressure element. Pressure elements with electrical contacts and cylindrical chemical seals should be used immediately downstream from all positive displacement pumps transporting wastewater sludge. This will provide a reliable system for emergency shutdown whenever the pump discharge pressure becomes excessive.

Chemical seals used to isolate corrosive fluids from pressure elements are available in a great variety of materials. Care must be exercised in the application of any chemical seal to ensure that it has sufficient displacement to operate the measuring element. Use of chemical seals for ranges of less than 50 pounds per square inch (345 kN/m^2) can be expected to introduce significant errors in the measurement.

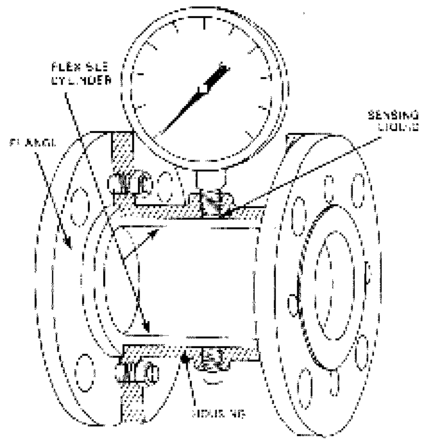


FIGURE 17-3

CYLINDRICAL CHEMICAL SEAL FOR
SLUDGE PRESSURE MEASUREMENT

17.2.3.2 Diaphragms

Pressure Element

Where a direct mechanical readout is not required from a pressure element, the diaphragm pressure transmitter is suitable for any application where bourdon tubes or bellows would be used. The force-balance is the oldest type of diaphragm pressure transmitter and continues to be widely applied in industry and wastewater treatment. Newer types such as the strain gauge, reluctance, and capacitance, are functionally similar and are becoming more common. Diaphragm pressure transmitters are available to measure gauge pressure, differential pressure, or absolute pressue, with ranges as low as 1-inch water column to 10,000 pounds per square inch (250 N/m^2 to 80 MN/m^2) or higher.

Chemical Seals

Chemical seals are not generally required with diaphragm pressure transmitters for solids bearing fluids because the measuring element itself is an essentially flat diaphragm. Chemical seals are still frequently used for corrosion protection and, in high temperature applications, to separate transmitter electronics from temperatures above permissible levels. Chemical seals are also used with differential pressure configurations to permit flush-mounting of the diaphragms to the process at two physically separated locations.

17.2.4 Temperature Measurements

Stabilization, disinfection, conditioning, composting, and heat processes in sludge treatment all may require temperature information to assure successful operation. Temperature instrumentation is relatively simple; however, successful application requires locating probes to obtain representative readings without obstructing sludge flow. The designer must be aware of these application restrictions and locate and specify instruments correctly.

17.2.4.1 Resistance Temperature Detectors (RTDs)

Resistance temperature detectors (RTDs) are applied at temperatures up to about 1,000°F (540°C). This is well within the range of most sludge temperatures. RDTs work on the basis of the fact that the electrical resistance of metals changes with temperature. Electronic amplifiers measure this resistance change and provide an output proportional to temperature.

Thermistors are sometimes used for special temperature measurement applications. A thermistor is a temperature-sensitive semi-conductor. Like RTDs, the thermistor's resistance changes with temperature, but the change is extremely non-linear. The advantage of using a thermistor is that a large change in resistance can be obtained over a very narrow temperature range.

17.2.4.2 Thermocouples

For processes with temperatures in excess of approximately 1,000°F (540°C) (for example, incineration), RTDs are not suitable and thermocouples must be used. Thermocouples consist of two junctions of dissimilar metals. One junction, the measuring junction, is placed in or on the material to be measured. The second, or reference, junction is located in a constant temperature zone, or the measuring instrument may include an artificial reference junction. The Peltier effect states that at any junction of dissimilar metals, an electric motive force (voltage) will be produced. Thus, two voltages, (one at each junction) are produced in a series circuit. The measuring instrument detects the difference between these two voltages and produces an output proportional to process temperature. Thermocouples produce very small voltages at low temperatures. More importantly, the difference in voltage produced by the reference and measuring junction is very small. For this reason, thermocouples are not generally used to measure small variations in temperature. Thermocouples are generally less expensive than RTDs but require greater attention to installation procedures to reduce electrical interference. Wiring for thermocouples must be especially matched to the thermocouple junction material.

17.2.5 Weight Measurements

Two types of weight measurements are of interest in sludge handling facilities. The first is the common static measurement. The second is the weight per unit of time, which is actually a mass flow measurement.

17.2.5.1 Static

Mechanical scales are frequently used for static weight measurements. Such scales consist of a platform or vessel and a system of pivots and levers to provide a usable readout. Mechanical scales are constructed to measure anything from 0.40 ounces (11g) in the laboratory to 100,000 pounds (45.4 Mg) or more to weigh a railroad car. Many modern scales use load cells under the platform to eliminate the complex lever and pivot system. Load cells are placed under one or more of the platform support points, and the output of the cells is summed to obtain the total weight. In some cases, the number of load cells can be lower than the number of support points because load symmetry allows multiplying the output of the installed cells by a factor to account for the missing cells. Load cells may be either the hydraulic or strain gauge type. Hydraulic load cells resemble a piston that converts force to a hydraulic pressure. This pressure is readily monitored by pressure instruments, as previously described. Strain gauge load cells consist of a calibrated structural member to which a resistance wire element is attached. When the structural member is strained by an applied force, the resistance wire element's dimensions change. Hence, its electrical resistance changes. Suitable electronic circuitry converts these small resistance changes to an electrical output proportional to the force applied to the cell.

17.2.5.2 Mass Flow

Mass flow measurements involve a fixed transport system such as a belt conveyor. Mass flow measurement on a belt conveyor is made by supporting one or two conveyor belt idler rollers on a scale, measuring the conveyor speed as described in Section 17.2.8, and multiplying weight and speed together to obtain mass flow. Modern belt scales using load cells and two idlers are very accurate and are easily maintained. Nuclear belt scales can provide this function without contacting either the belt or the material being weighed. This may be an advantage in some installations. Nuclear scales are almost identical in operation to nuclear density meters. The only difference is that a nuclear scale is calibrated to monitor total mass in its path rather than the change in mass caused by suspended solids in a liquid. This is a less difficult application, and premium radiation monitors are not required, but nuclear source decay still causes the calibration to drift. The radioactive source is a controlled substance subject to United States Nuclear Regulatory Commission restrictions and regulations. It requires special training, safety precautions, and testing. This adds to operation and maintenance costs.

All conveyor mass flow scales measure the total mass of material on the platforms or belt. No differentiation is made between solids and water; therefore, the reading is most accurate if the moisture content is constant or can be measured.

17.2.6 Density and Suspended Solids Measurements

Sludge density and suspended solids are the same measurement from an instrumentation point of view. However, they are quite different from the operation standpoint. Sludge density is a common term used to describe the concentration of solids in sludge mixtures in which solids are the favored component. Sludge density is usually expressed in percent solids by weight. Suspended solids is a common term used to describe the concentration of solids in water in which the liquid element is the favored component--for example, the solids present in the plant influent or the solids left in the supernatant after gravity thickening. Suspended solids are usually expressed in weight of solids per unit volume of water. There is no instrument available that directly measures either sludge density or suspended solids. Instruments that are used actually measure nuclear radiation absorption, light transmission or reflection (optical), or sonic attenuation characteristics of the mixture. These measurements are then empirically correlated to sludge density or suspended solids concentration. In most cases, this correlation does not remain constant, and periodic recalibration is necessary. The frequency of this recalibration is dependent on the characteristics of the liquid being monitored. In no case do these instruments provide adequate accuracy for reporting purposes, although they can be used for control. Laboratory analysis is usually required to obtain the accuracy necessary to develop QFD (see Chapter 3) diagrams. Nuclear and opacity density measurements can be used in conjunction with control systems to allocate sludge automatically to various process facilities on a mass flow basis. Sonic density measurements are usually only applicable to the on and off control of sludge pumping equipment.

17.2.6.1 Density

<u>Nuclear</u>

Nuclear density gauges usually work well on primary and mixed primary and secondary sludges in the higher concentration range. They usually have limited applicability to secondary sludge alone. The nuclear density gauge consists of a small radioactive source, usually cesium-137, and a detector placed on opposite sides of the pipe. Gamma radiation is emitted and absorbed by the material in the pipe in direct proportion to its density. However, the difference in radiation absorption between plain water and water containing the suspended solids concentration must be significant for nuclear meters to function well. These meters are generally effective where suspended solids concentrations are in the range of 1 to 10 percent. The radioactive source itself decays, and the high gain amplifiers suffer from gain changes resulting from component aging. Both factors cause the instrument calibration to change rapidly, and frequent adjustment is required to maintain accuracy. When nuclear density gauges are to be used to measure sludge solids concentration, they must be specified with special premium low-drift amplifiers. The source is a controlled substance subject to United States Nuclear Regulatory Commission restrictions and regulations. When properly installed and maintained, nuclear density gauges have functioned quite successfully with wastewater sludge.

Optical

Optical type meters are usually used to measure sludge density concentrations of less than 3 percent. These instruments use either light transmittance or a combination light transmittance/scatter measurement and are suitable for concentrations from 0.2 percent to 10 percent solids. Units that employ a mechanical wiper to keep the optics clean have been very successful. Caution must be exercised in the application of these units to primary sludge, which may contain grit that damages optical surfaces and wipers.

Ultrasonic

The sonic density gauge is a relatively new product proposed for measuring the density of primary sludge. The sonic density gauge consists of two ultrasonic transducers mounted on opposite sides of a pipe section. Ultrasonic signals emitted from one transducer pass through the material in the pipe to the second transducer. Suspended solids in the signal path attenuate this signal. The signal received decreases in strength with an increase in suspended solids. The relationship between the strength of the signal received and the suspended solids concentration is non-linear but sufficiently predictable to be used for control of sludge pumps. Sonic density meters have been used successfully and are much less expensive than nuclear density meters.

17.2.6.2 Suspended Solids Measurements

The optical instrument described for providing density measurements is also suitable for suspended solids measurements. Instruments are available with a range from 0-30 to 0-30,000 mg/l. The mechanical wiper optical unit is generally the most suitable for this application. Surface scatter types with no optics in contact with the process fluid are also usable. Care should be taken to exclude larger solids, such as particles of floating debris, that are frequently present in the liquid being monitored. More information on suspended solids instrumentation is available (3).

17.2.7 Time Measurements

Digital and synchronous motor batch (reset) timers are available for control of sludge management and support services. Digital timers provide one second resolution up to about 2 3/4 hours. Synchronous motor timers provide 0.1 minute resolution up to 16 hours and 0.1 hour resolution up to 1,000 hours. Both types use power line frequency as a time reference. They are designed to reset at zero at the completion of a cycle. If time functions cannot be interrupted by power failure or the wastewater plant generates all its own electrical power, the designer must take special precautions to see that all control timers function as required on the emergency standby or continuous plant electric power frequency. Digital timers can be obtained with an internal quartz crystal to provide their frequency reference. They can therefore operate independently of power line frequency.

17.2.8 Speed Measurements

Speed is readily measured either by a tachometer-generator coupled to equipment or by a reluctance pick-up. Tachometer-generators are generally more expensive and require higher maintenance than reluctance pick-ups. This is because tachometers have their own bearings, brushes, and usually a timing belt coupling. A reluctance pick-up installation consists of a split gear bolted around a shaft on the equipment. The pick-up is then mounted in close proximity to the gear teeth. Suitable electronics amplify the pulses that come from the pick-up each time a gear tooth passes and converts these pulses to a voltage or current output proportional to speed.

Electronic trip units can be used with either tachometer-generators or reluctance pick-ups to permit these devices to be used as underspeed switches. Mechanical underspeed switches are also available. Tachometer-generators and mechanical units are not reliable for operating speeds that are normally below 50 revolutions per minute. Reluctance pick-up systems can provide reliable operation at virtually any speed.

17.2.9 Moisture Content Measurements

Measurement of the moisture content of dewatered sludge is necessary if the output of weighing equipment is to be directly interpreted as weight of dry solids.

There is no proven on-line instrumentation for measuring moisture in sludge. Consideration of available options leads to essentially two possibilities--a manual resistance probe and laboratory tests. A manual resistance probe must be considered a very approximate instrument since it is not actually measuring moisture, and resistance measurements (moisture content) will vary significantly with the contact pressure between the monitored material and the probe. However, the portable resistance probe can provide the accuracy needed for immediate process control measurements; for example, compost piles or windrows. The laboratory test is the only moisture measurement method, however, that can provide the repeatable accuracy demanded for QFD calculations (see Chapter 3). Special infrared drying equipment with integral weighing instrumentation is available to make such laboratory testing both convenient and efficient.

7.2.10 Dissolved Oxygen Measurements

Three types of dissolved oxygen probes are commonly used in wastewater treatment plants for measuring the dissolved oxygen level in liquid streams containing high levels of suspended solids. These include the galvanic cell type, the polarographic cell type, and the thallium cell type.

Each of these cell types has its own proponents. The galvanic cell is probably the most commonly used in existing wastewater treatment plants. Both the galvanic cell and the polarographic cell use a membrane (usually teflon) through which oxygen can migrate into an electrolyte in which the electrodes are immersed. Membrane cleaning and electrolyte replenishment require a significant maintenance effort with these cells. The thallium cells dispense with the membrane and immerse the electrodes directly in the fluid to be analyzed. None of these cells is applicable for measuring dissolved oxygen in liquids having solids contents much higher than 2 percent.

17.2.11 pH Measurements

Modern selective-ion pH sensors with "non-flowing" reference electrodes are suitable for measuring the pH of sludge. The non-flowing reference electrode replaced the liquid reference junction in which the electolyte (generally potassium chloride) flowed continually from a reservoir into the process stream. These systems sometimes plugged, causing erroneous readouts. Non-flowing reference electrodes use a semi-solid electrolyte that does not require frequent replenishment or reservoir pressurization to maintain flow. Electrodes should be installed in lines where sludge flows pass the sensor, maintaining a fresh sample at the measuring point; for example, circulation lines. Electrode assemblies should be designed to hold electrodes essentially flush with the pipe wall. The electrodes should be easily removable for cleaning or replacement.

17.2.12 Chemical Oxygen Demand Measurements

Often liquid sidestreams from sludge treatment processes carry significant levels of organics back into the liquid processing system. The chemical oxygen demand measurements can be useful in determining the strength of these sidestream organic loadings and, therefore, provide input on their effect on the liquid treatment processes downstream from their point of recycle. Automated wet chemistry analyzers are capable of making a standard chemical oxygen demand (COD) analysis, but these units have not given satisfactory service under wastewater treatment plant conditions. The total organic carbon (TOC) analyzer is more suitable operationally, providing suitable correlation can be established between TOC analyzer measurements and COD laboratory data. There are several units on the market, and each operates somewhat differently. Operation of one TOC unit is as follows: The sample is treated with HCl to remove inorganic carbon as CO_2. It is then oxidized in a thermal reactor and the resulting CO_2 measured by an infrared analyzer.

TOC analyzers operate with moderate-sized samples and can handle suspended solids. However, they are high maintenance devices requiring daily servicing.

17.2.13. Ammonia Measurements

A selective-ion electrode is available for measuring ammonia. Ions other than ammonia frequently interfere with accurate measurement and elimination of interferences requires treatment of the sample before the measurement is made. Package analyzers are available to prepare the sample and make the measurement. Since custom sample preparation is frequently required, a sample should be submitted to the analyzer manufacturer prior to purchasing this type of equipment.

17.2.14 Gas Measurement and Analysis

17.2.14.1 Composition Analyzer

The composition of digester gas is a useful parameter for monitoring the health of the anaerobic digestion process (see Chapter 6). The chemical process industries make extensive use of on-line gas chromatographs for measuring gas composition. The heart of the chromatograph is the "column." The column is a length of tubing filled with an absorbent material. As a gas sample passes through this column, different gas components are first absorbed, then released back into the gas stream. The rate of absorption/release is different for each component and, as a consequence, each component emerges from the column at a different time. The components are thus separated from one another. A detector at this exit measures the eluting gas, and its output is plotted as a function of time. The resulting plot consists of a series of peaks and valleys, with each peak representing the detector's response to one of the gases being measured. Each peak can be associated with a specific component, since the time (relative to sample injection) at which the component peak will emerge from the column is known. The area under each of the peaks is proportional to the gas concentration. Even though this unit is called "on-line" it is a batch instrument which, at best, might make four measurements per hour. The on-line mass spectrometer is also capable of these measurements but is even more expensive than the chromatograph.

Digester gas samples for analysis must be stripped of hydrogen sulfide and filtered to remove solids before passing through analysis equipment. Sample lines must be heat-traced to avoid moisture condensation. With adequate sample preparation, gas analysis instruments should function without undue maintenance; however, at present, no data is available on a successful wastewater treatment plant installation of any of these instruments.

17.2.14.2 Calorimeter

A suitable instrument for measuring the heat value of digester gas is a calorimeter, which essentially burns a gas sample. The instrument must be located in an area free of drafts, which can affect its accuracy or even extinguish the flame. Instrument response is slow. This should be of no consequence during monitoring applications, however, since digester gas composition will normally change slowly. Care must be exercised, however, if the instrument is to be used to control mixing of digester gas with other gases to maintain a constant heat value or if the instrument is to be used with a multiple sampling scheme for monitoring several digesters. Calorimeters have been used successfully in full-scale operations at wastewater treatment plants.

17.2.15 Stack Gas Measurements and Analysis

On-line analysis of boiler or furnace stack gas composition is used frequently and has proven successful. It is directly applicable to wastewater solids systems incorporating heat drying and high temperature processes. These measurements are used for combustion control and are usually mandatory if air pollution is to be minimized. Obtaining a representative sample and conditioning it for the analyzer are the biggest problems in application of these instruments. There are a number of different parameters that may require measurement to meet air pollution control requirements, but oxygen is the parameter normally used to control the air-fuel ratio. Two types of stack gas oxygen analyzers are commonly used. The older unit is the paramagnetic type and the more modern is the catalytic type. A new system uses a ceramic element for which the manufacturer claims satisfactory operation on dirty flue gases without clean-up. Precautions are required where sulfides are present. Oxygen analysis equipment is normally included as part of the combustion control system of a furnace.

17.2.16 Odor Measurements

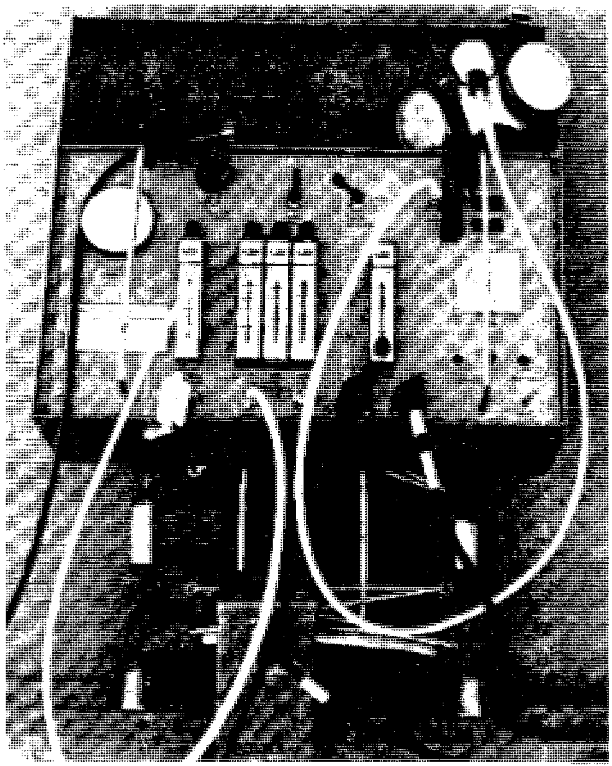
Odor measurements are required during sludge management to assure that the treatment and disposal processes selected meet regulatory agency requirements (no nuisance). There are no instruments for on-line measurement of odors. A device called a "direct reading olfactometer" (DRO) provides a means to make a semi-objective manual measurement of odors directly in the location affected. Figure 17-4 shows a close-up of the DRO assembly and a DRO in use with subject and controller. The DRO is essentially a breathing mask with carbon filter, rotameters, and valves to permit mixing known ratios of filtered and unfiltered ambient air. The subject conditions his nose by breathing 100 percent filtered air and then the operator adds increasing amounts of unfiltered air until the subject indicates he detects an odor. Repeated measurements with the same subject permit detection of changes in odor conditions or odor levels at different locations, within an accuracy of about plus or minus 25 to 50 percent. However, no absolute measurement exists. Standard test procedures call for the use of odor panels (usually six people) who rate odor levels from bagged samples taken at the location affected. The panel usually works in a filtered air environment, where absence of extraneous odors can be guaranteed.

17.2.17 Aerobic Condition Measurements

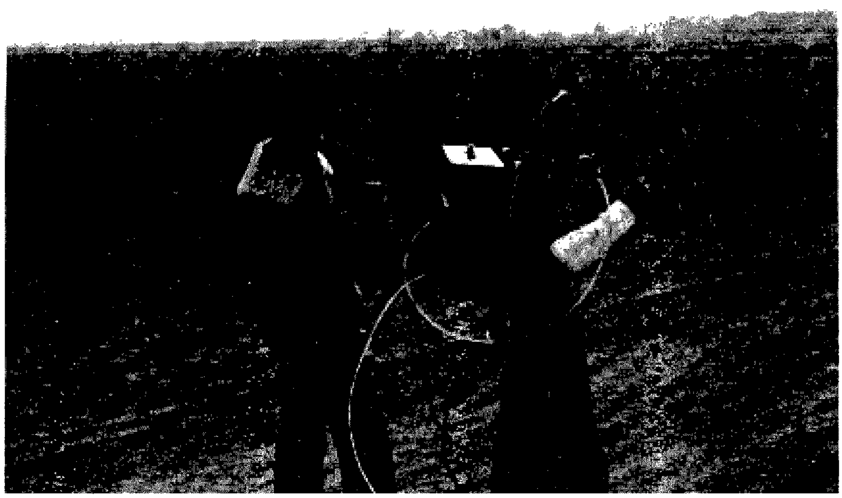
Aerated pile composting operations require the measurement of oxygen concentration in the pile. The portable oxygen indicator frequently used for personnel safety monitoring is applicable to this service. These instruments operate on the same principle as the catalytic or polarographic cell dissolved oxygen analyzers described in Section 17.2.10 but are designed to be portable, with a hand pump for drawing a gas sample.

17.2.18 Blanket Level Measurements

Measurements of sludge blanket level in sedimentation tanks and gravity thickeners can be accomplished with optical (turbidity) type instruments and with ultrasonic instruments, as described in Section 17.2.6. The success of this measurement is dependent on the characteristics of the sludge blanket. A well defined blanket interface provides a readily detectable change in suspended solids concentration. Where the blanket is poorly defined, this measurement is not satisfactory.



ASSEMBLY DETAILS OF DRO SHOWING
SUBJECT'S MASK AND CONTROL'S DILUTION METERS



SUBJECT AND CONTROL MEASURING FOR ODORS IN FIELD
BATTERY PACK USED FOR PORTABILITY

FIGURE 17-4

DIRECT READING OLFACTOMETER (DRO) (4)

Air-lifts with intakes at multiple elevations have been provided in a number of plants for drawing a sludge sample. The individual air lifts for a tank can be manifolded together and the flow passed through a turbidimeter to provide remote monitoring. The individual air lifts are actuated in sequence, and a sludge profile is obtained. A turbidimeter of the falling stream type is recommended for this service. It should be installed at the air-lift location.

17.2.19 Hydrocarbons and Flammable Gas Detectors

Methane is the flammable gas most likely to occur in sludge management. Catalytic detectors, available from a number of manufacturers, are sensitive to any flammable gas and ordinarily may be installed in the space to be monitored, thus eliminating sampling systems. The detector consists of a heated catalytic element exposed to the ambient air and a similar reference element isolated from ambient air. If flammable gas is present, the exposed element temperature will rise above the reference probe as the gas is oxidized. This temperature difference results in a change in electrical resistance, which is measured by the detector's electronics. These units should be calibrated periodically with a standard reference gas. Catalytic probe life is definitely limited, and periodic replacement is required. Under very severe conditions, the probe may lose sensitivity in less than a year. When these conditions occur, a sampling system to clean up the sample and remove the moisture should be considered.

17.2.20 Radiation Monitoring

If gamma radiation is used in sufficient quantities to effect treatment, safety monitoring will be required to protect personnel. Note that nuclear density and weight equipment uses such small gamma sources that no significant hazard exists, and personnel safety monitoring is not required. Personnel safety monitoring requires monitoring of the radiation levels in the exposed spaces to detect abnormal leakage from the process and individual monitoring to detect exposure of that individual to radiation. Space monitoring is accomplished by suitable geiger counters. Personnel who are not normally exposed to radiation can be adequately monitored by badges containing photographic emulsion. Personnel who may absorb radiation during job performance will have to carry instrumentation capable of accurately accumulating the amount of radiation absorbed to control dosage to acceptable limits. Specialists in nuclear monitoring must be consulted if this type of process is contemplated.

17.2.21 Machinery Protection

Wastewater solids treatment and disposal machinery requires protection similar to that required by the machinery in other wastewater treatment systems. However, some solids system protective instrumentation is unique. This section deals with this unique protective instrumentation.

17.2.21.1 Empty Pipe Detectors

Empty pipe detectors were developed to provide protection for sludge pumps that might be operated with no fluid in the suction pipe. This protection is particularly applicable to positive displacement or progressive cavity pumps, which can suffer extensive stator damage if operated without fluid. Capacitance elements fabricated as a wafer to fit between pipe flanges are most commonly used. The theory of operation is identical to the capacitance level elements described earlier. Nuclear level switches can also be used for this application but require more mounting space. The nuclear device clamps onto the outside of the pipe and operates much like the nuclear density meter described earlier. This is a very simple application of the nuclear unit. The unit used has a much lower cost than nuclear units required for density measurement. The nuclear device may be easier to install in existing plants since existing piping would not have to be disturbed as long as sufficient space is available.

17.2.21.2 Vibration - Acceleration and Displacement Systems

Vibration detectors are provided for most machinery that operates at high rotational speeds--for example, centrifuges. Vibration detectors are usually capable of giving advance warning of incipient machine failure. This allows for orderly shutdown, thereby minimizing damage to both process and machinery. The cost of the protection afforded is usually justified only for larger pieces of equipment. Two types of detectors are generally applicable: acceleration and displacement. Accelerometers are less expensive than displacement systems and provide moderate protection to lower value machinery, such as thickening or dewatering centrifuges. Displacement probes are mounted rigidly to a bearing pedestal or similar stationary object and provide a very accurate measure of actual shaft movement in the journals. A large number of displacement probes are required to provide full protection. Their installation and alignment is rather complex when compared to the accelerometer, which is simply attached to the machine housing. As a result, displacement installations must be carefully engineered and are relatively expensive. Displacement systems are generally used on large, high-speed machinery, such as centrifugal blowers in sizes of 500 horsepower or greater.

17.2.21.3 Flow Loss Monitors

Gas or air flow can be effectively monitored for loss of flow by vane switches, differential pressure switches, and thermal flow switches. Vane switches are the simplest, but require fairly high velocities for reliable operation. A differential pressure rise from the suction to the discharge side of a fan or blower, or a differential pressure loss from the suction to the discharge side of a filter or other piping element provides a simple monitor of flow that is adequate for most purposes. Where precision operation is required, particularly at low velocities, a thermal flow switch is most suitable. These devices consist of a heated element that is convection-cooled by air flow. The change in heat loss of the element provides reliable detection of gas or air flow.

Vane switches, differential pressure switches, and thermal flow switches are also applicable to liquid flows. However, the vane switch is unsuitable for solids-bearing fluids, such as sludge. One thermal flow switch is constructed as a smooth rod. If installed at an angle with the pipe radius or into an elbow, this unit is applicable to solids bearing fluids. Differential pressure devices must be provided with chemical seals if they are to be successfully applied to solids-bearing fluids.

17.2.21.4 Overload Devices

All electric motor drives at wastewater treatment plants are provided with thermal overloads. However, these units are not fast enough to protect the driven machinery from damage due to mechanical blockage. Collector drives, in particular, are virtually always provided with some type of instantaneous protection from excessive torque. One of the most common applications involves the circular collector of secondary sedimentation tanks and circular gravity thickeners. The simplest overload device for such equipment is the shear pin. The shear pin has the disadvantage of working only once. When it has provided protection for one overload, it must be replaced with an identical pin. As a result, several mechanical resetable overload devices have been used. The one most commonly used today is an instantaneous over-current relay or ammeter with high alarm contacts installed in the motor circuit. These units are simple, very reliable, and also provide a continuous indication of load. This is useful for detecting any abnormal load build-ups.

17.2.21.5 Flame Safeguard Equipment

Wastewater solids systems that use boilers or furnaces to maintain anaerobic digestion, heat drying, or high temperature processes require flame safeguard instrumentation. Flame safeguard equipment shuts off the oil and gas burners in case of ignition loss. Ultraviolet light detectors provide virtually instantaneous protection since ultraviolet energy is present only in the actual flame. This equipment is normally provided as part of the burner control package. This package also includes sequencing systems as necessary to ensure the purging of explosive gases from the fire boxes before burner relighting following a flame-out.

17.3 Sampling Systems

Sampling systems include sample transport and sample conditioning. Where practical, measuring elements should be installed directly into process vessels. In some cases, however, immersing a measuring element directly into the process is not possible or desirable. Some analyzers simply are not adaptable to direct on-line measurements. In other cases, the cost of an analyzer is so great that it must be time-shared between several sample streams.

Anytime a sample must be transported a significant distance, care must be taken to ensure that the sample delivered to the analyzer is fresh and that critical characteristics do not change during the transport time. Pumps and piping materials must not be corroded by the sample nor should they in any way affect the sample composition. Fluid velocities in transport lines must be kept high enough to prevent solids settlement and to limit transit time. Flow to the analyzer should be continuous to maintain clean lines and deliver a fresh sample immediately to the analyzer, where sample switching is practiced. Where pumps are required, they must be suitable for continuous operation without excessive maintenance. Where switching systems are used to direct multiple samples into an analyzer, three-way diverter valves are required for each sample stream, with one port to the drain and the other to the sampler.

Solenoid-controlled, pneumatically operated ball valves are recommended for sample switching. These units are capable of handling many operations without excessive maintenance and can provide slow operation of the ball valve and, therefore, smooth switching of the sample stream. Electric motor-operated ball valves can be used but life expectancy of ball valves in repetitive operations is short. Rapid direct switching with large solenoid valves causes significant pressure stress on sample valve piping. If solenoid valves are used to switch samples directly, some system must be provided to absorb water hammer. Large, three-way solenoid valves with suitable characteristics are not readily available; therefore, two two-way valves, one normally open and one normally closed, are usually required to obtain the three-way switching function.

Some type of program timer is required to control sample valves and synchronize readout devices with the samples. The time program must also consider the settling time of an analyzer after switching samples. The settling time includes both transport delays required to get new samples through piping between switching valves and time for the analyzer itself to reach new readings. In many cases, an analysis is used only for recording or indication (that is, not for control purposes), and it is acceptable to provide a single output instrument with some means of identifying the sample source currently being measured. In systems where the output of the analyzer is used for control, some means must be provided of holding the last value of the parameter during periods that the analyzer is working on other samples. It is also essential to review control system dynamics in an intermittently sampled data environment. In general, completely different control strategies are required for intermittently sampled data systems than for continuous data systems.

Gas sample lines should be heat-traced to avoid condensation within the lines. In cold climates, exposed liquid samples will also require heat tracing to avoid freezing.

Sample preparation is critical to satisfactory operation of analysis equipment. The degree of grinding and/or filtering required depends on the nature of the analysis and the equipment. In general, the aid of the analyzer manufacturer should be enlisted in working out a suitable system. More information on sample transport is available (5).

17.4 Operator Interface

17.4.1 Location

Modern electronic instruments that provide information to operators (for example, indicators and recorders) are designed for installation in clean, air-conditioned control rooms. Field locations are usually not suitable for these instruments unless additional protection is provided. Hydrogen sulfide is present in many process areas, and if it is allowed to contact instruments that are not designed for this atmosphere, failures may result from corrosion. Some process areas are classified as hazardous, so that electrical equipment must be explosion-proof. Explosion-proof electronic operator interface instruments are not available. To be usable in a hazardous area, non-explosion-proof instruments must be enclosed in a suitable box. This makes them virtually inaccessible and, therefore, difficult to use and maintain. Where instruments must be located in a contaminated or hazardous process area, pneumatic instruments, which are inherently explosion-proof and are fairly resistant to dirt and corrosion, should be considered. Where pneumatic instruments are not practical, air purging of cabinets or special filters may provide adequate protection to electronic instruments. A suitable remote control room is the most desirable solution.

17.4.2 Indicator Boards

Sludge handling systems are frequently designed with considerable operating flexibility, with large numbers of valves and many possible flow configurations. As a minimum, some means is required to tell the operator what the present flow configuration is. A chalk board can be used for this purpose, but it does not readily provide a graphic picture of the piping configuration. Therefore, in more complicated plants, some type of graphic indicator board is desirable to prevent errors. In the simplest form of indicator board, a graphic panel is produced with manually moveable flags or indicating lights with which the operators indicate current valve positions and pump operation. Such a system can give an excellent picture of the present operating configuration, but is dependent on the operators to set the flags correctly. The use of limit switches on valves and indicating lamps is more reliable and also provides the operator with a ready means to check the validity of the valve settings and pump selection. Figures 17-5 and 17-6 show two examples of graphic panels with indicating lights for showing valve or gate positions.

17.5 References

1. USEPA. Instrumentation and Automation Experiences in Wastewater Treatment Facilities. MERL. Cincinnati, Ohio 45268. EPA-600/2-76-198. October 1976.

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3. USEPA. Advanced Automatic Control Strategies for the Activated Sludge Treatment Process. ERIC. Cincinnati, Ohio 45268. EPA-670/2-75-039. May 1975.

4. Courtesy of Eutek, Inc. Sacramento, California.

5. USEPA. Wastewater Sample Transport and Conditioning System. Cincinnati, Ohio 45268. EPA-600/2-76-146. October 1976.

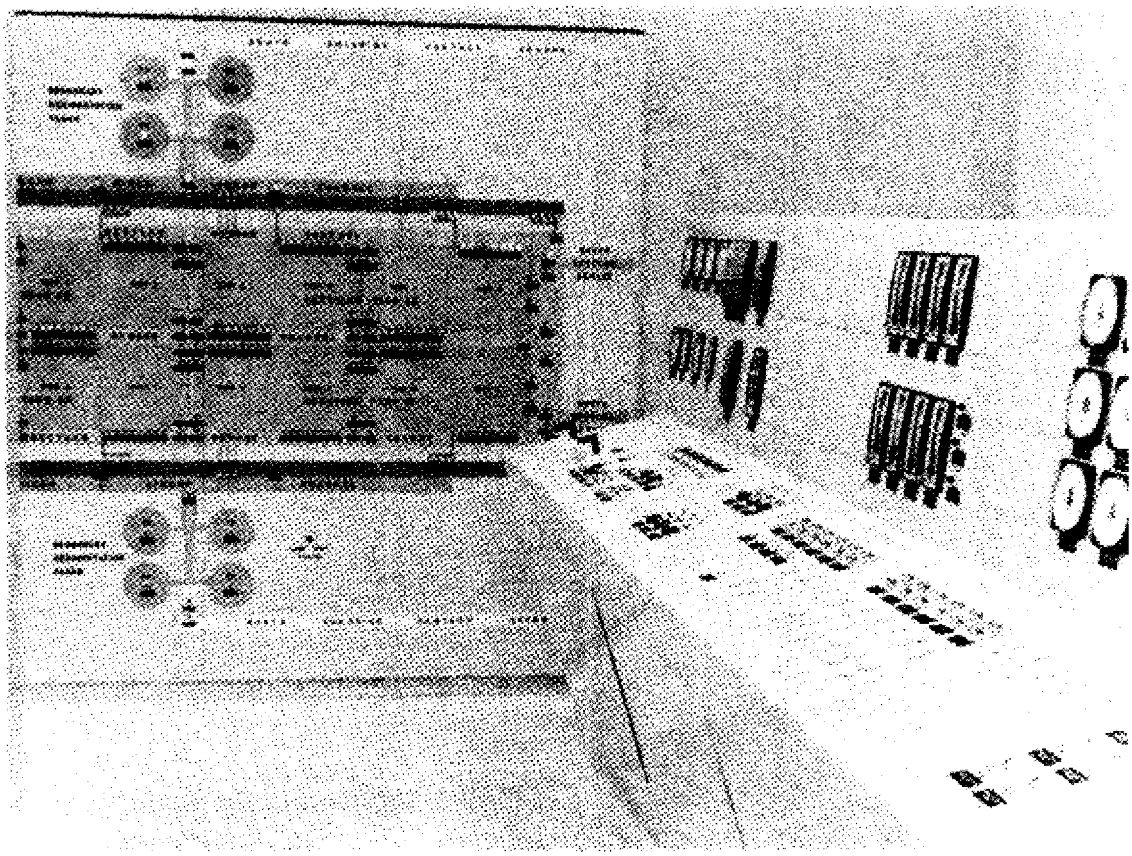

FIGURE 17-5

AERATION CONTROL GRAPHIC PANEL AND CONSOLE
LIGHTS SET MANUALLY ON GRAPHIC PANEL

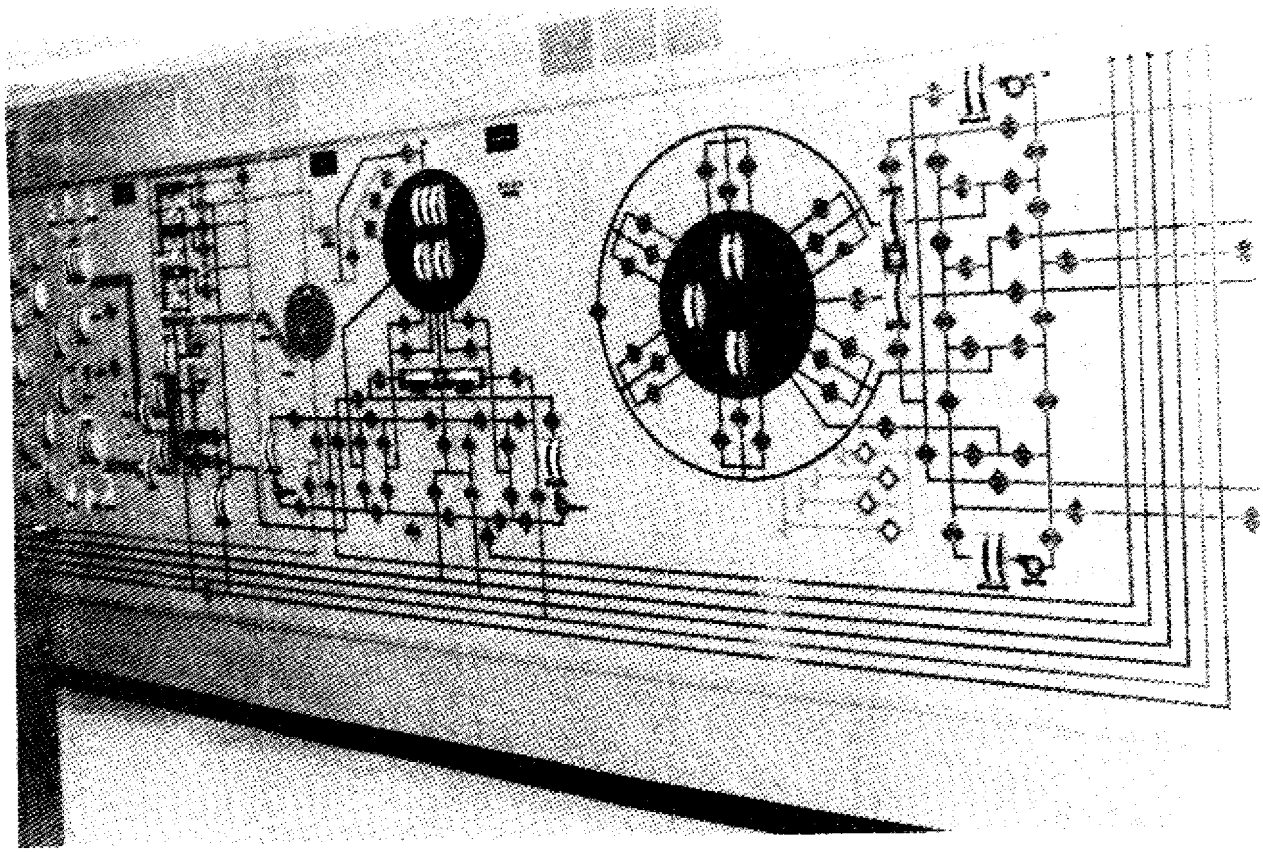

FIGURE 17-6

INCINERATOR-DIGESTER CONTROL GRAPHIC PANEL
LIGHTS CONTROLLED BY REMOTE VALVE LIMIT SWITCHES

EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 18. Utilization

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 18

UTILIZATION

18.1 Introduction

Utilization refers to the beneficial use of sludge or sludge by-products. Sludge disposal options that do not involve beneficial use (for example, when disposal is the only goal) are discussed in Chapter 19.

Sludge may be used as a:

- Soil amendment. Sludge contains both crop nutrients and organic matter. Sludge can be used as a fertilizer and in the reclamation of disturbed lands, such as construction sites, strip-mined lands, gravel pits, and clear-cut forests. It may be used to stabilize bank spoils and moving sand dunes.

- Source of heat and work. Energy may be recovered from the gas produced during anaerobic stabilization, or partial or full pyrolysis of sludges, and from the direct burning of sludges. This energy may be converted to heat or work and put to a variety of in-plant uses, or exported for uses outside the plant.

- Source of other useful products. Other useful products include waste treatment chemicals, landfill toppings, industrial raw materials, animal feed, and materials of construction.

The thrust of recent legislation has been to encourage beneficial reuse. The Federal Water Pollution Control Act of 1972 (PL 92-500) stated that "The Administrator shall encourage waste treatment management which results in the construction of revenue producing facilities for . . . the recycling of potential sewage pollutants through the production of agriculture, silviculture, or agricultural products, or any combination thereof." The Clean Water Act (CWA) of 1977 (PL 95-217) offered further incentives for projects that involved innovative and alternative technology (for example, sludge utilization, energy recovery). In addition, the CWA requires the establishment of industrial waste pretreatment programs with the objective of reducing toxic pollutant loadings to municipal treatment facilities. Implementation of pretreatment programs will make more municipal solids suitable for reuse.

The pretreatment program supplements programs established by the Toxic Substance Control Act (PL 94-469) which authorized USEPA to obtain production and test data from industry on selected chemical substances and regulate them where they pose an unreasonable risk to the environment. Steps towards the goal of furthering sludge utilization were taken by the Resources Conservation and Recovery Act (RCRA) (PL 94-580), which authorized USEPA to develop treatment and application rate criteria for sludge to be applied to land growing food-chain crops, as well as to nonagricultural areas. RCRA also authorized funds for research, demonstrations, training, and other activities related to development of other resource recovery schemes.

At the same time, it is recognized that there are potential hazards associated with wastewater sludge utilization and that utilization without careful planning, management, and operation could present a danger to human health and to the environment.

18.2 Sludge as a Soil Amendment

Approximately 1.3 million dry tons per year (1.2 million t/yr), or 31 percent of the treated municipal sludge generated in the United States today, is applied to the land for productive use. The quantities of treated sludge projected for ultimate disposal by 1990 range from 5.6 to 7.6 million dry tons per year (5.1 to 6.9 t/yr). The sludge quantities generated will depend in great part upon the extent to which municipalities adopt land treatment of wastewater. Land treatment, which is an alternative to conventional forms of wastewater treatment, reduces substantially the amount of sludge produced.

18.2.1 Perspective

The impact of sewage sludge on the national commercial fertilizer market is relatively insignificant. This is shown in Table 18-1, where the amount of nutrients in currently utilized and potentially usable sludges are compared against the nutrients presently consumed in the form of commercial chemical fertilizers. Nitrogen, phosphorus, and potassium in currently utilized sludges are estimated to be only 0.2, 0.9, and 0.1 percent, respectively, of those nutrients consumed with chemical fertilizers. If all United States wastewater sludges were applied to land, these percentages would increase to 0.6, 3.2, and 0.4 percent, respectively. If the value per pound of nutrient in the sludge was the same as that paid by farmers for the corresponding commercial nutrient, the monetary value of utilized nutrient sludges in 1978 was $9.5, $26.0, and $1.7 million per year for nitrogen, phosphorus, and potassium, respectively.

TABLE 18-1

COMPARISON OF CURRENT AND POTENTIAL SLUDGE UTILIZATION TO COMMERCIAL FERTILIZER CONSUMPTION IN THE UNITED STATES (1)

	Nutrient usage, 1,000 ton/yr				
Nutrient	A. Nutrients in currently utilized sludges	B. Nutrients in potentially useable sludges	C. Nutrients presently consumed in commercial fertilizers	A, as percent of C	B, as percent of C
Nitrogen as N	21.6[a]	65.3[a]	10,642	0.2	0.6
Phosphorus as P	21.5	80.7	2,453	0.9	3.2
Potassium as K	4.3	18.9	4,841	0.1	0.4

[a] Nitrogen in sludge expressed as available N, assumed to be 50 percent of total N.

While the values of nutrients in sludge are small relative to the current dollar values of commercial fertilizers, they are by no means insignificant to those who would benefit monetarily. For example, wastewater treatment plants could reduce operating costs by sludge sales or by elimination of more expensive treatment and disposal methods. Sludge users, for example, private citizens, can obtain nutrients for lawns and gardens at low cost.

It is estimated that by the year 1990, annual savings in treatment costs could be $100-$500 million if sewage sludge utilization were increased to about 50 percent (2). This utilization increase could result, in part, from the incentives for innovative and alternative technologies provided by the 1977 CWA if various constraints to sludge utilization, including regulations, are not overly stringent. If 50 percent of sewage sludge were utilized on land, about $50 million (1978 dollars) in nutrients and organic matter could be recovered and utilized for growing crops and improving soil structure.

A number of locations where various sludge utilization options are currently being employed are listed in Table 18-2. Some of these operations have only recently started up (for example, Madison, Wisconsin), while others have been in operation for as long as 50 years (for example, Los Angeles County, California).

18.2.2 Principles and Design Criteria for Applying Wastewater Sludge to Land

Certain basic elements are common to all land application projects, no matter how or where the sludge is to be applied. These elements include preliminary planning, site selection, process design (which includes determination of sludge application rates), facilities design, and facility management and operation. Full and complete discussions of each of these elements are too lengthy to be included in this manual. Therefore, this section will provide only a brief outline. For full details, the reader should consult Reference 3. At this writing, this is USEPA's primary reference for the utilization of sewage sludges on land. The entire subject of sludge use on land will be covered more extensively in a future Technology Transfer design manual.

TABLE 18-2

EXAMPLES OF COMMUNITIES PRACTICING LAND UTILIZATION (2)

Communities	Wastewater flow, MGD	Sludge utilized, dry ton/day	Description[a]
Landspreading of liquid sludges			
Clinton, New Jersey	1	0.5	PO, PL
Rochester, Indiana	1	0.8	MO, PL
Little Falls, Minnesota	1	0.6	MO, ML, PL
Peru, Indiana	2.5	0.8	MO, PL
Bowling Green, Ohio	3.5	1.7	MO, PL
Muncie, Indiana	17	10	MO, PL
Salem, Oregon	30	8	MO, PL
Madison, Wisconsin	36	27	FO, PL
Seattle, Washington	150	28	PO, PL
Chicago, Illinois	909	165	MO, ML
Composting			
Durham, New Hampshire	0.8	0.7	MO, GAM
Burlington, Vermont	5.8	2.3	MO, PL, ML
Toms River, New Jersey	6.5	7.8	ML, PL
Bangor, Maine	7	2	MO, GAM
Windsor, Ontario	21	25	MO
Camden, New Jersey	32	12	MO, GAM
Philadelphia, Pennsylvania	113	30	MO, ML, PL
Washington, D.C.	300	55	PO, GAM, S
Los Angeles, California	440	150	MO, S
Drying			
Little Falls, Minnesota	1	0.4	Drying bed, ML, PL
Largo, Florida	8	2.5	Heat dry, S
Marion, Indiana	9	0.2	MO, PL
Fort Worth, Texas	75	41	Drying bed, MO, ML
Houston, Texas	73	18	Heat dry, S
Toledo, Ohio	78	35	PO, PL, Filter cake
Milwaukee, Wisconsin	132	190	Heat drying, MO, S
Denver, Colorado	140	125	MO, ML, Filter cake
Chicago, Illinois	909	131	Heat dry, MO, S

[a] PO - Privately operated (contractor)
PL - Private land
MO - Municipally operated
ML - Municipal land
FO - Farmer operated
GAM - Giveaway to municipality
S - Sale

18.2.2.1 Preliminary Planning

Preliminary planning consists of the following steps:

- A planning team is formed of individuals who are interested in the proposed program and whose expertise and support are required. A major activity of the planning team is to solicit and obtain public support for the program, particularly the support of potential sludge users and local government. The importance of obtaining public support cannot be overemphasized. Many utilization projects have failed because planners have failed to recognize this necessity.

- Basic data is collected, including sludge quantities and characteristics, climatic conditions and local, state, and federal regulations.

18.2.2.2 Site Selection

Site selection consists of:

- Preliminary screening. A rough estimate of total acreage required is obtained by dividing total sludge quantity by an assumed application rate. Land that might be available within about 30 miles is identified; obviously unsuitable sites are immediately eliminated. If this rough analysis indicates that sufficient land is available, a more detailed study of potential sites is initiated.

- Site identification. Potentially available sites remaining after preliminary screening are characterized as to topography, land use, soil characteristics, geology, and distance from treatment plant. The characterization at first is general, taken from published and readily available sources of information, such as soils surveys and topographical maps. The least suitable sites are eliminated by an objective ranking procedure, similar to the second-cut analysis described in Process Selection Logic, Chapter 3. The procedure is reiterated, with more detailed and site-specific information in each iteration, until finally the best site or sites are determined.

- Site acquisition. Sites are acquired either by outright purchase or by the municipality obtaining a contract for the right to use private land for sludge utilization.

18.2.2.3 Process Design

Process design involves selecting suitable crops and determining appropriate sludge application rates as well as application methods. Although basic design goals (maximization of crop yield and quality, and minimization of environmental damage) remain constant regardless of projected land use, design procedures differ for applications on agricultural, forested, and reclaimed lands:

- Application on agricultural land. Sludge should be applied to agricultural land at a rate equal to the nitrogen uptake rate of the crop unless lesser application rates are required because of cadmium limitations. Annual loading rates for cadmium on soils have been set at 1.8 pounds per acre per year (2.0 kg/ha-yr) for food chain crops; however, this value can be regarded as provisional and may be revised on the basis of ongoing and future research and future federal regulations. The basis for the nitrogen criterion is to minimize nitrate leaching to groundwater. The annual limit for cadmium is chosen to minimize uptake by crops and the potential for long-term, sub-clinical adverse effects on human health. Site lifetime limits are established on the basis of maximum cumulative loadings of lead, zinc, copper, nickel, and cadmium. These limits are designed to allow growth and use of food-chain crops at any future date.

- Application on forested land. As with agronomic crops, the harvesting of a forest stand removes the nutrients accumulated during growth. However, the amounts removed in forest harvesting annually are significantly lower than in agronomic crop harvesting. Uptake by vegetative cover is negligible. Therefore, forest systems rely primarily on soil processes (denitrification) to minimize nitrate leaching into groundwater. As a result, nutrient loadings on forested lands must generally be less than those on agricultural sites. No annual limitations are set for cadmium, since no food-chain crops are grown. Lifetime metals limits used for agricultural sites are suggested for forested land; this would minimize metal toxicity to trees and allow growth of other crops if the area were cleared at a future date.

- Application on reclaimed land. Sludge is usually applied to impoverished lands at rates sufficient to satisfy the nutrient requirements of the cover crop.

18.2.2.4 Facilities Design

Once the site has been chosen and crops and approximate sludge application rates have been decided upon, the project can proceed to the facility design stage. This phase of the project is site-specific and consists of:

- Detailed site investigations. On-site soil analyses are conducted to determine such factors as available phosphorus and potassium, soil pH and lime requirements, cation exchange capacity, and organic matter. Such information will allow for finalizing sludge application rates determined in the Process Design phase. Soil should be characterized to provide baseline data against which subsequent analyses can be compared. This will allow documentation of changes in the physical and chemical properties of the soil due to sludge applcation.

- Determining pre-application treatment. This refers to upstream sludge treatment, including thickening, stabilization, disinfection, conditioning, dewatering, and drying (see Chapters 5 through 10 for detailed discussions). For new plants, the method of sludge disposal or utilization may dictate the preapplication processing configuration. For existing plants, pre-application treatment influences sludge form and composition, and thus affects application rate, the method of spreading, and the mode of sludge transportation.

- Determining sludge application mode. The application mode depends upon the sludge form. Liquid sludge can be spread by tank truck, sprayed, injected, or applied by the ridge-and-furrow technique. Dewatered sludges are usually applied by conventional fertilizer spreading equipment. See Chapter 19 for a discussion of sludge application techniques.

- Determining sludge storage requirements. Storage should be provided when sludge cannot be spread (for example, during inclement weather). Storage can also provide additional stabilization and disinfection. See Chapter 15 for information on storage.

18.2.2.5 Facility Management, Operations, and Monitoring

Once the system has been constructed, it must be made to run smoothly and efficiently:

- Operations must be scheduled. Spreading must be timed to satisfy farming requirements. If the municipality grows its own crops, tilling, planting, and harvesting operations must also be scheduled.

- Operations must be managed to reduce off-site impacts (odors, contamination of groundwaters, and surface waters).

- Operations must be monitored to assure that the system is operating as intended. Sludge must be analyzed to ensure its acceptability to the user and to provide a record of nutrient and metal additions to the soil. Soil, crops, groundwaters, and surface waters need to be monitored only if sludge nutrients are applied at rates exceeding the uptake capacity of crops or soils.

18.3 Sludge as an Energy Source

Whether produced from direct burning of sludge or from the combustion of sludge-derived fuels such as digester gas or pyrolysis gas, the end product is energy. Heat can be made to perform a variety of useful functions.

18.3.1 Perspective

The precipitous rise in energy prices during the 1970s has generated intense interest in the conservation and recovery of this precious commodity. For example, the United States Energy Research and Development Administration (now the Department of Energy) has proposed one-seventh of the United States energy requirements be produced by bioconversion processes (for example anaerobic digestion) by the year 2020 (4). Clearly, however, this awesome quantity of energy will not be generated from municipal wastewater sludge; there is simply insufficient sludge. Very large external organic sources (for example, manure from feed lots or municipal refuse) and external processing systems (energy farms) will be required to effect such production. As with utilization of sludge on land, the impact of energy recovery from municipal sludges will be largely local, that is, it will be felt most strongly at the treatment plant and in its immediate vicinity. Here, the effects can be significant.

As Figure 6-32 indicates, the energy value of methane generated from the anaerobic digestion process exceeds the energy requirements of the digestion process. The excess can be used to supply the energy needs of other plant processes. In some instances, the gas generated is sufficient to supply the energy needs of the entire wastewater treatment plant, with excess gas available for sale. Notable examples are the British Southern and Mogden plants and the County Sanitation Districts of Los Angeles County Joint Disposal Plant (5). Heat recovery is possible even if digestion is not used, for example, heat recovery from coincineration of sludge and municipal refuse is expected to provide all the energy needs of the Central Contra Costa Sanitary District (CCCSD) plant in Concord, California (6).

In January 1978, the State of California Public Utilities Commission (PUC) passed a resolution directing all state utilities to augment cogeneration projects by setting up new rate schedules covering interruptible electric service; by creating new specific rates to encourage cogeneration, including revisions to standby rates; and by developing guidelines covering the price and conditions for the purchase of energy and capacity from cogeneration facilities owned by others (7). The term cogeneration in this context means the production of power by utilization of waste heat; it also covers power produced through the burning of alternative fuels, such as municipal waste. The resolution significantly changes the economics of power generation at California wastewater treatment plants and encourages the use of in-plant energy recovery.

On June 27, 1979, the Federal Energy Regulatory Commission issued proposed regulations providing for the qualification of small power production and cogeneration facilities under Section 201 of the Public Utility Regulatory Policies Act of 1978 (8). The proposed regulations are set up to assure opportunities for small power producers (<80 MW) to sell electricity to electric utilities when such electricity is generated through the use of renewable energy sources (such as sludge) or recovered process heat.

These regulatory actions are an indicator of future trends in the United States as the country seeks to increase its non-fossil fuel energy production. The designer should be aware of their impacts on future planning for using sludge as an energy source.

The recovery of energy in the form of fuels and heat from municipal sludges will be discussed in detail in the following sections.

18.3.2 Recovery of Energy From Sludge

Figure 18-1 shows on one diagram processes which release energy from sludge; devices which convert the released energy to useful forms; useful energy forms; and suggested applications of recovered energy, either at the wastewater treatment plant or off-site. Special consideration must be made when designing processes to recover energy from wastewater sludge. Some of these considerations are discussed below.

18.3.2.1 Treatment of Digester Gas

The treatment required depends on the digester gas' anticipated use. Treatment is minimal if the gas is burned in a boiler or in a high temperature internal combustion engine. Conversely, if it is sold for utilities as a natural gas substitute it must be upgraded to natural gas quality. This involves treatment to remove particulates, H_2S, CO_2, and water. As a general rule, gas treatment should be avoided to as great a degree as possible. It is preferable to set up recovery systems that can be operated with untreated digester gas.

Particulates are carried over with the gas as it leaves the digester. They may be removed in large sedimentation traps and cyclonic separators.

H_2S is most commonly removed by iron-sponge scrubbers. The "sponge" consists of wood shavings impregnated with iron oxide. H_2S reacts with iron oxide to form nonvolatile ferric sulfide. The sponge can be regenerated with air. Sponge capacity is

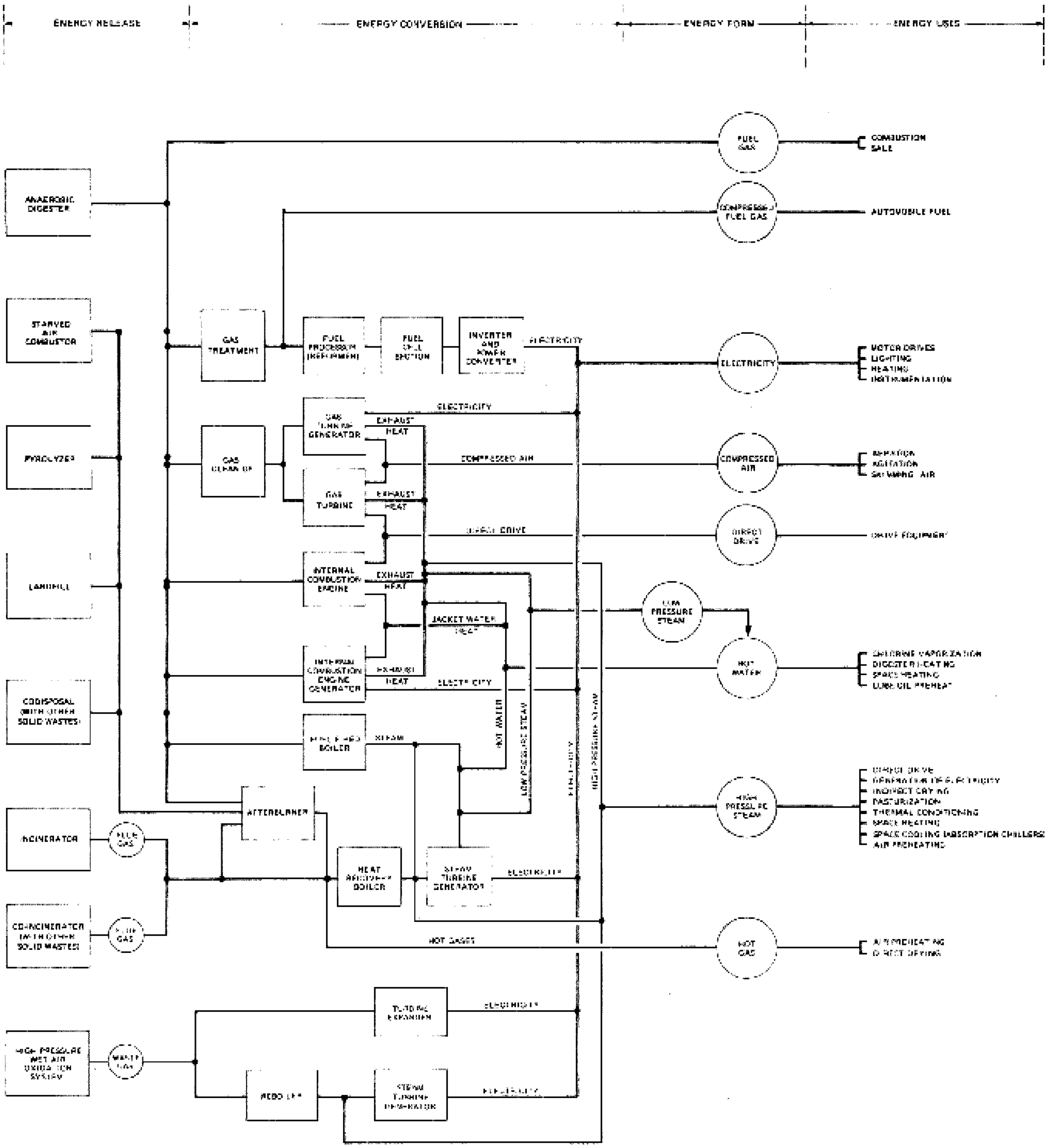


FIGURE 18-1

THE RELEASE, CONVERSION, FORMS AND USES OF ENERGY FROM SLUDGE

about 0.6 pounds of sulfur per pound of iron oxide (0.6 kg/kg). Problems have been experienced with fouling of the iron-sponge by oils and greases entrained in the digester gas. Iron-sponge scrubbers are commercially available. Other H_2S scrubbing processes are less commonly used and are proprietary.

CO_2 removal processes can be divided into three broad categories; absorption (both physical and chemical), adsorption, and cryogenic processing. Many CO_2 removal processes also remove H_2S. The only process which has received much use in wastewater treatment plants is absorption in water; this process has been tested at Modesto, California, and Los Angeles County, California. In 1976, total costs for a water scrubbing unit of 1,000,000 cubic feet per day (28,300 m^3/d) capacity were estimated at $2.50 per million Btu ($2.37/GJ) of energy (9). Some methane is also absorbed during the scrubbing process; costs were based on energy leaving the scrubber as opposed to energy in the untreated gas. Of this, $0.15 per million Btu ($0.14/GJ) was attributed to the cost of iron-sponge H_2S removal, which must necessarily precede the water scrubber. It was estimated that this unit would produce 2 MGD (87 l/s) of spent scrubbing water. Costs for treating the spent scrubbing water were included in the estimate. These units are commercially available.

Gas leaves the digestion system at approximately 95°F (35°C) and is saturated with water vapor. During transport the gas is cooled. Condensate formed must be removed to protect downstream equipment. Water traps should be installed at low spots in the gas pipe and at frequent intervals. If moisture must be reduced substantially, adsorption drying or glycol dehydration can be used.

18.3.2.2 Gas-Burning Equipment

Corrosion Factors

One of the major problems associated with recovering heat from digester gas is corrosion caused by SO_2 and SO_3, the combustion products of H_2S. If the exhaust gas temperature is allowed to drop below its dewpoint, the condensate which forms is acidic as the result of absorbing SO_2 and SO_3. The acidic condensate is corrosive to metallic elements of the exhaust-carrying system. There are two alternatives to alleviate the problem. The first is scrubbing of H_2S from the gas before combustion. The second is maintaining the exhaust gas at temperatures considerably greater than its dewpoint, to prevent condensation. This generally requires that the water temperature of any boiler or engine using unscrubbed gas be at least 212°F (100°C). Also, stack gas temperatures should not be allowed to drop below 350° to 400°F (177° to 204°C). Use of unscrubbed digester gas is preferred. Equipment fueled by unscrubbed digester gas should not be used in intermittent service, since condensation will occur each time the unit is shut down.

Shutdowns should be minimized. Similarly, the equipment should be designed so that even when operated at its lowest loadings, exhaust gas temperatures are sufficiently high to prevent condensation.

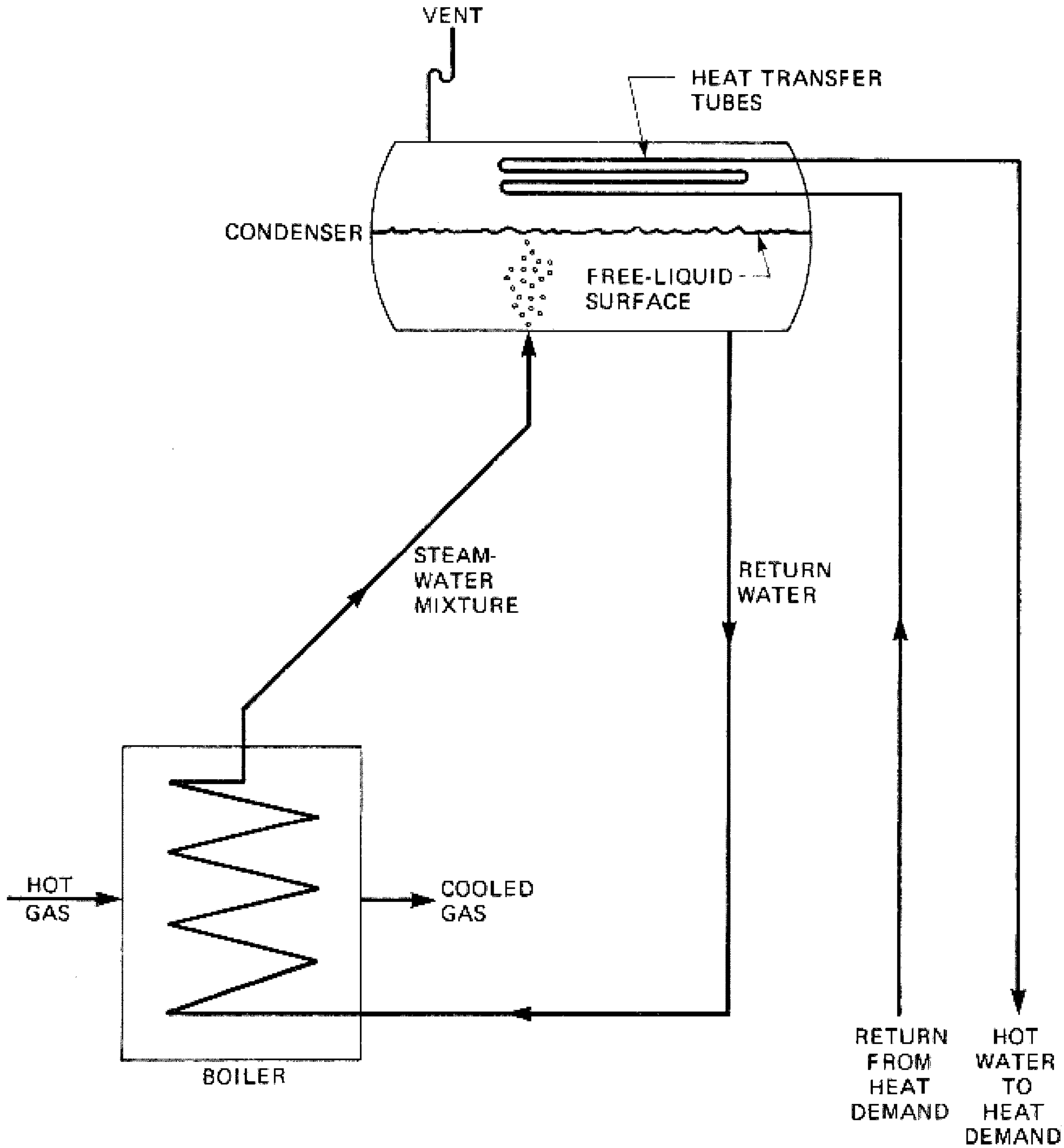


FIGURE 18-2

SCHEMATIC OF COMBINED BOILER/CONDENSER SYSTEM FOR HOT WATER PRODUCTION

Boilers

Scotch-type tube boilers and cast iron sectionalized boilers have both worked well with untreated digester gas as long as the water or steam temperatures are maintained above 212°F (100°C). Figure 18-2 illustrates an effective method for hot water production using boilers. The heat source (the boiler) and heat demands are not directly tied together, but separated by a condenser. The condenser is mounted directly above the boiler. The specific gravity of the steam/water mixture produced in the boiler tubes is less than that of the water returning to the boiler. The mixture is displaced upward into the condenser, gives up its heat, then flows by gravity back to the boiler. A natural circulation pattern is thus set up.

If heat supply exceeds heat demand, the excess heat is released by venting steam from the condensers. Temperature control is automatic, being set by the vent pressure. Advantages of this system are simplicity, elimination of costs associated with pumping, automatic temperature control, and independent operation of the boiler from other heat sources and heat demands. Independent operation is particularly important; it allows the boiler to operate at its own best conditions, without being affected by the operations of other components of the system.

Prime Movers

Digester gas can be used to fuel reciprocating engines and gas turbines. Prime movers convert part of the fuel's energy to work, rejecting the remainder as waste heat. Thermal efficiency can be dramatically improved if portions of the rejected heat can be recovered and used for process or building heating. Waste heat recovery is more efficient if prime movers are run hot, since heat rejected at higher temperatures can be put to a greater variety of uses than heat rejected at low temperature. Also, exhaust systems last longer because SO_2-SO_3 corrosion is reduced.

Reciprocating Engines. Engines may be cooled using either a forced circulation system in which water is pumped through the engine, or a natural draft system. The equipment configuration for natural circulation cooling is similar to that described for boiler natural circulation systems except the engine replaces the boiler in the flow diagram (see Figure 18-2). The advantages of natural circulation cooling are the same as those discussed for natural circulation boiling. Cooling system pressures are limited to about 10 psig (69 kN/m^2); if operated at higher pressures cooling water could leak past the cylinder liner seals and into the cylinder. The maximum cooling water temperature is thus about 240°F (116°C), corresponding to the temperature of saturated steam at 10 psig (69 kN/m^2). Engines using natural circulation cooling are relatively small, typically developing less than 1,500 horsepower (1,120 kW). Flow rates developed by natural circulation cooling may be insufficient to cool larger engines. Flow rates may be increased by installing a booster pump in the circulating loop near the entrance to the engine jacket. There are reciprocating engines on the market designed to operate at temperatures in the 160° to 180°F (71° to 82°C) range. However, they are not recommended for services with unscrubbed digester gas because of potential problems with SO_2-SO_3 corrosion. Heat recovered from the engine jacket is typically used to sustain the digestion process and for space heating.

Reciprocating engines commonly employed in wastewater treatment plants fall into two categories; dual-fuel (compression ignited) and spark ignited engines. Dual-fuel engines use a blend of diesel fuel and digester gas; the fraction of diesel fuel can be varied from a minimum of 4 percent all the way to 100 percent of the mixture. Dual-fuel engines are typically used if there is insufficient digester gas to satisfy power demands. Dual-fuel engines have been specified for new plants where digester gas production is expected to lag behind power demands for several years.

Spark-ignited engines are generally used when there is sufficient digester gas to satisfy power demands. Spark-ignited engines can operate on several different types of fuel (for example, digester gas and natural gas). Special carburetors are provided to blend digester gas with an air-diluted backup fuel (for example, natural gas) during infrequent periods when not enough digester gas is available to satisfy power requirements. Spark-ignited engines are less complex then dual-fuel engines, are available in smaller sizes, and are less costly to operate since expensive diesel fuel is not required.

Naturally aspirated feed systems are preferred to turbocharged systems for spark-ignited engines. Turbocharged systems require that gas be delivered at high pressure, which means the gas must be first compressed, then delivered through a fuel metering system with restricted openings. Gas impurities (oils, greases, and water) are condensed when the gas is compressed and cooled; these impurities often clog the fuel metering system. Naturally aspirated systems operate at low pressures (<0.5 psig [3.4 kN/m^2]). With careful design of the gas transport systems, compression of the feed gas is not required. Low pressure fuel metering systems also have relatively large openings compared to metering systems used with turbocharged units. For these reasons, naturally-aspirated fuel systems are therefore less susceptible to clogging than systems with turbocharged units.

Engines represent a large capital investment and should be conservatively designed to protect that investment. For four-stroke engines it is recommended that brake mean effective pressure (BMEP) not exceed 80 to 85 psig (550 to 590 kN/m^2) to minimize strain on the equipment. Engine speeds in the 700 to 1,000 rpm are preferred as are average piston speeds in the range of 1,200-1,500 feet per minute (370 to 460 m/min). Heavy-duty industrial engines should be specified, not automotive engines.

Gas Turbines. Gas turbines have had relatively limited use to date. Where used, there have been fouling problems which are inherent with compressing a dirty gas through fuel metering systems with small clearances. However, new developments in the turbine field and the fact that less NO_x is produced by turbines than by reciprocating engines has led to a second look at turbines, particularly in nonattainment air quality areas. A new system that uses a relatively low (4/1) pressure ratio turbine with recuperation has the potential to solve many of the problems which plagued earlier installations (10). The normally low efficiency of the low pressure ratio turbine is boosted by preheating the compressed air with heat recovered from the exhaust gas. Ignition for this turbine can be staged to minimize NO_x generation. Emissions control is particularly important in non-attainment areas where new stationary sources must use Best Available Control Technology (BACT). BACT for reciprocating engines is considered to be catalytic denitrification, while BACT for low pressure ratio turbines can be staged ignition.

18.3.2.3 Generators

Generators may be synchronous or induction types. Synchronous generators are by far the most common. However, in smaller sizes (below 5 or 10 MW) induction units are generally less expensive than synchronous units. They are also easier to maintain since they require no governor or synchronizing equipment. Induction generators have the disadvantage of being unable to operate unless parallelled with synchronous generation, either utility or in-plant. Thus an induction generator by itself cannot be used to provide emergency power.

18.3.3 Examples of Energy Recovery

The following two examples demonstrate calculations for two of the most commonly encountered energy recovery practices. Other examples and case histories can be found in References 11 and 12.

18.3.3.1 Energy Recovery from Digester Gas

Gas from an anaerobic digestion system is to be utilized to help supply plant energy needs in a 30 MGD (1.3 m^3/s) activated sludge plant. Digester gas will be used to fuel a spark-ignited internal combustion engine equipped with natural circulation cooling. The engine will drive an electrical generator. The electricity generated will be used to power various plant motor drives. Heat recovered from the engine cooling jacket and from the exhaust silencer will be used for space and process heating. It is hoped that sufficient heat will be recovered to supply at least digester heat requirements; any excess heat recovered will be used for "other" process heating. It is anticipated that heat recovered from the engine jacket (usually low temperature heat) will be used to make hot water for digester heating, while heat recovered from the exhaust silencer (high temperature heat) will be used to generate steam. Figure 18-3 is the system flowsheet.

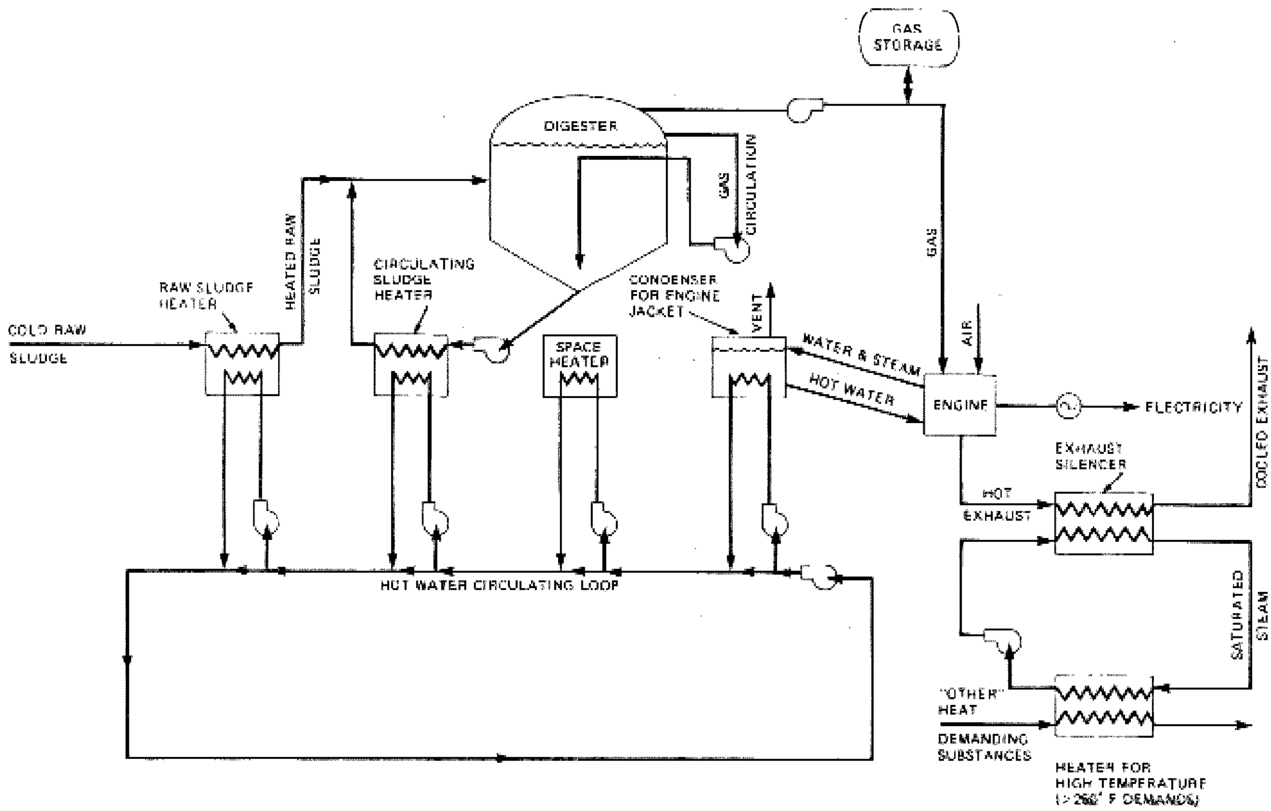


FIGURE 18-3

PROCESS SCHEMATIC FOR EXAMPLE OF ENERGY RECOVERY FROM DIGESTER GAS

The following data is estimated for the sludges and digester gas:

- Digester feed = 50,000 pounds per day (22,700 kg/d), dry weight basis. The feed solids are 75 percent volatile. The sludge is 4 percent solids by weight.

- Fifty percent of the volatile solids (VS) are destroyed during digestion.

- Raw sludge temperature is 60°F (16°C).

- Fifteen standard cubic feet (0.42 m^3) of digester gas are generated for every pound (0.454 kg) of VS destroyed.

- The gas composition is 66 percent CH_4, 28.3 percent CO_2, and 5.7 percent water (by volume). Other gases (H_2, H_2S, N_2) are present but not in sufficient quantities to affect the heat balance.

- 619 Btu (648 kJ) of heat are produced for every standard cubic foot (28.3 liters) of digester gas combusted.

The plant has the following energy requirements, which could be supplied in part or in whole by energy recovery from digester gas:

- 1,000 kW of electricity.
- Energy for raw sludge and digester heating (to be computed).
- 15 x 10^6 Btu per day (15.8 x GJ/d) for miscellaneous heating.

The following calculations are required:

- Determine the energy value of the digester gas.
- Determine if energy that can be recovered from the combusted gas is sufficient to satisfy the energy requirements listed above.
- Provide an energy flow diagram.
- Determine overall heat recovery efficiency.

To make comprehension of this example easier, the energy flow diagram is presented first (see Figure 18-4). The calculation is divided into four sections, as illustrated by the numbered "boxes" on the diagram. The magnitudes of the energy streamd shown on Figure 18-4 are developed in the following calculations:

<u>Determine the Energy Value of the Digester Gas (Box 1)</u>

1. Digester gas flow rate

$$= \left(\frac{50{,}000 \text{ lb solids}}{\text{day}}\right)\left(\frac{0.75 \text{ lb VS}}{\text{lb solids}}\right)\left(\frac{0.5 \text{ lb VS destroyed}}{\text{lb VS fed}}\right)$$

$$\times \left(\frac{15 \text{ scf}}{\text{lb VS destroyed}}\right) = 281{,}250 \text{ scfd } (8{,}157 \text{ m}^3/\text{d})$$

2. Energy value of the gas

$$= (281{,}250 \text{ scfd})(619 \text{ Btu/scf})$$

$$= 174 \times 10^6 \text{ Btu per day } (183.5 \text{ GJ/d})$$

Strictly speaking, the energy value of the digester gas should include not only the heat of combustion but the heat contents (enthalpy) of the reactants (air, fuel gas) calculated with respect to a selected base temperature. However, the heat contents of the reactants are very small compared to the heat of combustion and may be neglected with very little loss of accuracy and with a substantial reduction in amount of calculations necessary.

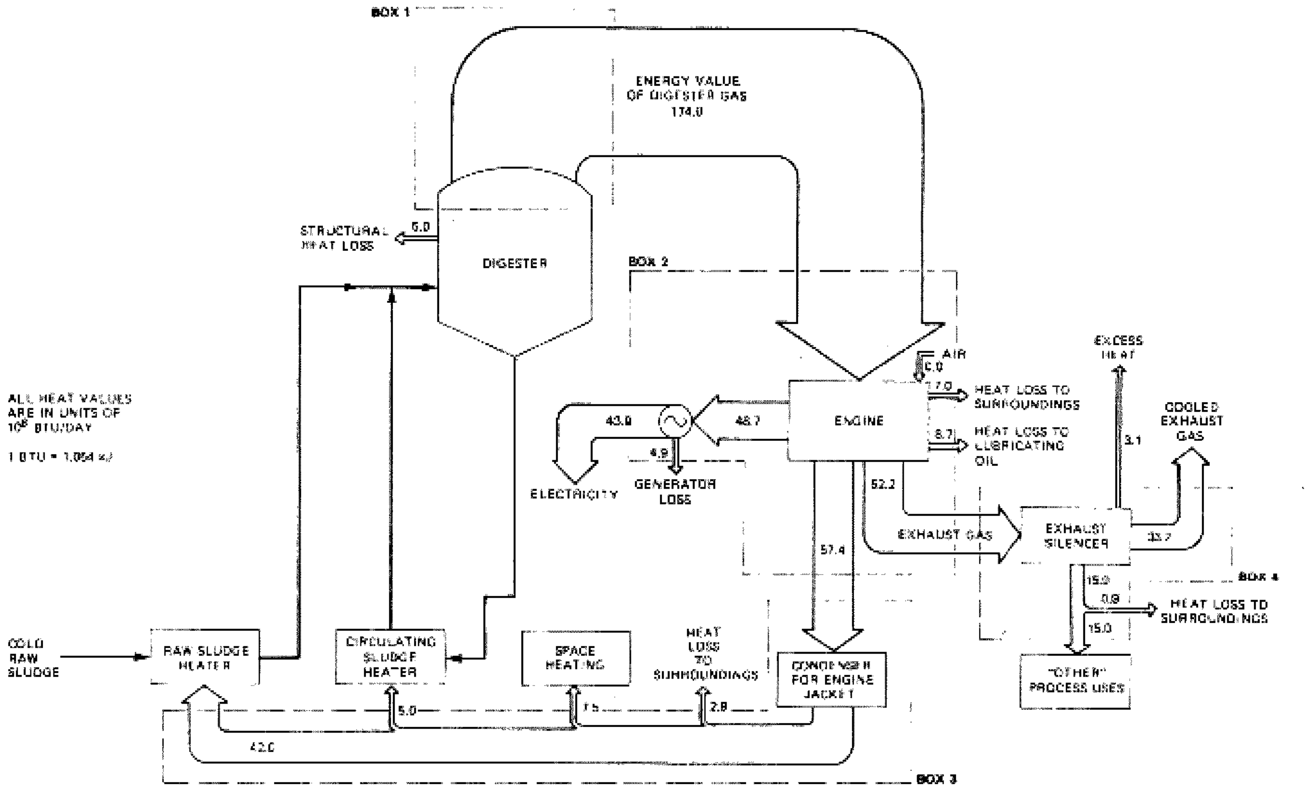


FIGURE 18-4

ENERGY FLOWSHEET FOR EXAMPLE OF ENERGY RECOVERY FROM DIGESTER GAS

<u>Make a Heat Balance Around the Engine/Generator (Box 2)</u>

1. Assume 28 percent of the energy value of the fuel gas is converted to work.

   Work produced

   $= 0.28\ (174 \times 10^6\ \text{Btu/day})$

   $= 48.7 \times 10^6$ Btu per day (51.3 GJ/d)

   Assume 90 percent of the work produced can be converted to electricity.

Electricity

$= 0.90\ (48.7 \times 10^6\ \text{Btu/day}) = 43.9 \times 10^6\ \text{Btu/day}\ (46.2\ \text{GJ/d})$

This is equivalent to 535 kW. Since average plant electrical demand is 1,000 kW, auxiliary power must be purchased.

2. Assume 33 percent of the energy value of the fuel gas is recovered in the engine jacket water.

   Energy recovered in the jacket water

   $= 0.33\ (174 \times 10^6\ \text{Btu/day})$

   $= 57.4 \times 10^6$ Btu per day (60.5 GJ/d)

3. Assume the radiant heat loss from the engine is 4 percent of the energy value of the fuel gas.

   Radiation loss

   $= 0.04\ (174 \times 10^6\ \text{Btu/day}) = 7.0 \times 10^6$ Btu per day (7.4 GJ/d)

4. Assume 5 percent of the energy value of the fuel gas is transferred to lubricating oil.

   Heat loss to oil

   $= 0.05\ (174 \times 10^6\ \text{Btu/day}) = 8.7 \times 10^6$ Btu per day (9.2 GJ/d)

5. Heat in the exhaust gas is the difference between the energy value of the fuel gas and the heat losses determined in items 1 through 5.

   Heat in the exhaust gas

   $= (174.0 - 48.7 - 57.4 - 7.0 - 8.7) \times 10^6$

   $= 52.2 \times 10^6$ Btu per day (55.0 GJ/d)

Determine Whether Sufficient Heat can be Recovered From the Jacket Cooling Water to Satisfy Digester Heating Requirements (Box 3)

1. Energy required to heat raw sludge

   $$= \left(\frac{50{,}000\ \text{lb solids/day}}{0.04\ \text{lb solids/lb sludge}}\right)\left(\frac{1.0\ \text{Btu}}{\text{lb sludge/°F}}\right)\ (95 - 60°\text{F})$$

   $= 42.0 \times 10^6$ Btu per day (44.3 GJ/d)

2. Determine energy required for circulating sludge heating. The purpose of the circulating sludge heater is to make up for any heat lost through the digester structure. Heat

loss calculations similar to these shown in Chapter 6, Section 6.2.6.2, indicates that for the digester of this example, losses are on the order of 5.0 x 10^6 Btu per day (5.3 GJ/d).

3. Determine heat loss in the hot water circulating loop. There is very little heat loss because this is a closed system (see Figure 18-3). The only losses will be through the insulation. It is roughly assumed that heat loss is 5 percent of the heat leaving the engine jacket.

   Heat loss

   = 0.05 (57.4 x 10^6)= 2.9 x 10^6 Btu per day (3.0 GJ/d)

4. Total heat required for the digestion system

   = (42.0 + 5.0 + 2.9) x 10^6 = 49.9 x 10^6 Btu/day (52.6 GJ/d)

5. Heat available in the cooling water minus total heat required for the digestion system

   = (57.4 - 49.9) x 10^6 = 7.5 x 10^6 Btu/day (7.9 GJ/d)

   To keep the internal combution engine adequately cooled, this heat must be rejected in some manner. The heat may be rejected by venting steam from the condenser. In this case, however, the designer has chosen to use the extra heat for building heat, thereby utilizing rather than wasting it.

Determine if Sufficient Heat can be Recovered from the Hot Combustion Gases Leaving the Engine to Satisfy "Other" Process Requirements (Box 4)

From previous calculations, the heat available in the hot combustion gas is 52.2 x 10^6 Btu per day (55.0 GJ/d). Not all of this heat can be recovered for use. Practical limits exist to the degree to which the hot gas can be cooled. For example, the hot gases must be substantially warmer than the material being heated to carry out heat transfer in an exchanger of reasonable size and cost. In this example, however, the lower temperature limit is set at 350°F to preclude corrosion that might occur by condensation of water vapor on the inside of the exhaust stack walls. The designer must therefore determine if sufficient heat can be obtained to satisfy "other" process uses when the hot combustion gases are cooled to 350°F (117°C) in the exhaust silencer. Since the heat content of the hot combustion gases is known (52.2 x 10^6 Btu per day [55.0 GJ/d]), heat available can readily be calculated once the heat content of the gas at 350°F (117°C) has been determined. This is calculated as follows:

1. First calculate the volume of exhaust gas. Gas production can be predicted from stoichiometry:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \qquad (18\text{-}1)$$

a. CO_2 present = CO_2 in digester gas plus CO_2 formed by combustion of methane.

1. From previous calculations, digester gas production is 281,250 standard cubic feet per day (8,157 m^3/d).

2. Unburned digester gas contains 28.3 percent CO_2 by volume.

   CO_2 associated with digester gas

   = 0.283 (281,250 scfd) = 79,593 scfd (2,252 m^3/d)

3. From Equation 18-1, one cubic foot of CO_2 is formed for every cubic foot of methane burned. Digester gas contains 66 percent methane by volume.

   CO_2 formed by combustion of methane

   = 0.66 (281,250 scfd) = 185,625 scfd (5,253 m^3/d)

4. Total CO_2 volume

   = 79,593 + 185,625 = 262,218 scfd (7,505 m^3/d)

b. CH_4 present: none, all converted to CO_2.

c. O_2 present: assume that air supplied exceeds theoretical requirements by 10 percent. Oxygen associated with this excess is not consumed. From Equation 18-1, theoretical oxygen requirements are two cubic feet of oxygen for every cubic foot of methane burned.

Oxygen in excess of theoretical requirements

$$= (2)(0.10)\left(\frac{0.66\ ft^3\ CH_4}{ft^3\ \text{digester gas}}\right)(281{,}520\ \text{scfd})$$

= 37,125 scfd (1,050 m^3/d)

d. N_2 present: N_2 associated with the air passes through the system unchanged in quantity.

N_2 flow

$$= 281{,}250 \text{ scfd} \left(\frac{0.66 \text{ ft}^3 \text{ CH}_4}{\text{ft}^3 \text{ digester gas}}\right)$$

$$\times \left(\frac{[1.10 \times 2] \text{ ft}^3 \text{ O}_2 \text{ delivered}}{\text{ft}^3 \text{ CH}_4}\right) \left(\frac{0.79 \text{ ft}^3 \text{ N}_2}{0.21 \text{ ft}^3 \text{ O}_2}\right)$$

= 1,536,265 scfd (43,476 m^3/d)

e. H_2O present = H_2O in digester gas plus that created by combustion of methane.

   1. Digester gas contains 5.7 percent H_2O by volume.

      H_2O in digester gas

      = 0.057 (281,250 scfd) = 16,031 scfd (453 m^3/d)

   2. From Equation 18-1, two cubic feet of H_2O are formed for every cubic foot of methane burned.

      H_2O formed

$$= 281{,}250 \text{ scfd} \left(\frac{0.66 \text{ ft}^3 \text{ CH}_4}{\text{ft}^3 \text{ digester gas}}\right) \left(\frac{2 \text{ ft}^3 \text{ H}_2\text{0}}{\text{ft}^3 \text{ CH}_4}\right)$$

      = 371,250 scfd (10,506 m^3/d)

   3. Total water = 16,031 + 371,250 = 387,281 scfd (10,960 m^3/d)

f. Total gas flow = 262,218 + 37,125 + 1,536,265 + 387,281 = 2,222,889 scfd (62,907 m^3/d)

2. Next calculate the heat content of the exhaust gas at 350°F (117°C). The heat content of the exhaust gas is the sum of the heat contents of its individual components. The heat content of any component at 350°F is the sum of the sensible and latent heats required to raise the component from an arbitrarily selected base temperature to 350°F (177°C). Mean heat capacity data for several gases is shown on Figure 18-5. The base temperature for Figure 18-5 is 77°F (25°C). The mean heat capacity of a gas over the range 77°F to 350°F is the value found at 350°F.

   a. Heat content of CO_2

$$= \left(\frac{9.5 \text{ Btu}}{\text{lb mole/°F}}\right) \left(\frac{\text{lb mole}}{359 \text{ scf}}\right) (350° - 77°\text{F}) (262{,}218 \text{ scfd})$$

      = 1.9 x 10^6 Btu per day (2.0 GJ/d)

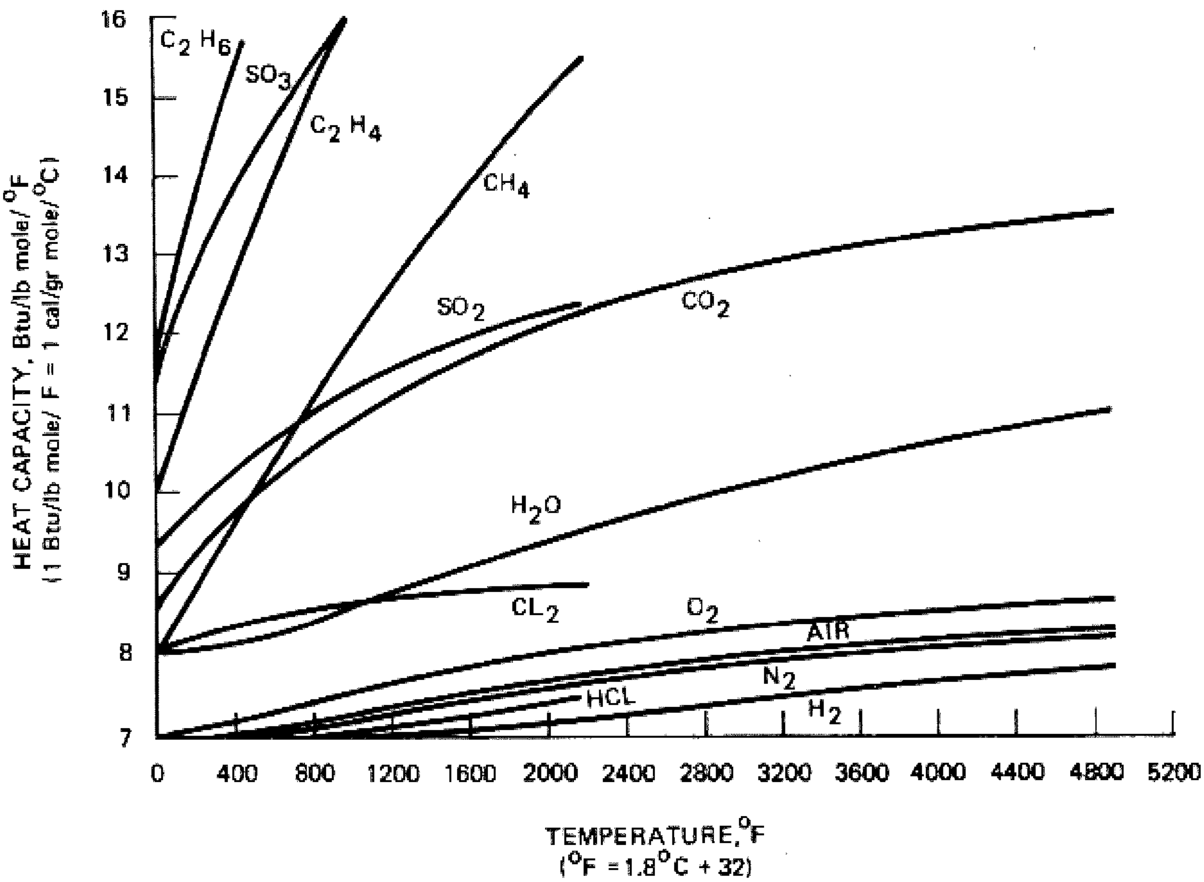


FIGURE 18-5

MEAN MOLAL HEAT CAPACITIES OF GASES AT CONSTANT PRESSURE (13) (MEAN VALUES FROM 77° to T°F)

b. Heat content of O_2

$$= \frac{7.2 \text{ Btu}}{\text{lb mole/°F}} \left(\frac{\text{lb mole}}{359 \text{ scf}}\right) (350°-77°\text{F}) \ (37{,}125 \text{ scfd})$$

$= 0.2 \times 10^6$ Btu per day (0.2 GJ/day)

c. Heat content of N_2

$$= \frac{6.8 \text{ Btu}}{\text{lb mole/°F}} \left(\frac{\text{lb mole}}{359 \text{ scf}}\right) (350°-77°\text{F}) \ (1{,}536{,}265 \text{ scfd})$$

$= 7.9 \times 10^6$ Btu/day (8.4 GJ/d)

d. Heat content of water. In this calculation, water is pictured as heated in a liquid state to the dew point, evaporated, and heated as a vapor to final temperature. Other approaches can also be used; these are described in thermochemistry textbooks.

1. Water comprises $\left(\frac{387,281 \text{ scfd } H_2O}{2,222,889 \text{ scfd total}}\right) 100$

$= 17.4$ percent by volume of the exhaust gas. The dew point for gas containing 17.4 percent water by volume is 135°F (58°C).

2. Heat to raise liquid water to the dew point

$$= \left(\frac{387,281 \text{ scfd}}{359 \text{ scf/lb mole}}\right)\left(\frac{18 \text{ Btu}}{\text{lb mole/°F}}\right)(135\text{-}77\text{°F})$$

$= 1.1 \times 10^6$ Btu per day (1.2 GJ/d)

3. Heat to vaporize water at the dew point

$$= \left(\frac{387,281 \text{ scfd}}{359 \text{ scf/lb mole}}\right)\left(\frac{18,720 \text{ Btu}}{\text{lb mole}}\right)$$

$= 20.2 \times 10^6$ Btu per day (1.19 GJ/d)

4. Heat to raise water vapor from the dew point to 350°F

$$= \left(\frac{8.2 \text{ Btu}}{\text{lb mole/°F}}\right)\left(\frac{387,281 \text{ scfd}}{359 \text{ scf/lb mole}}\right)(350°\text{-}135\text{°F})$$

$= 1.9 \times 10^6$ Btu per day (2.0 GJ/d)

5. Total heat content of water $= (1.1 + 20.2 + 1.9) \times 10^6 = 23.2 \times 10^6$ Btu per day (24.5 GJ/d).

e. Heat content of exhaust gas at 350°F (117°C)

$= (1.9 + 0.2 + 7.9 + 23.2) \times 10^6 = 33.2 \times 10^6$ Btu per day (35.0 GJ/d)

3. Energy available to satisfy "other" requirements

$= (52.2 - 33.2) \times 10^6 = 19.0 \times 10^6$ Btu per day (20.0 GJ/d).

4. Determine heat loss in steam/condensate circulating loop. There will be very little heat loss because this is a closed system (see Figure 18-3). Assume losses are roughly 5 percent of the heat transferred from the exhaust silencer.

Heat loss

$= 0.05\ (19.0 \times 10^6$ Btu/day$) = 0.9 \times 10^6$ Btu per day (1.0 GJ/d)

5. Heat available for "other" process demands

   $= (19.0 - 0.9) \times 10^6 = 18.1 \times 10^6$ Btu per day (19.1 GJ/d)

   The available heat is sufficient to satisfy the demands.

Determine Efficiency of the Energy Recovery System

There are several methods for evaluating the efficiency of the energy recovery system. One approach is to compute the useful heat and work recovered as a percentage of the energy input.

1. Useful heat and work:

   a. Electrical energy = 43.9×10^6 Btu per day (46.2 GJ/d).

   b. Raw sludge heating = 42.0×10^6 Btu per day (44.2 GJ/d).

   c. Circulating sludge heating = 5.0×10^6 Btu per day (5.3 GJ/d).

   d. "Other" process heating = 15.0×10^6 Btu per day (15.8 GJ/d).

   e. Space heating = 7.5×10^6 Btu per day (7.9 GJ/d).

2. Energy input from digester gas = 174×10^6 Btu/day (183.4 GJ/d).

3. Computed efficiency $= \left(\dfrac{43.9 + 42.0 + 5.0 + 15.0 + 7.5}{174.0}\right) 100$

   $= 65$ percent

This activated sludge plant is not able to supply all its energy needs using digester gas (insufficient electrical energy). Generally, digester gas is sufficient to satisfy the energy requirements of most primary treatment plants but not activated sludge plants, since aeration blowers generally have high electrical demands.

18.3.3.2 Recovery of Energy from Incinerator Flue Gas

A wastewater treatment plant of 125 MGD (5.48 m^3/s) capacity uses incineration to process 190,000 pounds per day (82,260 kg/d) of combined primary and waste-activated sludges. Heat is recovered from the flue gases as electricity and steam in a steam turbine power cycle, using a waste heat boiler. The designer's objective is to maximize work production (electricity and direct power).

Steam is not used for space or process heating. A flow sheet of the process is shown on Figure 18-6. The following additional information is provided:

- The flue gas heat content is 606 x 10^6 Btu per day (639 GJ/d), based on an assumed gas composition and gas temperature, using methods described in the example of Section 18.3.3.1. Similarly, the heat content of the stack gas is 250 x 10^6 Btu per day (263 GJ/d). Heat losses from the boiler structure are 18 x 10^6 Btu per day (19 GJ/d).

- The boiler produces superheated steam at 615 psia (4,261 kN/m^2) and 825°F (441°C), which is then fed to a steam turbine, called the "main turbine."

- Steam is withdrawn from the turbine at three points. First, 50,000 pounds per day (22,700 kg/d) are withdrawn at 165 psia (1,143 kN/m^2) and applied to drives for pumps and compressors. This is called "process" steam. Second, a quantity (to be computed) is withdrawn and used for preheating of the boiler feedwater. This is called "preheat" steam. The remaining steam, which is "primary" steam, is exhausted at 1 psia (6.9 kN/m^2). The efficiency of the turbine (actual to theoretical work output) is assumed to be 76 percent.

- Exhausted "process" steam from the pump and compressor drives is condensed at 1 psia (6.9 kN/m^2), combined with the "primary" condensate, and sent to the feedwater heater. "Primary" and "process" condensates are assumed to be saturated water at the exhaust pressure (1 psia [6.9 kN/m^2]).

- "Preheat" steam is mixed with "primary" and "process" condensates in the feedwater heater to produce a saturated feedwater at 300°F (149°C).

- The feedwater is pressurized to 615 psia (4,261 kN/m^2), and returned to the boiler.

The following information is desired:

- Steam and condensate flow rates.

- Electric power generated.

- Pump and compressor work produced by the "process" steam.

- Energy recovery efficiency.

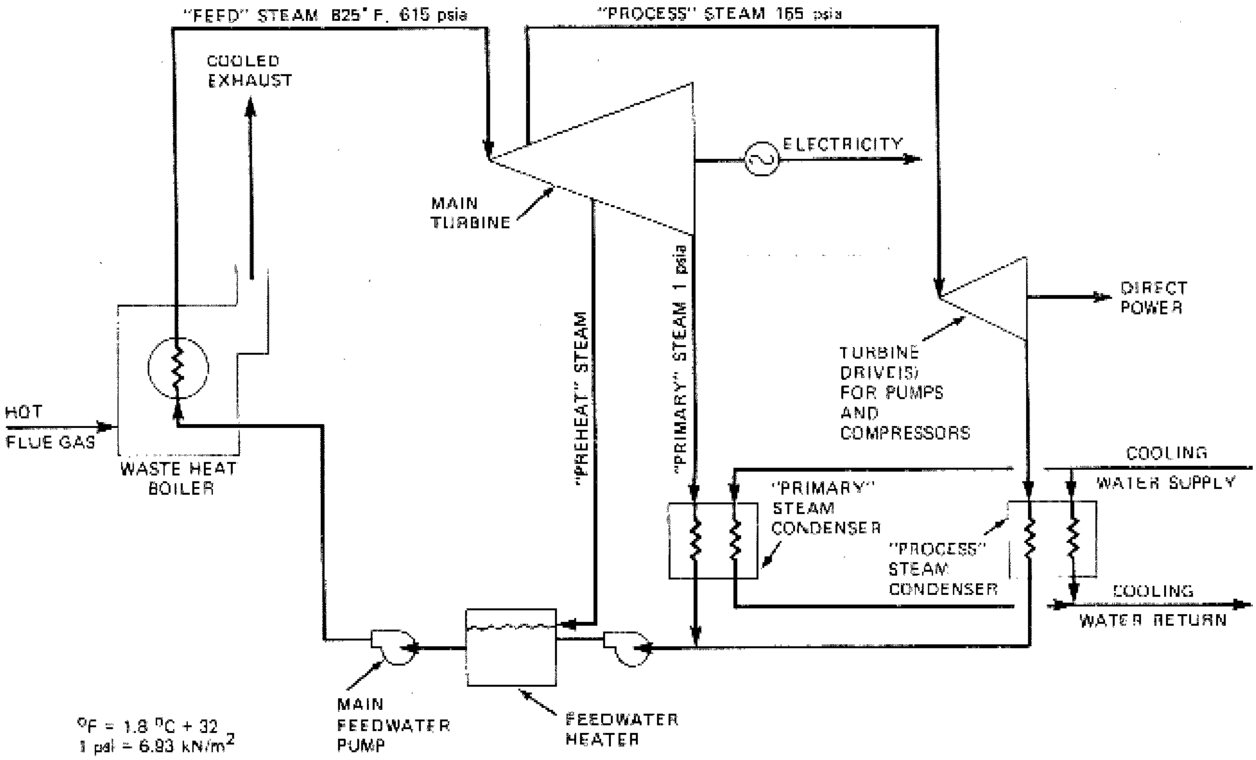


FIGURE 18-6

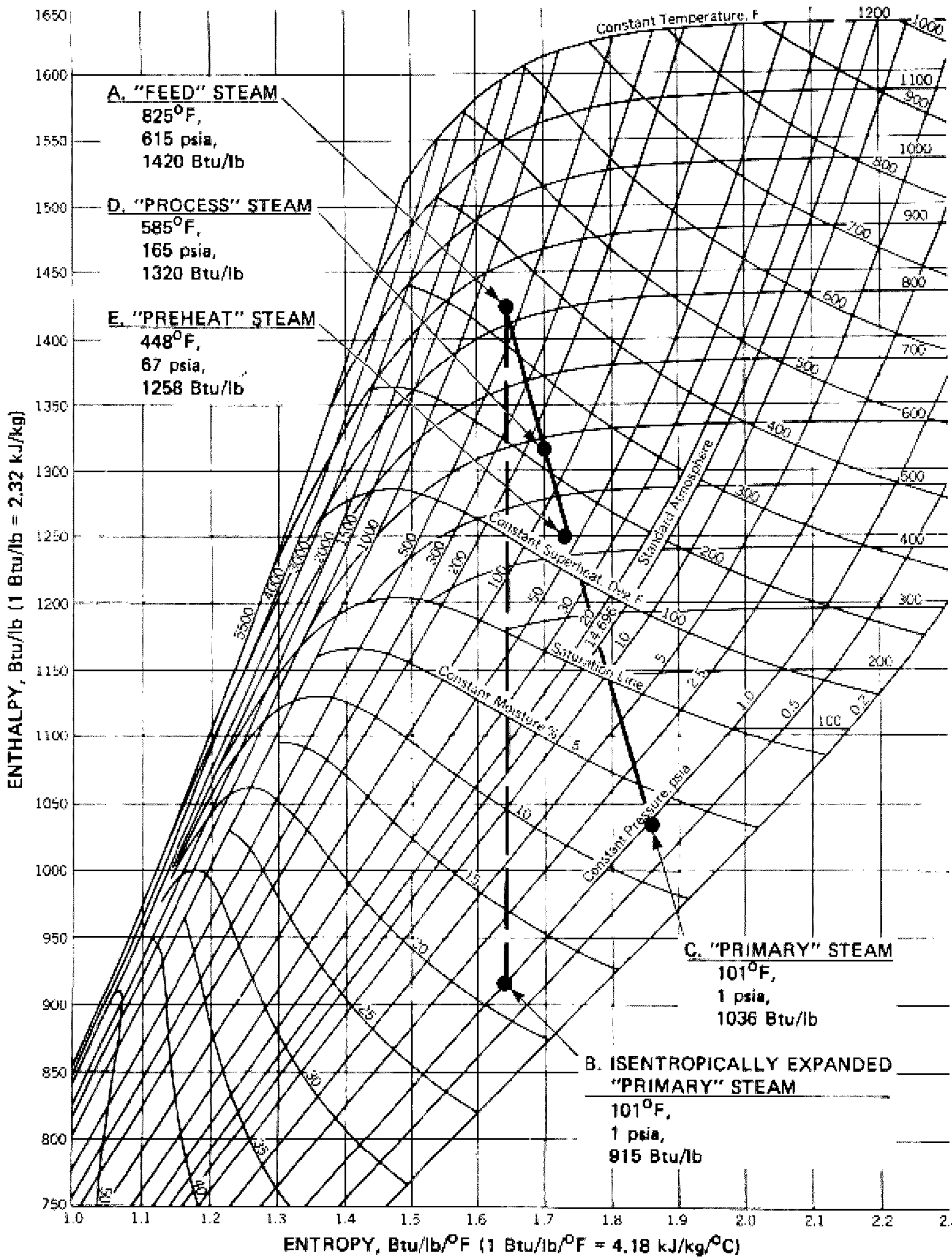
FLOWSHEET FOR EXAMPLE OF ENERGY RECOVERY FROM INCINERATOR FLUE GAS

Analyze the Operation of the Main Turbine

Turbine operations can be analyzed using a Mollier diagram. A Mollier diagram is a plot of enthalpy versus entropy for specific two-phase systems which display lines for constant pressure, temperature, percent moisture, and superheat, among others. Figure 18-7 is a Mollier diagram for the steam-water system. Note that the terms "enthalpy" and "heat content" are equivalent and will be used interchangeably in the following discussion.

The "state line" concept is used for turbine analysis. The state line describes the steam condition at every point within the turbine. The line can be drawn once any two points describing steam conditions in the turbine are established. For this example, the turbine feed steam and the "primary" steam exhaust conditions will be determined, then plotted on the Mollier diagram of Figure 18-7.

1. The turbine feed steam condition (615 psia [4,261 kN/m^2]), 825°F [441°C]) is plotted as point A on the Mollier Diagram (see Figure 18-7). Figure 18-7 is not detailed, so that data points and state lines can be clearly seen. More detailed diagrams are available (14,15).



MOLLIER CHART COURTESY OF BABCOCK AND WILCOX

FIGURE 18-7

STEAM CONDITIONS FOR EXAMPLE OF RECOVERY OF ENERGY FROM INCINERATOR OF FLUE GAS

2. Determine the "primary" steam exhaust condition. If the turbine were 100 percent efficient, the steam would expand isentropically, that is, the entropy of the steam at any point in the turbine would be identical to the entropy of the feed steam and the state line would be vertical (dashed line in the Mollier Diagram). The "primary" exhaust steam condition would be located at the intersection of the vertical state line and the exhaust pressure (1 psia [6.9 kN/m^2]), at point B. Enthalpy of the steam at point B is 915 Btu per pound (2.13 MJ/kg).

However, turbines are not 100 percent efficient since isentropic expansion is never attained. The energy which can be extracted from the steam in practical applications is only a percentage of that which can be extracted by isentropic expansion. This is expressed by Equation 18-2.

$$\text{Turbine efficiency} = \left(\frac{H_1 - H_{2p}}{H_1 - H_{2i}} \right) 100 \qquad (18\text{-}2)$$

Where:

H_1 = enthalpy of inlet steam, Btu/lb.

H_{2p} = enthalpy of steam exhausted from a practical turbine, Btu/lb.

H_{2i} = enthalpy of steam exhausted from an ideal turbine, Btu/lb.

The efficiency described by Equation 18-2 is the actual work output relative to theoretical output--it is less than 100 percent because of irreversibility in the expansion of gases in the turbine. Mechanical losses in the turbine and generator are not included.

For the practical turbine, enthalpy of the exhausted steam (H_{2p}) can be computed from Equation 18-2. For the turbine of the example (76 percent efficient).

$$H_{2p} = \left(1{,}420 - \frac{76}{100} \right) (1{,}420 - 915) \qquad (18\text{-}2)$$

= 1,036 Btu per pound (2,405 kJ/kg)

The "primary" exhaust steam condition for the practical turbine is located at point C, the intersection of the exhaust pressure (1 psia [6.9 kN/m^2]) and enthalpy value 1,036 Btu per pound (2,405 kJ/kg). The state line for the practical turbine is then drawn between points A and C.

3. The "process" steam condition must lie on the state line. It is located at the intersection of the state line and the "process" steam operating pressure (165 psia [1,145 kN/m^2]), at point D.

4. As with the "process" steam, the "preheat" steam condition can be determined once its pressure is known. Pressure can be determined by the following reasoning:

   a. "Preheat" steam pressure is essentially equal to the pressure in the feedwater heater (pressure drop through the lines connecting the turbine and feedwater heater is assumed negligible).

   b. The feedwater heater is a direct contact device. Sufficient "preheat" steam is mixed with "primary" and "process" condensates to form a two-phase system at 300°F (149°C). Thus the feedwater heater system is a saturated system.

   c. The feedwater heater pressure, therefore is the pressure of saturated steam at 300°F (149°C), which is 67 psia (464 kN/m^2).

The "preheat" steam condition is located at the intersection of the state line and the 67 psia (464 kN/m^2) constant pressure line (point E). Enthalpy of the "preheat" steam is 1,258 Btu per pound (2,921 kJ/kg).

Determine Steam and Condensate Flows

1. Circulating steam rate is computed by a heat balance around the boiler.

   a. Enthalpy of the water entering the boiler is assumed equal to that leaving the feedwater heater; that is, pumping affects the enthalpy value negligibly. This is a justifiable assumption for the pumping of liquids. From steam tables (14,15), the enthalpy of saturated water at 300°F (149°C) is 270 Btu per pound (627 kJ/kg).

   b. By previous calculations, enthalpy of superheated steam leaving the boiler is 1,420 Btu per pound (3,297 kJ/kg).

   c. From the problem statement, heat absorbed in the boiler

      $= 338 \times 10^6$ Btu per day (356 GJ/d).

   d. Therefore steam circulating rate

$$= \frac{338 \times 10^6 \text{ Btu/day}}{(1{,}420 - 270) \text{ Btu/lb}}$$

      = 293,900 pounds per day (133,400 kg/d).

2. "Process," "primary," and "preheat" steam rates are determined by mass and heat balances around the feedwater heater. Let X and Y be the flow rates for "primary" and "preheat" steam, respectively. Equation 18-3 is the mass balance around the feedwater heater.

$$293,900 = X + Y + 50,000 \tag{18-3}$$

Equation 18-4 is the heat balance for the feedwater heater.

$$293,900\ (270) = 70\ X + 1258\ Y + 70\ (50,000) \tag{18-4}$$

Enthalpies of the "process" and "primary" condensates (70 Btu per pound or 162 kJ/kg) are for saturated water at 1 psia (6.93 kN/m^2). Solving Equations 18-3 and 18-4 simultaneously, "primary" and "preheat" steam rates are 194,626 pounds per day (88,350 kg/d) and 49,274 pounds per day (22,370 kg/d), respectively.

At this point, construction of an energy flowsheet should be initiated (see Figure 18-8). This allows the designer to see all pertinent data on one sheet and gives a feeling for the magnitude of the various energy flows.

Determine Electrical Energy Generated

Work produced is the sum of the total enthalpy changes across the turbogenerator:

1. Work from "process" steam

   = 50,000 lb/day (1,420 - 1,320 Btu/lb)

   = 4.90 x 10^6 Btu per day (5.16 GJ/d)

2. Work from "preheat" steam

   = 49,274 lb/day (1,420 - 1,258 Btu/lb)

   = 7.98 x 10^6 Btu per day (8.41 GJ/d)

3. Work from "primary" steam

   = 194,620 lb/day (1,420 - 1,036 Btu/lb)

   = 74.73 x 10^6 Btu per day (78.77 GJ/d)

4. Total work produced

   = (4.90 + 7.98 + 74.73) x 10^6

   = 87 x 10^6 Btu per day (92.3 GJ/d)

5. Assume mechanical efficiency of the turbine/generator combination is 95 percent.

Net electricity produced

= 83.2 x 10^6 Btu per day (87.7 GJ/d)

This is equivalent to 1,015 kW of electricity.

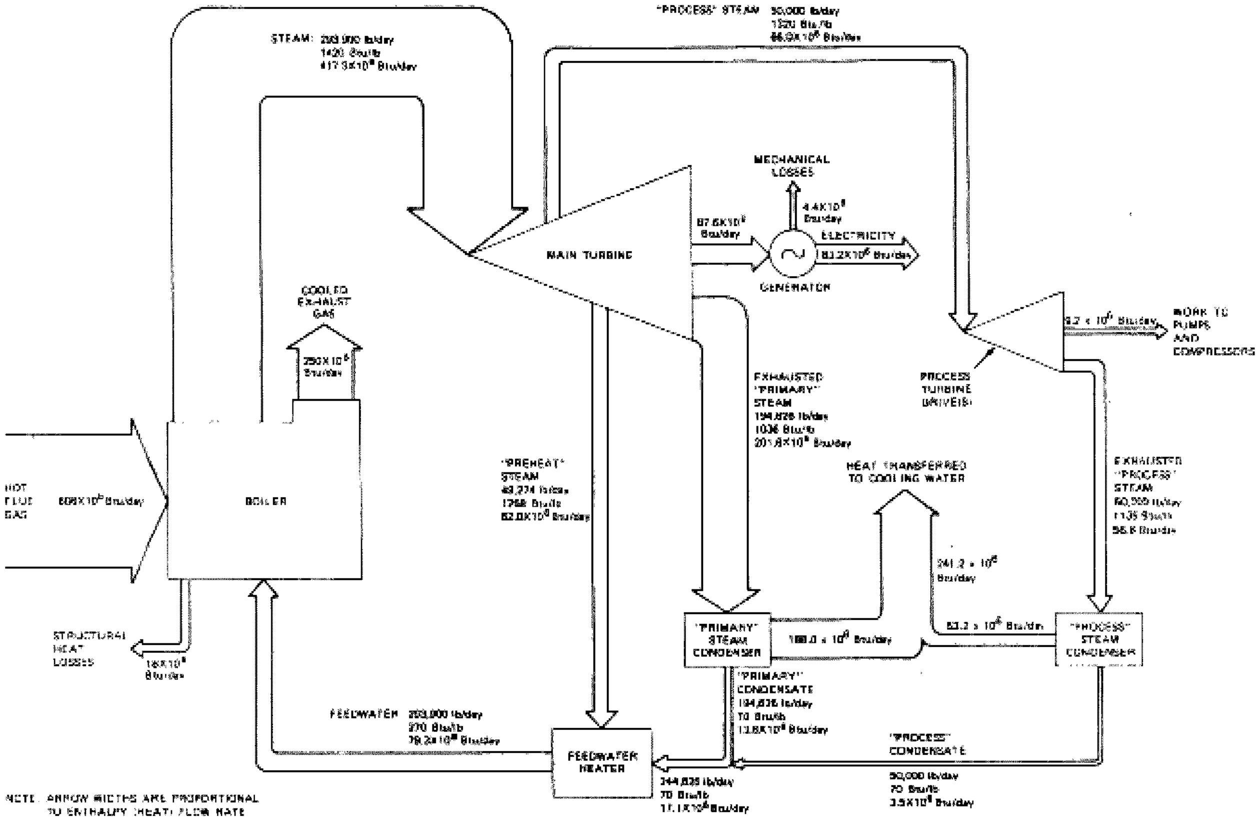


FIGURE 18-8

ENERGY FLOWSHEET FOR EXAMPLE OF ENERGY RECOVERY FROM INCINERATOR FLUE GAS

<u>Determine Work Produced in the "Process" Steam Cycle</u>

Enthalpy of the "process" steam is 1,320 Btu per pound (3,065 kJ/kg). Enthalpy of the exhausted steam can be determined using the same technique employed for analysis of the main turbine. Isentropic expansion of process steam (initially at point D, Figure 18-5) to 1 psia (6.9 kN/m^2) produces an exhaust gas of enthalpy 950 Btu per pound (2,206 kJ/kg). Assume process turbines are 50 percent efficient.

1. Enthalpy of exhausted steam

$$= 1{,}320 - \frac{50}{100}\ (1{,}320 - 950)$$

$$= 1{,}135 \text{ Btu per pound } (2{,}635 \text{ kJ/kg})$$

2. Work produced

$= (50{,}000 \text{ lb/day}) (1{,}320 - 1{,}135 \text{ Btu/lb})$

$= 9.2 \times 10^6$ Btu per day (9.7 GJ/d)

3. Assuming mechanical losses of 5 percent, work delivered

$= (9.2 \times 10^6 \text{ Btu per day}) (0.95) = 8.8 \times 10^6$ Btu per day (9.3 GJ/d)

This is equivalent to 107 kW.

Determine Energy Recovery Efficiency

Assume heat removed in the condensers is not used beneficially, but discharged to the atmosphere via cooling towers.

1. Energy recovery, based on heat transferred to steam

$$= \left(\frac{(83.2 \times 10^6 + 8.8 \times 10^6)}{338 \times 10^6}\right) 100 = 27.2 \text{ percent}$$

2. Energy recovery, based on heat in the incinerator flue gas

$$= \left(\frac{(83.2 \times 10^6 + 8.8 \times 10^6)}{606 \times 10^6}\right) 100 = 15.2 \text{ percent}$$

Compare the recovery of this example (15 percent) against the recovery of energy from digester gas (65 percent), as illustrated by the example in Section 18.3.3.1. Greater efficiency was obtained by the internal combustion system because:

1. No heat was lost prior to the work producing step. In contrast, fully 41 percent of the heat available in the incinerator flue gas was rejected in the waste heat recovery boiler before any useful work could be extracted (see Figure 18-8).

2. With the internal combustion system, waste heat from the work producing step was used beneficaly (for digester and space heating). In contrast, waste heat from the steam condensers was not used beneficaly but rejected to the environment. It is difficult to use this heat since it is available at only a very low temperature (102°F [39°C]).

These two examples demonstrate the general rule that energy recovery schemes whose sole effect is the production of work are not likely to be efficient.

It should not be inferred from the examples that energy recovery from flue gases must necessarily be inefficient. In this example, the objective of the designer in recoverying heat from incinerator flue gas was to maximize work. Had he chosen to exhaust steam from either of the turbines at higher pressures and used it for heating purposes or had he used "process" steam solely for heating, some work would have been sacrificed but thermal efficiency could have been substantially improved. The point to be made here is that the designer should examine a wide range of options when analyzing energy recovery operations.

18.3.4 Other Factors Affecting Heat Recovery

The previous calculations point out some of the factors a designer must consider in conducting a heat recovery analysis. They are by no means the only factors; much more detail must be added. For example:

- The full range of conditions expected at the plant must be evaluated, not just average conditions. Energy supply and energy demand schedules must be established. Heat recovery equipment must be sized to handle peak demands. Storage requirements for primary and backup fuels must be determined.

- A source of backup energy must be available in the event that plant energy recovery systems experience partial or total failure.

- The physical and chemical nature of flue gases generated must be considered (for example, temperature, corrosiveness, particulate concentration, and moisture content).

- The equipment must be designed to withstand the conditions to which it will be subjected. Appropriate materials of construction must be used.

- Any solid, liquid or gaseous residual from the heat recovery operation must be collected and disposed of in a safe and environmentally sound manner.

- Chemical and physical treatments for makeup and circulating water or steam must be established.

- Manpower to operate the heat recovery system must be determined. Specialists may be required for certain equipment, for example, stationary engineers for high pressure boilers and engine specialists for internal combustion engines.

- Control strategies must be decided upon, and instrumentation to carry them out must be provided.

- Economic analyses must be performed to determine if the system can be economically justified. As a rule-of-thumb, the larger the plant, the more sophisticated the heat recovery system which can be justified.

18.4 Other Uses of Wastewater Solids and Solid By-Products

Wastewater solids may sometimes be used beneficially in ways other than as a soil amendment or as a source of recoverable energy. Lime and activated carbon have been recovered from sludges for many years at plant scale. These applications are discussed in Chapter 11. Stabilized sludge, when mixed with soil, is used as interim or final cover over completed areas of refuse landfills (see Chapter 19). Wastewater scum has been collected (sometimes purchased) by renderers at several treatment plants for use as a raw material in the manufacturing of cosmetics and other products. Grit, particularly incinerated grit, may be used as an aggregate, for example, as a road sub-base.

Other beneficial uses of wastewater solids have been considered; some have been tested on a laboratory or plant scale. These include:

- Recovery of ammonia from the filtrate or centrate following anaerobic digestion and dewatering of sludge. Ammonia is stripped from the liquor, absorbed in sulfuric acid and crystallized as ammonium sulfate.

- Recovery of ammonia and phosphates by precipitation of $MgNH_4PO_4$ from digester supernatants. The precipitate is used as a fertilizer.

- Addition of sludge to processes designed to compost or anaerobically digest municipal refuse. In such situations, sludge serves principally as a nutrient source.

- Recycling of wastewater solids for use as a foodstuff for livestock (cattle, sheep, goats, poultry, and fish). Note that solids used for this purpose have generally not originated from municipal wastewater treatment plants, but from systems treating purely industrial or animal wastes. However, the use of dried municipal sludge disinfected by gamma irradiation is being investigated as a food source for grazing animals.

- Use of wastewater solids as an organic substrate in worm farming (see Chapter 13).

- Use of sludge as a raw material for the production of powdered activated carbon (see JPL/ACTS process, Chapter 11).

18.5 References

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Chapter 19. Disposal to Land

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

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CHAPTER 19

DISPOSAL TO LAND

19.1 Introduction

Wastewater sludge may not always be used as a resource because of land acquisition constraints or because they contain high levels of metals and other toxic substances. In these situations, the sludge must be further processed by other methods. Non-utilization disposal processes are the subject of this chapter.

As discussed in Chapter 2, ocean disposal is no longer considered appropriate. Consequently, land disposal processes are being optimized so that the increasing amounts of municipal wastewater sludge produced by the adopted secondary treatment standards can be accepted. Two principal land disposal methods, landfilling and dedicated land disposal, differ in application rates and methods of application. Typical landfill operations involve dewatered-sludge subsurface application rates, often several feet in depth. Dedicated land disposal operations, however, typically involve repetitive liquid sludge applications, which may only raise the land surface a few inches per year.

19.1.1 Regulatory Agency Guidance

Development of formalized methods for sludge disposal to land is recent. Major efforts in this area have been encouraged and funded by the USEPA since 1974. The reader is referred to Chapter 2 for a discussion of some of the guidance and regulatory documents which deal with the recent federal laws to control the disposal of wastewater solids. State and local guidance has also been provided. Extensive sludge research is being funded by USEPA and various states.

19.2 Sludge Landfill

19.2.1 Definition

Sludge landfill can be defined as the planned burial of wastewater solids, including processed sludge, screenings, grit, and ash at a designated site. The solids are placed into a prepared site or excavated trench and covered with a layer of soil. The soil cover must be deeper than the depth of the plow zone (about 8 to 10 inches [20.3 to 25.4 cm]). For the most part, landfilling of screenings, grit, and ash is accomplished with methods similar to those used for sludge landfilling.

19.2.2 Sludge Landfill Methods

Sludge landfill methods can be grouped into three general categories: sludge-only trench fill, sludge-only area fill, and co-disposal with refuse. General site and design criteria are discussed under these categories. A detailed discussion of sludge landfills is presented in the USEPA Technology Transfer Process Design Manual, Municipal Sludge Landfills (1). The remaining parts of the landfill portion of this chapter summarize the information presented in this design manual. Other information on the disposal of wastewater sludge in sanitary landfills is available (2).

19.2.2.1 Sludge-Only Trench Fill

The sludge-only trench method involves excavating trenches so that dewatered sludge may be entirely buried below the original ground surface. In some locations, liquid stabilized and unstabilized sludges (Blue Plains, Washington, D.C. and Colorado Springs, Colorado) have been buried by the trench fill method. In this method, the sludge is deposited directly into the trench from a haul vehicle. Normal operating procedure requires daily coverage. Trench disposal is appropriate for unstabilized sludge, because the immediate application of cover material reduces associated odors. Vector control requires daily cover, except during very cold weather.

Narrow Trenches

Trenches are defined as narrow when their widths are less than 10 feet (3 m). Disposal in narrow trenches is applicable to sludges with a relatively low solids content of from 3 to 28 percent. The application rates range from 1,200 to 5,600 cubic yard of sludge per acre (2,270 to 10,580 m^3/ha). Excavated material can be either used immediately to cover adjacent sludge - filled trench or stockpiled alongside and used to cover the trench from which it was removed. The surface soil cover thickness is about 4 feet (1.3 m). Excavation and covering equipment operates from surface areas adjacent to the trench.

Wide Trenches

Trenches are defined as wide when they have widths greater than 10 feet (3 m). Material excavated from the trenches is stockpiled neatly and used as cover for the trench. Disposal in wide trenches is suitable for sludges with solids contents of 20 percent or greater. The application rates range from 3,200 to 14,500 cubic yards of sludge per acre (6,050 to 27,400 m^3/ha).

The surface cover thickness depends on the solids concentration of the sludge. The covered sludge will only be capable of supporting equipment when the solids concentration of the sludge exceeds 25 to 30 percent and the sludge has been topped with 3 to 5 feet (1 to 2 m) of soil.

The wide trench method has two distinct advantages; it is less land-intensive than the narrow trench method and groundwater protection can be provided by liners. The use of liners permits deeper excavations. The primary disadvantage of the wide trench method is the need for sludge solid contents of greater than 20 percent. Sludge with solid contents of greater than 30 to 35 percent will not flow, and extra effort is therefore required to spread them evenly in the trench. Figure 19-1 provides two views of a wide trenching operation at the North Shore Sanitary District just north of Chicago, Illinois.

19.2.2.2 Sludge-Only Area Fill

In the sludge-only area fill method, the sludge is mixed with soil and the mixture is placed on the original ground surface. This method requires substantial amounts of imported soil but may be suitable in areas where groundwater is shallow (liners can be easily installed) or bedrock prevails (that is, where excavation is neither possible nor required). Stabilized sludge is best suited for this method, since daily cover is not usually provided. Adequate drainage and runoff control are necessary to prevent contamination of nearby surface waters.

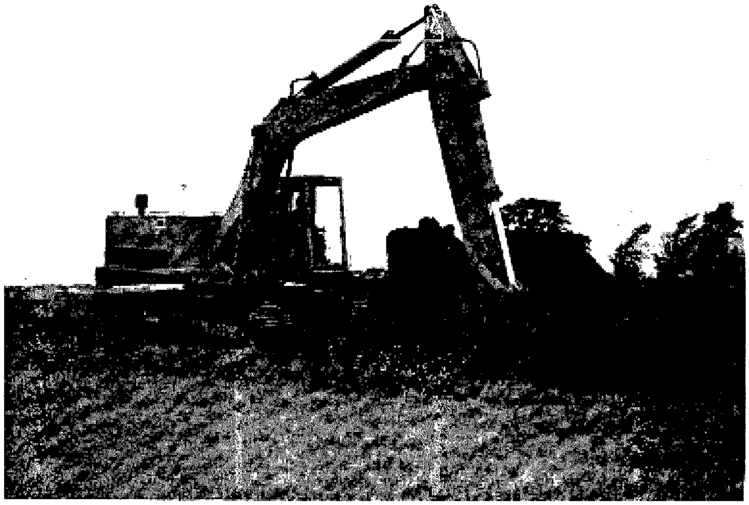
Area Fill Mound

Area fill mound applications are generally suitable for stabilized sludges with solids concentrations of 20 percent or more. Soil is mixed with sludge to provide bulk and stability before hauling to the filling area. At the filling area, the mixture is placed in 6 foot (2 m) mounds and then covered with 3 to 5 feet (1 to 1.5 m) of soil. A level area is required for disposal; however, the use of earthen containment structures permits disposal in hilly areas.

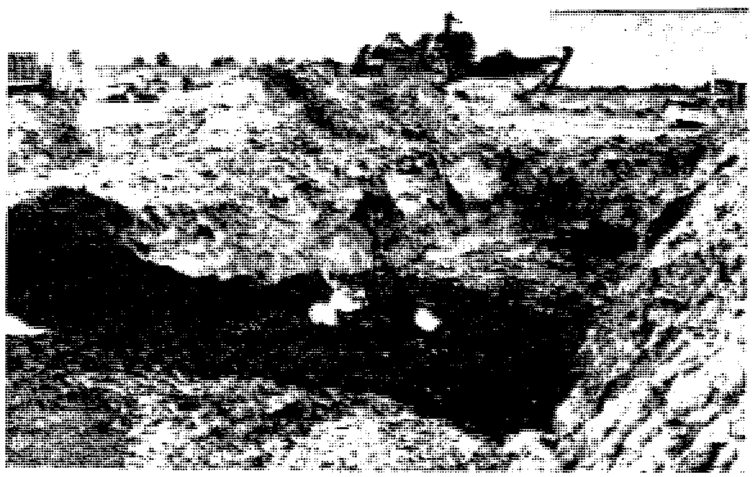
Area Fill Layer

Area fill layer applications are suitable for stabilized sludge with solids as low as 15 percent. Soil is mixed with sludge, either at the filling area or at a special mixing area. The sludge/soil mixture is spread in even layers of approximately 1 foot (0.3 m) thick, and 3 to 5 feet (1 to 1.5 m) of soil are added for final cover.

Level ground is preferred for this type of operation, but mildly sloping terrain can be used.



The District's operation consists of opening 20 feet (6.1 m) deep trenches on 300-acre (121.5 ha) site with large backhoe equipment. This same equipment is used to cover each layer of sludge with a layer of soil and cap each trench with several feet of soil. Production in 1976 was 30 dry tons/day (27 t/day).



Dewatered sludge is dumped from trucks directly into the trench. Various equipment is shown in the background. Also, the dewatered sludge storage building is shown in the background. Sludge is stored inside the building on weekends for transfer to trenches during daytime hours Monday through Friday.

FIGURE 19-1

WIDE TRENCHING OPERATION, NORTH SHORE SANITARY DISTRICT

Dike Containment

Dike containment applications require sludge with a solids content of 20 percent or greater. This method is suitable for either stabilized or unstabilized sludge. Sludge is usually not mixed with a bulking agent. If the disposal site is level, earthen dikes are used on all four sides of the containment area. If the site is at the toe of the hill, only a partial diking is required. Access is provided to the top of the dike so that haul vehicles can dump sludge directly into the containment. Depending on the type of equipment used, the interim cover will vary from 1 to 3 feet (0.3 to 1.0 m) and the final cover from 3 to 5 feet (1.0 to 1.5 m). Although diked containment is an efficient disposal method from the standpoint of land use, it may necessitate controls for leachate outbreaks.

19.2.2.3 Co-Disposal with Refuse

The term co-disposal is used when municipal sludge is disposed of at a refuse landfill. There are distinct trade-offs in using co-disposal method rather than the sludge-only methods.

Sludge can be disposed of in this manner if it is mixed with refuse or with soil. Mixing techniques are discussed in detail in the USEPA Office of Solid Waste Report, Disposal of Sewage Sludge into a Sanitary Landfill (2).

Sludge/Refuse Mixture

Stabilized or unstabilized sludge with a solids content of three percent or greater is mixed with the refuse. Normally sludge content is approximately ten percent of the sludge/refuse mixture. The sludge is applied on top of the refuse at the working face of the landfill. The sludge and refuse are thoroughly mixed before they are spread, compacted, and covered with soil. An interim cover of approximately one foot (0.3 m) and a final cover of two feet (0.6 m) is used. Application rates range from 500 to 4,200 cubic yards of sludge per acre (950 to 7,900 m^3/ha).

Sludge/Soil Mixture

In this operation, sludge is mixed with soil and the mixture is used as cover for a refuse landfill. This method requires stabilized sludge with at least a 20 percent solids content. It promotes vegetation growth over completed landfill areas without the use of fertilizer. However, it may cause odors, since the sludge is not completely buried. A final soil cover could be added if necessary to eliminate this problem.

19.2.2.4 Suitability of Sludge for Landfilling

Some wastewater treatment sludges may not be suitable for landfilling by any of the methods described above. For sludge-only landfills, the solids concentration should be 15 percent or more. Although soil may be used as a bulking agent to effectively increase the solids concentration to this level, cost-effectiveness may become a problem. Solids concentrations down to three percent are tolerated for co-disposal, but the absorptive capacity of the refuse should not be exceeded. An assessment of the suitability of various sludge types is given in Table 19-1. In general, only stabilized and dewatered sludges are recommended for landfill disposal.

19.2.3 Preliminary Planning

The purpose of the preliminary planning activity is to select a disposal site and suitable method(s) of disposal. Preliminary planning is followed by detailed design, initial site development, site operation and maintenance, and final site closure.

Site selection is the major activity during the preliminary planning phase. Since the selection of a site is not completely independent of the selection of a method, the preliminary planning phase should also include the determination of sludge characteristics and the identification of alternate landfill methods for each site. Chapter 2 of Municipal Sludge Landfill (1) provides an excellent discussion on public participation in this and other phases of the project.

19.2.3.1 Sludge Characterization

Sludge must be characterized as to quantity and quality. Chapter 4 provides further discussion on sludge characterization.

Sludge Quantity

An estimate of the average sludge quantity is necessary to establish landfill area requirements and the probable life of the disposal site. Data on minimum and maximum sludge quantities are important for developing an understanding of daily operating requirements. Maximum daily sludge quantities will govern equipment and storage facility sizing and daily operating schedules.

Sludge Quality

The character of the sludge to be landfilled is directly related to the choice of a landfill method. Sludge quality and the corresponding leachate can be roughly correlated; design of leachate treatment facilities is more effective if sludge quality is known.

TABLE 19-1

SUITABILITY OF SLUDGES FOR LANDFILLING

Type of sludge	Sludge only landfilling		Co-disposal landfilling	
	Suitability	Reason	Suitability	Reason
Liquid - unstabilized				
Gravity thickened primary, WAS and primary, and WAS	NS	OD, OP	NS	OD, OP
Flotation thickened primary and WAS, and WAS without chemicals	NS	OD, OP	NS	OD, OP
Flotation thickened WAS with chemicals	NS	OP	NS	OD, OP
Thermal conditioned primary or WAS	NS	OD, OP	MS	OD, OP
Liquid - stabilized				
Thickened anaerobic digested primary and primary, and WAS	NS	OP	MS	OP
Thickened aerobic digested primary and primary, and WAS	NS	OP	MS	OP
Thickened lime stabilized primary and primary, and WAS	NS	OP	MS	OP
Dewatered - unstabilized				
Vacuum filtered, lime conditioned primary	S	-	S	-
Dewatered - stabilized				
Drying bed digested and lime stabilized	S	-	S	-
Vacuum filtered, lime conditioned digested	S	-	S	-
Pressure filtered, lime conditioned digested	S	-	S	-
Centrifuged, digested and lime conditioned digested	S	-	S	-
Heat dried				
Heat dried digested	S	-	S	-
High temperature processed				
Incinerated dewatered primary and primary, and WAS	S	-	S	-
Wet-air oxidized primary and primary, and WAS	NS	OD, OP	MS	OD, OP

WAS - Waste-activated sludge
NS - Not suitable
MS - Marginally suitable
S - Suitable
OD - Odor problems
OP - Operational problems

Parameters that should be analyzed are discussed briefly below. Although all of these may not be critical to the design of a particular disposal system, a complete analysis is necessary, because the sludge must be adequately characterized.

- Concentration. Concentration or solids content of sludge is related to the nature of wastewater treatment and sludge processing steps. The type and operation of dewatering equipment may have a significant effect on the sludge concentration. A certain degree of flexibility should be incorporated into the design of landfills to compensate for the variability in solids concentration of dewatered sludge.

- Volatile content. Volatile solids are a measure of the organic content present in the solid fraction of sludge. This organic matter is eventually broken down into methane gas and other digestion by-products. Typically, volatile solids represent 60 to 80 percent of the total solids in raw primary sludge and 30 to 60 percent in anaerobically digested primary solids.

- Nitrogen. Nitrogen found in sludge is a potential source of groundwater pollution. The total quantity and type of nitrogen are of importance. Nitrate is relatively mobile in soil and is therefore of concern.

- Inorganic ions. Inorganic ions such as heavy metals are found in most municipal sludges. These are more readily leached if soil and sludge are acidic. If near neutral or alkaline conditions are maintained, the metals will not be as readily leached from the sludge or through the soil.

- Bacteriological quality. Sludge treatment systems reduce the number of pathogens and the possibility of pathogenic contamination associated with landfilling of sludges; however, they do not provide a sterile product.

- Toxic organic compounds. Toxic organic compounds can present potential contamination problems. Solids contaminated with toxic materials must be placed in appropriately designated disposal facilities.

- pH. Acidic conditions promote leaching of heavy metals and other compounds from the sludge.

19.2.3.2 Selection of a Landfilling Method

Relationships between the characteristics of alternative landfill sites, the characteristics of the sludge to be landfilled, and the landfill method need to be considered in the preliminary planning process. These relationships are summarized in Table 19-2.

19.2.3.3 Site Selection

Site selection is a critical process in the planning of a sludge landfill project. It is directly related to the method of ultimate disposal. The site finally selected must be suitable for the type of sludge to be disposed of and situated in a convenient, yet unobtrusive, location. Chapter 4 of Municipal Sludge Landfill (1) provides an in-depth approach to site selection.

TABLE 19-2

SLUDGE AND SITE CONDITIONS

Method	Sludge solids content, percent	Appropriate sludge characteristics	Appropriate hydrogeology	Appropriate ground slope
Narrow trench	15 - 28	Unstabilized or stabilized	Deep groundwater and bedrock	<20 percent
Wide trench	≥20	Unstabilized or stabilized	Deep groundwater and bedrock	<10 percent
Area fill mound	≥20	Stabilized	Shallow groundwater or bedrock	Suitable for steep terrain as long as level area is prepared for mounding
Area fill layer	≥15	Unstabilized or stabilized	Shallow groundwater or bedrock	Suitable for medium slopes but level ground preferred
Diked containment	≥20	Stabilized	Shallow groundwater or bedrock	Suitable for steep terrain as long as a level area is prepared inside dikes
Sludge/refuse mixture	≥3	Unstabilized or stabilized	Deep or shallow groundwater or bedrock	<30 percent
Sludge/soil mixture	≥20	Stabilized	Deep or shallow groundwater or bedrock	<5 percent

Site Considerations

The following factors must be considered during the evaluation of possible landfill sites. Information on these factors should therefore be collected and assessed in advance of the final decision making process.

- Haul distance. The most favorable haul conditions combine level terrain and minimum distances.

- Site life and size. The site life and size are directly related to the quantity and characteristics of the sludge and the method used for landfilling. Since the entire site cannot be used as fill area, both the gross area and the usable or fill area must be considered in determining the site size. Initially, the life of the site can be estimated. As the landfill is used, the expected life should be reevaluated to ensure adequate capacity for future operations.

- Topography. In general, sludge landfilling is limited to sites with minimum slopes of one percent and maximum slopes of 20 percent. Flat terrain tends to result in ponding, whereas steep slopes erode.

- Surface water. The location and extent of surface waters in the vicinity of the landfill site can be a significant factor in the selection process. Existing surface waters and drainage near proposed sites should be mapped and their present and proposed uses outlined. Leachate control measures including collection and treatment may be required as part of the landfill design.

- Soils and geology. Soil is an important determinant in the choice of an appropriate sludge landfilling site. Properties such as texture, structure, permeability, pH, and cation exchange capacity, as well as the characteristics of soil formation, may influence the selection of the site. The geology of possible landfill sites should be thoroughly examined to identify any faults, major fractures and joint sets. The possibility of aquifer contamination through irregular formations must be studied.

- Groundwater. Data on groundwaters in the vicinity of potential landfill sites is essential to the selection process. Knowledge of characteristics such as the depth to groundwater, the hydraulic gradient, the quality and use of the groundwater, and the location of recharge zones is essential for determining the suitability of a potential landfill site.

- Vegetation. The type and quantity of vegetation in the area of proposed landfill sites should be considered in the evaluation. Vegetation can serve as a natural buffer, reducing visual impact, odor, and other nuisances. At the same time, clearing a site of timber or other heavy vegetation can add significantly to the initial project costs.

- Meteorology. Prevailing wind direction, speed, temperature and atmospheric stability should be evaluated to determine potential odor and dust impacts downwind of the site.

- Environmentally sensitive areas. Environmentally sensitive areas such as the wetlands, flood plains, permafrost areas, critical habitats of endangered species, and recharge zones of sole source aquifers should be avoided if at all possible when selecting a landfill site.

- Archaeological and historical significance. The archaeological and historical significance of proposed sites should be determined early in the evaluation process. Any significant finds at the selected site must be accommodated prior to final approval.

- Site access. Haul routes should be major highways, or arterials, preferably those with a minimum of traffic during normal transport hours. Proposed routes should be studied to determine impacts on local use and the potential effects of accidents. Transport through nonresidential areas is preferable to transport through residential areas, high-density urban areas, and areas with congested traffic. The access roads to the site must be adequate for the anticipated traffic loads.

- Land use. Zoning restrictions, and future development on potential sites should be considered in the selection process. Ideally, the sludge landfill site should be located on land considered unsuitable for higher uses; however, the designer should be aware that this may be a politically sensitive issue and maximum public participation must be assured.

- Costs. Cost-effectiveness of each potential landfill site must be evaluated. Factors to be included in the economic evaluation include capital costs and operating and maintenance (O&M) costs. In the latter category, sludge hauling may prove to be a significant component. The trade-offs between high capital and high O&M costs will depend on the design life of the landfill. These trade-offs will become evident when the total annual (amortized capital and O&M costs) are compared. This evaluation should be performed in accordance with the methods outlined in the cost-effectiveness analysis section discussed in Chapter 3.

Site Selection Methodology

The selection procedure can be roughly divided into three phases: initial inventory and assessment of sites, screening of potential sites, and final site selection.

Initial inventory and assessment is designed to develop a list of potential sites that can be evaluated and rapidly screened to produce a manageable number of candidate sites. Information used in this phase is generally available and readily accessible. Investigation of each option becomes more detailed as the selection procedure progresses.

Initial Assessment of Site

Initial assessments will consist of identifying Federal, State, and local regulatory constraints, eliminating inaccessible areas, locating potential sites, roughly assessing the economic feasibility of such sites, and performing preliminary site evaluations. The less desirable sites are eliminated on the basis of preliminary economics, regulatory, and technical information. A public participation program is initiated (4). Attitudes of the public should be determined early. The public may assist in identifying candidate sites.

Screening of Candidate Sites. Sites remaining after the initial assessment are subjected to closer scrutiny. Information used in evaluating each option is more detailed and somewhat more site-specific than in the initial assessment. Remaining sites may be rated by a scoring system including both objective and subjective evaluations (Chapter 3). Table 3-4 serves as an example of a rating system. Candidate systems with lowest overall ratings are eliminated, and the higher rated systems are carried forward for final evaluation.

Site selection findings for the remaining candidate systems should provide input into an environmental impact report, if required. Public attitudes toward the remaining sites should also be determined.

Final Site Selection and Site Acquisition. Methodology for final site selection is similar to that for the screening procedure just discussed, in that rating systems are still used. However, each site remaining is investigated in greater detail. Public hearings may also be scheduled so that final inputs can be received from local government officials and the public.

Once the best sites are determined, they must be acquired. Site acquisition should begin immediately following acceptance of the program by local, State, and Federal regulatory authorities. The several acquisition procedures include: purchase option, outright purchase, lease, condemnation and/or other court action, and land dedication.

It will generally prove advantageous to purchase the site rather than hold a long-term lease. The managing agency's responsibility will normally extend well beyond the life of the site. Certain advantages may also be gained by leasing with an option to buy the site at the time of planning approval. A purchase option assures the availability of land upon completion of the facility planning process. This approach also allows time for the previous owner to gradually phase out operations, if desired.

19.2.4 Facility Design

19.2.4.1 Regulations and Standards

Local, State, and Federal regulations and standards must be fully understood before the landfill is designed. Consideration must be given to requirements governing the degree of sludge stabilization, the loading rates, the frequency and depth of cover, monitoring, and reporting. The design should conform to all building codes and should include adequate buffer zones to protect public roads, private structures, and surface waters.

Obtaining permits for construction and operation of sludge landfills can be a long and costly process. To minimize delays associated with this task, permit application should be initiated early in the design stage. A sound regulatory-consultant relationship and a mutual understanding should be developed.

The following is a partial list of the permits which may be required:

- NPDES permit--if landfill is in wetlands.
- Army Corps of Engineers permit--for construction of levees, dikes, or containment structures to be placed in the water in a wetlands area.
- Office of Endangered Species permit--if landfill is located in critical habitat of an endangered species.
- Solid Waste Management permit.
- Special Use permit.
- Highway Department permit.
- Construction permit.
- Building permit.
- Drainage and/or Flood Plain Alteration permit.

19.2.4.2 Site Characteristics

Site characteristics should be clearly described and analyzed to ensure the suitability of the landfill site and the method of landfilling. Design phase work will build upon planning phase data but will be carried to a higher level of detail and include working drawings.

Site Plan

The site plan should contain the following minimum information:

- Boundaries of fill area and buffer zones.
- Topographic features and slopes of fill area and buffer zones.
- Location of surface water, roads, and utilities.
- Existing and proposed structures and access roads.
- Vegetation to remain and to be removed; areas to be revegetated.

Soils

The soil characteristics at the landfill site should be thoroughly catalogued and mapped. The information of most importance to the design and operation of the landfill includes depth, texture, structure, bulk density, porosity, permeability, moisture, stability, and ease of excavation. Areas with rocky soils or extensive rock outcrops should be noted. The pH and cation exchange capacity have a direct bearing on heavy metal transport through the soil. Translocation of metals must be considered to ensure protection of surface and groundwater supplies.

Groundwater

The groundwater aquifers underlying the landfill site must be located. Depth of the aquifer under varying conditions should be determined at several locations. Other characteristics such as the direction and rate of flow, the hydraulic gradient, the quality, and present and planned uses should also be established. Location of the primary recharge zones is critical in protecting quality.

Subsurface Geology

The geological formations underlying the landfill are important in establishing the design parameters. Critical design parameters include the depth, distribution, and characteristics of subsurface soils in relation to stability and groundwater transmissability.

Climate

Climate can influence many factors in the design of landfills. Climatic conditions effect rate of organic decomposition, the composition and quantity of leachate and runoff, the day-to-day fill operations, and the dispersion of odors and dust. Information such as seasonal temperature, precipitation, evaporation, wind direction and speed and atmospheric stability, can be obtained from a local weather station.

Land Use

The present and proposed use of the landfill site and adjacent properties should be evaluated. If the site is already dedicated to refuse or sludge disposal, it is unlikely that expanding it will result in adverse impacts. However, if the site is located in or near a populated area, extensive control measures may be needed to eliminate concerns and minimize any public nuisance which would detract from the value of adjacent properties.

19.2.4.3 Landfill Type and Design

More than one sludge landfill method may be suitable for the selected site, as shown in Table 19-21. If this is the case, a method must be selected before the final design is begun.

Maximizing utilization of the site is an important consideration in method selection. If daily cover is to be applied, the daily sludge generation rate will affect the net capacity of the site. If several days are required to fill a trench, as the result of low sludge generation, and cover is required each day, then the ratio of sludge/cover will be less than for sites managing larger sludge quantities. The net sludge capacity will be higher at sites where trenches are filled each day.

The amount by which the net capacity of the site will be reduced will vary with the landfill methods, the specific site, and the daily sludge generation rate. Before a final method is selected, estimates of net capacity and site life should be made for each.

Additional design criteria are summarized in Table 19-3 (1).

TABLE 19-3

LANDFILL DESIGN CRITERIA

Method	Sludge solids content, percent	Trench width, ft	Bulking required	Bulking agent	Bulking ratio[a]	Cover thickness, ft: Interim	Cover thickness, ft: Final	Imported soil required	Sludge application rate, cu yd/acre[b]	Equipment
Sludge only-trench fill										
Narrow trench	15-20[c]	2-3	No	-	-	-	2-3	No	1,200-5,600	Backhoe with loader, excavator, trenching machine
	20-28[c]	3-10	No	-		-	3-4			
Wide trench	20-28[c]	10	No	-		-	3-4	No	3,200-14,500	Track loader, dragline, scraper, track dozer
	≥28[d]	10	No	-			4-5			
Sludge only-area fill										
Area fill mound	≥20[c,d]	-	Yes	Soil	0.5-2 soil: 1 sludge	3	3-5	Yes	3,000-14,000	Track loader, backhoe with loader, track dozer
Area fill layer	≥15[d]	-	Yes	Soil	0.25-1 soil: 1 sludge	0.5-1	2-4	Yes	2,000-9,000	Track dozer, grader, track loader
Diked containment	20-28[c]	-	No	Soil	0.25-		3-4	Yes	4,800-15,000	Dragline, track dozer, scraper
	≥28[d]		No	Soil	1 sludge					
Codisposal with refuse										
Sludge/refuse mixture	≥3[d]	-	Yes	Refuse	4-7 tons refuse: 1 wet ton sludge	0.5-1	2	No	500-4,200	Dragline, track dozer
Sludge/soil mixture	≥20[d]	-	Yes	Soil	1 soil: 1 sludge	0.5-1	2	No	1,600	Tractor with disc, grader, track loader

[a]Volume basis unless otherwise noted.
[b]In actual fill areas.
[c]Land-based equipment.
[d]Sludge-based equipment
[e]But sometimes used.

1 ft = 0.305 m
1 cu yd = 0.765 cu m
1 acre = 0.405 ha

19.2.4.4 Ancillary Facilities

Ancillary facilities may be needed in association with the landfill site. These are described briefly in the following sections.

Leachate Controls

Leachate from the landfill site must be contained and treated to eliminate potential water pollution and/or potential public health problems. In many cases, leachate containment and treatment may be required by state or local regulations. Numerous methods are available for controlling leachate, including drainage, natural attenuation, soil or membrane liners, or collection and treatment. The method and the design features chosen are specific for each project. Table 19-4 depicts sludge-only leachate quality for one site sampled over two years.

TABLE 19-4

LEACHATE QUALITY FROM SLUDGE-ONLY LANDFILL

Constituents	Values[b]
Constituents	
pH	6.7
TOC	1,000[c]
COD	5,100[d]
Ammonia nitrogen	198[d]
Nitrate nitrogen	0.28[d]
Chloride	6.7
Sulfate	10
Specific conductivity	3,600[e]
Cadmium	0.017
Chromium	1.1
Copper	1.3
Iron	170
Mercury	0.0004
Nickel	0.31
Lead	0.60
Zinc	5.0

[a]Data from "Site 8" monitored from July 1975 through September 1977. First received sludge in 1973. Receives unstabilized primary and WAS, gravity thickened and centrifuged. Sludge is lagooned, allowed to dry, and covered with soil. Soil characteristics: sand and gravel, glacial deposites.

[b]Specific conductivity in micromhos/cm, pH in units, all others in mg/l.

[c]Ranged from 3,000 mg/l to 1 mg/l.

[d]Limited to early part of sampling program.

[e]Ranged from 10,000 micromhos/cm 340 micromhos/cm.

Gas Control

Gas produced by decomposition of organic matter is potentially dangerous. This condition is of particular concern if the landfill is located near a populated area. Methane gas, in particular, is highly explosive if confined in an enclosed area.

Control of the gases produced at the landfill must be provided. Two widely accepted methods control paths of gas migration. Permeable methods usually consist of a gravel-filled trench around the fill area for intercepting migrating gas and venting it to the atmosphere. Impermeable methods consist of placing a barrier of low permeability material, such as compacted clay, around the fill area to minimize lateral movement of gas. This method provides for gas venting through the cover material. In general, methane recovery is not cost-effective at sludge-only or small co-disposal sites.

Roads

Paved access and on-site roads are necessary at the landfill site. Temporary roads may be constructed of well compacted natural soil or gravel. Considerations should include grades, road surface and stability, and climate. Grades in excess of ten percent should be avoided. Provisions should be made to allow trucks to turn around within the site area.

Soil Stockpiles

Storage area should be provided for on-site stockpiling of transported soils where on-site soils are insufficient or their use inappropriate. The quantity and type of soil to be stockpiled depends on the individual demands of the landfill. Stockpiles may also be desirable for winter operations where frozen ground may limit excavation.

Inclement Weather Areas

Special landfill areas should be placed near the entrance to the site so that operations may be continued during inclement weather. Paved or all-weather roads should be provided for working these sites.

Structures

An office and employee facilities should be located at the landfill site. For large operations, a permanent structure should be provided. At smaller sites a trailer might suffice. An equipment barn and shop may be desirable for some locations.

Utilities

Electrical, water, communication and sanitary services should be provided for large landfill operations. Chemical toilets, bottled water, and on-site electrical generation may reduce the cost of obtaining services from utility companies. This approach may be appropriate for remote sites.

Fencing

The landfill site should be fenced. Access should be limited to one or two secured entrances. The height and type of fence should suit local conditions. A 6-foot (1.8 m) chain link fence topped with barbed wire will restrict trespassers; a wooden fence or hedge is effective for screening the operation from view, and a 4-foot (1.2 m) barbed wire fence will keep cattle or sheep away from the site area.

Lighting

Portable lighting should be provided if landfill operations are carried out at night. Permanent lights should be installed for all structures and heavily used access roads.

Wash Racks

A cleaning program should be required for frequently used equipment. A curbed wash pad and collection basin should be provided to contain the contaminated washwater for treatment.

Monitoring Wells

It is crucial to monitor groundwater. The number, type, and location of monitoring wells and monitoring frequency should be designated to meet specific conditions associated with the landfill.

Landscaping

Depending on the size and location of the landfill, landscaping may be an important design factor. The aesthetic acceptability of the landfill is critical, especially in an urban or densely populated area. In general, shrubbery chosen should require little maintenance and become an effective visual barrier.

19.2.4.5 Landfill Equipment

A wide variety of equipment may be required for a sludge landfill. The type of equipment depends on the landfill method employed and on the quantity of sludge to be disposed of. Equipment will be required for sludge handling, excavation, backfilling, grading, and road construction. Table 19-5 presents typical equipment performance characteristics for various sludge landfilling methods.

19.2.4.6 Flexibility and Reliability

Because sludge characteristics and quantities may change, a landfill site should be designed with maximum flexibility. Since the life of a landfill is difficult to accurately predict, expansion may be needed sooner than originally planned or it may be delayed. Any change in wastewater treatment or sludge management processes may affect the nature and quantity of sludge produced. Operational modifications may be needed if these changes are drastic. The landfill design should be such that changes can be made without major disruption to operations.

TABLE 19-5

LANDFILL EQUIPMENT PERFORMANCE CHARACTERISTICS

			Equipment type									
Landfill method	Submethod	Equipment function	Trenching machine	Backhoe with loader	Excavator	Track loader	Wheel loader	Track dozer[a]	Scraper	Dragline	Grader	Tractor with disc
Trench	Narrow trench	Trench construction	G	G	G	-	-	-	-	G	-	-
		Covering	G	G	F	G	G	G	-	G	-	-
	Wide trench	Trench construction	-	-	-	G	F	G	G	G	-	-
		Covering	-	-	-	F	-	G	-	G	-	-
Area fill	Mound	Soil hauling	-	F	-	F	G	-	G	-	-	-
		Mixing	-	F	-	G	F	G	-	-	-	-
		Sludge hauling	-	F	-	F	G	-	F	-	-	-
		Mounding	-	G	-	G	F	F	-	-	-	-
		Covering	-	F	-	G	F	G	-	G	-	-
	Layer	Soil hauling	-	F	-	F	G	-	G	-	-	-
		Mixing	-	F	-	G	G	G	-	-	-	-
		Sludge hauling	-	F	-	F	G	-	F	-	-	-
		Layering	-	-	-	F	-	G	G	-	G	-
		Covering		-		F	-	G	G		G	
	Diked containment	Soil hauling	-	F		F	G	-	G		-	
		Dike construction	-	-		F	F	G	G	-		
		Covering			-	-	-	G	-	G	-	-
Codisposal	Sludge/refuse	Spreading	-			F	-	G	-	-	-	-
		Covering	-	-	-	F	-	G	F		-	
	Sludge/soil	Sludge spreading	-	-	-	F	-	G	-	-	F	-
		Mixing	-	-	-	-	-	F	-	-	-	G
		Hauling	-	-	-	G	F	-	F	-	-	-
		Covering	-	-	-	F	F	G	F	-	-	-

Legend
G = Good. Fully capable of performing function listed. Equipment could be selected solely on basis of function listed.
F = Fair. Marginally capable of performing function listed. Equipment should be selected on basis of full capabilities in other function.
- = Not applicable. Cannot be used for function listed.

[a] Caterpillar D-6 generally is the largest track dozer appropriate for a sludge landfill although some engineers are investigating the use of the Caterpillar LG-T, double-wide track dozer.

Reliability is another important factor in designing a landfill operation. Operation should continue even in inclement weather. Special work areas and storage facilities should be available on site for emergency operations or unexpected equipment failures.

19.2.4.7 Expected Performance

Although the overall performance of a sludge landfill may be difficult to predict accurately, certain operating parameters should be estimated. The site life depends on many factors; an estimate is needed for purposes of economic evaluations and future planning. Sludge application rate and soil cover requirements should be estimated before scheduling initial operations. Performance can be more closely predicted after actual operating experience is gained.

19.2.4.8 Environmental Impacts

Specific areas of environmental impact vary among landfill locations. Crucial impact areas include: traffic, land use, air quality, surface and groundwater quality, public health, aesthetics, wildlife, and habitats of endangered species. Adverse impacts should be mitigated during the site selection process or by specific measures in the design.

19.2.5 Operation and Maintenance

A sludge landfill should be viewed as an ongoing construction site. Unlike conventional construction, however, the operating parameters of a sludge landfill often change and may require innovative alterations and contingency plans. An effective landfill requires a detailed operational plan. Equipment selection should be compatible with sludge characteristics, site conditions, and landfill method.

Operational procedures can be separated into those specific to the landfill method and those applicable to sludge landfills in general. Method-specific procedures include: site preparation, sludge unloading, sludge management and covering. These procedures are discussed in detail in Municipal Sludge Landfill (1).

General procedures include scheduling, equipment selection and maintenance, management and reporting, safety, and environmental controls. These items are discussed in Sanitary Landfill Design and Operation (2). Important points are summarized below.

19.2.5.1 Operations Plan

As with any construction activity, sludge landfilling must proceed according to detailed plans and operating schedules. The operation plan should address all relevant method-specific or general operating procedures for the landfill, including:

- Hours of operation.
- Measuring procedures.
- Traffic flow and unloading procedures.
- Special wastes handling.
- Cover excavation, stockpiling, and placement.

- Maintenance procedures and schedules.
- Inclement weather operations.
- Environmental monitoring and control practices.

An operations plan is an important tool for providing continuity of activities, monitoring and control of progress, and personnel training.

19.2.5.2 Operating Schedule

Major features of the operating schedule include: hours of operation, availability of qualified personnel, site preparation schedules, and equipment maintenance schedules. The hours of operation must be such that the site is open when sludge is to be received. If variations in the rate of receipt are expected during the day, it may be desirable to schedule for equipment and personnel accordingly. The schedule may need to provide for the application of daily soil cover.

19.2.5.3 Equipment Selection and Maintenance

Equipment selection depends largely upon the landfill method, design dimensions, and sludge quantity. Selection must be based upon the functions to be performed and the cost of alternate machines. Table 19-5 summarized general selection criteria. Table 19-6 presents examples of equipment choices for seven landfill schemes.

TABLE 19-6

TYPICAL EQUIPMENT TYPE AND NUMBER AS A FUNCTION OF LANDFILL METHOD AND SITE LOADING

	Trench method										Area fill method															Codisposal method[a]									
	Narrow trench					Wide trench					Mound					Layer					Diked containment					Sludge/refuse					Sludge/soil				
Equipment	1[b]	2[c]	3[d]	4[e]	5[f]	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Trenching machine				1	2																														
Backhoe with loader	1	1		1[g]	1							1[g]	1[g]	1[g]	1																				
Excavator			1																																
Track loader						1	1[g]	1		1[g]	1	1	1	1	1															1			1[g]	1[g]	2[g]
Wheel loader														1	1					1[g]															
Track dozer		1[g]	1	1	2[g]		1[g]	1	1	2[g]			1[g]	1	1	1	1	1	2[g]	2	1	1[g]	1[g]	1	2[g]			1[g]	1	1					
Scraper									1[g]	1			1[g]	1[g]	1		1[g]	1[g]	1[g]	1			1[g]	1	1										
Dragline																						1	1	1	1										
Grader																																		1[g]	1
Tractor with disc																															1	1	1[g]	2[g]	2
Total	1	2	2	3	5	1	2	2	2	4	1	2	4	5	5	1	2	2	3	4	1	2	3	3	4	-	-	1	1	2	1	1	2	4	5

[a]Additional equipment only.
[b]Scheme 1 - 10 wet TPD.
[c]Scheme 2 - 50 wet TPD.
[d]Scheme 3 - 100 wet TPD.
[e]Scheme 4 - 250 wet TPD.
[f]Scheme 5 - 500 wet TPD.
[g]May not receive 100 percent utilization.

Equipment maintenance can be more expensive than the amortized annual purchase cost. A scheduled preventive maintenance program should be followed to control maintenance costs. Operators should perform routine daily maintenance (for example, check fluid levels, cleaning, etc.). The operating schedule should provide periods for thorough maintenance.

19.2.5.4 Management and Reporting

Management and reporting activities include the maintenance of activity records, performance records, required regulatory reports, cost records, on-site supervision and public relations activities. Activity records include equipment and personnel accounts, sludge and (if applicable) solid waste receipts, cover material quantities and used site area layouts. These records become bases for scheduling site development, gauging efficiency, and any billing as required.

Performance records may be required as a part of the regulatory process. Regulatory agencies may perform periodic inspections on a scheduled or an unscheduled basis. Operating and supervisory personnel must be aware of these requirements.

For the purposes of safety and control, the site should be staffed with two or more persons. At smaller sites, where only one operator is required, daily visits or phone checks should be made.

19.2.5.5 Safety

Providing a safe working environment at the landfill site should be a part of general O&M, and certain safety features should be built into the design. Certain practices must be followed daily to provide safe working conditions. The operations plan should have a separate safety section, as well as specific safety guidelines for each operation and feature of the landfill.

<u>Soil and Fill Stability</u>

The stability of the soil and fill can present a critical safety problem, particularly with the use of large equipment. Disturbed and filled areas should be approached cautiously as should muddy areas or areas subject to erosion.

<u>Equipment Operation</u>

The operation of large, earth-moving equipment presents the potential for accidents. Only fully trained operators should be allowed to use such equipment. Regular maintenance and safety checks can greatly reduce the number of accidents associated with equipment failure and operator error.

Gas Control

Caution must be used when dealing with gas control equipment. The O&M manual should contain a complete set of instructions on the safe servicing of gas control and monitoring equipment, and the operation of this equipment should be explained periodically at operation and safety training sessions.

19.2.5.6 Environmental Controls

The protection of the environment and public health are important aspects of the landfill operation. The operations plan should contain guidelines for providing this protection and actual operations should conform to the guidelines. General requirements are summarized in Table 19-7. Critical areas are discussed below.

TABLE 19-7

POTENTIAL ENVIRONMENTAL PROBLEMS AND CONTROL PRACTICES

	Environmental problems									
Control practice	Spillage	Siltation and erosion	Mud	Dust	Vectors	Odors	Noise	Aesthetics	Health	Safety
Safety program										X
Maintain washrooms for personnel									X	
Training of new personnel	X	X	X	X	X	X	X	X	X	X
Use safety clamps on truck tailgates	X									X
Maintain road markings and trench barriers	X									X
Maintain fencing								X		X
Apply insecticide					X				X	
Maintain buffer areas and grass		X	X	X		X	X	X		
Proper equipment maintenance	X						X			X
Spray water/oil/liquid asphalt			X	X						
Truck wash pad (to clean trucks)			X	X		X				
Maintain grass waterways, diversion ditches, rip rap		X	X					X		
Final grading of disturbed areas		X						X		
Revegetation of disturbed areas		X	X	X				X		
Chemical masking agent						X				
Lime on site	X				X	X			X	X
Workers supplied with aerators				X		X			X	X
Cover sludge daily					X	X		X	X	X
Water diverted away from site		X	X							

Environment

Environmental protection is generally focused on leachate and runoff controls for preventing surface and groundwater contamination. Trench liners must be kept intact during and after filling operations. Drainage systems should be checked to see that they are functioning as designed. If monitoring indicates that adverse environmental impacts are occurring or pending, immediate corrective action should be taken.

Public Health

Protection of public health should be a foremost concern in the operation of sludge landfills. Protection of water supplies and particularly sole source aquifers is an obvious responsibility. In addition, control of potential disease by reduction of vectors, the adequate venting of explosive or toxic gases, and the restriction of access to the landfill site are the responsibility of the operators.

Social Welfare

Minimizing the negative aesthetic impacts of a sludge landfill can greatly increase public acceptance. Control of odors, noise, and other nuisances is generally straight-forward and should be accomplished as part of the daily operating routine. Efforts should be made to reduce the undesirable social impacts of the fill operation.

19.2.6 Site Closure

In closing a sludge landfill site, certain criteria must be met to make the site publicly acceptable. These criteria are established according to the type of landfill and the location, size, and ultimate use of the site. The procedures for site closure should be included in the operations manual and updated or modified as the original landfill plan is altered.

19.2.6.1 Ultimate Use

The ultimate use of the site should be described and illustrated in the O&M manual or in a separate document describing the closure of the site. The actual work involved in completing the site will depend on its ultimate use and on the care taken in day-to-day fill operations.

19.2.6.2 Grading at Completion of Filling

When each section of the landfill is completed, the final cover should be graded according to a predetermined plan. It is imperative that no sludge become or remain exposed after the grading has been completed.

19.2.6.3 Final Grading

Final grading of the site is to be performed after sufficient time has elapsed to allow for initial settlement. The final grading plan should be designed in accordance with the intended ultimate use of the landfill site. It is important that all sludge be completely covered to the specified depth with cover material.

19.2.6.4 Landscaping

The landscaping plan should reflect the intended ultimate use of the landfill site. Where practical, landscaping may be done on completed sections before the entire fill project is completed.

19.2.6.5 Continued Leachate and Gas Control

Since decomposition of the organics in the sludge may continue even after the landfill has been completed, an ongoing monitoring and control program must be maintained. Leachate and gas must be controlled even after the filling operations have stopped. The completion plans should clearly outline this program.

19.2.7 Landfilling of Screenings, Grit and Ash

Screenings and grit normally contain some putrescible materials and, if landfilled, should be covered every day. Odors from temporarily uncovered solids may be alleviated by sprinkling the solids with lime. Special care should be exercised to assure vector control (for example, safe poisons for rodent control, spraying for flies, and animal-proof fencing to keep pets from the area).

Residues (ash from the combustion of municipal wastewater solids) generally contain high concentrations of trace metals. Leachate from sites where incinerator ash is landfilled must be controlled to prevent metals contamination of groundwater. In California, for example, wastewater sludge furnace ash must be placed in a "protected" Class II-1 site. See Chapter 11 for more information.

19.3 Dedicated Land Disposal

19.3.1 Definition

Dedicated land disposal means the application of heavy sludge loadings to some finite land area which has limited public access and has been set aside or dedicated for all time to the disposal of wastewater sludge. Dedicated land disposal does not mean in-place utilization. Dedicated sites typically receive liquid sludges. While application of dewatered sludges is possible, it is not common. In addition, disposal of dewatered sludge in landfills is generally more cost-effective.

As with any other land disposal technique, dedicated land disposal requires the wastewater sludge be stabilized prior to application. Once the sludge has been stabilized, however, it can be applied to the dedicated land in either the liquid or the dewatered state. Use of anaerobically digested sludge minimizes odor and potential nuisances.

Many existing wastewater treatment plants practice some form of dedicated land disposal. However, precautions necessary for assuring that this method of disposal is not harmful to the environment have not always been practiced.

19.3.2 Background

Dedicated land disposal was first developed as an informal practice in response to the need to reduce high operational costs associated with sludge disposal. The practice was applicable particularly in cases where the plant site had adequate acreage or where adjacent land was available and hauling costs to the nearest landfill were high. Groundwater contamination, odor production, and aesthetic concerns were not usually addressed in this informal practice.

A more sophisticated approach to dedicated land disposal had to be taken as sludge quantities increased with higher treatment levels, and on-site sludge disposal was perceived as associated with environmental problems. Recent research on this method of sludge disposal has developed key environmental controls which are covered in subsequent sections.

The use of dedicated land disposal has several major advantages. These include flexibility in managing sludges in excess of utilization demand; minimum land use because sludge application rates per acre are maximized; inexpensive dewatering through the use of solar energy instead of the relatively expensive electrical energy required for mechanical dewatering; relatively low capital and operating costs (6).

Dedicated land disposal is applicable as a disposal method for liquid, dewatered, or dried sludges. To maximize the advantage of low-cost solar drying and minimize the cost of upstream sludge processing, disposal of liquid sludge is the most cost-effective approach. Disposal of sludges in the liquid form requires storage capacity. Facultative sludge lagoons (FSLs), as discussed in Chapter 15, can provide that storage. FSLs provide a buffer between continuous sludge production and intermittent land disposal operations. Disposal of the thickened (solids concentration of 6 to 8 percent) sludges from the FSLs will commence 1 to 5 years after the first anaerobically stabilized sludge is discharged into FSLs.

19.3.3 Site Selection

There are five major considerations in selecting an appropriate dedicated land disposal (DLD) site. These considerations are ownership, groundwater patterns, topography, soil types, and availability of sufficient land. All are discussed briefly in the following paragraphs.

19.3.3.1 Ownership by Wastewater Treatment Authority

By definition, the selected DLD site will be dedicated in perpetuity to the sludge disposal function. Long-term buildup of heavy metals and salts in the soil surface layers will make the site unsuitable for future direct agricultural use. Public access to these sites must be restricted because of their potential pathogen contamination. These factors require complete control and thus ownership of the site by the wastewater treatment authority. However, merely because certain elements accumulate to toxic concentrations on that site does not mean that the surface soils are forever useless.

19.3.3.2 Groundwater Patterns

Groundwater movement must be considered in the selection of a DLD site. Groundwater flow patterns must be known in order to protect present or future domestic water supply wells. The following three control options are possible:

1. Choice of a site with an isolated groundwater pattern. This option requires that there be well-defined groundwater migration to a river or the ocean; In this case, there must be no intermediate domestic source wells. An adequate subsurface buffer strip between the site and the receiving waters should be provided to permit further potential pollutant attenuation, uptake, or dilution.

2. Choice of a site with a tight/low permeability surface and/or subsurface soil layer which essentially prevents DLD leachate from reaching the groundwater. In this option, additional monitoring wells may be required to confirm the design assumptions over the long term.

3. Construction of an artificial leachate control barrier composed of a minimum 2-foot (0.6 m) depth clay layer under the entire site and deep cutoff trenches at the groundwater downstream end of the site for leachate collection and recycling. It should be noted that when there are low-permeable soils too close to the surface, liquid disposal operations can be hindered. Shallow clays can cause ponding and reduced loading rates with these systems.

19.3.3.3 Topography

Natural topography is an important consideration in selecting a DLD site. Natural slopes greater than 0.5 percent will have to be modified to prevent erosion. The lack of vegetation on the disposal site increases the potential erosion problem and subsequent runoff control. The use of level or nearly level land eliminates erosion problems. Graded or terraced sites can be used, but increased earthmoving costs are involved.

19.3.3.4 Soil Types

Most soil types can accommodate one or another form of DLD system with proper protection of ground and surface waters as outlined above. Preference should, however, be given to soils with a moderate to high cation exchange capacity (CEC), typically greater than 10 milliequivalents per 100 grams.

Desirable soil conditions include restrictive permeability, minimal ponding, and freedom from boulders. Technical assistance in the areas of soil science, soil agronomy, and soil engineering is recommended, so that the impacts of specific soil types on the project can be accurately evaluated.

19.3.3.5 Availability of Sufficient Land

The amount of land required depends upon the quantity of sludge generated and upon the acceptable loading rates. Sufficient land must be available to ensure the integrity of the system.

19.3.4 Storage

Storage should be considered for DLD systems under certain climatic conditions and for increased operational efficiency and control. As discussed earlier, FSLs are recommended to meet these conditions and to assist in flow buffering (see Chapter 15).

19.3.4.1 Climatic Influences

In most areas of the country, rainfall is seasonal, and in some the ground may be frozen to a depth which makes it unworkable during the winter. These conditions mean that dedicated land disposal operations can occur only during the drier months. As a minimum, provision for six months of sludge storage is required. Systems designed for handling liquid sludge in Sacramento, California (6), and in Corvallis, Oregon (7,8,9), are designed for 18 to 60 months storage of anaerobically digested sludge in FSLs. This allows upstream systems to operate through a winter-summer-winter cycle and without disposal problems during a wet spreading season.

19.3.4.2 Operational Storage

Even where climate is not severe enough to require sludge storage, storage may still be warranted for operational efficiency. If storage is provided, routine equipment maintenance can take place during normal work hours. Emergency situations, such as those which require the retention of unstabilized sludge for very short periods during any plant upset, can be responded to effectively (10).

19.3.5 Operational Methods and Equipment

Dedicated land disposal has achieved recent prominence because of its application to the problem of direct disposal of liquid sludges. Systems that are designed to deliver and manage liquid sludges on DLD sites are of primary interest (11).

19.3.5.1 Liquid Sludge

Application of liquid sludge is desirable because it simplifies upstream processes. Dewatering processes are not required, and inexpensive liquid transport and application systems can be used. Four common surface application methods for the liquid sludge are described in the following paragraphs. The first three are irrigation systems and the fourth is a mobile tank application system subsurface applications methods are described in the final paragraph. Summaries of certain characteristics of those methods are given in Tables 19-8 and 19-9.

<u>Spraying</u>

Wastewater sludge can be applied to the land using either fixed or portable irrigation systems. These systems must either be designed specifically to handle solids without clogging, or liquid sludges must be screened. A 1/8-inch (0.32 cm) mesh rotary strainer will perform satisfactorily.

It is advantageous to spray sludges because operating labor is reduced, less land needs to be prepared, and a wide selection of commercial equipment is available. Fixed irrigation systems can be highly automated, whereas operator attention is required for portable sprinkler systems. Sprinklers can operate satisfactorily on rough, wet land unsuitable for tank trucks or injection equipment.

Disadvantages of spraying sludges include power costs associated with the use of high-pressure pumps, the potential for aerosol pollution from entrained pathogens, odors, potential for ponding of the sludge, and adverse public reaction. Preferred spray systems direct the sludge toward the ground. Modified versions of center pivot systems provide for low pressure at the nozzles, minimizing odors and aerosols. Such designs minimize direct airborne transport of sludge, control application rates and distribution, and minimize aerosol formation and transport.

TABLE 19-8

SURFACE APPLICATION METHODS AND EQUIPMENT FOR LIQUID SLUDGES

Method	Characteristics	Topographical and seasonal suitability
Spray (sprinkler) fixed or portable	Large orifice required on nozzles; large power and low labor requirement; wide selection of commercial equipment available; sludge must be flushed from pipes when use stops for longer than 2 to 3 days.	Can be used on a sloping land; can be used year-round if the pipes are drained in winter; odor and aerosol nuisances may occur.
Overland flow and flooding	Used on sloping ground with or without vegetation with no runoff permitted; suitable for emergency operation; difficult to get uniform aerial application; use of gated or perforated pipe requires screening of sludge prior to application; sludge must be flushed from pipes when use stops for longer than 2 to 3 days.	Can be applied from all-weather ridge roads.
Ridge and furrows	Land preparation needed; lower power requirements than spray; limited to low solids concentration (less than 3 percent works best).	Between 0.3 and 1.0 percent slope depending on solids concentration and condition of soil. Fillable land not usable on wet or frozen ground.
Tank truck	Capacity 500 to 3,800 gallons; larger volume trucks will require flotation tires; can use with temporary irrigation setup; with pump discharge can spray from roadway onto field.	Tillable land; not usable on very soft ground.

1 gal = 3.8 l

Overland Flow and Controlled Flooding

Overland flow (wild flooding) and controlled flooding (border check flooding) are common irrigation techniques. Both of these use gated or perforated pipe to assure aerial uniformity. DLD experiments with these techniques on stabilized lagooned sludge at Sacramento, California (12), indicate that neither resulted in the satisfactory surface spreading of such sludge. Wild flooding spread the sludge too far laterally and quite unevenly downslope. Border check flooding took care of the lateral spreading, but the downslope could not be adjusted to varying sludge solids concentrations. Therefore, the sludge either collected at the top of the sloped field (when there was too little slope for the percent solids concentration) or at the bottom of the sloped field (when there was too much slope for the percent solids concentration). Both flooding techniques resulted in the accumulation of excessive amounts of sludge on limited areas; reapplication was thus limited and problems such as odors and vectors were an outcome. In both techniques, clogging problems were experienced with standard water irrigation gated and perforated piping. This indicated that either special distribution piping would be required for use with sludge or the sludge would have to be screened in a manner similar to that indicated for sprinkler application.

TABLE 19-9

SUBSURFACE APPLICATION METHODS AND EQUIPMENT FOR LIQUID SLUDGES

Method	Characteristics	Topographical and seasonal suitability
Flexible irrigation hose (umbilical cord system) with subsurface injection or surface discharge[a]	Pipeline or tanker pressurized supply; 650 ft hose connected to manifold discharge on plow or disc pulled by tracked vehicle; abrasive wear can result in short hose life; subsurface injection by means of very small furrow behind knife-edge cutting disk and/or narrow plow; surface discharge into furrow immediately ahead of plow-application rate of 50 to 100 wet ton/acre/pass.	Tillable land; not usable on wet or frozen ground.
Tank truck with subsurface injection or surface discharge[a]	500 - 3,800 gallon 4-wheel drive commercial equipment available; subsurface injection by means of very small furrow behind knife-edge cutting disk and/or narrow plow; surface discharge into furrow immediately ahead of plow-application rate of 50 to 100 wet ton/acre/pass.	Tillable land; not usable on wet or frozen ground.
Farm tank trailer and tractor with surface discharge[a]	Sludge discharged into furrow ahead of plow mounted on tank trailer - application of 170 to 225 wet ton/acre/pass. Sludge spread in narrow bank on ground surface and immediately plowed under - application rate of 50 to 125 wet ton/acre/pass.	Tillable land; not usable on wet or frozen ground.
Farm tank trailer and tractor with subsurface injection[a]	Sludge discharged into channel opened and covered by a tillable tool mounted on tank trailer - application rate 25 to 50 wet ton/acre/pass.	Tillable land; not usable on wet or frozen ground.

[a]Vehicle reaccess to area receiving application dependant on water content and application rate of liquid sludges.

1 gal = 3.8 l
1 ton/acre = 2.25 t/ha

Ridge and Furrow

The ridge and furrow sludge application method is similar to that used in agricultural systems. At the high application rates and given low solids content, the ridge and furrow method offers better control than gated or perforated pipe systems used for overland flow or controlled flooding. Key factors in the success of ridge and furrow application are the solids concentration of the sludge, the furrow slope, and the condition of the soil. The effect of the solids concentration and the furrow slope on sludge application, determined from a study in Sacramento, California area (34), is summarized in Table 19-10. Generally, for a well-stabilized sludge, the furrow slope should be about 0.1 to 0.2 percent per one percent sludge solids concentration, particularly for sludges which behave like water (less than 3 to 4 percent solids). Sludges with much greater solids concentrations cannot be successfully surface spread by the ridge and furrow technique. As long as the soil remains loose and friable, satisfactory ridges and furrows can be created and friction losses can be tolerated. Excessive reapplications of sludges with high moisture contents can create soils which clump. This makes ridge and furrow construction difficult and increases friction losses to intolerable levels.

Advantages of ridge and furrow irrigation include simplicity, flexibility, and lower energy requirements. Disadvantages include the settling of solids at the heads of furrows, the need for a well-prepared site with proper gradients, and the impossibility of maintaining a friable soil. In addition, ponding of sludge in the furrows can result in odor problems.

Often, ridge and furrow sludge irrigation also involves a covering operation. This must be carefully considered, laid out, and tested prior to installation so that maximum efficiency in application and land use is assured.

Tank Truck Surface Spreading

A common method of liquid sludge surface application is direct spreading by tank trucks, tractors, and farm tank wagons with capacities of 500 to 3,800 gallons (2 to 14 m^3). Sludge is spread from a manifold on the rear of the truck or wagon as the vehicle is driven across the field. Application rates can be controlled either by valving the manifold or by varying the speed of the truck.

The principal advantages of a tank truck system are low capital investment and ease of operation. The system is flexible in that a variety of application sites, pastures, golf courses, farmland, athletic fields and the like, can be served. This permits utilization of sludge, with a dedicated land disposal system as a reliable backup disposal mode.

TABLE 19-10

FURROW SLOPE EVALUATION

Slope,[a] percent	Percent solids[b]	Observations[c]
0.1	3.1	Sludge ponded or flowed very slowly. On slopes this flat slight variations in grade causing ponding. Generally unsatisfactory.
.2	3.1	No ponding, sludge flowed slowly. Minimum grade for 3 percent solids. Would be too flat for 5 percent solids.
.3	3.1	Sludge flowed evenly at a moderate rate. Excellent slope for 3 percent solids.
.4 - .5	2.7	Sludge flowed evenly at a moderate rate. If sludge-furrow was not covered when full all the sludge would flow to the low end and pond.

[a]0.1 percent equals 0.1 ft of fall/100 ft of run. (0.1 m/100 m)

[b]Percent solids expressed determined in a dry weight basis.

[c]All observations are based on 12 in. (.30 cm) deep furrows. Soil in excellent friable condition. Deeper furrows would permit the use of flatter slopes.

Disadvantages of this system include wet-weather problems and the high operating costs for sludge hauling. Standard, highway-operable tank trucks are not able to enter sites when the ground is soft. Consequently, storage or wet-weather handling alternatives must be available. Another disadvantage is that truck traffic damages soil structure and compresses the soil, thus yielding higher bulk densities and reduced infiltration capacities.

To maximize disposal time during days when the site can be used, a highway vehicle with a 3,000 to 6,000 gallon (11.7 to 22.7 m^3) capacity tank can be used to transport the sludge to the DLD site. Sludge is then transferred to one or more off-road application trucks. These trucks should be equipped with high flotation tires and four-wheel drive for working wet sites.

Subsurface Injection

Subsurface injection involves a principle of incorporation, which involves cutting a furrow, delivering sludge into that furrow, and covering the sludge and furrow, all in one operation. Modifications include methods in which the sludge is injected beneath the soil surface or incorporated by use of a disk.

Advantages of incorporation include: immediate mixture of sludge and soil, elimination of potential odor and vector problems from ponding, and control of surface runoff. Incorporation procedures are also favored when sludge utilization is desired, because less nitrogen is lost from the soil through ammonia volatilization.

The principal disadvantages of incorporation are its complex management procedures and the fact that the equipment cannot be effectively used on wet or frozen ground.

19.3.5.2 Dewatered Sludge

Application of dewatered sludge is similar to application of solid or semi-solid fertilizers, lime, or animal manure. Sludge can be spread with bulldozers, loaders, graders, or box spreaders and then plowed or disked in. Spiked tooth harrows used for normal farming operations may be too light to bury sludge to the required depth. Use of heavy-duty industrial discs or disk harrows may be required. Methods and equipment for application of dewatered sludges are shown in Table 19-11. Figure 19-2 shows views of Denver Metro's dewatered sludge landspreading operations.

The principal advantage of using dewatered sludge is that conventional equipment for application of fertilizer and lime and for tillage can be used. Another advantage is that dewatered sludge may be applied at higher rates than liquid sludge. Problems of flooding and ponding and subsequent site access associated with the high hydraulic loading rates of liquid sludge applications are avoided. The disadvantage is the higher energy and operational costs associated with sludge dewatering and the treatment required for resulting sidestream. The disadvantages appear to outweigh the advantages, since dewatered sludge is infrequently used for DLD.

TABLE 19-11

METHODS AND EQUIPMENT FOR APPLICATION OF DEWATERED SLUDGES

Method	Characteristics
Spreading	Truck-mounted or tractor-powered box spreader (commercially available); sludge spread evenly on ground; application rate controlled by over-the-ground speed; can be incorporated by disking or plowing.
Piles or windrows	Normally hauled by dump truck; spreading and leveling by bulldozer or grader needed to give uniform application; 4 to 6 inch layer can be incorporated by plowing.
Reslurry and handle as in Tables 19-8 and 19-9.	Suitable for long hauls by rail transportation.

19.3.5.3 Sludge Application Rates

Sludges should be applied such that soils can dry sufficiently between sludge applications to allow the passage of sludge distribution vehicles. Sludge application does not create excess leachate or runoff. Application should also be managed so that the soil does not become anaerobic and generate odors.

Adverse moisture conditions can be avoided for the most part if sludge application rates are not allowed to exceed the net soil evaporation rate (that is, evaporation minus precipitation). Using this guideline, water should be removed by evaporation as rapidly as it is added with the sludge and the fields should dry out prior to subsequent sludge applications. Since on the average, all water is removed by evaporation, none should remain to percolate or become runoff. The environmental hazard and operating costs associated with controlling these streams are thus minimized. Given this premise, sludge should be applied only when the net soil evaporation rate is positive. The Colorado Springs case example discusses this approach. Operations will tend to be seasonal, intensive during warm, dry conditions and slowed down during wet or cold conditions. Sludge application must, of course, be terminated when the ground is frozen.

The Denver Metro uses large trucks to transport dewatered sludge cake to its relatively isolated disposal site at the former Lowry Bombing Range 25 miles (40 km) from the treatment plant. This picture shows transfer of sludge to smaller dump trucks for spreading in the field. Sludge is spread by allowing it to drop from the truck as it is driven through the field. At one time the District used a manure spreader instead of dump truck for sludge spreading purposes.

After spreading, sludge is incorporated into the soil by plowing with this 6-bottom, 2-way moldboard plow. Annual application was about 30 dry tons per acre (67 dry t/ha) in 1976. Nine or ten months later, the same land received another application of sludge.

FIGURE 19-2

DEWATERED SLUDGE LANDSPREADING, METROPOLITAN DENVER SEWAGE DISPOSAL DISTRICT NO. 1, DENVER, COLORADO

It should be noted that runoff and leachate controls are still required even though the system, on the average, eliminates all water by evaporation. Leachate and runoff must be expected, since periods will occur when the net soil evaporation rates are less than expected or where more sludge than permissible is applied.

Organic rather than hydraulic limitations may govern, particularly when dewatered sludges are applied. Odors can develop if the soil/sludge layer does not remain aerobic. Maintenance of the aerobic condition depends on rate of sludge application, the sludge to soil ratio, temperature, and frequency of soil turning or disking.

19.3.6 Environmental Controls and Monitoring

In general, environmental controls for dedicated land disposal are not as severe as those for sludge utilization. The basic requirement is that activities do not cause any nuisance off-site. Control of all transport mechanisms for potential pollutants, specifically via surface and groundwater, and through aerosols and odor is required. If the sludge is well stabilized, vector controls will be negligible.

19.3.6.1 Site Layout

Good site planning is the key to environmental pollution control for DLD. Initial site selection should be based on slope, soil type, and isolation possibilities from ground and surface water. Subsequent detailed planning can significantly enhance final environmental control measures.

Division of the DLD site into several fields is desirable for operational and environmental controls. Individual fields should be in the range of 10 to 100 acres (4 to 40 ha), and 50 acres (20 ha) is typical. For the umbilical cord subsurface injection method, a minimum dimension of 1,300 feet (400 m) is desirable. This will allow a tractor dragging a 650-foot (200 m) hose to cover a field, side-to-side, when the sludge hydrant is located in the center of the field. Smaller sites are more amenable to the use of tank vehicle systems.

The breakdown of the site into smaller areas will permit easier terracing. First, fields with fairly uniform elevations must be chosen, and slopes must then be regraded for the chosen application method.

Beyond the site subdivision, plans for larger DLD systems should include a layout of "nurse centers." These are take-off points on a fixed distributional system for re-filling application trucks in order to minimize their unproductive travel time and undesirable extra field compaction. They also serve as hookups to the tractor-drawn umbilical cord system. Usually, the nurse centers consist of a small (4- to 6-inch [10 to 15 cm] in diameter) sludge force main riser with a quick connect coupling, coming from a pump station or dredge operating in a sludge storage lagoon. A small storage tank or vault (maximum volume twice the tanker capacity) is often added at the nurse center to simplify pumping control and to permit sludge pickup by a field tanker by means of suction. Sludge should not be allowed to remain unmixed in the vault for more than 30 minutes. Mixing of the tank contents will prevent liquid-solid separation, which could cause wide variations in solids concentrations at pickup and, therefore, uneven solids application rates to the site.

19.3.6.2 Groundwater Controls

There are two distinct kinds of groundwater control for DLD sites. The first involves complete collection of any and all leachate from the site followed by either recycling back to the treatment plant or further on-site treatment. The second involves monitoring groundwater migration patterns from the site and assuring that the quality of external waters are not reduced.

In the case of the first, the site should be underlain with an impervious soil, hardpan, or rock. Although it is possible to prepare this barrier artificially using clay or a liner, it is usually not economically feasible to do so. Thus, the original site selection determines the degree of vertical containment. Horizontal movement of groundwater is prevented by the use of diking and cutoff trenches. Leachate is then collected together with surface runoff.

In the case of the second, extensive surveys may be necessary to determine natural groundwater migration patterns. The direction of leaching must be determined. Design should be such that final concentrations of potential pollutants either in the off-site groundwater or in surface water do not exceed contamination guidelines preset by the applicable regulatory authority.

19.3.6.3 Surface Water Runoff Controls

Each DLD site should be graded such that all surface runoff would drain toward one point near the edge or toward the corner of the field. Each site should be surrounded by a berm to keep uncontaminated surface runoff out and to contain contaminated DLD runoff. A center drain should either direct the contaminated runoff back to the nearest manhole on a facultative sludge lagoon supernatant system, or be connected to a pump which directs the runoff back to the treatment plant or to a separate on-site treatment system. Temporary holding of the runoff to permit settling of settleable solids and monitoring may be desirable. If the stored water is found to be of sufficient quality to meet discharge standards, it can be released without any treatment.

The primary mechanism for water removal at most sites is evaporation. Runoff can be minimized by adjusting sludge loadings so that they are less than or equal to the net soil evaporation rate (evapotranspiration rate minus precipitation).

Runoff control can be aided by disking in the sludge soon after application, thereby preventing downward movement of the liquid sludge.

19.3.6.4 Air Pollution Control

Two air pollution concerns are aerosol transport and odor. There must be adequate buffer zones around the DLD site. Operationally, systems which minimize the length of time sludge is directly exposed to the air are preferred. It is possible to incorporate special design features for air pollution control, for example, vacuum stripping of the digested sludge to remove odors prior to land application.

19.3.6.5 Site Monitoring

Monitoring requirements for DLD are relatively straightforward. Groundwater monitoring is essential and should be conducted from a pattern of groundwater wells located primarily at the downstream boundary of the site. In addition to groundwater, collected leachate and surface water runoff streams must be monitored to determine if and when such streams must be treated. For air pollution control, olfactometer measurements (see Chapter 17) could be taken regularly, particularly during calm periods and preceding and during times of air inversions. If odors are a major problem, operations could be stopped during periods of calm winds and temperature inversion.

19.3.7 Costs

Extensive cost data are not available on DLD. Cost estimates are, however, available from a new system developed at Colorado Springs, Colorado, and a large prototype system at Sacramento, California. These cost estimates are discussed in the case examples to follow. These DLD costs are quite site-specific, and extrapolations from the Colorado Springs and Sacramento cost data should be made with caution.

19.3.8 Case Examples

The relatively recent acceptance of dedicated land disposal makes the selection of case examples limited, particularly for small plants. Colorado Springs, Colorado, a medium-sized system, and Sacramento, California, a large system, are discussed in the following sections.

19.3.8.1 Colorado Springs, Colorado

The analyses for and design of a sludge management program for Colorado Springs was based on population and average dry-weather flow figures (see Table 19-12).

TABLE 19-12

COLORADO SPRINGS POPULATION AND WASTEWATER FLOW PROJECTIONS

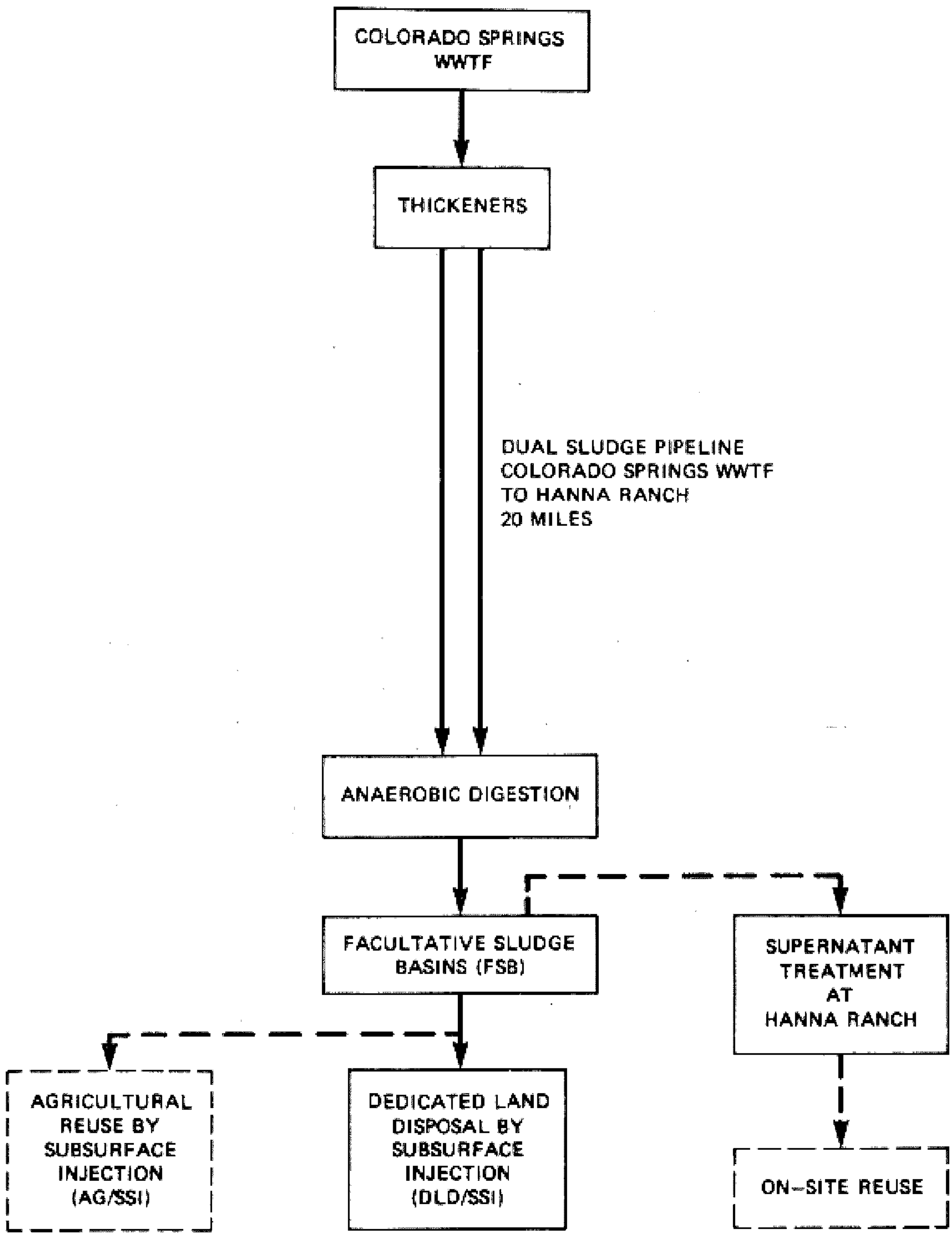
Year	Population, thousands	ADWF, mgd	Planning designation
1978	230	25	Present
1990	330	36	Phase I
2005	440	48	Phase II
Ultimate	--	60	Phase III

An interim sludge management system employs anaerobic digestion of primary and waste-activated sludge at the wastewater treatment plant site. 150,000 gallons (570 m^3) of digested sludge of 2.5 percent solids concentration is produced each day. The sludge is trucked from the treatment plant site to two 5-acre (2.0 ha) 15-feet (4.6 m) deep temporary storage lagoons located 20 miles (32 km) away. The sludge is later removed from the lagoons by two special four-wheel drive high flotation-tired tank vehicles equipped with suction devices and subsurface injected on an adjacent dedicated land disposal site. Capacities of the subsurface injection (SSI) vehicles are 3,600 and 3,800 gallons (13.6 and 14.4 m^3).

The Colorado Springs sludge management system is being substantially modified and upgraded (14). A schematic of the modified system is shown on Figure 19-3, and an overall layout of the sludge disposal site on Figure 19-4. Estimated capital and operating costs for the various facilities are shown in Table 19-13.

The soils at the DLD site consist of Verdos Alluvium, Piney Creek Alluvium, and a weathered Pieere Shale having low to very low permeabilities, in the range of 1.0×10^{-4} to 1.0×10^{-6} cm per second.

Monthly average temperatures range from 29°F to 71°F (-1°C to 22°C). Effective soil evaporation occurs to a depth of about 2 feet (0.6 m), and moisture profiles from SSI test sites show a maximum downward migration of moisture to a depth of 22 inches (57 cm), after application of liquid sludge.



THE TERM FACULTATIVE SLUDGE BASIN (FSB) IN USED INTERCHANGEABLY WITH FACULTATIVE SLUDGE LAGOON (FSL)

FIGURE 19-3

FLOW DIAGRAM SLUDGE MANAGEMENT SYSTEM, COLORADO SPRINGS, COLORADO

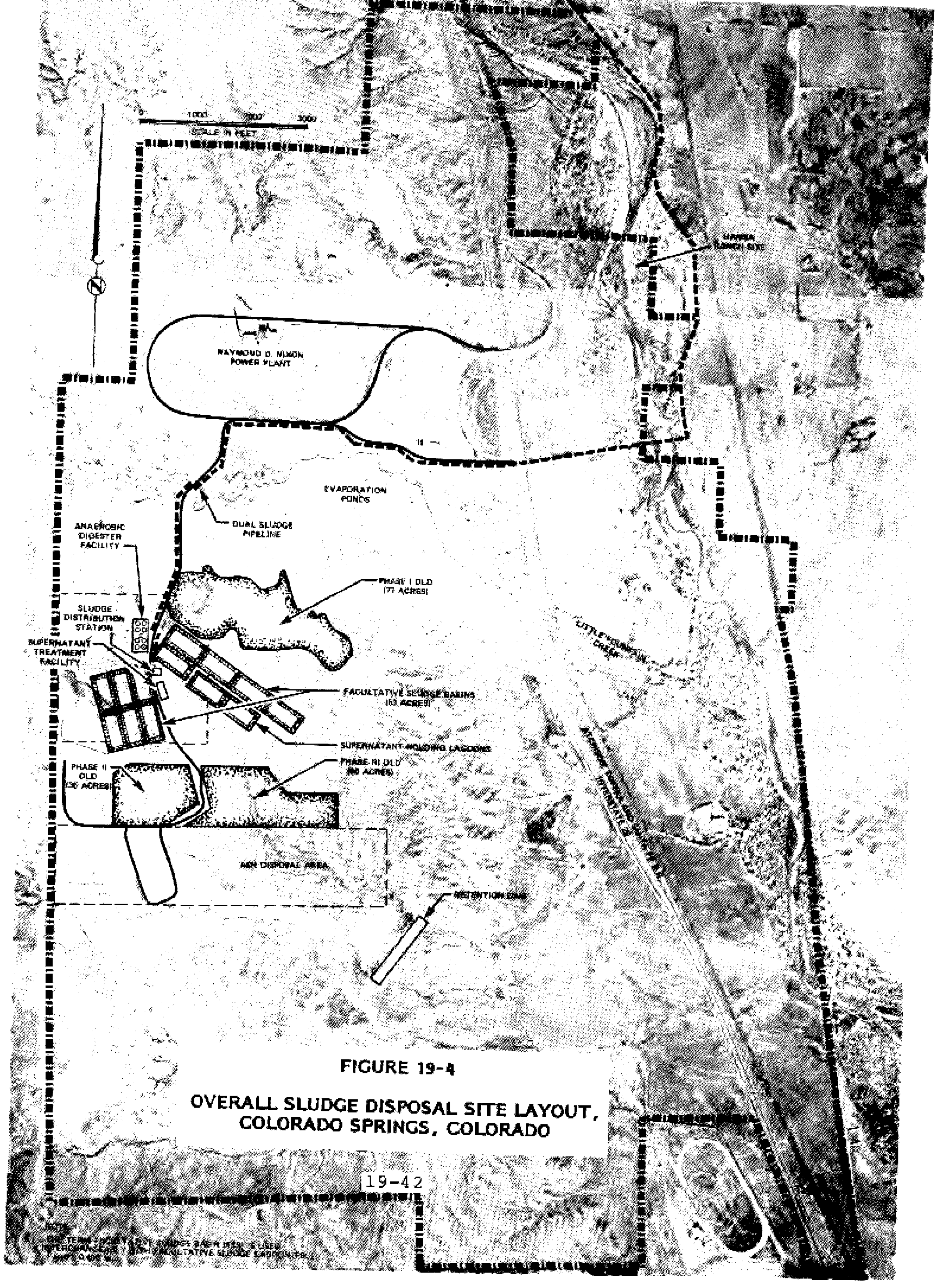


FIGURE 19-4

OVERALL SLUDGE DISPOSAL SITE LAYOUT, COLORADO SPRINGS, COLORADO

TABLE 19-13

COLORADO SPRINGS PROJECTED COST OF SLUDGE MANAGEMENT SYSTEM

Item	Phase cost, thousand dollars[a]		
	I	II	III
Capital cost			
Raw sludge conveyance system	3,552	98	98
Anaerobic digesters	5,539	2,289	2,313
Facultative sludge basins	3,924	1,236	2,068
Subsurface injection system[b]	1,696	756	841
Supernatant lagoons	461	-	75
Supernatant treatment facility	1,681	217	-
Subtotal, capital cost	16,853	4,596	5,394
Engineering and contingencies[c]	5,899	1,609	1,888
Total, capital cost	22,752	6,205	7,282
Present worth[d]			
Capital cost[f]	-	22,473[d]	N/A[e]
Operation and maintenance cost[g]	-	8,048	N/A
Total, present worth of project cost	-	30,521	N/A
Equivalent annual cost	-	2,881	N/A

[a] Costs based on an ENR cost index of 2600, March 1979, Denver.

[b] SSI system includes FSB dredge; harvested sludge distribution pumps, piping and nurse tanks; SSI tank vehicles; and site preparation including grading, cutoff trenches and monitoring facilities, but excluding land costs, which were approximately $1,400 per acre in 1972.

[c] Allowance for engineering and administrative expense and contingencies is based on 35 percent of construction cost.

[d] Present worth costs based on an interest rate of 7 percent and projected construction dates of Phase I and II facilities for a 20-year planning period.

[e] Phase III not included--beyond 20-year planning period.

[f] Salvage values based on assumed life of equipment and computed on straight-line depreciation.

[g] Based on uniform series present worth for fixed costs and gradient series for variable costs.

1 acre = .91 ha

Note: The term facultative sludge basin (FSB) is used interchangably with facultative sludge lagoon (FSL).

There were no groundwater supplies which could be endangered on the 160-acre (65 ha) disposal site or the immediately adjacent areas. However, to provide maximum protection of the environment, the system was designed to minimize percolate production. The design approach was to match sludge application and net soil evaporation rates. Net soil evaporation calculations are presented on a month-to-month basis in Table 19-14. Note that gross soil evaporation was estimated to be a fixed fraction (70 percent) of the evaporation which would occur from a free water surface (a lake).

TABLE 19-14

COLORADO SPRINGS CLIMATIC CONDITIONS AFFECTING SLUDGE DISPOSAL

Month	Lake evaporation[a,b]	Precipitation[a,c]	Net lake evaporation[a,d]	Net soil[a,e] evaporation
January	-	0.71	-0.71	-
February	-	0.73	-0.73	-
March	-	1.56	-1.56	-
April	5.15	1.91	3.24	1.70
May	6.44	2.14	4.30	2.37
June	7.62	2.16	5.46	3.17
July	8.26	3.00	5.26	2.78
August	6.99	2.32	4.67	2.57
September	5.39	1.55	3.84	2.22
October	4.13	1.11	3.02	1.78
November	-	0.95	0.95	-
December	-	0.67	0.67	-
Annual	43.98	18.81	25.17	16.59

[a]All values shown in inches.

[b]Developed from "Interim Study of Land - Incorporated Sewage Sludge" at Colorado Springs, Colorado, December 1978, by Waste and Land Systems, Inc.

[c]Includes precipitation and snow assuming 10 percent of snow depth is equivalent to precipitation depth in inches.

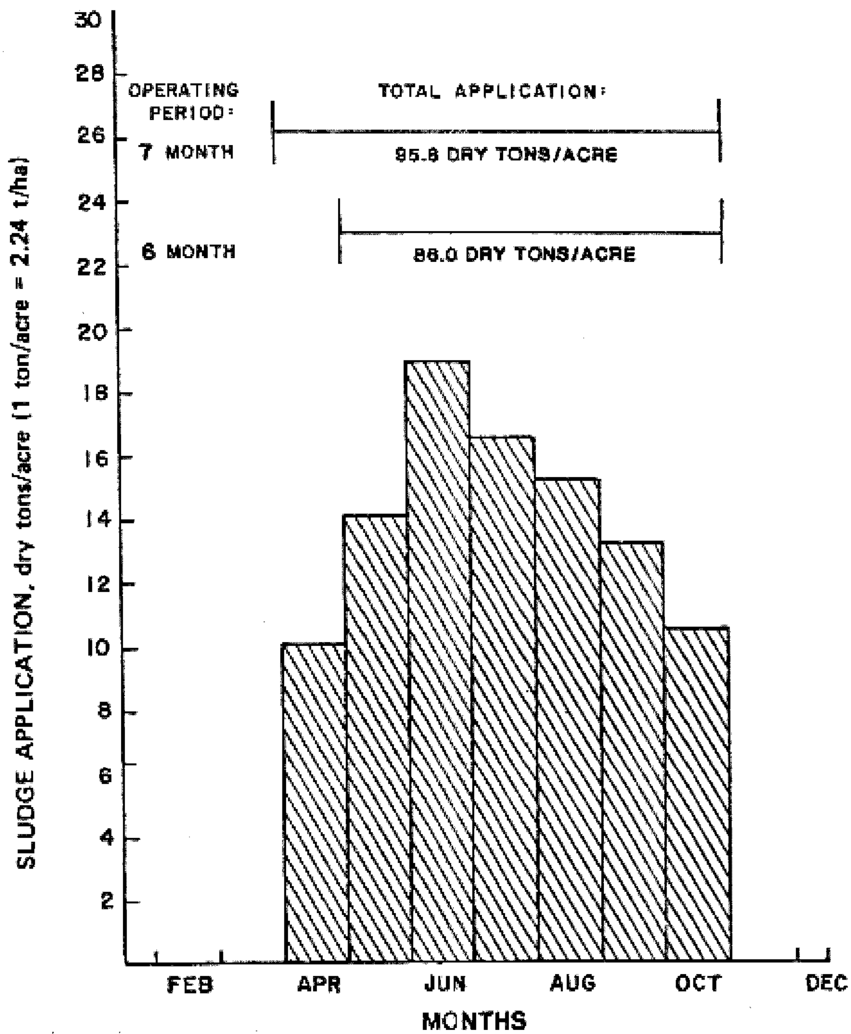
[d]Lake evaporation minus precipitation.

[e]Estimated net soil evaporation based on 70 percent of lake evaporation less precipitation.

1 in. = 2.54 cm

Allowable sludge application rates were calculated on a monthly basis for the months of April to October, assuming a sludge content of 5 percent. Results of this analysis, shown on Figure 19-5 indicated total allowable sludge application on a 6-month and 7-month operating basis to be 86.0 and 95.8 dry tons per acre (193 to 215 t/ha), respectively. The range of required land area for the more restrictive 6-month period is shown on Figure 19-6. Area required for average loadings (14.3 tons per acre per month [32.1 t/ha-mo]) is shown by the "average" curve. Area required if the sludge could be applied for all the months at the maximum June rate (18.6 tons per acre per month [41.7 t/ha-mo]) is shown by the "low range" curve. Similarly, area required if all the sludge were applied at the minimum October rate is shown by the "high range" curve. A second analysis shown on Figure 19-7, indicated the range of area requirements based on variations in sludge solids content of 4 to 6 percent, using average solids loadings (14.3 tons per acre per month or 32.1 t/ha-mo).

With respect to surface water controls, cutoff ditches will be constructed to prevent surface runoff from the disposal site. The injection pattern will be parallel to the contours of the area to reduce the potential for soil erosion and surface runoff from sludge-amended soils. To the south, the entire sludge disposal area is contained behind a retention dam designed to prevent runoff from reaching an existing ash disposal site. This dam, designed for a flood level equivalent to a once in a 1,000-year recurrence interval, provides containment of both surface runoff and upstream percolate. Although the operation of the tank vehicle SSI system was based on a well-defined DLD area with ground slopes typically 3 to 6 percent, portions of the mesa area which have slopes of less than 10 percent can also be used for injection. The maneuverability and freedom of movement of the detached vehicles allows maximum site utilization.



(1 t/acre = 2.24 t/ha)

FIGURE 19-5

SLUDGE APPLICATION RATE-DLD SYSTEM, COLORADO SPRINGS, COLORADO

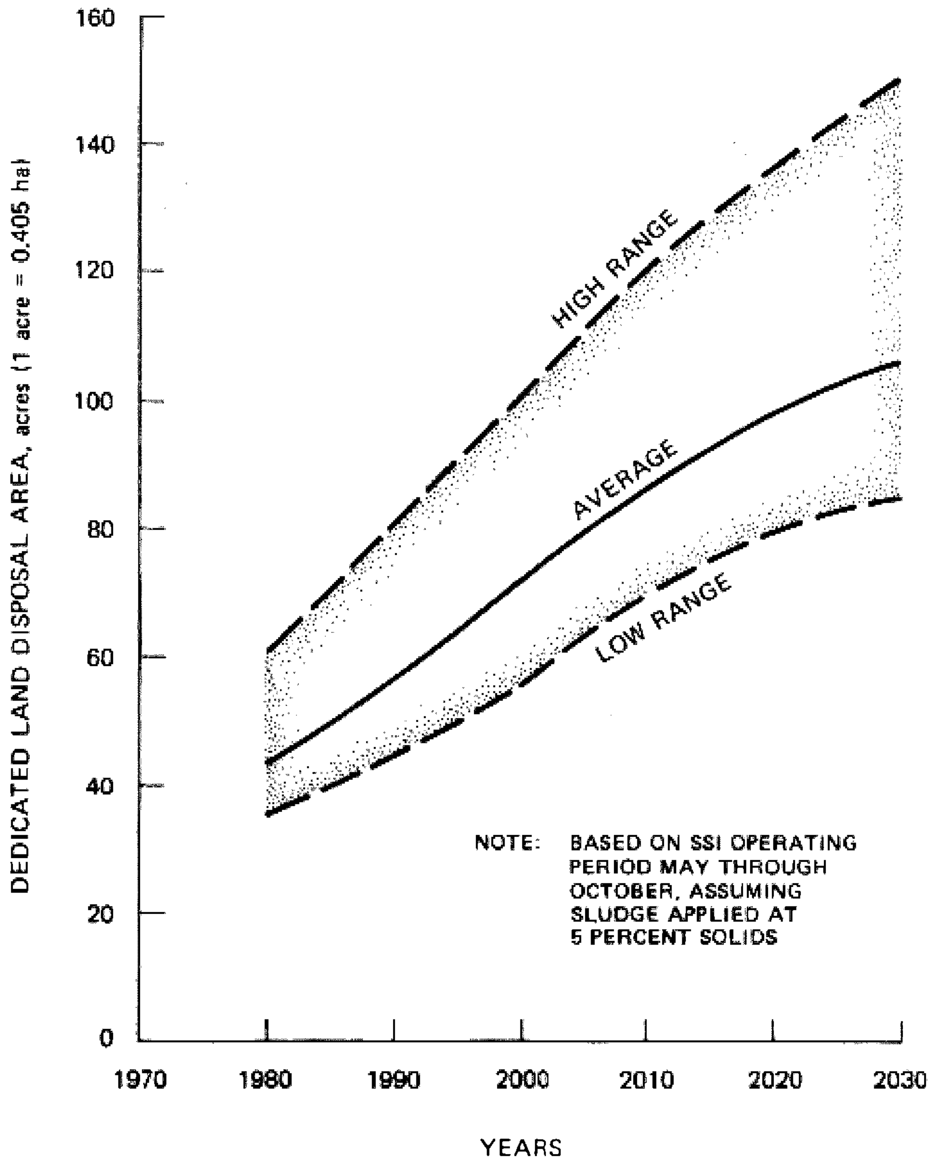


FIGURE 19-6

ESTIMATED NET DLD AREA REQUIREMENTS SLUDGE APPLIED AT 5 PERCENT SOLIDS CONCENTRATION, COLORADO SPRINGS, COLORADO

The operation of the DLD/SSI system commences with harvesting of the sludge from the facultative sludge basins (FSBs) (faculative sludge lagoons [FSLs]) are referred to as facultative sludge basins at Colorado Springs) (15). The sludge is transferred from the basin to a sludge receiving/distribution station by a dredge equipped with a diesel-driven pump. From the station, the harvested sludge is conveyed through a distribution system consisting of 12-inch (30 cm) diameter pipes to a series of DLD nurse tanks. The fiberglass nurse tanks are each 7,500 gallons, twice the volume of the SSI vehicle tank. The nurse tanks are

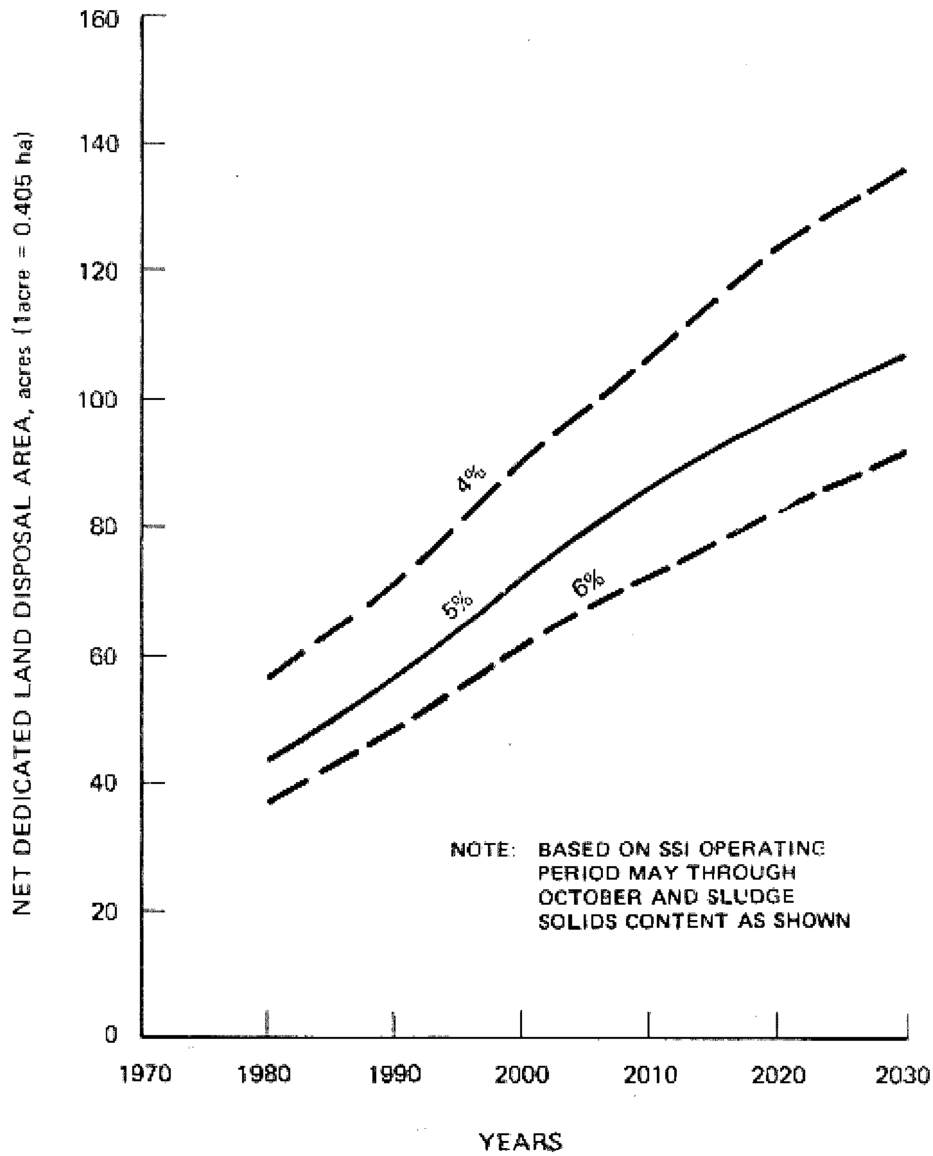


FIGURE 19-7

ESTIMATED NET DLD AREA REQUIREMENTS AT VARIOUS SLUDGE CONCENTRATIONS, COLORADO SPRINGS, COLORADO

buried below ground and protected with a concrete slab on grade. A steel pipe fitted with a gate valve and couplings extends from the bottom of the tank to above the ground surface to feed the SSI vehicles. The harvested sludge distribution system is valved to allow any combination or number of nurse tanks to be placed into service. The network is designed to allow approximately 1,000 lineal feet (305 m) of injection area between nurse tanks to optimize the injection operation and minimize downtimes caused by travel with empty tanks. Depending on climatic conditions,

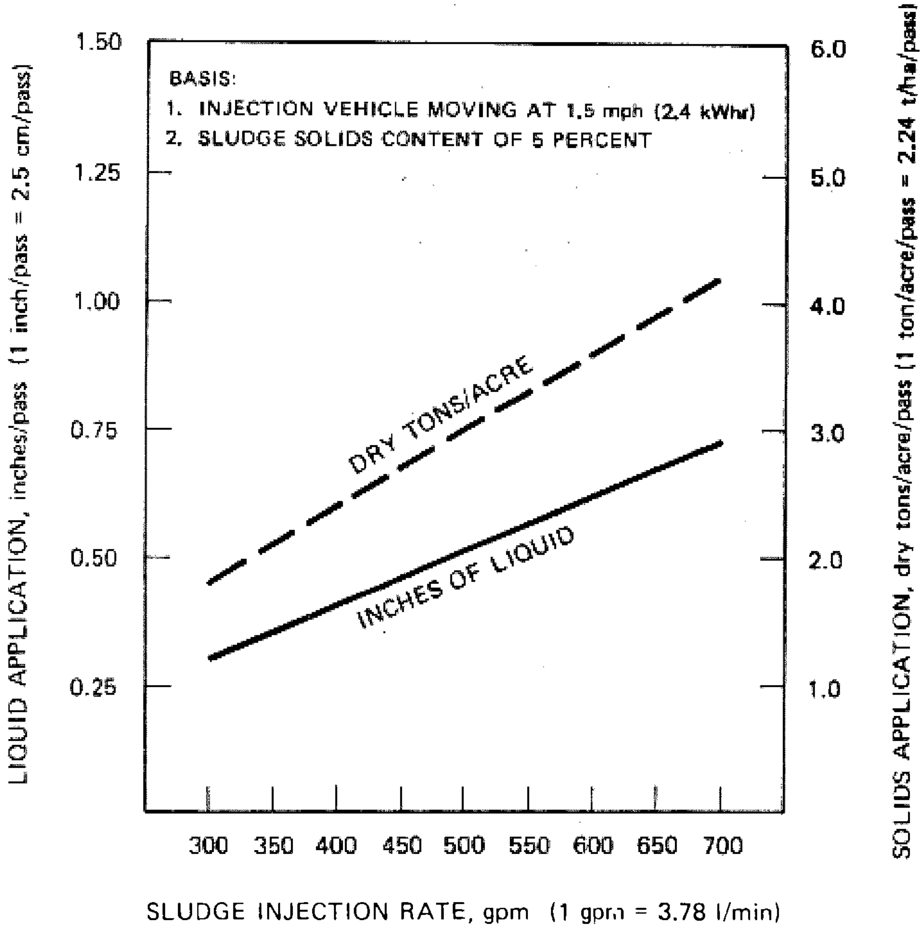


FIGURE 19-8

SLUDGE APPLICATION RATES BY SUBSURFACE INJECTION, COLORADO SPRINGS, COLORADO

the sludge injection rate can be adjusted to correspond with the soil conditions in the injection area and will vary through the sludge application season, as shown on Figure 19-5. The relationship between sludge injection rate and solids application rate on the basis of both liquid sludge and dry solids is shown on Figure 19-8. Based on the estimated turnaround time for tank refilling and normal maintenance, a net injection time of about 3 hours per day per vehicle can be expected. One dredge can harvest sludge from the FSLs at a rate sufficient to feed two SSI vehicles. Equipment requirements and operating characteristics are shown in Table 19-15.

While the DLD/SSI system for Colorado Springs is designed as a base disposal system, it can be used as a secondary, or utilization, option without significant additional expense. Eventual agricultural utilization of a major portion of the sludge production is, in fact, a defined goal of the chosen system. See Chapter 3 for discussion of base and secondary disposal options.

TABLE 19-15

COLORADO SPRINGS DEDICATED LAND DISPOSAL/ SUBSURFACE INJECTION SYSTEM DESIGN DATA

Item	Phase I	Phase II	Phase III
Facultative sludge basins (FSBs)			
Basin dredge			
Number	1	2	3
Maximum capacity, gpm	1,400	1,400	1,400
Solids capacity, percent			
Maximum	8	8	8
Average	5	5	5
Pumping head, feet	65	65	65
Diesel engine power, hp	175	175	175
Dedicated land disposal (DLD)			
Harvested sludge application			
Quantity, dry tons per day[a]	43.2	58.4	76.7
Volume, gpd[a,b]	203,790	274,360	360,440
Percent volatile	50	50	50
Average percent solids	5	5	5
Average annual application			
6-month operating period, dry tons per acre	86.0	86.0	86.0
7-month operating period, dry tons per acre	95.8	95.8	95.8
DLD area required, acres			
Maximum	85	115	150
Average	60	85	110
DLD distribution system			
Nurse tanks			
Number	12	18	24
Capacity, each gal	7,500	7,500	7,500
SSI vehicles			
Number	2	4	5
Tank capacity, each gal	3,600	3,600	3,600
Injection rate, gpm			
Maximum	700	700	700
Average	500	500	500
Average vehicle speed, mph	1.5	1.5	1.5
Injection width, feet	12	12	12
Volume injected, gallons per vehicle per day			
Maximum	116,000	116,000	116,000
Average	100,000	100,000	100,000
Vehicle coverage, acres per vehicle per day	6.5	6.5	6.5
Tillage tractors			
Number	1	1	1

[a]Assuming 120 day per year operation.

[b]Assuming 5 percent solids.

Note: The term facultative sludge basins (FSBs) is used interchangably with facultative sludge lagoons (FSLs).

1 gpm = 0.06 l/s
1 ft = 0.30 m
1 hp = 746 W
1 ton/day = .91 t/day
1 gpd = 3.8 l/day
1 ton/acre = 2.24 t/ha
1 acre = .405 ha
1 gal = 3.8 l
1 mph = 1.61 km/hr
1 gal/vehicle = 3.8 l/vehicle
1 acre/vehicle = .405 ha/vehicle

19.3.8.2 Sacramento, California

Sacramento, California has been the site of much of the work associated with the development of dedicated land disposal technical criteria. The Regional Wastewater Treatment Plant Sludge Management Program for the Sacramento Regional County Sanitation District was approved by the Regional Board of Directors in January 1979 (15) and the Environmental Impact Report (EIR) (6) was certified at that time. The sludge planning period for the treatment plant is divided into two phases; Stage I includes operations to be conducted from 1980 to 1992, and Stage II is devoted to operations for the period 1992-1999.

The sludge management program was approved after 3 to 4 years of monitoring and detailed investigations directed primarily at determining the engineering, economic, and environmental aspects of storing liquid anaerobically digested sludge in solid storage basins (SSBs) (12). Precise operational and design criteria were developed for the Sacramento SSB/DLD system to assure efficient operation and environmental acceptability. Most investigative work was conducted on a large prototype SSB/DLD subsurface injection system and therefore did not suffer the problems normally associated with scaling up a pilot system.

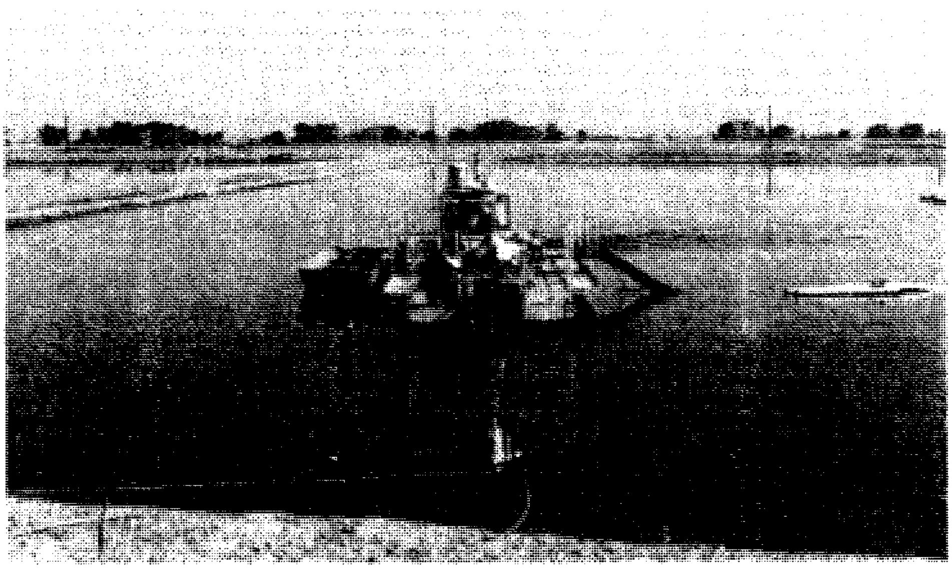


FIGURE 19-9

PROTOTYPE DREDGING OPERATION, SACRAMENTO REGIONAL COUNTY SANITATION DISTRICT

Initial work commenced in 1974. Site preparation included installation of groundwater monitoring wells. The prototype 20-acre DLD system has been in full operation since 1976, and data has been collected and analyzed for 1976 through 1978 and for part of 1979. Figure 19-9 illustrates the prototype dredging operations at Sacramento, while Figure 19-10 illustrates prototype subsurface injection operations with a close-up view of the injector units.

The sludge applied to the Sacramento DLD site has been anaerobically digested and then subjected to long-term storage in the SSBs. Application rates were planned at 100 dry tons/acre (224 dry t/ha); rates of 97 tons/acre (217 t/ha) were achieved without problems in the 1977 tests. The application rates are controlled by the water content of the sludge removed from the SSBs, since DLD operates primarily on a solar evaporation basis. New equipment installed at sludge removal operations in 1979 has increased the solids concentration to over 6 percent, with better than 8 percent achieved for several hours. It is expected that when the FSLs are fully developed, an average harvested sludge concentration of 6 percent can be sustained. The following text discusses the final DLD subsurface injection system for Sacramento based on experience gained over the 1976 to 1979 period.

Table 19-16 shows projected flows and loadings for the Sacramento wastewater treatment plant for 1985. Figure 19-11 is a flow diagram of the solids treatment and disposal system. The numbers thereon give the solids flow in dry tons per day for operations through 1992.

TABLE 19-16

SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT PROJECTED 1985 WASTEWATER FLOW AND LOADINGS

Parameter	Value
Seasonal[a]	
ADWF,[b] MGD	136.2
BOD_5, 1,000 lb/day	243.3
Suspended solids, 1,000 lb/day	246.3
Nonseasonal	
ADWF, MGD	122.7
PWWF,[c] MGD	248.7

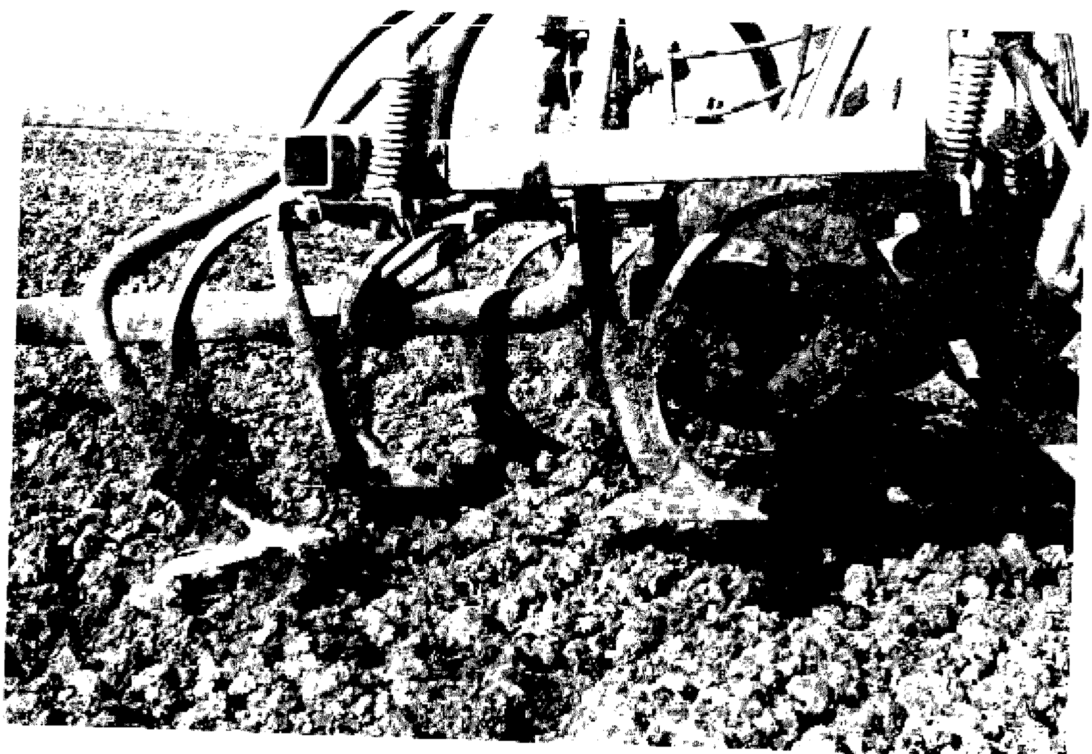
[a]Seasonal = canning season, mid-June to mid-October.

[b]ADWF = average dry-weather flow.

[c]PWWF = peak wet-weather flow.

1 lb/day = 0.454 kg/day.
1 MGD = 0.044 m^3/sec.

View of tractor pulling sludge injector units

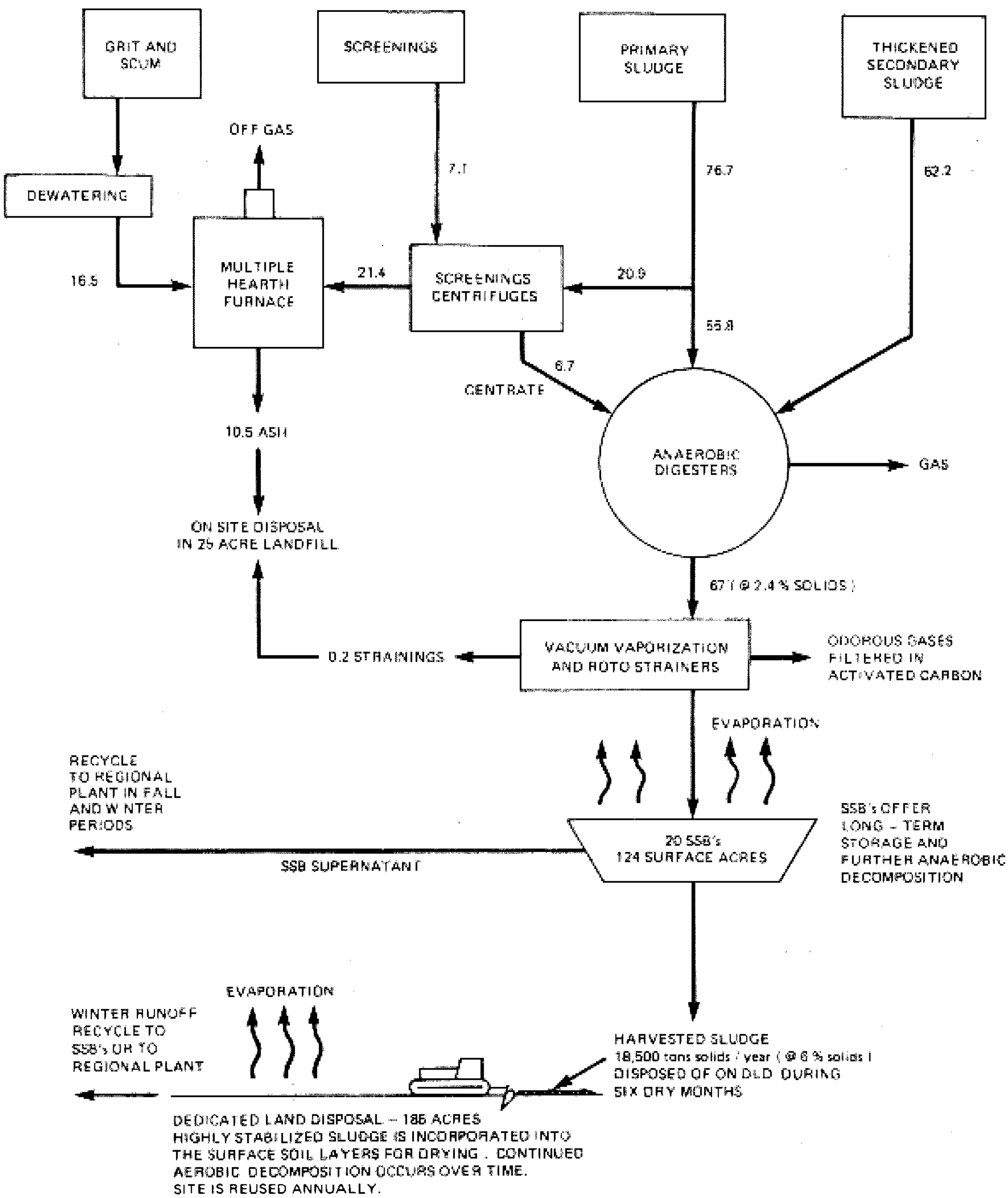


Close up view of prototype sludge injector units

FIGURE 19-10

PROTOTYPE SUBSURFACE INJECTION OPERATIONS, SACRAMENTO REGIONAL COUNTY SANITATION DISTRICT

RECOMMENDED PROJECT



THE TERM 'SOLID STORAGE BASINS' (SSB's) IS USED INTERCHANGEABLY WITH FACULTATIVE SLUDGE LAGOONS (FSL's)

(1 ton/yr = 0.91 t/yr)
(1 acre = 0.405 ha)

FIGURE 19-11

FLOW DIAGRAM - PROJECTED 1992 NORMAL SOLIDS TREATMENT AND DISPOSAL OPERATION, SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT

The flow schematic indicates that not all the sludge will be managed by the SSB/DLD subsurface injector system. Through the 1980s, there will be sufficient furnace capacity in an incinerator (designed for screenings, grit, and scum) to handle about 30 percent of the primary sludge production. A total of one month per year shutdown of the incinerator was assumed, two weeks for maintenance during the time of low solids production in spring, and two weeks miscellaneous upset. Estimated sludge production rates at the Sacramento plant are given in Table 19-17.

TABLE 19-17

SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT PROJECTED DIGESTED SLUDGE PRODUCTION

Estimated solids parameters	Solids concentration, percent	Volatile solids, percent	Total solids production, ton/day							
			Stage I						Stage II	
			1980		1985		1992		1999	
			Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Digested solids, with incinerators operating										
Average annual	2.2-2.5	57-59	51.2	2,278	54.2	2,366	67.0	2,818	75.5	3,035
Maximum seasonal	2.4-2.7	57-62	70.0	2,715	74.4	2,810	81.5	3,340	94.0	3,640
Digested solids, with incinerators not operating										
Average annual	2.5-2.7	57-60	65.0	2,500	70.0	2,600	77.4	3,070	85.0	3,380
Maximum seasonal	2.6-3.0	58-63	81.2	2,860	89.1	3,000	92.7	3,550	107.0	3,860
Average annual SSB[a] solids removed[b]	6	43.0	38.6	643	40.8	679	50.7	844	57.0	951

[a] The term solid storage basins (SSBs) is used interchangably with facultative sludge lagoons (FSLs).

[b] Actual daily removal rates are higher, since solids are harvested for only part of the year (May-October).

1 ton/day = 2.24 t/ha

The layout of the existing and future dedicated land disposal sites in relation to the Sacramento Regional Wastewater Treatment Plant is shown in Chapter 15, Figure 15-9.

Operation of the DLD system is practiced from May through October. Several methods of sludge application were tested, and for the prevailing conditions at the Sacramento site, subsurface injection utilizing a flexible hose and injection unit mounted behind a crawler-tractor fitted with extra-wide tracks worked best.

Two dredges will take care of operations through 1992, (Stage I) dredging solids at about a 6 percent solids concentration from the lower depths of the SSBs and pumping the sludge to the DLD site. Booster pumping is required to pump 6 percent solids material over the maximum 8,000-foot (2,440 m) distance. Four-inch (10 cm) diameter flexible hoses connect the tractor-injectors with hydrants located throughout the DLD sites. Four tractor-injectors are needed to handle the two-dredge disposal operation. In normal operation of these facilities, freshly applied solids remain unexposed to the atmosphere. The DLD sites are loaded at 100 dry tons to the acre (224 dry t/ha) each season. Sludge is supplied to approximately match the net soil evaporation rate. The soil evaporation rate in Sacramento is about half the evaporation rate which occurs from a free water surface (lake evaporation rate). Stage I DLD operations will utilize 185 acres (75 ha) in five 37-acre (15 ha) sites. Regular disking of the site is necessary to break up the soil/sludge surface and expose more of the loaded soil to the atmosphere.

Existing subsoils are fairly impervious and are underlain by hardpan. The local groundwater supply is not endangered. Free groundwater was measured at depths of 13 to 46 feet (4.0 to 14.0 m), with an average depth of 31.6 feet (9.7 m) for nine borings. The aggregate coefficient of permeability for the composite layered interval of the surface soils is on the order of 5×10^{-8} cm/sec. Cemented strata were encountered in the borings at depths ranging from 5 to 10 feet (1.5 to 3.0 m), with thicknesses of approximately 12 to 21 feet (3.7 to 6.4 m) and permeability coefficients of 2.2×10^{-8} cm/sec to 3.7×10^{-10} cm/sec. Effective sealing of the surface soils from vertical leachate movement to groundwater is thus achieved (6,12). Increases in the concentrations of nitrates and chlorides have not been observed below the impervious strata (12).

Runoff is collected in detention basins and returned to the regional plant influent after storm flows have subsided. Some data on DLD runoff water quality are given in Table 19-18.

TABLE 19-18

SACRAMENTO TEST DLD RUNOFF WATER ANALYSIS

Constituent	12/18/77	12/28/77	1/05/78	1/09/78
Zn, mg/l	0.05	0.05	0.25	0.12
Cu, mg/l	0.050	0.043	0.101	0.064
Cd, mg/l	0.001	0.001	0.001	0.001
Ni, mg/l	0.090	0.090	0.16	0.078
Pb, mg/l	0.014	0.008	0.016	0.028
Hg, mg/l	0.0001	0.0001	0.0002	0.0002
TKN,[a] mg/l	30	24	17	7.6
Turbidity, NTU	3.0	1.5	170	37
TSS, mg/l	26	16	442	38
EC x 10^3	4.0	3.6	1.9	1.1
pH	7.2	8.4	7.4	7.4
NO_3, mg/l	440	310	43	31
NH_4, mg/l	36	5	2	1

[a]Total Kjeldahl Nitrogen.

For runoff control, typical DLD sites are sloped transversely at a maximum of 0.5 percent and spread outward in both directions from the centerline. A longitudinal slope of 0.1 to 0.2 percent is also provided. Runoff drains from each DLD site to ditches on both sides. To prevent erosion, the maximum field slope will be held to 0.5 percent and water velocity in the ditches will be limited to 5 feet per second (1.5 m/s). Runoff from the ditches is collected in a fairly flat (0.1 percent transverse slope) detention basin, one per DLD site; the basin is situated approximately 3 feet (0.9 m) lower than the main operational part of the DLD site. Each basin has a capacity of 12.7 acre-feet (123 m^3) and a maximum depth of 2 feet (0.6 m). The basins are designed to contain two 4-inch (10 cm) 24-hour storms (the 25-year maximum rainfall for two 24-hour periods). The runoff is drained from the basins via corner inlet structures fitted with controlled release rate weirs and is transferred through a 21-inch (0.53 m) runoff return pipe to a flow metering structure. Then the runoff is drained to an interceptor sewer connected to the wastewater treatment plant. A flood control levee is constructed on the lowest three sides of the SSB/DLD area such that the entire site is protected from flooding. Provision is also made for the collection, retention, and pumping of uncontaminated site runoff trapped by the flood control levee. In this regard, facilities (including a pump station) are designed to handle the same storm conditions (two 25-year, 24-hour storms, one day apart) as are runoff facilities for the DLD sites. A runoff of 80 percent is assumed based on a saturated ground condition.

Final DLD sites have a gross area of about 50 acres (20 ha), including space for drainage, road access, and injector turning. As indicated earlier, this results in a net usable area of 37 acres (15 ha) for each of the five sites. Each site is approximately 1,300 feet (400 m) wide, which allows a tractor dragging a 650-foot (200 m) hose to cover the entire width of the field. The sludge hydrant is then located in the center of the field. Sites are approximately 1,600 feet (560 m) long, calculated from the area required to allow two injectors to operate continuously on the same field 6 hours per day, 5 days per week, during the peak dry months of June, July, and August.

Peak dry month operation assumes sludge removed from the FSLs can be applied to the same site twice a week. During May, September, and October, it is assumed the application of sludge removed from the SSBs will be limited to one once a week. Thus, application rates during June, July, and August are approximately double (10 inches per month [25 cm/month]) the rates of May, September, and October (5 inches per month [13 cm/month]). Each DLD site is provided with six field hydrants for injector feed connection, located at 230-foot (70 m) centers down the middle of each site. The field hydrants each have a foulproof pressure sensing device, a manual isolation valve, and a swivel-elbow assembly designed for quick coupling to a 4.5-inch (11 cm) injector feed hose.

Operationally, SSB sludge removal piping is flushed with FSL supernatant at the end of each week's run with the flushing water returned to the FSLs. Sludge removal operations themselves are restricted to reducing the water level in the FSLs no more than 14 inches (36 cm) below normal operational levels. The water level is never allowed to drop low enough to expose the sludge blanket. The blanket is maintained below its maximum elevation which is another 10 inches (25 cm) below the absolute minimum water level.

Key DLD equipment for Sacramento includes:

- Two SSB dredges, each generating 1,400 gpm (7,630 m^3/day) average flow at 6 percent solids concentration.

- Two 200- to 250-horsepower (150 to 187 kW) diesel powered floating booster pumps connected to the dredges with variable speed pump operation to compensate for variations in sludge solids concentrations.

- Four 60- to 80-horsepower (45 to 60 kW) crawler-tractors with 30-inch (0.76 m) wide tracks and nine to ten rear-mounted subsurface injector sweeps, each with 2-inch (5 cm) diameter feed hoses. Path width is 13 to 14 feet (4.0 to 4.2 m), speed 1.0 to 1.5 miles per hour (1.6 to 2.4 km/hr), and average capacity 700 gpm (3,800 m^3/day) each.

- One four-wheel drive, rubber-tired, 150-horsepower (112 kW) tillage tractor with heavy disk unit which can be raised clear of the ground.

Staffing requirements for full Phase I DLD operations are expected to reach 11 people on a 6-month seasonal basis, May through October, to remove the sludge from the SSBs and inject it into the soil at the five DLD sites. Personnel needs are given in Table 19-19. Fifteen other full-time personnel are needed for the whole solids processing and disposal system exclusive of anaerobic digestion, with their time only partially attributable to DLD operations. The 15 staff are composed of one at the screenings, grit and ash landfill, six in general operational maintenance, six in mechanical and electrical maintenance, and two in management and monitoring.

Ongoing requirements and possible concerns associated with DLD operations include the need to lime the soil (at about one ton of lime per acre per year [2.24 t/ha/yr]) to maintain a proper pH and hence decrease mobility of metal cations. Also, the useful life of the present type of 4-inch (10 cm) diameter feed hose is unacceptably short. The possibility of using different hose construction or a different brand is being explored. Finally, after a 20-year operation, DLD soils, building up at about 0.75 inch (1.9 cm) per year, will have increased in salinity to about 8,000 mg/l in the saturation extract. This concentration is not expected to affect the bacterial decomposition of the organic matter, however.

TABLE 19-19

SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT
PROJECTED 1985 DLD STAFFING REQUIREMENTS

Description	Number of staff
One operator for each dredge/booster pump combination	2
Relief operator for dredges	1
One operator for each tractor/injector	4
Relief operators for tractor/injectors	2
Operator for tillage tractor	1
Supervisor	1
Total	11

Costs for sludge treatment and disposal at Sacramento are given in Table 19-20. Costs do not include the main battery of anaerobic digesters but do include the costs of a blending digester (see Chapter 15).

19.4 References

1. USEPA. Process Design Manual: Municipal Sludge Landfills. Environmental Research Information Center, Office of Solid Wastes, Cincinnati, Ohio 45268. EPA-625/1-78-010, SW-705. October 1978.

2. USEPA. Disposal of Sewage Sludge into a Sanitary Landfill. Office of Solid Wastes, Washington, D.C. 20460. SW-71d. 1974.

3. Lukasik, G.D., and J.M. Cormack. "Development and Operation of a Sanitary Landfill for Sludge Disposal - North Shore Sanitary District." North Shore Sanitary District, Waukegan, Illinois. 1976.

4. USEPA. Regulations on Public Participation in Programs Under the Resource Conservation and Recovery Act, The Safe Drinking Water Act, and The Clean Water Act. Office of Waste and Hazardous Materials, Washington, D.C. 20460. 40 CFR 25, 44 CFR 10292. February 16, 1979.

TABLE 19-20

SACRAMENTO REGIONAL WASTEWATER TREATMENT PLANT PROJECTED COSTS OF SLUDGE MANAGEMENT SYSTEM FOLLOWING ANAEROBIC DIGESTION

Item	Costs, thousand dollars		
	Phase I: 1980-1992	Phase II: 1992-1999 additional costs	Total
Capital cost[a]			
Levee/drainage	670	-	670
Blending digester	3,910	-	3,910
Odor-stripping facilities	980	-	980
Solid storage basins (SSBs)	7,810	2,730	10,540
Existing SSB modifications	480	-	480
Barriers and wind machines	1,020	420	1,440
DLD sites	2,480	-	2,480
Electrical and controls	1,640	100	1,740
Wetlands/agricultural land	840	-	840
Landfill	280	-	280
Subtotal, construction cost	20,110	3,250	23,360
Administration, engineering and contingencies[b]	4,840	750	5,590
Land[c]	2,690	-	2,690
Sludge handling equipment	1,150	1,150	2,300
Total, capital cost	28,790	5,150	33,940
Operational cost, annual[d]			
Labor[e]	574	112	585
Materials and supplies[f]	248	25	273
Power and fuel[g]	126	18	144
Site monitoring	30	5	35
Total annual operating cost	978	160	1,138
Annual costs			
Stationary facilities[h]	2,218	359	2,577
Mobile equipment[i]	144	48	192
Land[j]	185	-	185
Operational costs	978	160	1,138
Total annual costs	3,525	597	4,122[k]

[a] Costs based on an ENR cost index of 3900, Sacramento, 1980.

[b] Allowance for administrative and engineering expense, and contingencies. Includes staging allowance for additional work in Stage I to accommodate Stage II.

[c] Land costs are $1,500/acre.

[d] Operational costs are based on estimated 1980 prices for solids loads at the midpoint of each stage, i.e., 1985 for Stage I and 1996 for Stage II.

[e] Total average annual cost per full-time individual of $28,000 in 1980, including all fringe benefits and administrative overhead expenses. (20 1/2 person staff 1985, 24 1/2 person staff 1996).

[f] Materials and supplies include special allowances for flexible hose for DLD operation ($25,000/yr), activated carbon for odor-stripping (11,200 lb/yr) percent allowances for equipment (3 percent), structures (1 percent), and earthwork (1/2 percent) construction costs.

[g] Electrical power projected at 2.9 cents/kWhr and diesel fuel at 80 cents/gal in bulk in 1980.

[h] Amortization at 6 7/8 percent over a 25-yr life.

[i] Mobile facilities have various useful lives. No salvage value assumed.

[j] Land value assumed the same at the end of 20 years.

[k] Weighted average annual total program cost $3,824,000.

1 acre = 0.405 ha
1 kWhr = 3.6 MJ
1 gal = 3.8 l
1 lb = 0.453 kg

5. USEPA. Subsurface Disposal of Municipal Wastewater Treatment Sludge. Office of Solid Wastes, Washington, D.C. 20460. SW-167c. 1978.

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12. Sacramento Area Consultants. Sewage Sludge Management Program Final Report, Volume 5. Dedicated Land Disposal Study. Sacramento Regional County Sanitation District. Sacramento, California 95814. September 1979.

13. USEPA. Comprehensive Summary of Sludge Disposal Recycling History. Office of Research and Development. Cincinnati, Ohio 45268. EPA-600/2-77-054. April 1977.

14. Brown and Caldwell. Preliminary Draft: Colorado Springs Long-Range Sludge Management Study. City of Colorado Springs, Colorado 80947. April 1979.

15. Sacramento Area Consultants. Sewage Sludge Management Program Final Report, Volume 1, SSMP Final Report, Work Plans, Source Survey. Sacramento Regional County Sanitation District. Sacramento, California 95814. September 1979.

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EPA 625/1-79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

Appendix A. Metric Equivalents

U.S. ENVIRONMENTAL PROTECTION AGENCY

Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

September 1979

APPENDIX A
METRIC EQUIVALENTS

METRIC CONVERSION TABLES

Recommended Units

Description	Unit	Symbol	Comments	English Equivalents
Length	meter	m	*Basic SI unit*	39.37 in. = 3.28 ft = 1.09 yd
	kilometer	km		0.62 mi
	millimeter	mm		0.03937 in.
	centimeter	cm		0.3937 in.
	micrometer	μm.		$3.937 \times 10^{-3} = 10^{3}$A
Area	square meter	m^2		10.744 sq ft = 1.196 sq yd
	square kilometer	km^2		6.384 sq mi = 247 acres
	square centimeter	cm^2		0.155 sq in.
	square millimeter	mm^2		0.00155 sq in.
	hectare	ha	The hectare (10,000 m^2) is a recognized multiple unit and will remain in international use.	2.471 acres
Volume	cubic meter	m^3		35.314 cu ft = 1.3079 cu yd
	cubic centimeter	cm^3		0.061 cu in.
	liter	l	The liter is now recognized as the special name for the cubic decimeter	1.057 qt = 0.264 gal = 0.81×10^{-4} acre ft
Mass	kilogram	kg	*Basic SI unit*	2.205 lb
	gram	g		0.035 oz = 15.43 gr
	milligram	mg		0.01543 gr
	tonne	t	1 tonne = 1,000 kg	0.984 ton (long) = 1.1023 ton (short)
Time	second	s	*Basic SI unit*	
	day	day	Neither the day nor the year is an SI unit but both are important.	
	year	yr or a		
Force	newton	N	The newton is that force that produces an acceleration of 1 m/s^2 in a mass of 1 kg.	0.22481 lb (weight) = 7.5 poundals

Recommended Units

Description	Unit	Symbol	Comments	English Equivalents
Velocity linear	meter per second	m/s		3.28 fps
	millimeter per second	mm/s		0.00328 fps
	kilometers per second	km/s		2.230 mph
angular	radians per second	rad/s		
Flow (volumetric)	cubic meter per second	m^3/s	Commonly called the cumec	15,850 gpm = 2.120 cfm
	liter per second	l/s		15.85 gpm
Viscosity	poise	poise		0.0672/lb/sec ft
Pressure	newton per square meter	N/m^2	The newton is not yet well-known as the unit of force and kgf cm^2 will clearly be used for some time. In this field the hydraulic head expressed in meters is an acceptable alternative	0.00014 psi
	kilonewton per square meter	kN/m^2		0.145 psi
	kilogram (force) per square centimeter	kgf/cm^2		14.223 psi
Temperature	degree Kelvin	K	*Basic SI unit*	$\frac{5F}{9} - 17.77$
	degree Celsius	C	The Kelvin and Celsius degrees are identical. The use of the Celsius scale is recommended as it is the former centigrade scale.	
Work, energy, quantity of heat	joule	J	1 joule = 1 N·m	2.778×10^{-7} kw hr = 3.725×10^{-7} hp-hr = 0.73756 ft-lb = 9.48×10^{-4} Btu
	kilojoule	kJ		2.778 kw-hr
Power	watt	W	1 watt = 1 J/s	
	kilowatt	kW		
	joule per second	J/s		

Application of Units

Description	Unit	Symbol	Comments	English Equivalents
Precipitation, run-off, evaporation	millimeter	mm	For meteorological purposes it may be convenient to measure precipitation in terms of mass/unit area (kg/m^3). 1 mm of rain = 1 kg/sq m	
River flow	cubic meter per second	m^3/s	Commonly called the cumec	35.314 cfs
Flow in pipes, conduits, channels, over weirs, pumping	cubic meter per second	m^3/s		
	liter per second	l/s		15.85 gpm
Discharges or abstractions, yields	cubic meter per day	m^3/day	1 l/s = 86.4 m^3/day	1.83×10^{-3} gpm
	cubic meter per year	m^3/yr		
Usage of water	liter per person per day	l/person day		0.264 gcpd
Density	kilogram per cubic meter	kg/m^3	The density of water under standard conditions is 1,000 kg/m^3 or 1,000 g/l	0.0624 lb/cu ft

Application of Units

Description	Unit	Symbol	Comments	English Equivalents
Concentration	milligram per liter	mg/l		1 ppm
BOD loading	kilogram per cubic meter per day	kg/m^3 day		0.0624 lb/cu-ft day
Hydraulic load per unit area; e.g. filtration rates	cubic meter per square meter per day	m^3/m^2 day	If this is converted to a velocity, it should be expressed in mm/s (1 mm/s = 86.4 m^3/m^2 day).	3.28 cu ft/sq ft
Hydraulic load per unit volume; e.g. biological filters, lagoons	cubic meter per cubic meter per day	m^3/m^3 day		
Air supply	cubic meter or liter of free air per second	m^3/s l/s		
Pipes diameter	millimeter	mm		0.03937 in.
length	meter	m		39.37 in. = 3.28 ft
Optical units	lumen per square meter	lumen/m^2		0.092 ft candle/sq ft

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