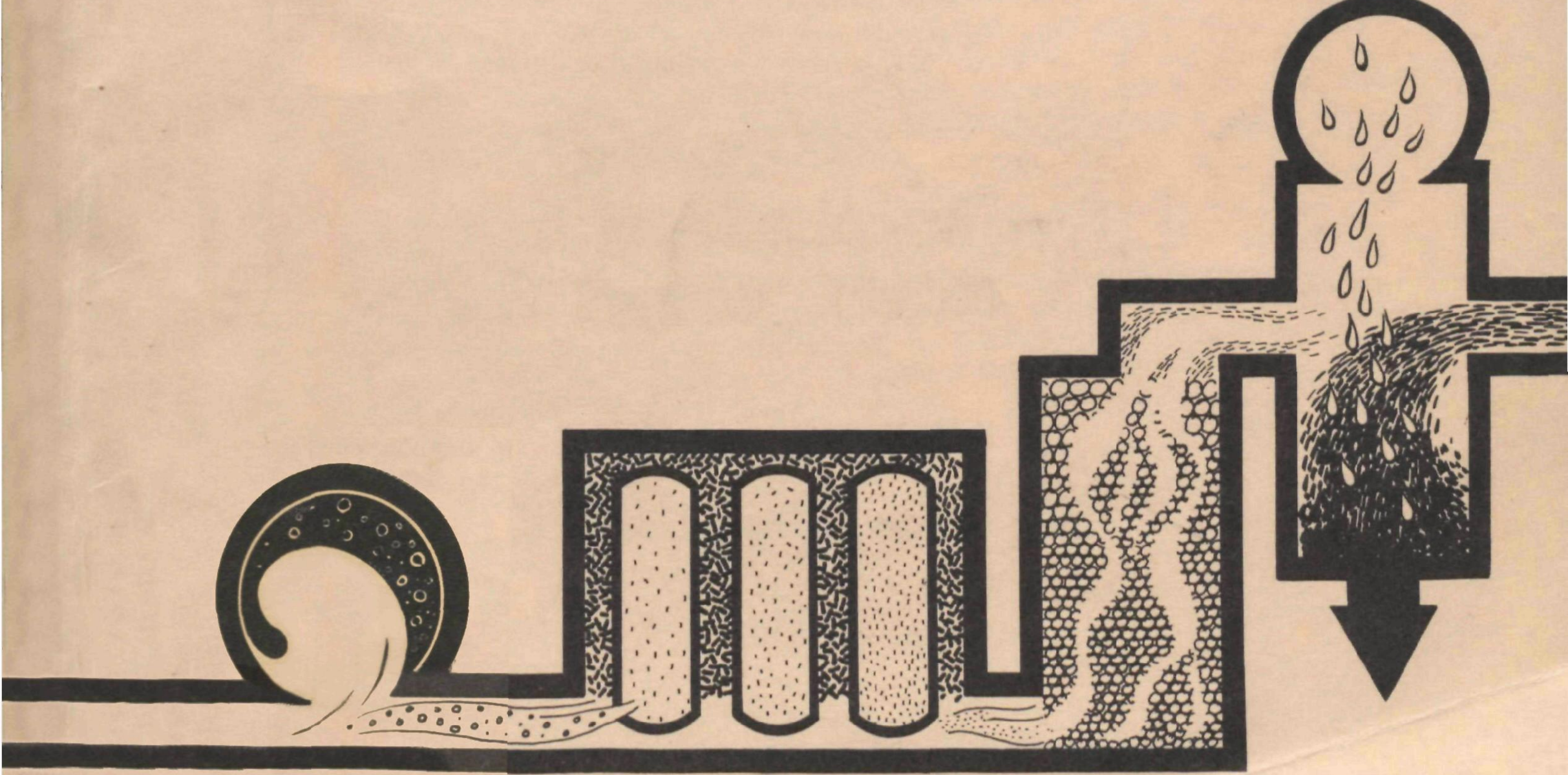
WATER POLLUTION CONTROL RESEARCH SERIES • 17070DIV 04/70

STATE OF THE ART REVIEW ON SLUDGE INCINERATION PRACTICE



U.S. DEPARTMENT OF THE INTERIOR • FEDERAL WATER QUALITY ADMINISTRATION

WATER POLLUTION CONTROL RESEARCH SERIES

The Water Pollution Control Research Reports describe the results and progress in the control and abatement of pollution of our Nation's waters. They provide a central source of information on the research, development, and demonstration activities of the Federal Water Quality Administration, Department of the Interior, through in-house research and grants and contracts with Federal, State, and local agencies, research institutions, and industrial organizations.

Water Pollution Control Research Reports will be distributed to requesters as supplies permit. Requests should be sent to the Planning and Resources Office, Office of Research and Development, Federal Water Quality Administration, Department of the Interior, Washington, D. C. 20242.

Errata

STATE OF THE ART REVIEW ON SLUDGE INCINERATION PRACTICE

WATER POLLUTION CONTROL RESEARCH SERIES 17070 DIV 04/70

Prepared for the Federal Water Quality Administration*
U. S. Department of the Interior

April, 1970

*Now Part of the Environmental Protection Agency

1. On Figures 11, 12, and 13, the ordinates are too high by a factor of ten.

2. On page 42, reference is made to a paper by Owen[1] inferring that Owen recommended use of the DuLong formula. The authors may have obtained this impression from the report, "Sludge Handling and Disposal"[2], where Owen is inadvertently misquoted. Actually, Owen recommended against use of the formula but suggested that heating value be determined in a bomb calorimeter.

   A check of limited data reveals that the standard deviation of the difference between the calorimeter heating value and the value calculated by the DuLong formula is about 5 percent. This result indicates that the DuLong formula gives a reasonably good approximation to the calorimeter value. Nevertheless, it should be made clear that Owen did not recommend use of the DuLong formula.

3. It appears to this writer that the material on pages 50-61 applies to fluidized bed incineration. It should not be presumed to apply to other types of incinerators except in a general sense.

4. On page 50 (see also pages 51, 56, 64), the statement is made that the minimum deodorizing temperature for conventional incineration units has been established at 1350°F to 1400°F. Figure 17 is given in support of this statement with no reference to its source.

   Figure 17 was taken from an article by Sawyer and Kahn[3]. Sawyer[4], in a communication to principal manufacturers of sludge incinerators, observed that it had come to his attention that the results reported in this paper were being quoted out of context. He pointed out that in their tests, time of exposure to the temperatures indicated was 0.7 second, and that longer contact times would undoubtedly reduce the minimum deodorizing temperature.

   The emphasis placed in this State of the Art Review on the need to have exit gas temperatures of at least 1350°F is in the view of this writer, unwarranted. Numerous multiple hearth incinerators are operated at much lower temperatures without complaints of odors. For example, the sludge incinerator at South Lake Tahoe is operated at an exit gas temperature in the vicinity of 700°F to 800°F and there have been no complaints of odors.

   The question of odor is frankly considered in a discussion of a paper presented by Sebastian and Isheim at the 1970 Incinerator Conference[5]. Isheim presents an explanation for the lack of odor when sludge is burned in a multiple hearth incinerator. His explanation is similar to that given by Owen[1]. He acknowledges that some odorous materials might leave the incinerator and be removed in the wet scrubber. He makes the very convincing point that he knows of many installations provided with afterburners, but that he does not know of any such sludge incinerators where the afterburners are actually used.

The nature of the gas-solid contact in a multiple hearth incinerator makes it reasonable to think that the stack gases can be odorous if the gases leaving the incinerator are between 700-800°F. As a result of the foregoing, this writer is convinced of two things: (1) the possibility of odor production under these conditions can never be categorically rejected, and (2) odor-free incineration under these conditions can generally be accomplished.

J. B. Farrell, Ph.D.
Chemical Engineer
February 2, 1971

References

(1) Owen, M. B., J. Sanit. Eng. Div., Proc. A.S.C.E., 1172-1 to 1172-27 (Feb. 1957), "Sludge Incineration".

(2) Burd, R. S., "Sludge Handling and Disposal", U. S. Dept. Interior, FWQA (Now EPA), Pub. WP-20-4, May 1968.

(3) Sawyer, C. N., and Kahn, P. A., JWPCF, 32, No. 12, 1274-1278 (Dec. 1960), "Temperature Requirements for Odor Destruction in Sludge Incineration".

(4) Sawyer, C. N., Memorandum to Bartlett-Snow-Pacific, Combustion Engineering, Dorr-Oliver, Nichols Engineering and Research (Oct. 26, 1966).

(5) Sebastian, F. P., and Isheim, M. C., "Advances in Incineration and Resource Reclamation", Discussion by J. B. Farrell and Response by M. C. Isheim, pp. 15-16 in "Discussions, 1970 National Incinerator Conference", pub. Am. Soc. Mech. Engrs., N. Y.

STATE OF THE ART REVIEW ON SLUDGE INCINERATION PRACTICE

by

S. Balakrishnan, Ph.D.
D. E. Williamson, P.E.
R. W. Okey, P.E.

Resource Engineering Associates
Wilton, Connecticut 06897

for the

FEDERAL WATER QUALITY ADMINISTRATION

DEPARTMENT OF THE INTERIOR

Program #17070 DIV
Contract #14-12-499
FWQA Project Officer, B. V. Salotto
Advanced Waste Treatment Research Laboratory
Cincinnati, Ohio
April, 1970

FWQA Review Notice

This report has been reviewed by the Federal Water Quality Administration and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Federal Water Quality Administration, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $1.25

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

ABSTRACT

This report on the "State of the Art Review on Sludge Incineration Practice" covers the current status of the incineration art and the cost of incineration. An up-to-date critical review of the effect of sewage character, methods of capturing and concentrating solids--including the sludge conditioning--and sludge incinerator systems are presented. This report also includes the primary considerations in the design of incinerators, the attitudes of state agencies and consulting engineers. The principal areas of discussion are: sludge thickening, sludge conditioning, sludge dewatering, sludge incinerator systems and the design and operation of incinerators.

The report concludes that:

1. Increasing pressures for complete or nearly complete "on site" disposal of solids are building up when compared to conventional sludge digestion and disposal on land.

2. The necessary pretreatment steps such as sludge dewatering and blending and their costs and operational aspects could be improved for benefits.

3. There are a number of sludge incinerator systems commercially available and an appraisal of the capital and operating costs of each type of system, as well as the cost of pretreatment, should be considered in selecting a system.

4. Incineration of materials other than municipal sludge with the sewage sludge could be used for the effective disposal of the mixture.

5. New approaches to the problem of sludge disposal are needed and additional research into the practical aspects of sludge treatment should be encouraged.

This report was submitted in fulfillment of Program No. 17070 DIV, Contract No. 14-12-499, between the Federal Water Quality Administration and Resource Engineering Associates.

SUMMARY

Sanitary engineering practices in the United States have followed markedly conventional patterns since waste management first became an essential municipal function. Even though there is little change over an accepted process, the one waste management operation that is undergoing gradual but substantial change is solids handling and disposal.

The accepted procedure for the disposal of solid wastes has been direct or indirect disposal to the ground. Such practices are becoming less acceptable for a variety of reasons and, presently, pressures are building up for complete disposal of solid wastes. Sludge should be considered a liability rather than an asset to any waste management; there is no known technique for making a profit on its collection and treatment. A system that is acceptable to all parties and the most economical is generally preferred.

Considerable developments in sludge disposal procedures have taken place and sludge handling and disposal is receiving more attention than in the past. It should be recognized that sludge handling and disposal is a costly operation and it represents 25 to 50 per cent of the total capital and operating cost of a wastewater treatment plant. The problem of sludge handling is the most annoying and is growing. It has been estimated that the volume of waste sludge will increase 60 to seventy per cent within the next 15 years.

Sludge handling processes such as incineration and heat drying require pretreatment of sludge. The pretreatment steps include grit removal, blending, thickening, conditioning and dewatering. Grit removal is a necessary step as it protects the pumps and other mechanical equipment against plugging, wear and tear. Also, it helps by increasing the heat value of sludge by increasing the volatile content of sludge. When different types of sludges are handled, blending of sludge improves the economic operation of the thickening, dewatering and incineration processes. When chemicals are used, the blending of sludge permits more efficient use of chemicals due to a predictable demand for chemicals.

Sludge thickening reduces the volume of the sludge to be handled in addition to equalization and concentration of different sludges. Reduction in sludge volume results in savings due to the reduction of plant size, labor, power and chemicals. Sludge thickening is accomplished in any one of the processes such as gravity thickening, flotation thickening and centrifugation.

The sludge conditioning methods primarily aim at the reduction of bound and surface water quantities and these include: heat treatment, chemicals, polymers and some unconventional methods such as

solvent extraction, artificial freezing and sonic vibration. Sludge dewatering processes include: centrifugation, vacuum filtration, plug presses and filter presses. Reduction of sludge moisture content to the extent of about 75% is achieved in these dewatering processes so that the fuel requirements for sludge incineration can be minimized.

The heat value of sludge depends on the amount of combustible elements such as carbon, hydrogen and sulfur present in the sludge. When chemicals are used in the pretreatment steps, the weight of the sludge increases by about 10% and, because of their inert nature, the heat content of the sludge is reduced.

The various incineration processes are discussed under sludge incineration systems in detail including their performance and operational problems. The present state of the art on sludge incineration is that it is generally more expensive than other sludge disposal systems. The capital and operating cost of incineration systems depends on the type and size of incinerator, nature and amount of sludge, and whether deodorization, dust collection and disposal are included. Supplemental fuels are invariably required for sewage sludge incineration but their requirements fluctuate depending on the characteristics of the sludge and these are reflected in the operating costs.

Based on a survey conducted on the attitude of consulting engineers on sludge incineration, the following are presented:

1. The overall attitude of consulting engineers is acceptance and even eagerness to employ incineration. Also, there is no evidence of emotional bias against the incineration.

2. The bulk of the engineers prefer incinerators for populations over 15,000. Multiple hearth and fluidized bed type incinerators are the preferred ones when compared to the others.

3. High capital and operating costs of incinerators, the cost of pretreatment steps, and air pollution problems are the major factors mitigating against incineration.

4. The consultants feel, universally, that greases, oils, screenings, and organic industrial wastes could best be disposed of by incineration.

INTRODUCTION

Sludge disposal is rapidly becoming one of the most important factors to be considered in the design of new plants and expansion of existing systems to meet increasing population and industrial pollution loads. The cost of the conventional digestion system constitutes a significant portion of the total cost of treatment plants and yet digestion does not provide for the maximum reduction nor the ultimate destruction of the remaining waste organic solids. Further, anaerobic reactors are extremely difficult to operate and frequently cause as many problems as all the rest of the plant combined.

It has become increasingly difficult since World War II to sell, give away or dump raw or partially dried sludges. Conventional methods of disposal such as dumping into lagoons, drying beds or land fills have become expensive even though they are not the most satisfactory methods of disposal. Attempts to sell treated and enriched sludge as a fertilizer or soil conditioner have met with failure or very limited success. Hence, there are pressures to find alternate procedures for sludge conditioning and disposal which involve easier sludge handling and less troublesome operation than anaerobic treatment.

There are other pressures which are derived from our society and the way it is changing and growing. First, the quantity of sludge will increase by some 60 - 70% by 1980, due both to the increase in population and in the degree of treatment requiring large areas for land disposal. Secondly, the factors mitigating against ground disposal will increase because of mounting desires to avoid the indiscriminate disposal of waste due to aesthetic and health reasons. Thirdly, sludge handling by the older techniques frequently represents twenty - 40% of the capital and operating cost of the treatment plant. These methods were evolved when labor was cheap and the situation now is dramatically different. Now, more sophisticated operational techniques requiring less labor are being evolved.

The on-site disposal of sludge is compatible with all these driving forces and combustion seems to be the only practical means presently known that can accomplish maximum reduction of waste solids. The new combustion methods have renewed the interest in investigating means other than digestion for total sludge disposal and, also, it is expected that future improvements in the sludge combustion practices will reduce costs even further. Also, complete conversion of the wastes into innocuous gases and inert solids is feasible by combustion to meet the tight air and water pollution control laws. Thus, the incineration of the sludge is able to meet the ultimate goal of the efficient disposal of solid waste material without causing air or water pollution or other nuisances to the community.

The present trend seems to be away from digestion on account of the increased capacity required owing to increased use of detergents and toward dewatering in vacuum filters or pressure filters and disposal of the sludge cake on land directly or after composting with ground-up refuse. There is increased interest in the country in refuse incineration and these sytems may be utilized to incinerate the sludge cake together with the refuse.

PRIMARY CONSIDERATIONS

Solids Production

The characteristics of the domestic sewage and the type of treatment received have a great influence on the build up of solids. The solids in the domestic sewage are in two major forms: suspended and soluble. The suspended solids fraction (60% settleable and 40% colloidal) equals 0.20 to 0.25 lb/cap./day, and the soluble fraction equals 0.30 to 0.35 lb/cap./day. Thus, the total dry solids in the domestic sewage ranges from 0.5 to 0.6 lb/cap./day.

In the primary treatment without coagulants, about 50 - 60% of the suspended solids and 30 - 35% BOD are removed. In the secondary treatment, most of the soluble BOD (up to 90 - 95%) is removed and converted to biological solids. In an activated sludge treatment process, the sludge build up can be estimated by the following relationship:

$$\text{sludge build up (lbs)} = aLr - b\,Sa$$

where: a = sludge synthesis coefficient
Lr = lb of BOD removed in the secondary process
Sa = lb of volatile biological solids under aeration
b = endogenous respiration rate

The solids production for primary and secondary plants is shown in Figure 1.

Characteristics of Sewage Solids

The composition of sewage sludges varies widely depending on a complexity of factors. Primary sludges are higher in caloric value than biological sludges because of their high grease content. It is more economical to burn undigested solids than the digested solids since digestion significantly reduces the heat content of the remaining solids.

The average characteristics of sewage solids as described by Owen[1] are summarized in Table I.

Sludge ratios of primary to secondary are generally 8 - 10 to 1 to insure aerobic conditions in the thickener. The primary to secondary sludge ratio directly affects both dewaterability and heat value of the sludge. Experience[2] shows that primary plus trickling

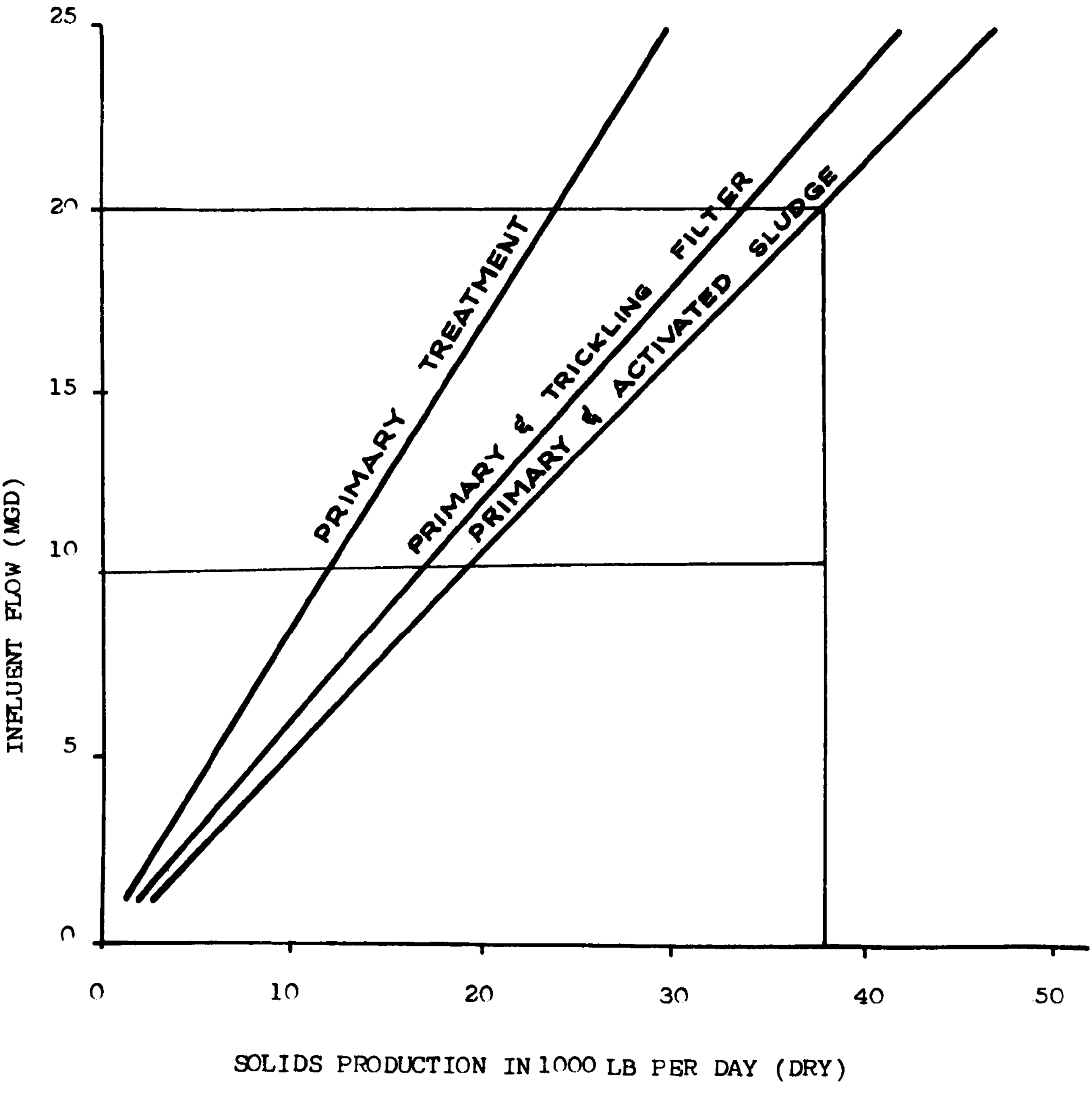


FIGURE 1

COMPARATIVE SOLIDS PRODUCTION FOR PRIMARY AND SECONDARY PLANTS

TABLE I

AVERAGE CHARACTERISTICS OF SEWAGE SLUDGE

Material	Combustibles (%)	Ash (%)	BTU/lb
Grease and scum	88.5	11.5	16,750
Raw sewage solids	74.0	26.0	10,285
Fine screenings	86.4	13.6	8,990
Ground garbage	84.8	15.2	8,245
Digested sewage Solids and ground garbage	49.6	50.4	8,020
Digested sludge	59.6	40.4	5,290
Grit	30.2	69.8	4,000

filter sludge will produce about 7% solids in the thickener and dewater to about 25% solids, whereas primary and activated sludge will thicken to 5% solids and dewater to 22% solids. The difference in terms of auxiliary fuel costs is between $2 - $3 per ton of dry solids.

Degritting

Grit can be described as small inorganic solids that are removed from the wastewater after screening and include sand, silt, gravel, ashes, coffee grounds and like substances. Grit volume is relatively smaller when compared to other solids collected in the treatment processes but their characteristics are such that they plug, wear out and even break pumps and other mechanical equipment. Further, they affect the heat value of the sludge to be incinerated considerably by decreasing the volatile content per pound of sludge.

Removal of grit in the conventional grit chambers is achieved to levels up to about 80 - 90% of 45 - 65 mesh material and this amounts to an average of 4 cubic feet of grit per million gallons of sewage[3]. Hence, a very efficient degritting device has to be employed to improve the volatile content of the sludge. Hydrocyclones have been used for this purpose and they remove 95% of the plus 200 - 270 mesh inorganics at a specific gravity of 2.65 and increase the volatile content of the sludge from 70 - 75% to 80 - 85%.

Sludge Blending

When disposing of sludge by incineration, different types of sludges such as primary, secondary and digested sludge must be handled. Blending of sludges is an essential and important step as it gives a uniform mixture for the efficient and economic operation of the sludge thickening, sludge dewatering and incineration operation.

Blending is usually done before the mechanical dewatering and incineration steps in primary clarifiers by recycling secondary sludges. The mixing and blending of the different types of sludges is aided further by sludge collecting mechanisms and picket thickening devices. Mechanical mixing and air agitation in storage tanks provide good blending but cause air pollution problems due to the liberation of gases and the subsequent odor nuisance. This could, however, be overcome by covering the tank. Air agitation has been found to be better than mechanical mixing as it freshens sludge and lowers filtration costs. Vigorous agitation must, however, be avoided to prevent deflocculation of the sludge which would increase the cost of dewatering.

When chemicals are to be used for improving the dewatering characteristics of sludge, blending of the sludge permits the more efficient use of chemicals as the blended sludge has a predictable and uniform demand for chemicals.

PRETREATMENT - SLUDGE THICKENING

This section includes sludge thickening, sludge conditioning by heat and chemicals and mechanical dewatering processes such as filtration, centrifugation and pressing.

Sludge thickening is practiced for equalization and concentration of primary and/or secondary sludge. Thickening helps reduce the volume of liquid sludge to be handled in the subsequent processes. Reduction in the volume of sludge brings about savings due to the reduction in physical plant size, labor, power and chemicals.

The initial composition of the raw wastes and the method of wastewater treatment are important factors that affect the degree of concentration of sludge. The other factors that affect the thickening process include: initial concentration of sludge, the size, shape and density of the particles, the temperature and age of the sludge and the ratio of organics to inorganics. The biological flocs are bulky and concentrated to a lesser extent than raw primary sludge. Better thickening is achieved in separate units than in the initial wastewater clarification units.

Sludge thickening is accomplished in one of the three processes:

1. Gravity thickening

2. Flotation thickening

3. Centrifugation

Even though flotation and centrifugation produce higher percentage of solids than the gravity thickening, they are comparatively expensive.

Gravity Thickening

Gravity thickening is the most common type of sludge concentration. Even though it does not produce as high a solids concentration as other thickening processes, it is a simple and inexpensive method. Thickening is generally achieved in two ways. One method is to provide a deep primary clarifier where primary solids are collected and secondary sludge recycled and resettled. As far as the fixed equipment costs are concerned, this is a least expensive method. Another method is to provide a separate thickener to collect the primary and secondary sludges. This method generally includes cyclones for grit removal and a sludge disintegrator to insure uniform sludge consistency.

The theory of gravity thickening has been presented by Mancini[4] in an exhaustive manner and is not included in this report for the sake of brevity. Studies by Kynch, Fitch, Talmadge and others[5,6,7] developed design parameters for the design of thickeners. Thickeners are designed on a lb dry solids/ft^2-day and the values are the generally recommended values for sewage sludges:

Primary sludge	22 lb/ft^2-day
Primary + trickling filter sludge	15 lb/ft^2-day
Primary + waste activated sludge	8 - 12 lb/ft^2-day
Waste activated sludge	4 lb/ft^2-day

Mixing of the primary and secondary sludge and/or digested sludge is desirable as secondary sludges release their water slowly and the mixtures respond well to thickening. Sludge ratios of primary to secondary are generally 8 - 10 to 1 to insure aerobic conditions in the thickeners. The primary to secondary sludge ratio directly affects the dewaterability and heat value of the sludge. The septicity and gasification interferes with optimum solids concentration and this can be prevented by using chlorine at a dosage to produce a residual of 0.5 to 1.0 mg/l. Excessive chlorine dosage disperses biological sludges and, therefore, overdosing must be avoided. Thickeners are circular and about 15 feet deep for better performance. A minimum detention of 6 hours and an overflow rate of 400 - 800 gal./ft^2-day are recommended.

To enhance the degree of sludge thickening and reduce odor nuisance, chemicals and heavy inert agents are used. Rudolfs[8] observed that alum and ferric salts did not improve sludge concentrations appreciably even after 24 hour compaction. Sulfuric acid, at a dosage of 600 - 1000 mg/l, was found to improve the compaction but the cost was prohibitive. Lime, at dosages of 250 to 500 mg/l, significantly increased the sludge compaction. Inert agents such as iron oxides, flyash and diatomaceous earth improved the compaction but only at high dosages.

Use of organic polyelectrolytes as aids to sludge thickening has been found to be very successful. Higher dosages of polymers produce higher degrees of compaction but increase the settled solids concentration. Filtrate from the vacuum filtration units containing residual polymers or inorganic flocculent are found to produce beneficial results when it is returned to the thickening tank.

Sludge blanket thickness in a thickener is an important parameter as it affects the ultimate solids concentration. Sludge blanket depths beyond 3 feet did not seem to increase the solids concentration[9] whereas it was found that underflow solids concentration decreased as the depth of the compression zone increased[10]. This may be due to the increase in the resistance to the flow of water from the sludge blanket. Further, sludge at greater depths becomes septic, produces gas and a bulky sludge which is not very conducive for sludge settling. Increased detention time of solids in the sludge blanket increases the ultimate solids concentration but a period of 24 hours is suggested for maximum compaction[10].

The degree of compaction depends on the type of sludge, and gentle agitation helps the compaction. Many attempts have been made to improve the compaction and one such is the use of pickets with the sludge collection mechanism. The pickets are vertical members that move through sludge blanket and create passages for entrained water and gas to reach the surface as well as aid agglomeration.

The total annual operating costs (capital and operating) for gravity thickening vary from $1.30 to $5.00 per ton of dry solids depending on the size of the plant and the local conditions. Gravity thickening has a future in the handling of wastewater solids and offers a good way to thicken mixed sludges at a low operating cost.

Flotation Thickening

Flotation is best applied to thickening aerobic biological sludges, especially activated sludge because of higher solids concentration and lower initial cost of equipment. Primary sludges and combinations of primary and trickling filter sludges are more economically thickened by gravity.

There are four methods of flotation, as listed below:

1. Dispersed air flotation where bubbles are generated by introducing air through an impeller or porous media.

2. Dissolved air-pressure flotation where air under higher pressure is put in solution and later released at atmospheric pressure.

3. Dissolved air-vaccum flotation in which a vacuum is applied to wastewater aerated at atmospheric pressure.

4. Biological flotation where the gases formed by natural biological activity are used to float solids.

Dissolved air-pressure flotation is the route very often used compared to the others. The biological flotation is used only at a few sewage treatment plants because of the limited advantages. The dispersed-air flotation and dissolved air-vacuum flotation are more applicable to wastewater clarification than thickening because appreciable increases in sludge concentrations are difficult to achieve.

Dissolved air-pressure flotation is used for the separation and concentration of sludges. The waste flow or a portion of clarified effluent is pressurized to 40 - 60 psi in the presence of sufficient air to approach saturation. When this pressurized air-liquid mixture is released to atmospheric pressure in the flotation unit, minute air bubbles are released from solution. The sludge flocs and suspended solids are floated by these minute air bubbles which attach themselves to and become enmeshed in the floc particles. The air-solids mixture rises to the surface where it is skimmed off.

The major variables for flotation thickening are:

1. Pressure

2. Detention period

3. Air-solids ratio

4. Feed-solids concentration

5. Solids and hydraulic loading rates

6. Type and quality of sludge

7. Recycle ratio

8. Use of chemical aids

Increased air pressure produces greater float solids concentration and a lower effluent suspended solids concentration. Higher air pressure breaks up fragile flocs and, therefore, an upper limit of 60 psi is used. The recycle of clarified effluent allows a larger quantity of air to be dissolved because there is more liquid which dilutes the feed sludge. Recycle ratios of 40% have been found to be the optimum[11] by the Chicago Sanitary District.

The concentration of sludge increases with the increase in detention period up to 3 hours[12]. Beyond 3 hours, no additional thickening was observed. Air-solids ratio influences the floated solids and effluent solids concentration. With the increase in air-solids ratio, an increase in floated solids was observed and a ratio of 0.02 pound of air per pound of solids was very effective[13]. Effluent solids concentration was found to be independent of the air-solids ratio[11] except for very low air input rates or very high solids loading rates. Variation in influent solids concentration would alter the air-solids ratio and frequently cause process upset.

Flotation thickening is especially applicable to a mixture of primary and activated sludges. Design of thickeners is based on rise rates and these usually range from 1.5 to 4.0 gpm/ft^2. A typical relationship between unit loadings, solids production and recovery of floated solids as observed in Chicago Sanitary District[11] is shown in Figure 2.

Cationic polyelectrolytes, long-chained high molecular weight polymerized organic coagulants, are most often employed as flotation aids to increase the float solids recovery to as high as 97%. The use of polyelectrolytes is justified economically because of their higher activity and subsequent advantages. The normal dosages range from 1 - 5 lb/ton of dry solids and the cost of polyelectrolytes is in the order of $1 - $5/ton of dry solids. Flotation without aids generally results in solids concentrations about 1% less than with flotation aids.

Rudolfs, while looking for a chemical that would flocculate and dehydrate solids, found that calcium hypochlorite was very effective at a dosage of 364 lb/ton and increased the solids concentration from 1.05 to 3.75% after 6 hours of compaction.

For normal activated sludges, 4% solids concentration (by weight) is specified as the minimum for design purposes. Attaining five to 6% solids is generally possible and further concentration can be achieved in a holding tank. A solids loading of 2 lb/sq ft per hour is used for the design of flotation units.

The flotation thickener is normally a prefabricated steel unit furnished complete with skimming device, drive unit, adjustable overflow weir, inlet assembly, recirculation pump, retention tank, flow meters and pressure-reducing valve.

The initial capital cost for flotation is lower than gravity thickening but the operating cost is higher. The operating cost of flotation thickening without aids is between $4 and $5 per ton dry solids and with aids it is between $9 and $11 per ton dry solids. The total annual cost (including amortization) of air flotation thickening is between $6 to $15 per ton of dry solids.

Flotation processes are not as simple, consistent or economical as compared to other thickening processes. However, for thickening waste activated sludge or low specific gravity, non-activated industrial sludge, flotation is very attractive.

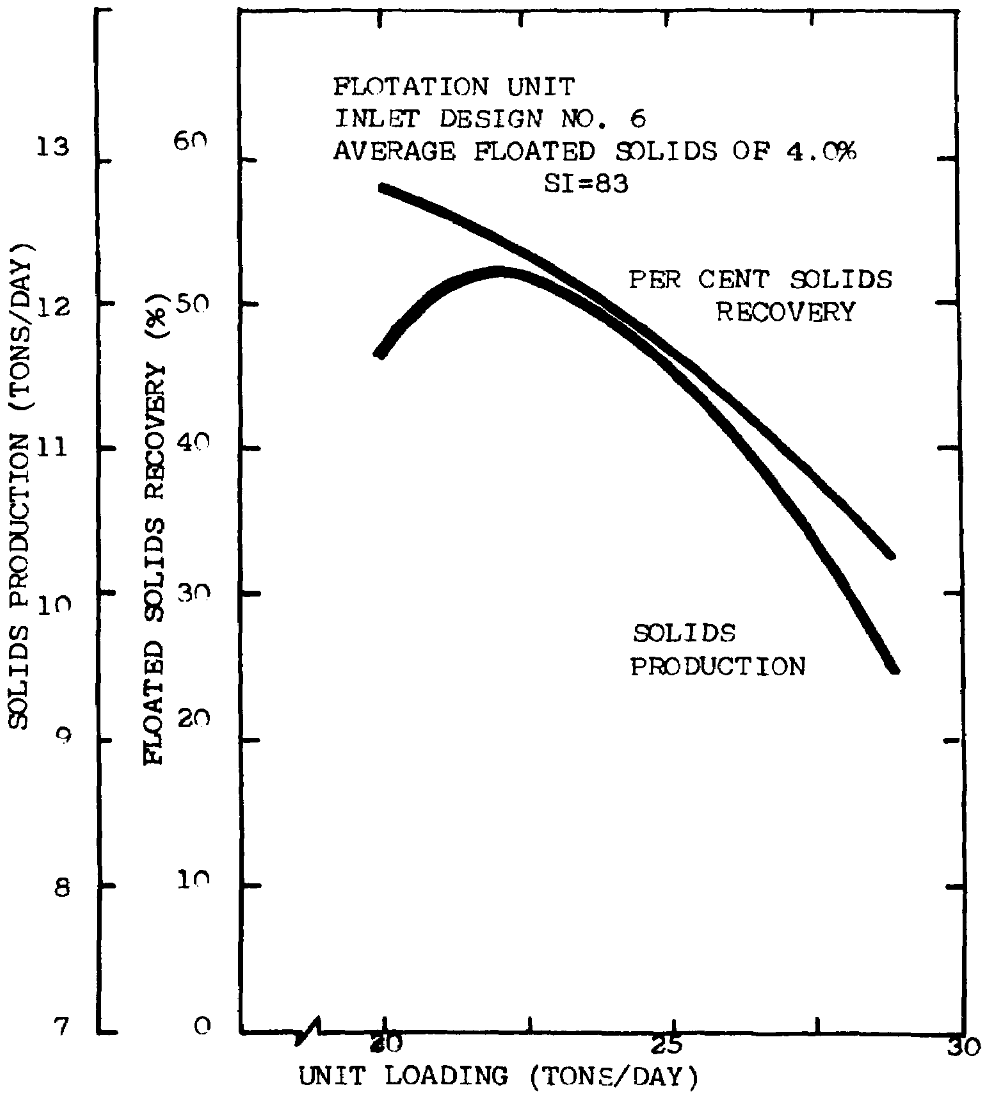


FIGURE 2

EFFECT OF LOADING ON FLOATED SOLIDS PRODUCTION AND RECOVERY

Natural biological flotation is successfully used to concentrate raw sludge at a few sewage treatment plants. Improvements on this natural flotation technique is achieved by the Laboon process[14] where control over temperature and detention could be asserted. The heating of the sludge to 95° F is accomplished in heat exchangers operated at 15 psi following the disintegration of the raw primary sludge. Concentration of sludge in tanks is achieved by biological means for 5 days and the escaping gases buoy and compact the sludge.

The Laboon process is being used to thicken raw primary and waste activated sludge at Charlotte, North Carolina[15]. The sewage treatment plant at Ashland, Ohio, thickens sludge to 15% by biological flotation without heat. The Laboon process at the Allegheny County treatment plant, Pennsylvania, produced an average sludge concentration of 18% from a feed sludge of 10.7%.

The biological flotation process is fairly expensive because of the sludge heating, the lengthy detention period and the need to blend sludges to be used as a feed to the incinerators. The mechanical dewatering step ahead of sludge incineration can be eliminated as is done in Ashland, Ohio, and Pittsburgh, Pennsylvania. When raw sludge thickening is practiced, there is a possibility of odor development and secondary sludges do not respond well to the treatment. Thus, biological flotation as a sludge concentration technique seems limited unless improvements are made in the process. Use of chemical additives and/or waste heat from incineration units can make the process less expensive and more efficient.

Centrifugation

Centrifugation is generally used for dewatering rather than for thickening. The thickened sludge from centrifugation is in a fluid stage that could be pumped. Centrifuges are a compact and flexible unit. The capital cost is relatively low but the operation and maintenance costs are high. Solids capture efficiency is very poor when chemicals are not used. On the whole, there are more advantages than disadvantages and, therefore, with the recent improvements in machine design, centrifugation will become more popular for thickening of primary sludges.

For activated sludge thickening, centrifugation is not as attractive, whereas flotation thickening would seem to be better suited. However, when chemicals are required in the flotation operation but not in centrifugation, centrifugation may be less expensive. Chemicals, when used in centrifugation, could cost $4 to $10 per ton.

A solid-bowl centrifuge[9] thickened a feed from 2.5 to 6% and the machine operating parameters were:

average speed - 2300 rpm

pool depth - 2-1/8 in.

Solids capture averaged from 85 - 97%. The relationship between solids recovery and concentration is shown in Figure 3.

Centrifugal thickening was used very successfully at the Yonkers sewage treatment plant of Westchester County, New York. Here, the digested and primary sludges are thickened prior to ocean barging.

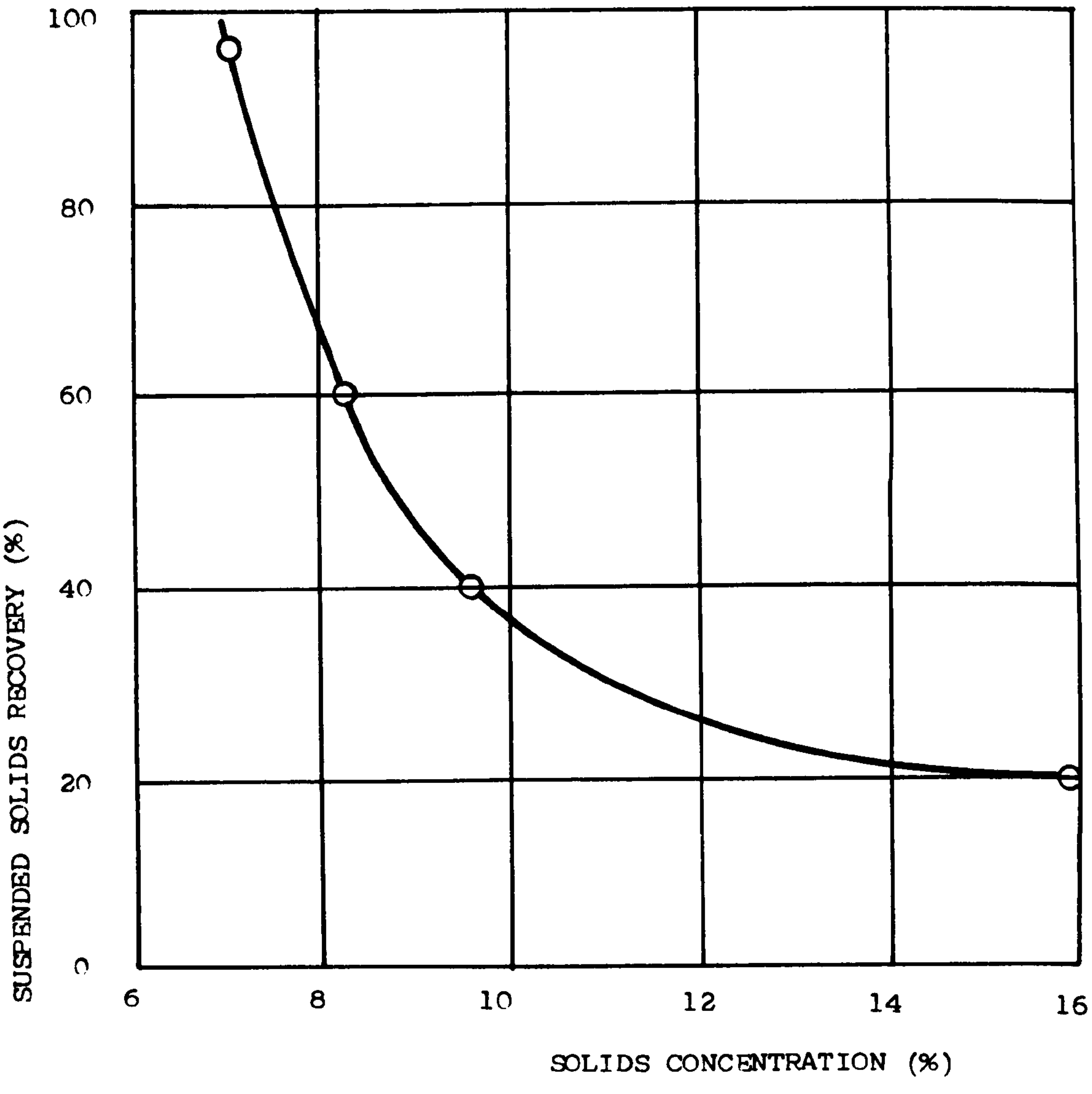


FIGURE 3

DECREASE IN RECOVERY WITH CORRESPONDING INCREASE IN SOLIDS CONCENTRATION FROM LOWERING LIQUID LEVEL IN CENTRIFUGE-ACTIVATED SLUDGE

PRETREATMENT - SLUDGE CONDITIONING

A typical biological sludge particle contains a large quantity of water. This water is contained within the cell as cell water, around the cell as bound water, and around the bound water as surface water. The total weight of water (cell water, bound water and surface water) is about 8 to 12 times the weight of the dry solids in the cell and the break up of this figure is as shown below:

cell water - 2 to 3 times that of dry solids

bound water - 4 to 6 times that of dry solids

surface water - 2 to 3 times that of dry solids.

Thus, it could be seen that a concentration of solids of about 8 to 12% can be achieved without the use of chemicals.

When chemicals are added, the bound and surface water quantities will be reduced due to coalescence and subsequent reduction in surface area. It is possible to concentrate the sludge to about 15% with the use of chemicals and the chemical cost is in the range of $15 - $30 per ton dry solids.

When the sludge is heated, the cell wall is broken and the contents leak out. In addition, hydrolysis of the bound water structure occurs. The surface water is also reduced in proportion to the remaining area of the cell wall. With all these reductions, the net effect is that the solids could be concentrated to 40 - 55% solids range by conventional dewatering methods.

In the following paragraphs, the sludge conditioning by heat treatment, chemical and polymer addition methods is discussed and analyzed.

Heat Treatment

When colloidal gels are heated, thermal activity causes water to escape from the ordered structure. This phenomenon, known as syneresis, has been shown to be effective in dewatering municipal sewage sludge by many researchers[16,17,18]. The heat treatment of sludge conditions the sludge for easy and efficient handling in drying, incineration and wet combustion of sludge. Easier handling of the sludge has implications to the design, costs, and operation of sludge disposal plants in the United States. The conditioning of the sludge by heat treatment would result in a saving in labor, space and treatment costs. An additional advantage of heating the sludge is that all the organisms are killed and the sludge so treated can be handled without health hazard or special precaution. The sludge from this process can either be dried and used as a totally nonpathogenic fertilizer or land fill, or used in its wet condition as a fuel in a heat recovery system.

The British have built three plants in 1939 and 1946[16,17,18]. A plant for heat treating sludge built in Switzerland in 1965 has provided a better economic base due to the use of improved technology[19]. A porteous plant has recently been built at Colorado Springs, Colorado, while several low-pressure Zimpro units (see section on Incineration) are also in operation. With the advent of organic flocculating compounds, improved filtration technology, and modern heat exchange equipment, it appears that heat treating of U.S. domestic sludge would find widespread acceptance.

The stability of a colloidal system such as sludge is governed by two important surface phenomena: electrostatic repulsion and hydration. A colloidal gel system is a homogenous mass and when heated, the velocity of the particles increases and overcomes the electrostatic repulsion resulting in the collapse of a gel structure. This decreases the hydration and water affinity of the solids.

Heating of the sludge has been shown to increase the filtration rate of domestic sewage sludge by many folds[16,17,19,20]. The filtration has been found to improve appreciably when the temperature was in excess of 130° C. Complete breakdown of the colloidal structure occurs when the temperature is raised between 160 and 190° C and held for 10 to 45 minutes[16,17]. This resulted in a sludge that was 200 to 1000 times more filterable than untreated sludge and 15 to 50 times more filterable than chemically conditioned sludge. The following data, given in Table II, show the relative dewatering rates of sludge conditioned by different agents.

While a holding time of about 20 minutes at a temperature of 170° C produced greatest filterability for raw primary sludge[21], a holding time of 30 minutes at a temperature of 180° C was required for secondary sludges to produce the same relative rate of dewatering. Higher temperatures and longer holding times did not improve the dewaterability of the sludge appreciably. It was also found that heat treatment solubilized a small fraction of the solid matter of the sludge and the bulk of the organic nitrogen of the sludge[22].

Using the heat treatment concept of sludge handling, two commercial processes have been developed and these are described below.

1. Porteous Process

TABLE II

RELATIVE DEWATERING RATES OF SLUDGE CONDITIONED BY DIFFERENT CONDITIONING AGENTS

Conditioning Agent	Relative Dewatering Rates: Primary Sludge	Relative Dewatering Rates: Secondary Sludge[1]
None	30	1
Sulfuric acid[2]	100	2
Aluminum sulfate[3]	200	10
Ferric sulfate[3]	300	15
Ferric chloride[3]	400	20
Lime[3]	1000	80
Heat treatment[4]	6000	1000

Note: 1. Mixed humus and activated sludge

2. At optimum pH value

3. At optimum dosage

4. One-half hour at 360° F

Porteous process is a unique system developed for treatment of organic waste. This process has been in use since the early part of this century to treat primary or secondary sludge in any proportion on a batch basis. Porteous process reduces moisture to 35 - 70%, and produces a final product that is sterile, compact, and easy to handle. Presently, it is an automated continuous process that requires no chemicals and the total power, fuel and water costs are as low as $2.00 per ton of dry solids.

The flow diagram of the Porteous process is shown in Figure 4. Raw sludge (primary or secondary) is stored in storage tank and after disintegration is pumped to the reaction vessel through heat exchanger. In the reaction vessel, temperatures of 350 - 390° F and pressures of 180 - 210 psi are maintained and a specially designed steam-jet circulator assures intimate mixing of sludge and steam.

The detention time in the reaction vessel is approximately thirty minutes and the hot conditioned sludge is passed back through the heat exchanger, gives up its heat to incoming raw sludge and enters the decanting vessel with a temperature of about 90° F. The solid material settles rapidly while supernatant water rises to the top where it is drawn off. The treated sludge at this point has been reduced to about one third its original volume. The dense product is passed for final dewatering to vacuum filters, filter presses or other mechanical dewatering equipment.

There are eleven installations in Europe[23] serving populations from 10,000 to 500,000; however, it is still a new process to the United States. This system has been proven to be an efficient and low-cost operation. This process could be added to almost any installation without changes in existing equipment. It also has variable capacity which could be used to increase the capacity with some hardware modifications.

2. Farrer System

The Farrer system of sludge conditioning is basically the same as the Porteous system in principle. The Farrer Company, after purchasing Mr. Porteous' patents, modified the process to bring the following improvements: a) to overcome the odorous steam release, and b) to prevent short circuiting in the vessel-type reactor when heat treating continuously. This process has been licensed to Dorr-Oliver (Stamford, Connecticut) in 1969, by William E. Farrer, Ltd. (Birmingham, England).

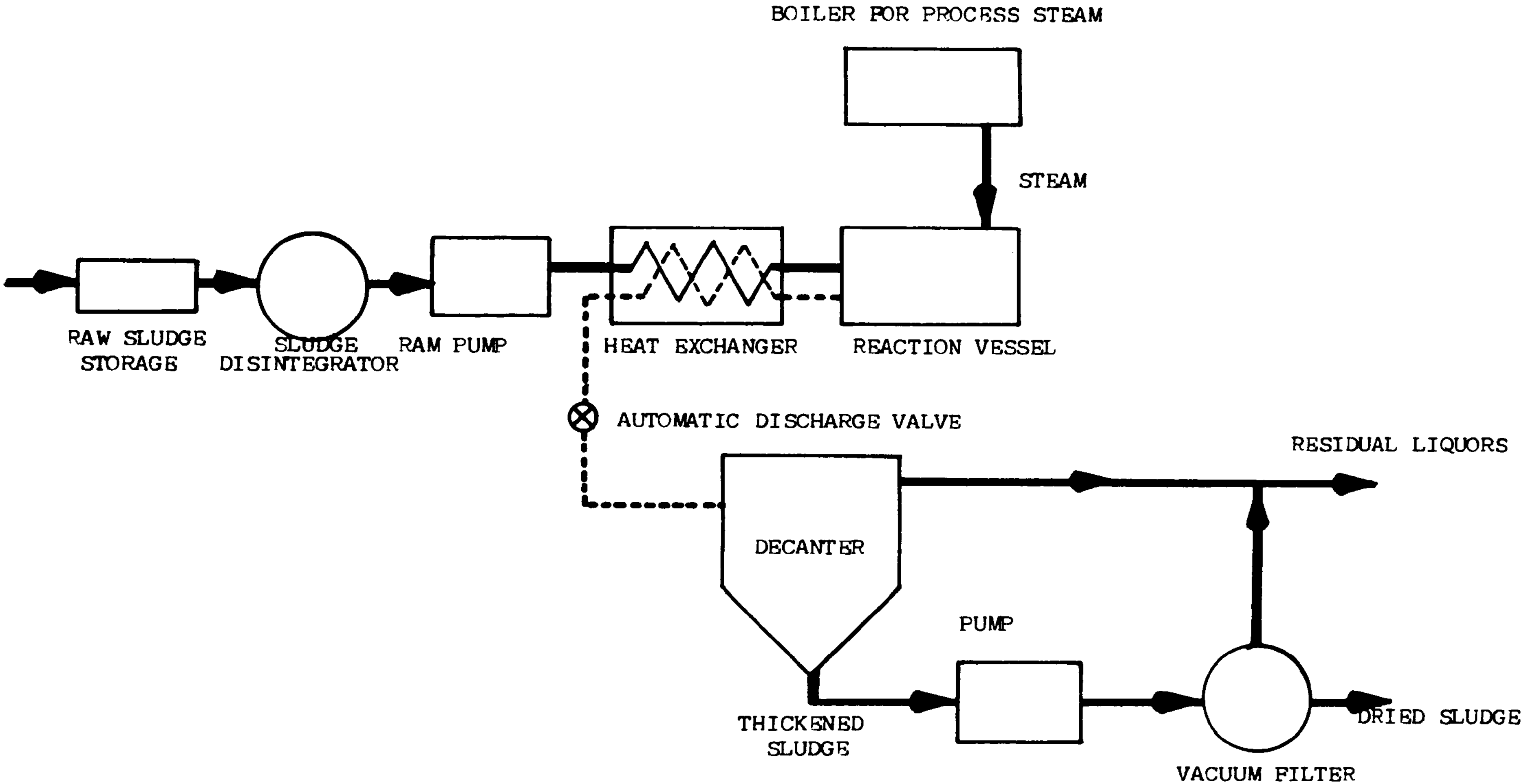


FIGURE 4

FLOW DIAGRAM OF THE PORTEOUS PROCESS

Heat treatment of sludge is a time-temperature relationship and the temperature and detention time requirements range from 350 to 400° F and 20 to 30 minutes, respectively, depending on the nature of the sludge. The Farrer system is a continuous sludge conditioning process as compared to the batch treatment of Porteous process.

The Farrer system is shown in Figure 5. This system contains a thickener, a disintegrator, heat exchangers, boilers, decanting and storage tank, and a dewatering device. The major improvement in this system over the Porteous system is that heating is accomplished in tube-type heat exchanger by indirect heat exchange using hot water through a closed loop. This technique replaces the injection of steam directly into the sludge practiced in the Porteous system and has the following major advantages:

A. Sophisticated deodorizing devices are not needed as there is no odorous steam release.

B. The feed volume to the reactor is not increased by condensed steam.

C. The need for a continuous water supply and treatment is eliminated as the water is used in a closed loop.

For economy, the heat treatment process is comprised of a two-stage heat exchanger followed by an economizer. The reactor is specially designed to eliminate short circuiting and to insure the desired detention time for sludge conditioning. When used in conjunction with a Dorr-Oliver fluosolids (FS) system, a waste heat boiler can be utilized for additional overall economy in operating costs. In addition to being a complete system in itself, the Farrer system may be integrated into the FS disposal system where the ultimate in solids disposal is desired. From an evaluated capitalized cost point, the addition of the Farrer system for medium to large-size plants will pay for itself. The capitalized cost evaluation for primary and activated sludge plants of one through 20 MGD capacity is shown in Figure 6. Lumb[20] reported the total operating cost of the Porteous process for the plant at Halifax, England, as $6.58 per ton of dry solids. This cost would be competitive with sludge conditioning and dewatering costs in the U.S.A.

Chemicals

Chemicals are used for the conditioning of the sludge as they increase the maximum efficiency of sludge dewatering. Chemical

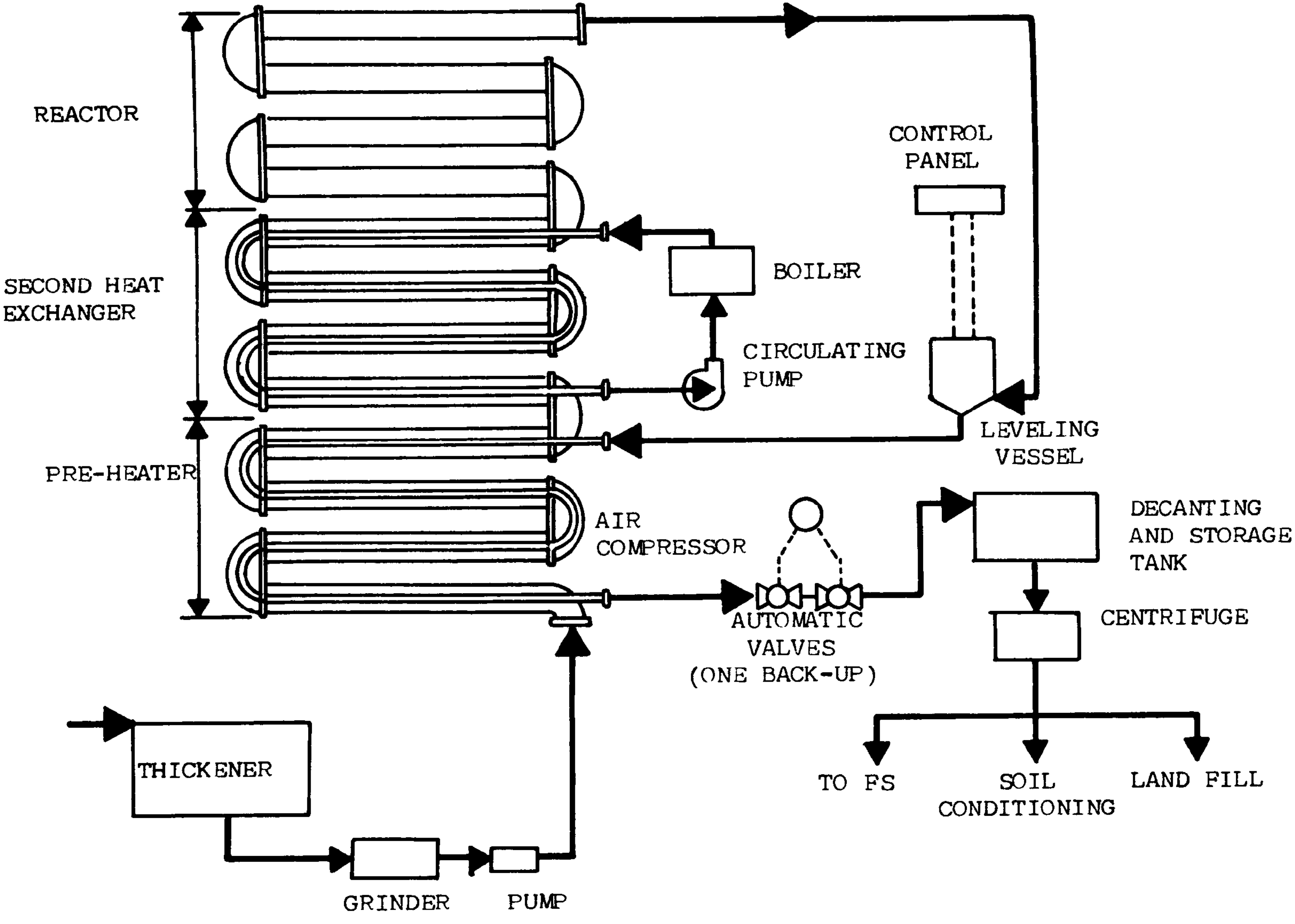


FIGURE 5

FLOW SHEET FOR THE DORR-OLIVER FARRER SYSTEM

CAPITALIZED COST COMPARISON

FS SYSTEM and FS/FARRER SYSTEM

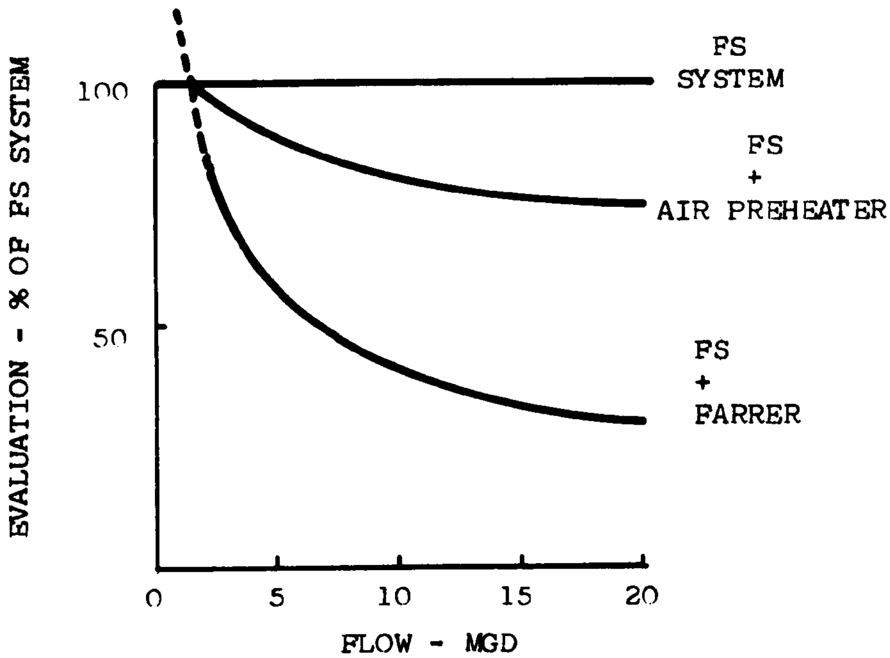


FIGURE 6

THE CAPITALIZED COST EVALUATION

FOR PRIMARY AND ACTIVATED SLUDGE PLANTS OF 1 THROUGH 20 MGD CAPACITY conditioning changes the colloidal structure of the sludge and causes the particles to coalesce and creates large uniform voids in the sludge so that water can pass through them.

A wide variety of chemicals have been evaluated for conditioning sludges and they are: ferric chloride, ferrous chloride, ferric sulfate, ferrous sulfate, sulfuric acid, nitric acid, hydrochloric acid, sodium dichromate, aluminum chloride, lime, chromic chloride, chlorine, sodium chloride, potassium permanganate, cupric chloride, aluminum chlorohydrate, zinc chloride, titanium tetrachloride, soap, aluminum sulfate, sulfur dioxide, phosphoric acid, dicalcium phosphate, and organic polyelectrolytes.

Ferric chloride, lime and cationic polyelectrolytes are the most popular ones for sludge conditioning in the United States and overseas. Aluminum chlorohydrate is a common flocculating agent along with lime and ferric salts. The optimum cost of chemical conditioning is brought about by suitable combination of ferric salts and lime. Ferric salts and lime, when added to raw sewage sludge, changes the pH and reduces the population of the microorganisms. The reduction of microorganisms is important to control odor problems but it is not possible to produce a sterile sludge by this process.

Polymers

The advent of synthetic polymeric flocculents has contributed to major advances in the sludge-handling field. Anionic and cationic polymers are very effective for raw waste activated sludge because they bring about charge neutralization and agglomeration of particles.

Physical filter aids are used along, or in conjunction, with chemicals to increase porosity and filtration rates. These include: coke, bone ash, peat, paper pulp, ground blast furnace slag, diatomaceous earth, ground garbage, flyash, clay, sawdust, crushed coal, animal blood and activated carbon.

PRETREATMENT - SLUDGE DEWATERING

Sludge dewatering is an important step in the sludge incineration practice in order to reduce the sludge moisture content to the required degree. There are a number of sludge dewatering processes such as centrifugation, vacuum filtration, plug presses, filter presses and other miscellaneous processes.

Centrifugation

Centrifuges are becoming the most popular mechanical device for dewatering sludge due to their low capital cost, simplicity of operation and effectiveness with difficult-to-dewater sludges. Centrifuges separate solids from the liquid through sedimentation and centrifugal forces. The machines are of different types: horizontal, cylindrical-conical, solid bowl, basket and disc. Disc-type machines do a poor job for dewatering even though they are good for clarification. The basket centrifuges, on the other hand, dewater sludges effectively but liquid clarification obtained is poor. All the other types of centrifuges are very effective for dewatering sludges.

In a solid bowl centrifuge, sludge concentration is accomplished by subjecting the thickener underflow to a force of 3000 gravities. This unit can concentrate the sludge to a moisture content lower than that achieved by vacuum filtration and without the use of chemical conditioners. The high speed of the rotor generally produces exceptional concentration and capture of the solids. In addition, in Merco Bowl centrifuges, a pump integrated with the centrifuge returns the centrate to the thickener feed or influent sewage. Thus, the centrate, which may be quite odorous, is kept out of contact with the atmosphere.

In a typical continuous centrifuge shown in Figure 7, sludge is fed through a stationary feed pipe from which it is thrown out through feed ports into the conveyor hub; the solids are settled out against the bowl wall by centrifugal force. From the bowl wall they are continuously conveyed by a screw to the end of the machine at which point they are discharged. A pool volume is maintained in the machine and the liquid effluent discharges out of effluent ports after passing the length of the pool under centrifugal force.

The major variables involved in centrifuge operation are the speed of rotation, the liquid throughput, the solids throughput, and the pool depth. Increasing the pool depth decreases the drainage beach for the dewatered solids and reduces the effluent solids. Readily dewaterable solids require less drainage time so that a higher pool depth can be maintained. Increasing the liquid flow rate will reduce the recovery

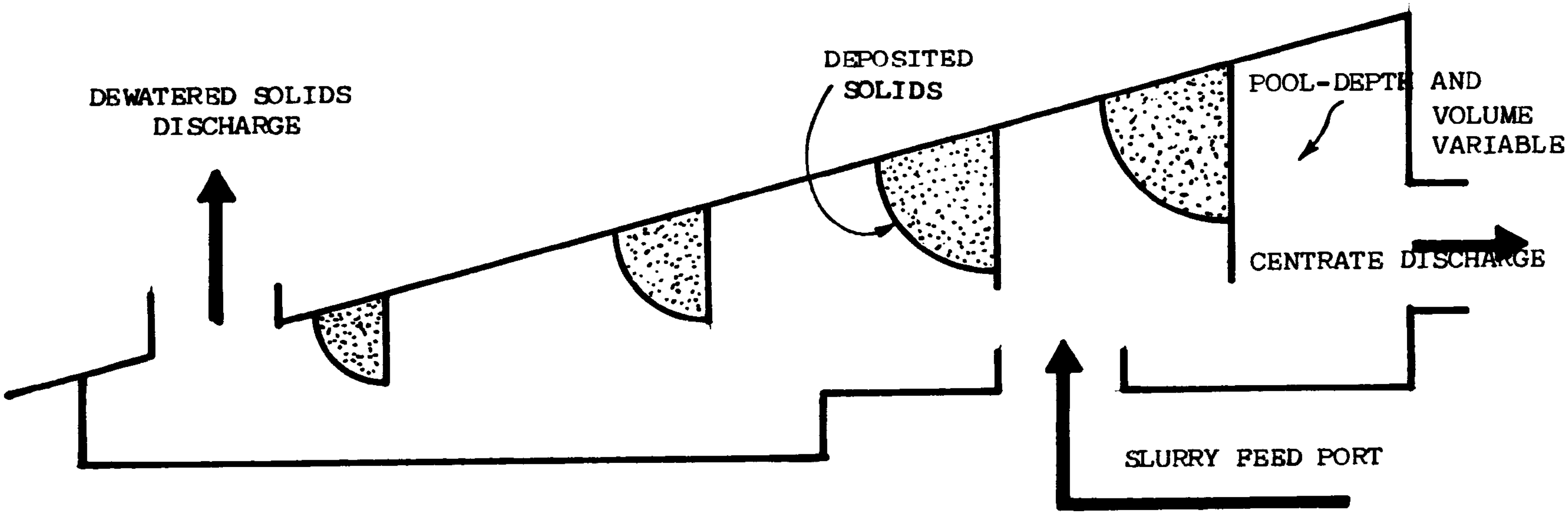


FIGURE 7

SCHEMATIC OF CONTINUOUS CENTRIFUGE

because of decreased retention in the pool. Increasing the mass flow rate will reduce the recovery because of the lessened conveyability of the deposited solids. The general relationships between the operating parameters such as pool depth, recovery, liquid flow rate and percent cake solids are shown in Figures 8 and 9.

The use of polyelectrolytes at low dosages increases the recovery at a given flow rate. The coagulants are usually added to the pool to minimize turbulence and resulting floc dispersion. However, chemical treatment usually lowers the cake dryness probably due to the capture of the fine solids and, therefore, a compromise on dryness versus recovery has to be reached. In general, polymers permit higher unit loadings as well as higher solids recovery.

For biological sludges, the solids capture in the centrifuge is very poor and the cost of chemicals to improve the recovery is very high. Further, the maintenance costs are high in addition to the production of poor quality centrate. The fine solids in the centrate are not removed in the settling tanks when recycled and, therefore, pose a problem. New techniques of handling centrate separately such as aeration for stabilization, mixing with incinerator ash prior to filtration, combining with digester supernatant liquor and lime to produce a liquid fertilizer when fully developed might improve the situation. Vacuum filters cannot be completely replaced where biological sludges are dewatered.

Los Angeles County Sanitary District has reported[24] the centrifuge dewatering cost, which includes capital, power, labor and maintenance, to be about $4.25 per ton of dry solids. Chemical costs vary from $6 to $20 per ton of dry solids depending on the type of sludge. The maintenance of centrifuges is a major operating cost as parts get worn out regularly. However, the capital costs are about 30% less than the capital cost of vacuum filters. The dewatering costs, in general, are more attractive than vacuum filtration except when biological sludges are handled. A typical average value for total annual costs is $12 per ton of dry solids with a range of $5 to $35 per ton.

Vacuum Filtration

Vacuum filtration is a major mechanical dewatering step applicable to all types of sewage sludges. Vacuum filters are very efficient for dewatering difficult biological sludges and prove economical for populations of 10,000 and greater. Vacuum filters are becoming very popular because of the production of drier cake for incineration, less floor space requirement, good solids capture and flexibility in operation. There are about 1300 vacuum filters installed in the United States for dewatering sewage sludges[25].

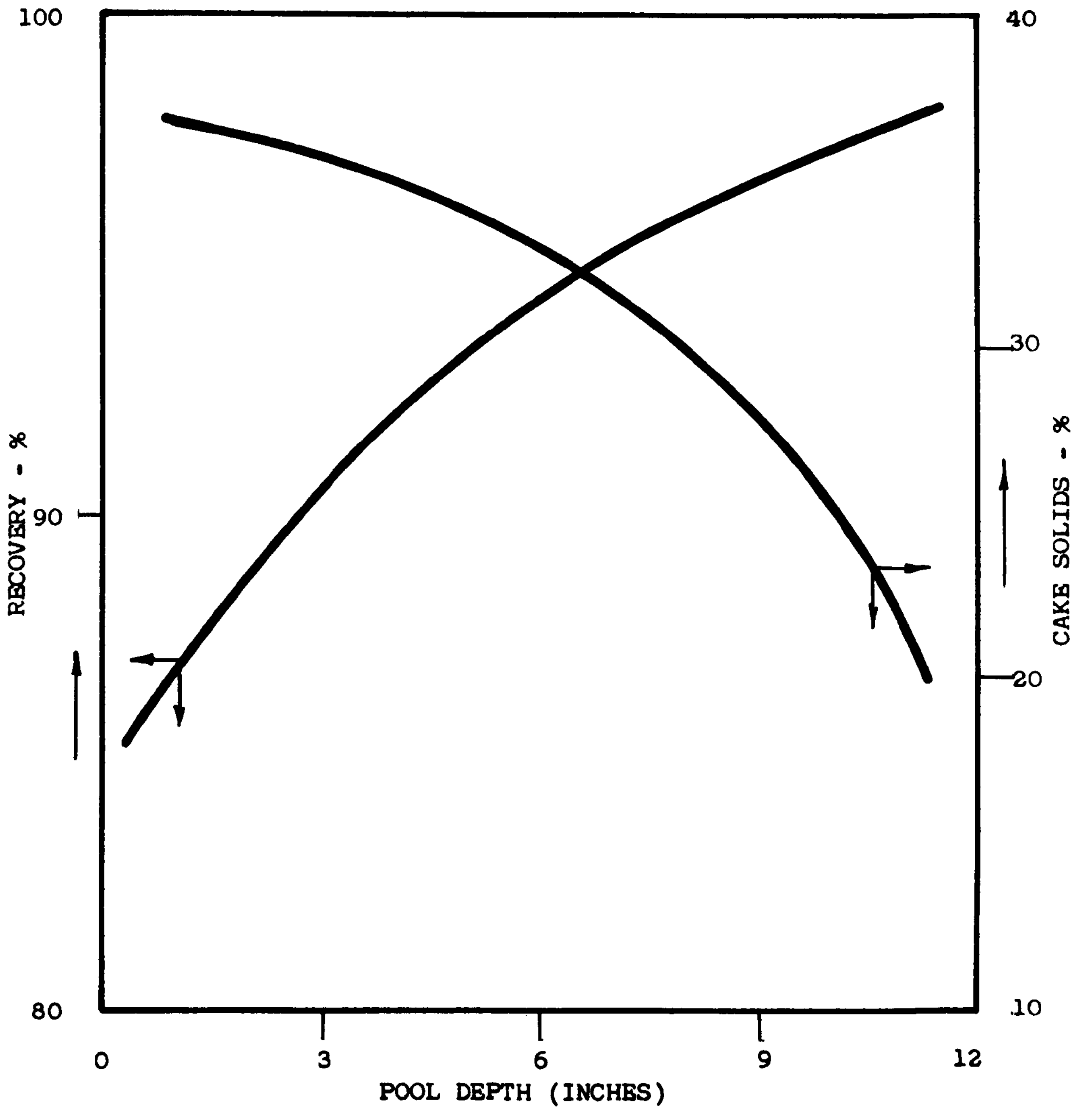


FIGURE 8

CENTRIFUGE OPERATING RELATIONSHIPS

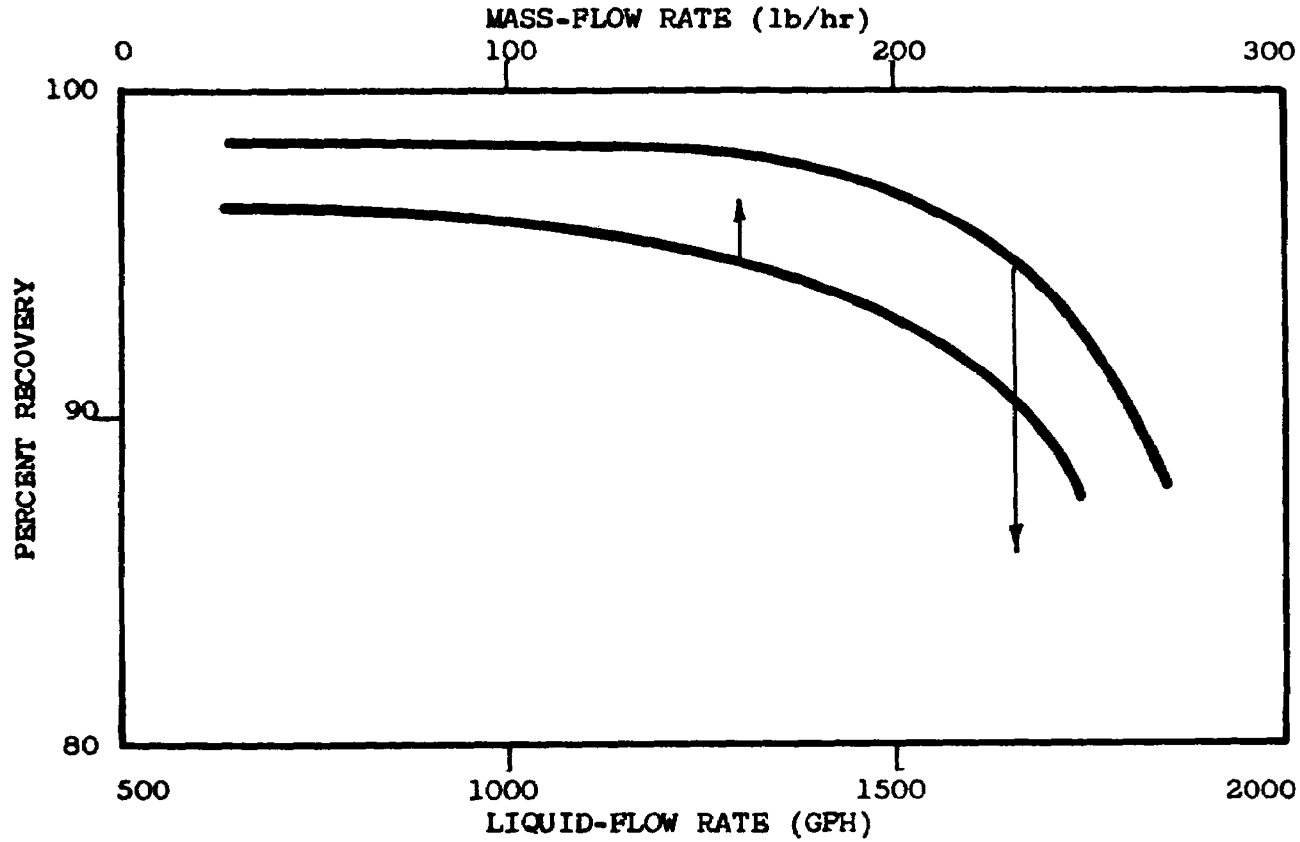


FIGURE 9

CENTRIFUGE OPERATING RELATIONSHIPS

Rotary-drum vacuum filtration is generally used for dewatering sewage sludges. In this type of filtration, a rotary drum passes through a sludge slurry tank in which solids are retained on the drum surface under applied vacuum (See Figure 10). As the drum passes through the slurry, a cake is built up and water is removed by filtration through the deposited solids and the filter medium. The drum is divided internally into drainage compartments which connect to the filtrate system. A portion of the drum ranging from 20 to 40% is submerged in the slurry and a sludge mat is formed on the filter media due to applied vacuum of about 10 to 26 in. of Hg. As the drum rotates, the sludge mat is out of submergence and is subjected to dewatering. At the end of a cycle, before the submergence in the sludge slurry once again, a knife edge scrapes the filter cake from the drum to a conveyor. The filter medium is usually washed with water sprays before it is immersed again in the slurry tank.

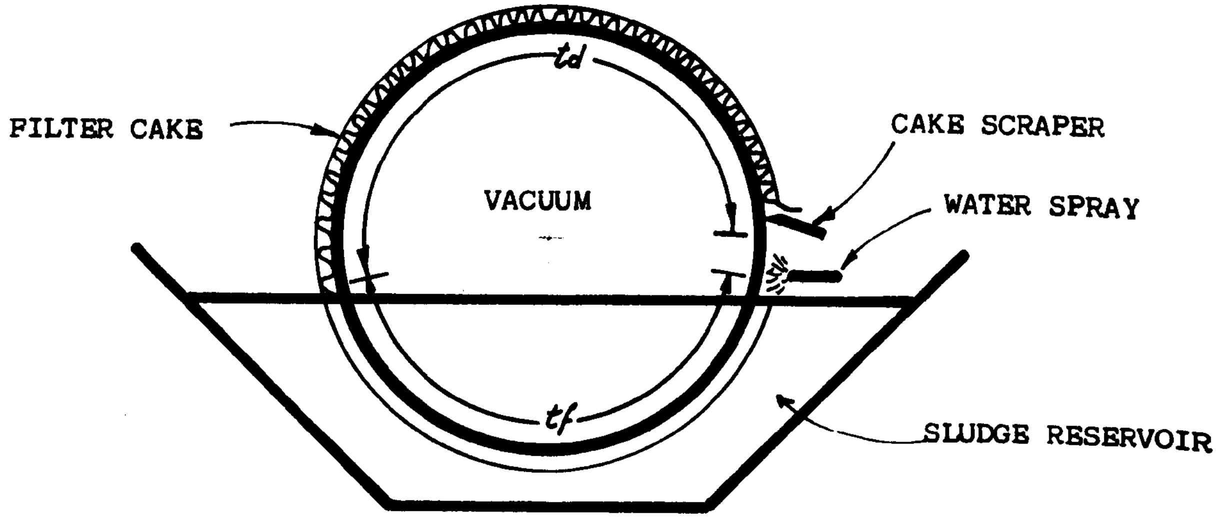
The amount of solids which can be dewatered per unit time and per unit area, and the dryness of the cake formed are dependent upon the sludge and operating variables. The sludge variables include: solids concentration, sludge age, temperature, viscosity, compressibility, chemical composition and the other sludge characteristics such as volatile content, bound water, size, shape and so forth. The operating variables are: applied vacuum, drum submergence, drum speed, degree of agitation, filter media and conditioning of sludge.

Increased feed solids concentration, up to about 8 to 10%, aid in increasing the yield[26] and beyond this upper limit chemical conditioning and sludge distribution becomes difficult. Added advantages of having a higher feed solids concentration are: the chemicals requirement for conditioning are reduced and a reduction in filter cake moisture is obtained. The relationship between feed solids concentration and filter loading is shown in Figure 11.

Ageing of the sludge affects the filterability of the sludge. Freshening of the sludge by re-aeration not only reduces the cake moisture but also reduces the ferric chloride requirement due to a decrease in alkalinity and to the oxidation of reducing compounds.

The effect of vacuum is such that the higher the vacuum, the greater the yield up to a point and this upper limit appears to be in the range of 15 to 20 psi. For very compressible cakes, vacuum filter design generally incorporates two independent vacuum systems--one operating to apply moderate vacuum while the cake is being formed to prevent media plugging, and the other operating at high vacuum to produce a cake of minimum moisture content. The effect of the increase in applied vacuum on filter loading is shown in Figure 12.

Drum submergence and speed affects the filter yield and filter cake moisture. Increase in drum submergence results in greater



NOTE: t_d - DRYING CYCLE TIME
t_f - FORM CYCLE TIME

FIGURE 10

TYPICAL MECHANISM OF VACUUM FILTRATION

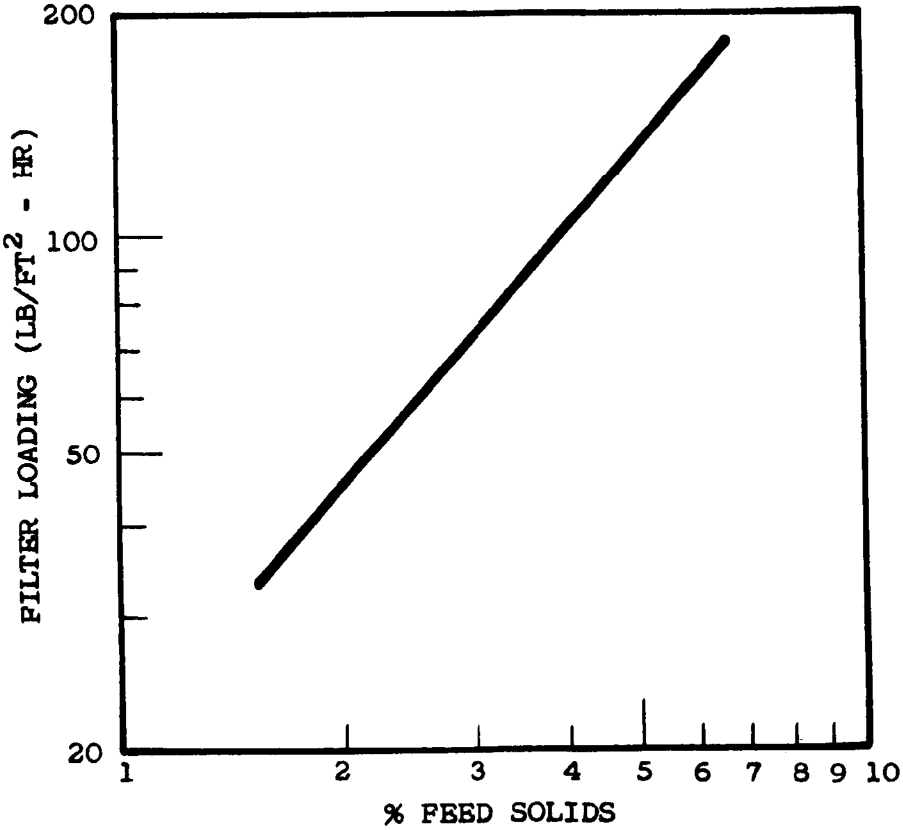


FIGURE 11

RELATIONSHIP BETWEEN FEED SOLIDS CONCENTRATION AND FILTER LOADING

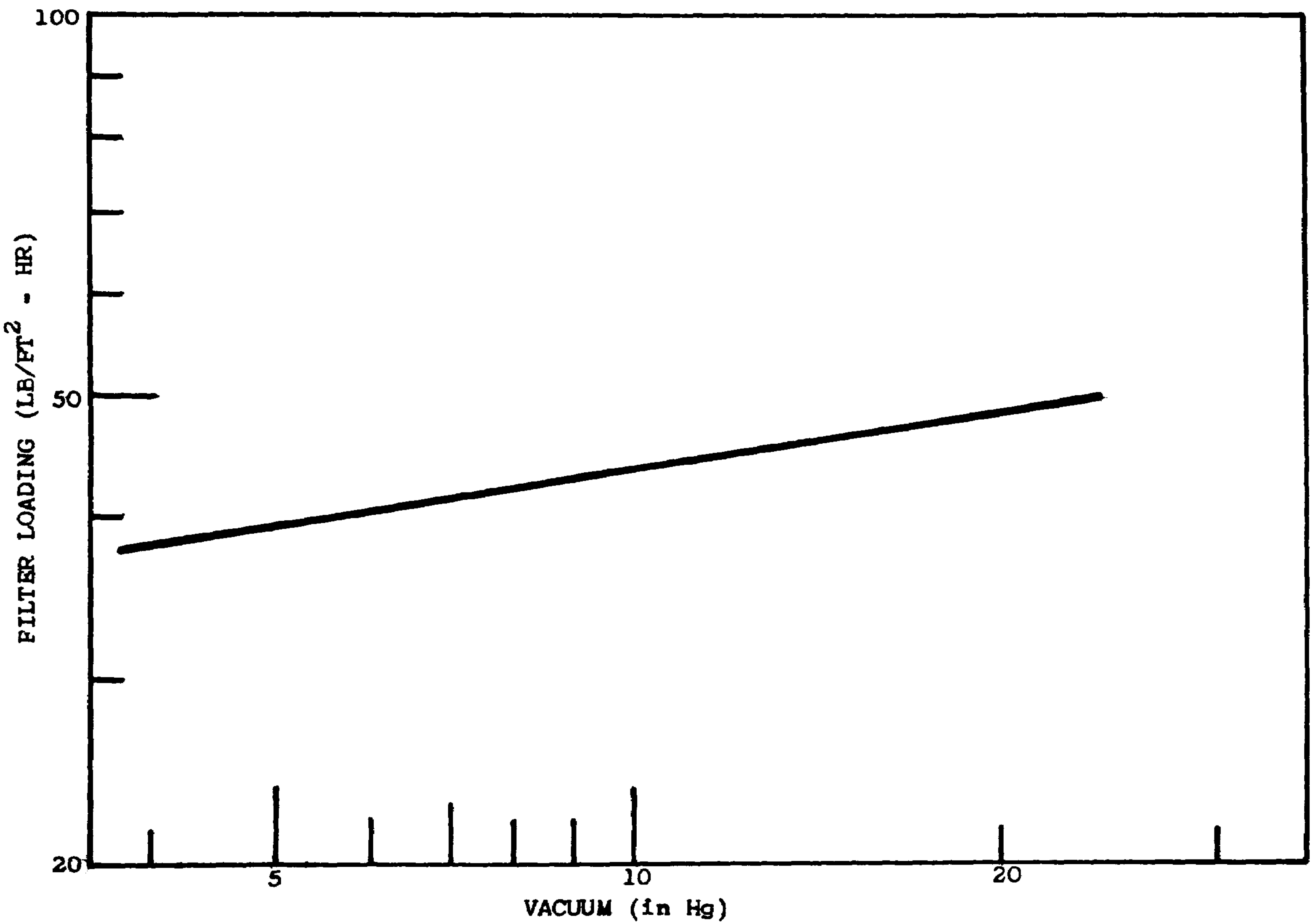


FIGURE 12

EFFECT OF INCREASE OF APPLIED VACUUM ON FILTER LOADING filter yield but also produces a higher cake moisture. An increase in cycle time decreases the filter cake moisture due to an increase in drying cycle but the production rate is reduced. The relationship between form time and filter loading is shown in Figure 13.

Following chemical conditioning, agitation of the sludge is desirable. Variable speed mixing equipment is usually included with the vacuum filtration equipment in order to provide violent agitation while mixing with the chemicals and gentle agitation later on to keep the solids in suspension.

The maximum efficiency of sludge dewatering is increased by chemical conditioning. The chemicals and polymers used in sludge conditioning are discussed in the chapter, Pretreatment - Sludge Conditioning.

The capital cost of a vacuum filtration system includes the cost of filters with auxiliaries together with the cost of the building to house the filter. The cost of filters, including auxiliaries, range from $95 to $275 per square foot depending on the size of the installation and the filter media. When the building cost is included, the capital outlay may double[27].

The operating cost generally includes the cost of hauling filter cake to land fill sites, etc., in addition to the cost of labor, power, chemicals and maintenance. The total operating cost reported by Simpson and Sutton[28], based on cost surveys of a number of sewage treatment plants, varied from $5.34 to $30.17 per ton dry solids. The breakdown of the direct operating cost is given in Table III.

The operating costs reported by Dietz[29], based on a survey of vacuum filtration costs at sewage treatment plants, were $8.20 to $32.40 per ton with a median of about $20 per ton. The chemical costs obtained from operating records from about sixty sewage treatment plants are shown in Table IV.

Plug Presses

Pressing techniques are limited to a two-stage dewatering system installed prior to incineration. In order to minimize the need for chemicals, plug presses taking advantage of free water drainage when subjected to low pressures are used. The "Roto-Plug"[30] and the "DCG Solids Concentrator"[31] are the two proprietary systems that use this technique. The two major objectives in these types of presses are: 1) to avoid the critical pressure that would break the structure of sludge solids and blind the filter media, and 2) to avoid large dosages of flocculents necessary to build a firm solids structure.

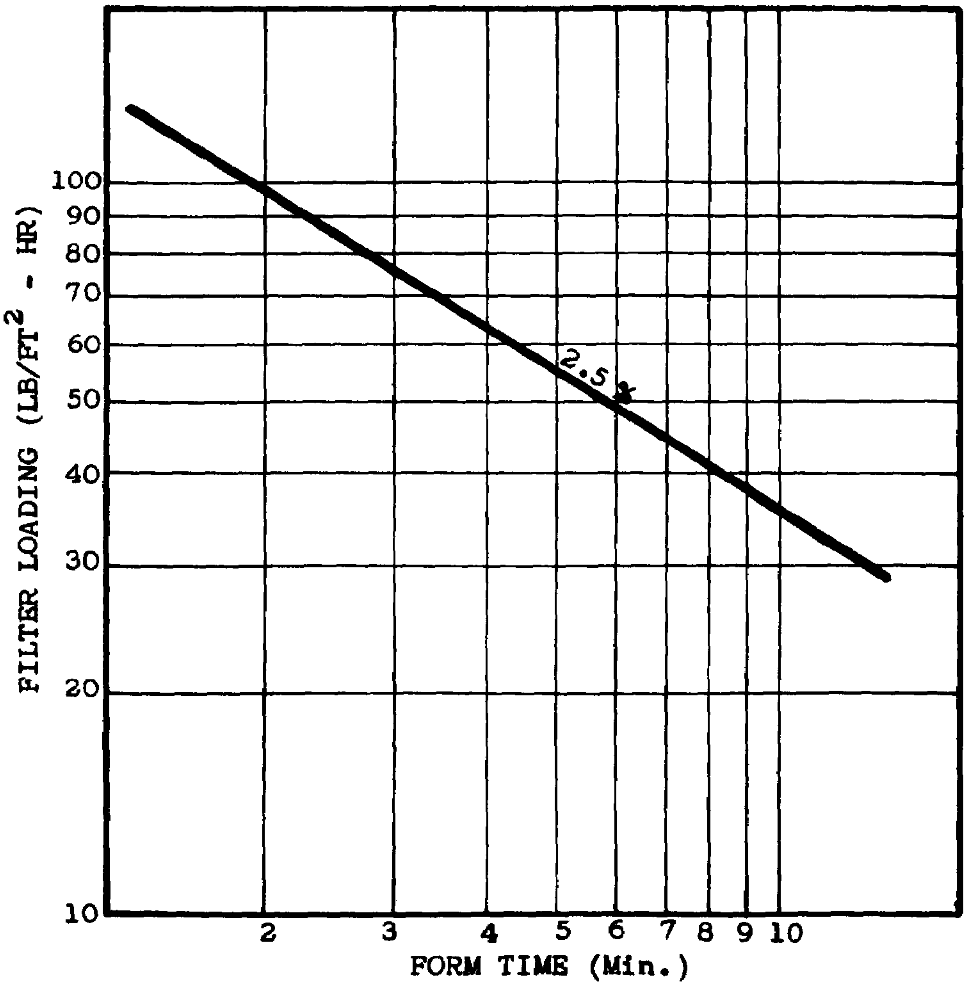


FIGURE 13

RELATIONSHIP BETWEEN FORM TIME AND FILTER LOADING

TABLE III

DISTRIBUTION OF VACUUM FILTRATION COSTS

Labor and direct supervision	39%
Chemicals and supplies	37%
Electric power	8%
Maintenance	16%
Total	100%

TABLE IV

CHEMICAL AND OPERATING COSTS - VACUUM FILTRATION FACILITIES

Sludge Type	Small Plants* ($/ton) Chemical Cost	Small Plants* ($/ton) Total Operating Cost	Large Plants** ($/ton) Chemical Cost	Large Plants** ($/ton) Total Operating Cost
Raw primary	$ 7.00	$17.50	$ 3.00	$ 7.50
Digested primary	$11.50	$38.70	$ 5.50	$13.75
Elutriated digested primary	$ 4.00	$10.00	$ 3.50	$ 8.75
Raw primary + filter humus	$10.20	$25.50	$ 6.50	$16.30
Raw primary + activated	-	-	$10.50	$26.20
Digested primary + filter humus	$21.50	$53.80	$ 9.50	$23.80
Digested primary + activated	$13.00	$32.50	$12.50	$31.25
Raw activated	-	-	$ 6.50	$16.30
Elutriated digested primary + activated	-	-	$ 8.50	$21.28

*Flow less than 10 MGD
**Flow more than 10 MGD

The dewatering is accomplished in successive stages with increasing pressure in each stage. Polymers or waste paper pulp are used for conditioning septic or digested sludges to prevent structural collapse of the solids whereas such chemicals are found unnecessary[31] with fresh sludges due to the presence of natural floc. The Roto-Plug flow diagram is shown in Figure 14 and the process starts with a thickening step using free drainage of easily separated water through a nylon cloth under a low pressure of 1 to 1.5 inches of water. A plug is formed as solids accumulate and squeeze the water from the sludge due to its own weight. The plug forces the thickened sludge into the cake formation unit where the sludge is pressed at about 10 to 15 psi between a wedge-wire drum and rubber covered rollers. Pressed sludge is incinerated or hauled away to land disposal.

The manufacturers claim that very little sludge conditioning is required, power requirements are low, the area required for equipment installation is small and the equipment is simple and economical. The pressing techniques, however, are not widely adopted as the resultant cake is not sufficiently dry and the separated water contains excessive solids.

Filter Presses

Mechanical filter presses are commonly used in Europe for dewatering sewage sludge, and they use the principle of free water drainage followed by the application of low pressures. However, in the U.S., the filter presses are used in industries more than in sewage treatment plants for dewatering purposes. The major objections to this process being used in this country are the high labor and maintenance costs.

Filter presses are operated in batches and chemical conditioning of the sludges is invariably done. The chemicals used include: lime, aluminum chloride, aluminum chlorohydrate and ferric salts. Flyash has also been used successfully for precoating. The only major advantage of press filters over vacuum filters seems to be the minimum chemical costs. The conditioned sludge is pressed at about 90 psi for 3 hours[32]. The filter cakes formed varied in thickness from 1/2 to 1-1/4 inches with moisture content as low as 40%.

The variations in the filter pressing operations include: leaf filters, screw and hydraulic leaf filters. These dewater quickly and require less space. However, filter presses have major disadvantages as compared to vacuum filter operation due to the high moisture content in the cake and high operation costs. Screw and hydraulic presses require a thickened sludge feed of 6 to 8% solids for effective

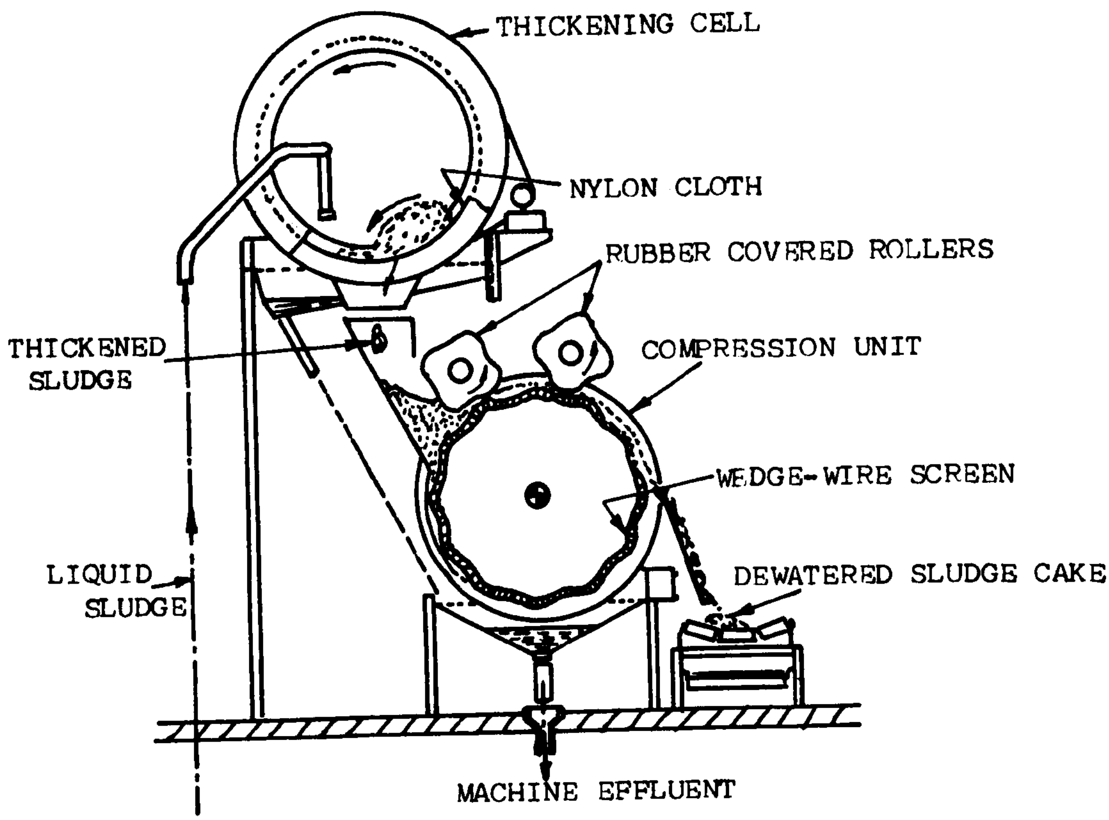


FIGURE 14

ROTO-PLUG FLOW DIAGRAM

dewatering and this appears to be a major disadvantage for the application of sewage sludges.

Unconventional Methods

In an attempt to eliminate the need for chemicals and to increase production rates, a number of unconventional approaches have been undertaken and these are summarized in the following paragraphs.

The use of electricity for sludge conditioning has been tried by many researchers[33,34,35] in laboratory and pilot-plant scale studies. Slagle and Roberts, in their laboratory studies using electrodialysis, found that the filterability of sludge increased following the passage of a direct current, as shown in Table V.

In their pilot plant, Slagle and Roberts found that the electrodialysis reduced the pH of the sludge system to 3.4 and the sludge could be filtered without the use of chemical conditioners. It was also found that the sludge settles rapidly and seems to be stabilized as there was very little gas produced during extended detention. For a fresh sludge at 6.56% solids, a comparison of the electrodialysis and chemical conditioning has been found[33] per ton of solids as shown in Table VI.

The most economical current density was found to be about 0.3 amp per square foot of anode surface with a potential drop of 4 volts between the electrodes. For economic comparison, the price of flocculents and electricity at a particular location must be known. Based on the typical data, 181 KWH is equivalent to 408 pounds of ferric chloride and pricing electrical energy at $0.01/KWH, the cost of electrodialysis appears to be less than the cost for chemical treatment[33].

Cooling and coworkers reported a process[35], electro-osmosis, for conditioning digested sludge. From his experiments, Cooling found that the quantity of water removed from sludge was proportional to the electricity transported. An electro-osmosis permeability of 0.006 gallons per square foot per hour per inch per volt and a constant equal to 0.02 gallons per ampere-hour was used. The consumption of electricity was too high to make the process practical and a high degree of maintenance was required.

High sludge-drying costs at Chicago provided the incentive to seek a way to decrease the vacuum filter-cake moisture. Beaudoin[34], working on this problem, obtained best results by conditioning the filter cake with 25 volts for 2 minutes. Even though the use of electricity was effective, the process was not economically feasible.

TABLE V

INCREASE IN FILTERABILITY WITH ELECTRODIALYSIS

Degree of Treatment	Water Removed by Vacuum Filtration
Untreated sludge	12%
Sludge electrodialyzed for 15 min.	43%
Sludge electrodialyzed for 30 min.	65%

TABLE VI

COMPARISON OF ELECTRODIALYSIS AND CHEMICAL CONDITIONING

Electrodialysis Conditioning	Chemical Conditioning
181 KWH expended	89 lb ferric chloride used
Filter cake moisture - 70%	Filter cake moisture - 59.5%
Filter cake solids - 2065 lb	Filter cake solids - 1440 lb
Filter cake water - 4665 lb	Filter cake water - 2130 lb
pH - 6.2	pH - 3.4

Note:

1. Comparison is for fresh sludge having a 6.56 percent solids concentration.
2. The figures given are per ton of dry solids.

The dewatering qualities of the sludge are enhanced when the pH of the sludge is reduced. When autotrophic sulfur bacilli are added to digested sludge, acids are produced under aerobic conditions. This principle has been investigated as a sludge conditioning method but no data are yet available to describe the performance or economics of the bacterial process.

Solvent extraction is an interesting approach to sludge dewatering and has been tested at the Rockford, Illinois, treatment plant. The process, known as McDonald process[36], involves the following steps: dewatering by contrifugation, solvent extraction with carbon tetrachloroethylene and distillation. This process has been described as impractical.

Artificial freezing of sludge has been found successful by many researchers[37,38] in promoting rapid dewatering. It is speculated[39] that freezing disrupts the cell walls retaining the internal moisture in sludge and, thereby, allows the water release and drainage. Clements and co-workers reported that freezing was an effective sludge conditioning process for all types of sludges and that the use of flocculents with freezing was helpful but not necessary. They also reported that the slow and complete freezing of the total sludge was necessary for good results and the method of thawing was not critical as long as it is not accompanied by vigorous agitation.

The operating cost for freezing includes: power, flocculents and refrigerants. It has been reported that it takes 28 BTU to lower the temperature of one pound of sludge from 60° F to 32° F and 142 BTU to freeze a pound of sludge[38]. Clements, et al., have quoted a total operating cost for freezing of $5.60 per ton of dry sludge while others have quoted[40] as high as $32 to $45 per dry ton. The freezing technique by artificial means undoubtedly aids sludge dewatering but because of the high operating cost, it may never become practical unless the economics are improved greatly.

The British laboratories have explored[41] the conditioning of sewage sludges by ultra or supersonic vibration. This process has not been found successful because ultrasonic vibrations tend to destroy sludge flocs resulting in fine solids that are more difficult to dewater. The only advantage found in this process is that the vibrations degasify which aid sludge dewatering.

HEAT VALUE OF SEWAGE SLUDGE

The combustible elements of sewage sludge are carbon, hydrogen and sulfur and these elements are chemically combined in the organic sludge as grease, carbohydrates and protein. The combustible portion of sewage sludge has a BTU content equal to that of lignite coal. Air is added to provide oxygen to support the combustion of the combustible elements.

The reactions of these elements with oxygen are as given in Table VII.

The composition of elements in sewage sludge varies[42] from plant to plant as shown in Table VIII.

The heat value of sewage sludge can be estimated if its ultimate analysis is known. DuLong's formula (1) can be used to compute the heat value:

$$Q = 14{,}600\ C + 62{,}000\ \left(H - \frac{O}{8}\right) \qquad (1)$$

where: Q = BTU/lb of dried sludge
C = % carbon
H = % hydrogen
O = % oxygen

A reduction in the thermal value of the sludge occurs when inorganic chemicals are added to aid filtration. These chemicals used are inert and, therefore, lower the heat content per pound of filter cake. The other disadvantage is that the weight of the sludge is increased by 10 to 15% by the addition of chemicals[42]. The heat energy available for sustaining combustion will be reduced if ferric hydroxide and calcium hydroxide sludges are burned with the sewage sludge due to the heat used up in the dehydration of these hydrous sludges.

TABLE VII

COMBUSTION REACTIONS OF SEWAGE SLUDGE

Reaction			Heat Release (BTU/lb)
1. Carbon + oxygen		carbon dioxide	
C	+ O_2	---------→ CO_2	14,500
(1 lb)	(2.67 lb)	(3.67 lb)	
2. Hydrogen + oxygen		water	62,000
$2H_2$	+ O_2	-------→ $2H_2O$	
(1 lb)	(7.94 lb)	(8.94 lb)	
3. Sulfur + oxygen		sulfur dioxide	4,500
S	+ O_2	---------→ SO_2	
(1 lb)	(1 lb)	(2 lb)	

TABLE VIII

ELEMENTAL COMPOSITION OF SEWAGE SLUDGE

Elemental Composition	Source* No. 1	No. 2	No. 3	No. 4
Carbon (%)	64.3	65.6	55.0	51.8
Hydrogen (%)	8.2	9.0	7.4	7.2
Oxygen (%)	21.0	20.9	33.4	38.0
Nitrogen (%)	4.3	3.4	3.1	3.0
Sulfur (%)	2.2	1.1	1.1	Trace
Volatalite (%)	47.9	72.5	51.4	82.0
V.S.S. (BTU/lb)	12,840	12,510	10,940	8,990
T.S.S. (BTU/lb)	6,160	9,080	5,620	7,380

*Source No. 1 - Cleveland Southerly Plant, 1955

No. 2 - Detroit, Michigan, 1955-56

No. 3 - Minneapolis, Minnesota, 1955

No. 4 - New Rochelle, New York, 1960-62

IMPROVEMENTS IN THE HEAT VALUE OF SLUDGE

Improvements in the heat value of sludge can be achieved only by improving the volatile content of sludge as fed to the combustion unit as no control can be exercised over the stoichiometry of sludge combustion. The volatile content of a given sludge may be improved by a very efficient degritting system. Hydrocyclones[43], used for this purpose, have shown removals of 95% of the plus 200 - 270 mesh inorganics at a specific gravity of 2.67 and increases in the volatile content of the sludge from 70 - 75% to 80 - 85%. The effect of volatile content on the operating cost of sludge combustion is shown in Figures 15 and 16.

A flocculation process[2] used in conjunction with clarification in the primary treatment area, increases the sludge settling rates and, therefore, the ratio of primary to secondary sludge. This process removes about 70% suspended solids and 40 - 50% BOD depending upon the strength of the sewage influent. Assuming an overall removal of 95% for conventional activated sludge, the sludge resulting from such a process will thicken (7%) and dewater (25%) to the same degree as primary plus trickling filter. Therefore, we save on fuel and increase a combustion unit's capacity. The other benefit is the reduction in the required size of the secondary system, due to the higher BOD removals in the primary treatment.

Consideration must also be given to materials present which will react endothermically at combustion temperatures. The moisture content of the calcium carbonate ($CaCO_3$) sludge and the endothermic decomposition to calcium oxide (CaO) materially increases the thermal burden. The off gas cleaning requirement would also be increased. Further, a highly alkaline sludge would be more difficult to dispose of than the original calcium carbonate, except in some cases where liming of soils is required. Therefore, the calcium carbonate sludge should be handled separately and dewatered further, if necessary, for final disposal by land fill.

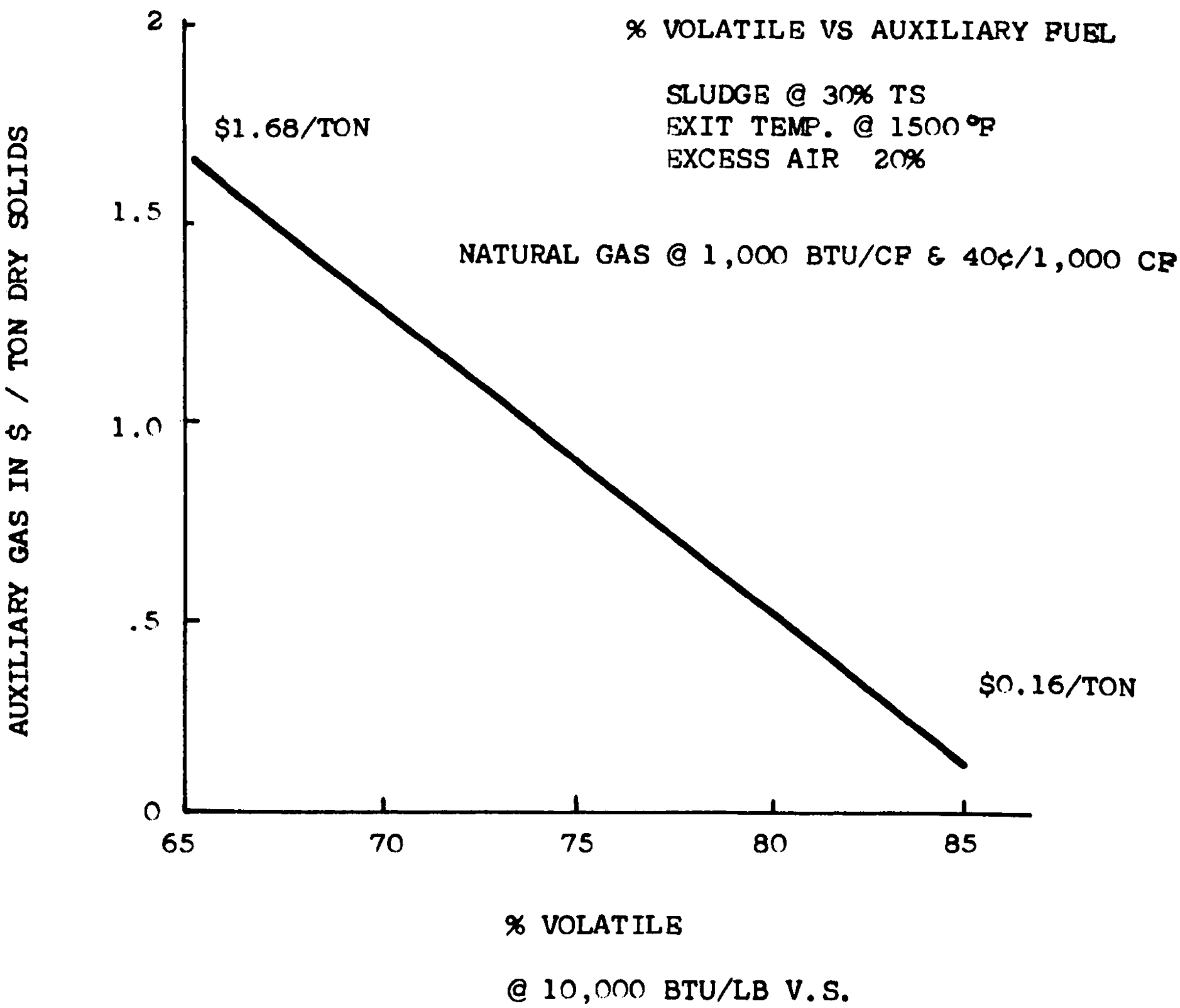


FIGURE 15

EFFECT OF VOLATILES IN SLUDGE ON FUEL (NATURAL GAS) COST

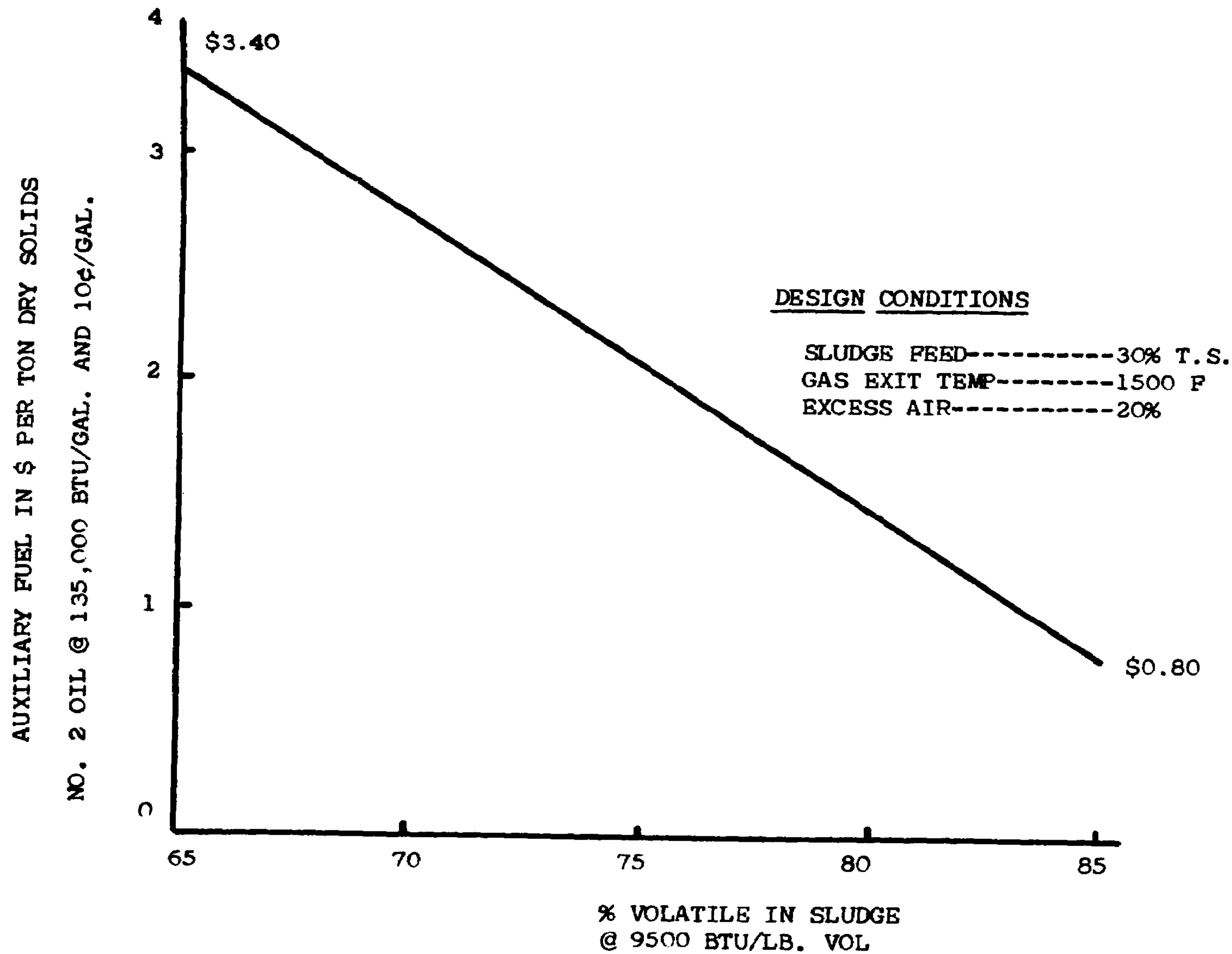


FIGURE 16

EFFECT OF VOLATILES IN SLUDGE ON FUEL (NO. 2 OIL) COST

AUXILIARY FUEL REQUIREMENTS

The two important factors that affect the auxiliary fuel requirements are the heat value of the sludge and the heat required for adequate burning. By adequate burning, it is meant the heat required for complete incineration of the sludge and to raise the temperature of the gases to a sufficient level to insure odor control. The magnitude of the temperature requirement depends upon the nature of the sludge being burnt but the minimum deodorizing temperature for conventional incineration units has been established at 1350° F - 1400° F as shown in Figure 17.

The heat required for the incinerator system depends primarily on the efficiency of burning and the degree of excess air required. The following constitute the total heat requirements:

1. Heat required in raising the temperature of sludge from about 60° F to 212° F; evaporating water from sludge; increasing the water vapor and air temperature of the gas; and increasing the temperature of dried volatiles to the ignition point.

2. Heat required to raise the temperature of the exhaust gas to the deodorizing temperature.

3. Heat required to raise the temperature of the air supply required for burning plus the excess air.

4. Heat losses due to radiation.

5. Cooling air losses.

6. Heat required for other endothermic reactions taking place.

The heat content of the organic sludge solids serves to raise the end products of combustion along with the moisture content of the filter cake. The sludge solids draw sufficient heat from the surroundings to reach kindling temperature before combustion can start. When the heat released is sufficient to replace the amount withdrawn, combustion will be maintained. When the quantity of heat released is insufficient to maintain combustion temperature at deodorizing level, heat is recovered from the stack gases and reused, or heat is supplied from an outside source.

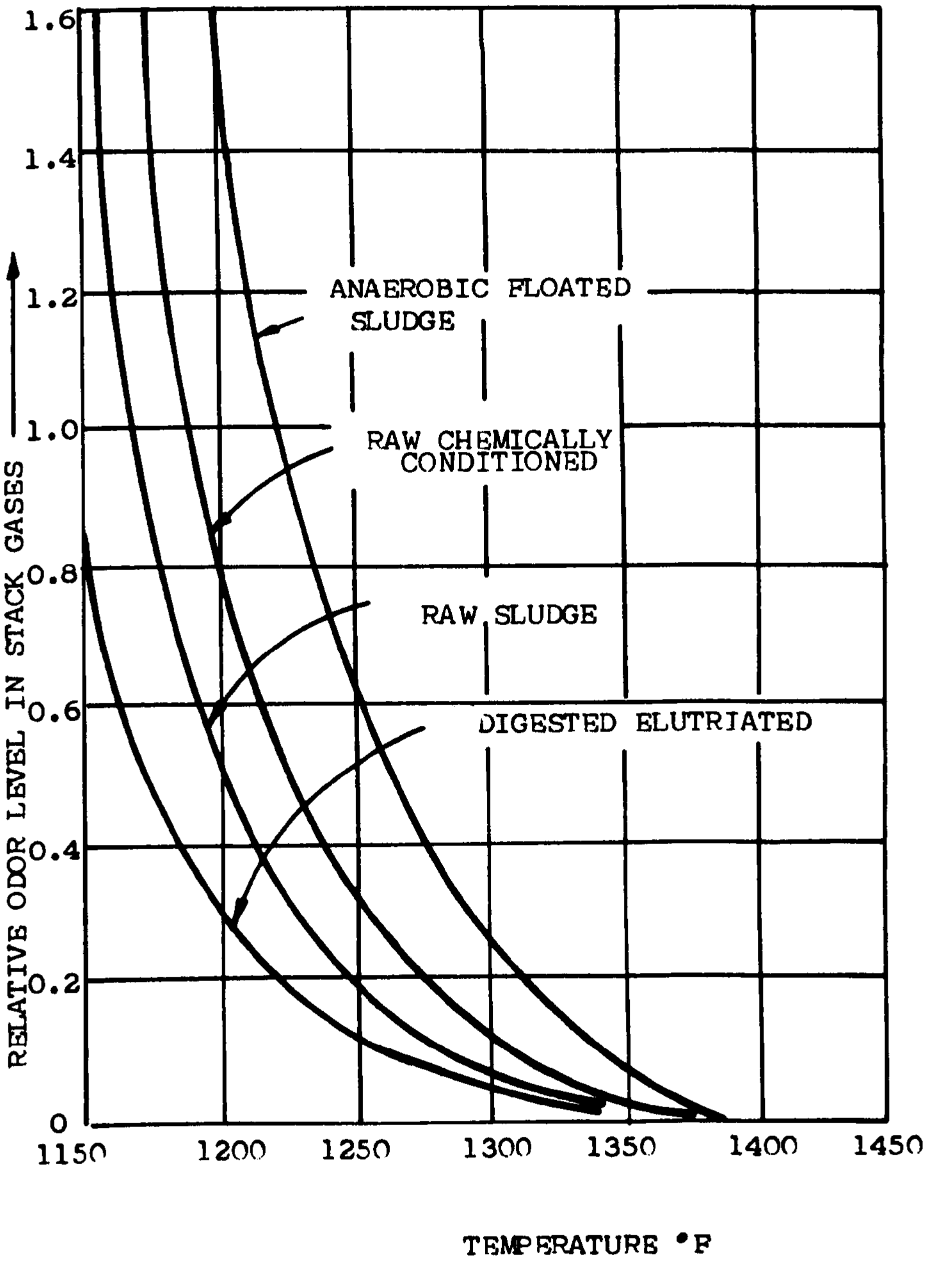


FIGURE 17

RELATIONSHIP OF ODOR LEVEL IN STACK GASES TO HIGHEST PROCESS TEMPERATURE ENCOUNTERED

PROCESS VARIABLES

Excess Air

Because of the normal variations in the organic characteristics of the sludge and the feed rate, excess air is added to the combustion chamber. The excess air also increases the opportunity of contact between fuel and oxygen which is necessary if combustion is to proceed. To insure complete thermal oxidation, it has been necessary to maintain 50 to 100% excess air over the stoichiometric amount of air required in the combustion zone. This much excess air is undesirable in that it quenches the reaction temperature by acquiring 12 to 24% of the input BTU's to heat the excess air. If excess air is not supplied for this reason, it may be difficult to maintain the minimum deodorizing temperature. Therefore, a closely controlled minimum excess air flow is desirable for maximum thermal economy. The amount of excess air required varies with the type of burning equipment, the nature of the sludge to be burned, and the disposition of the stack gases. The impact of use of excess air on the cost of fuel in sludge incineration is shown in Figures 18 and 19.

When the amount of excess air is inadequate, only partial combustion of the carbon occurs, resulting in the formation of carbon monoxide, soot and odorous hydrocarbons in the stack gases. Further, the heat recovered from the partial burning of the carbon is substantially reduced as the heat value of carbon monoxide is only 4400 BTU/lb.

Preheating and Heat Recovery

Preheating of air is an important step in improving the thermal economy. Air preheat affords an increase in capacity for a given size reactor since the combustion gas volume is used most effectively and since this eliminates the otherwise necessary quantity of auxiliary fuel. The marked effect of preheating air on the cost of auxiliary fuel for various solids concentrations to sustain combustion is shown in Figure 20.

Preheating of air can be avoided in exceptional circumstances where the following conditions are satisfied:

1. The excess combustion air volume is maintained at the minimum required to insure combustion.

2. The grit and inert chemical agents are eliminated.

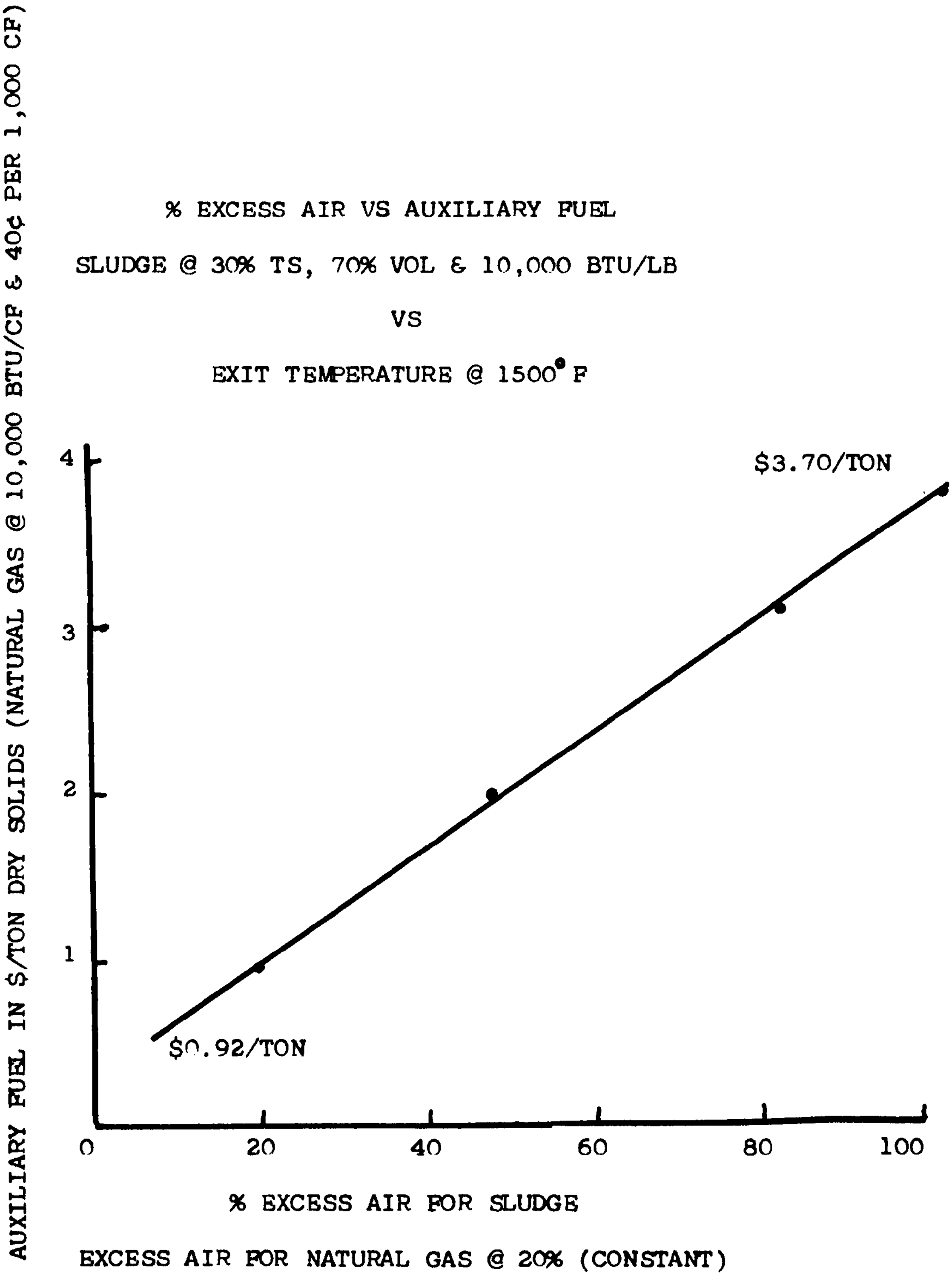
3. The moisture content is reduced to a point not often

% EXCESS AIR VS AUXILIARY FUEL

SLUDGE @ 30% TS, 70% VOL & 10,000 BTU/LB

VS

EXIT TEMPERATURE @ 1500° F



% EXCESS AIR FOR SLUDGE

EXCESS AIR FOR NATURAL GAS @ 20% (CONSTANT)

FIGURE 18

THE IMPACT OF EXCESS AIR ON THE COST OF NATURAL GAS IN SLUDGE INCINERATION

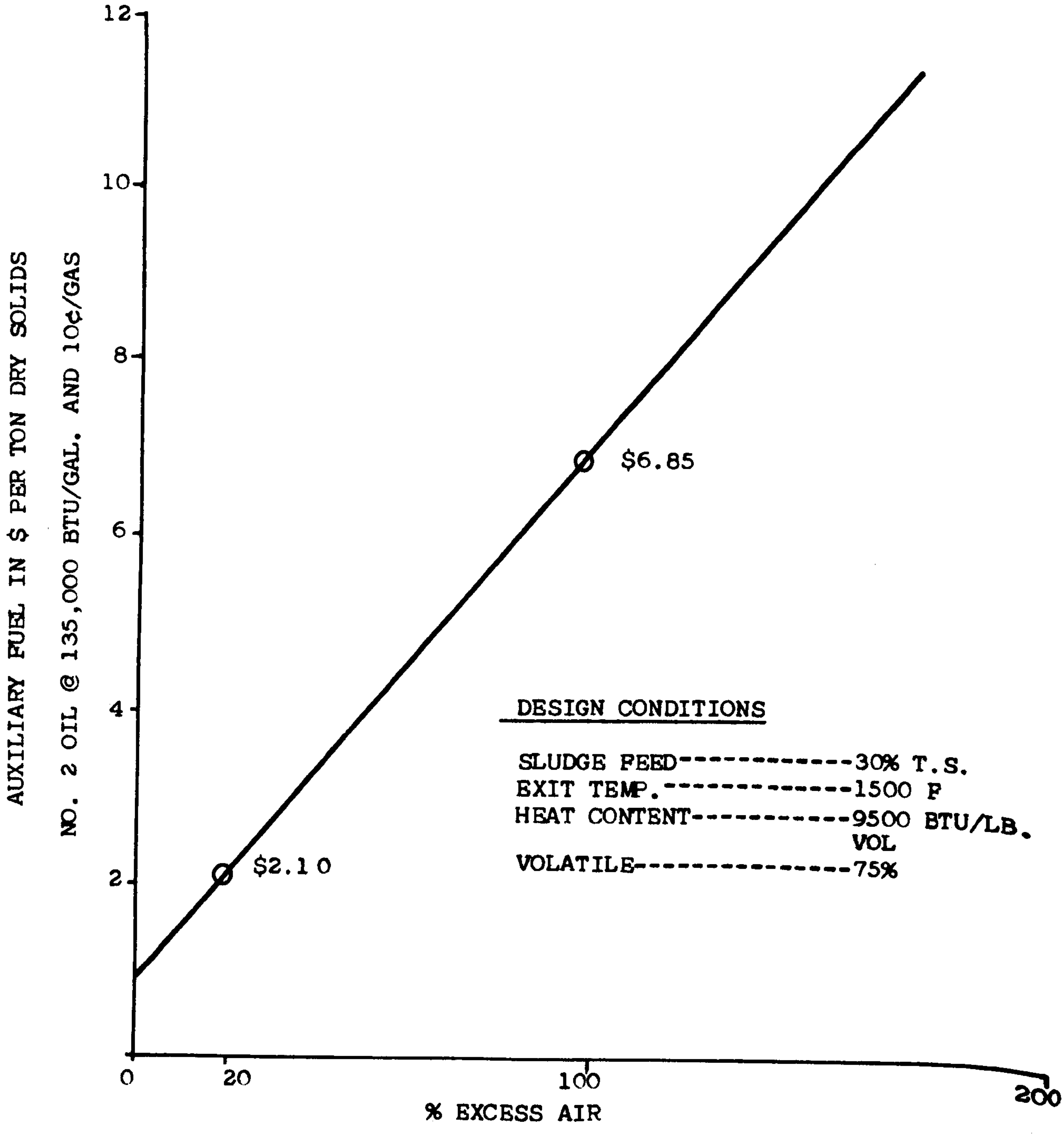


FIGURE 19

THE IMPACT OF EXCESS AIR ON THE COST OF NO. 2 OIL IN SLUDGE INCINERATION

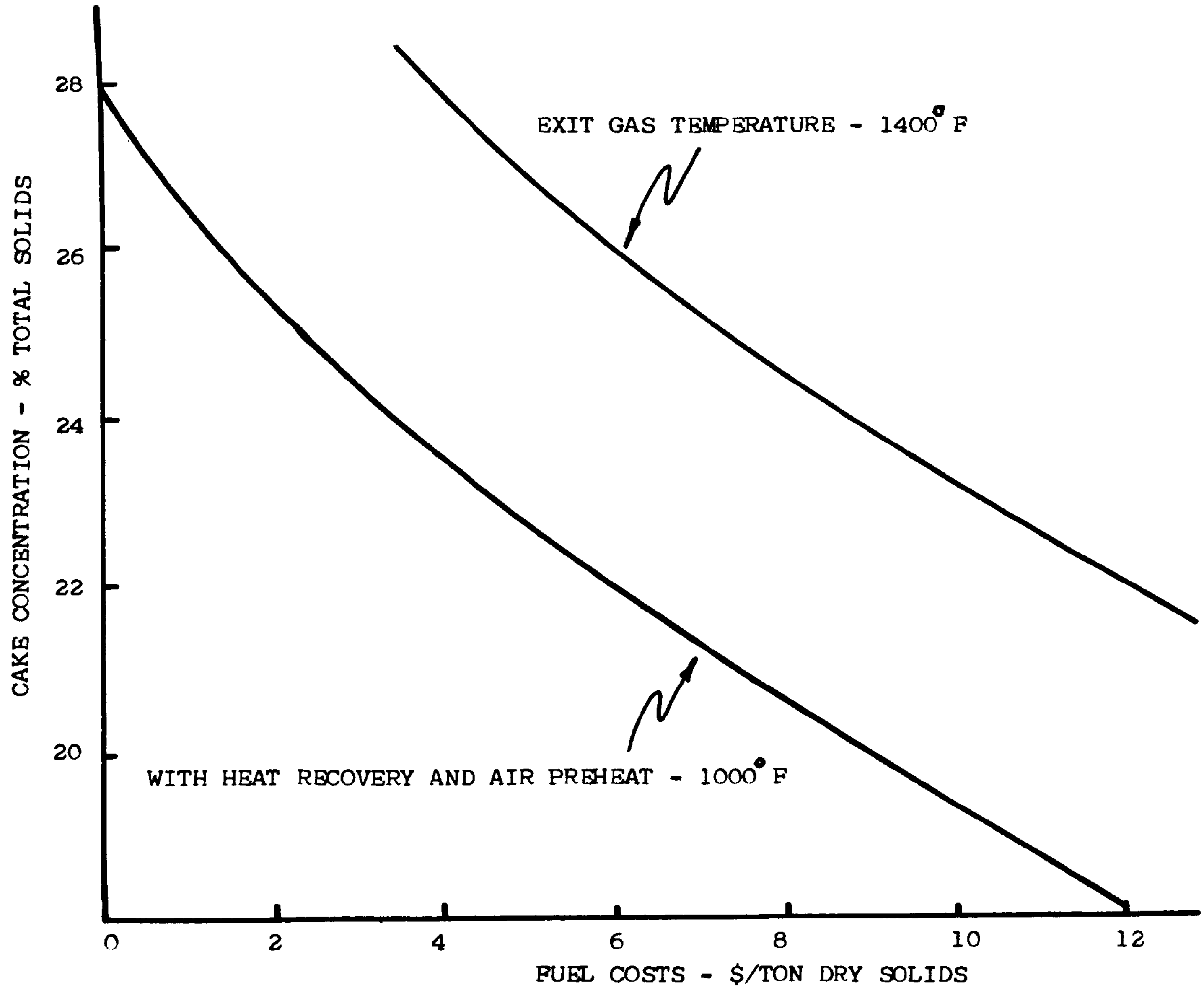


FIGURE 20 THE EFFECT OF PREHEATING AIR ON FUEL COSTS

attainable by vacuum filtration.

4. The volatile content of the total solids exceeds 70%.

Heat is recovered from stack gases and the advantage of recovering heat is shown in Figure 20. It should be noted that the preheat exchanger represents a significant capital cost and it is to be recommended only after a complete economic evaluation of the process.

Solids and Free Moisture

Most of the sludges to be disposed of by incineration will not support autogenous combustion because of an excessive water content. Thus, auxiliary fuel becomes a prime factor in process evaluation. When the sludge feed is drier, a smaller sized combustion unit is needed and the burning is more efficient. The impact of free moisture on the cost of auxiliary fuel required to sustain combustion for systems with and without heat recovery is shown in Figures 21 and 22. The importance of obtaining a solids concentration greater than 30% can be illustrated with Figure 23. For example, at 25% total solids there is only enough heat available to raise the combustion products and moisture to 900° F and this temperature is far below the accepted 1350 - 1400° F necessary for deodorizing the stack gases of a conventional combustion unit.

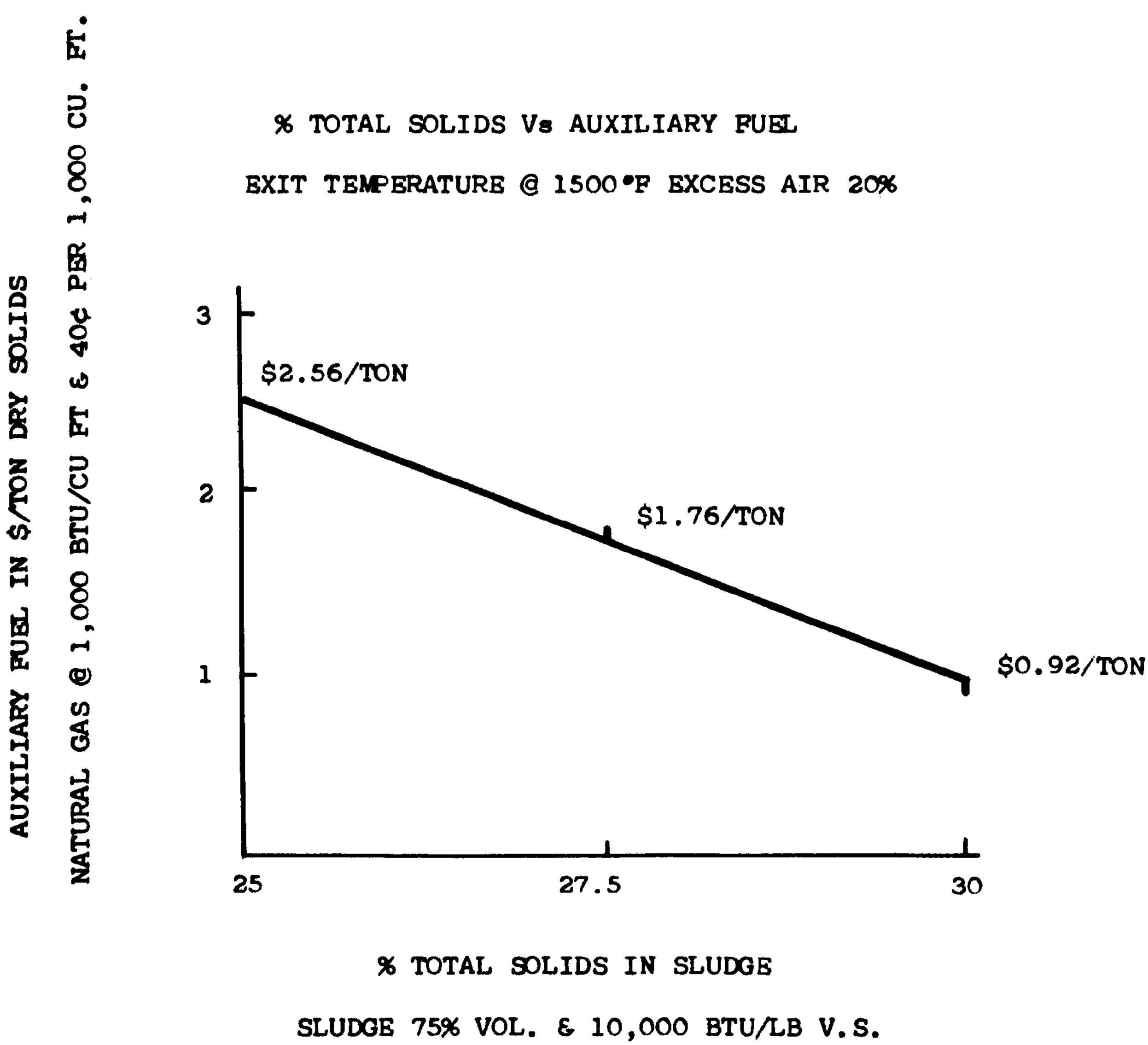


FIGURE 21

THE EFFECT OF MOISTURE CONTENT ON THE COST OF SLUDGE COMBUSTION

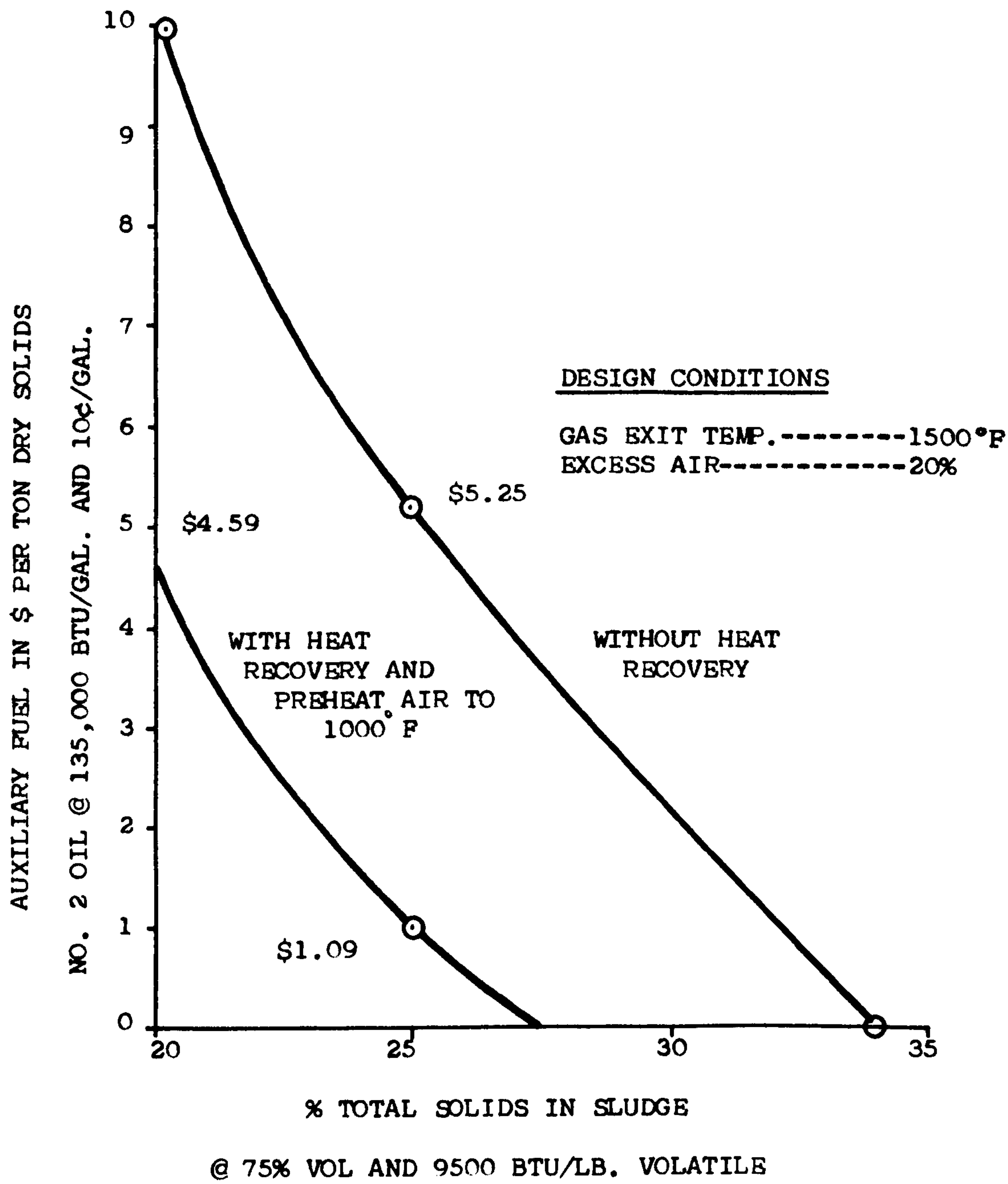


FIGURE 22

EFFECT OF MOISTURE CONTENT ON THE COST OF SLUDGE COMBUSTION SYSTEMS WITH AND WITHOUT HEAT RECOVERY

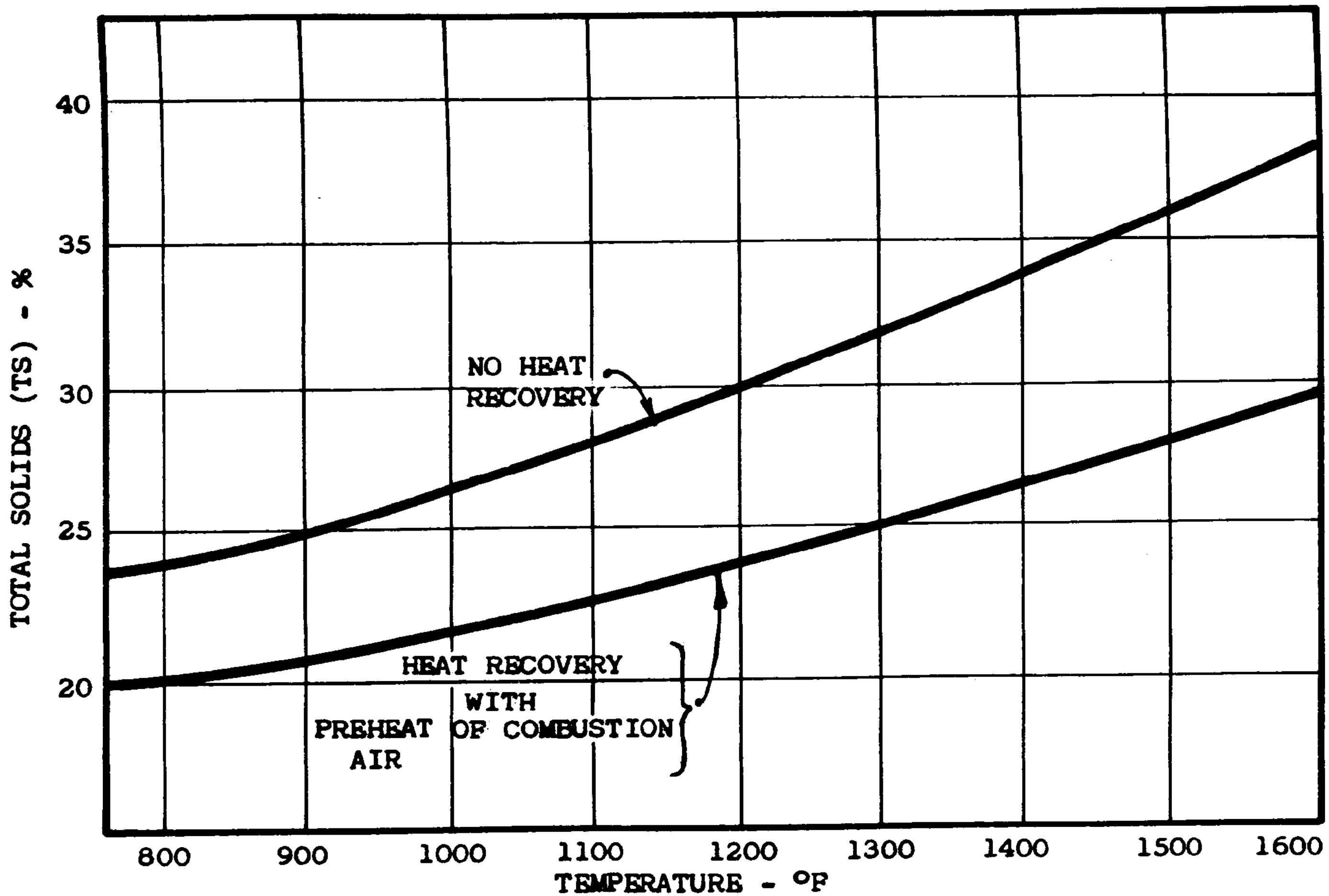


FIGURE 23

EQUILIBRIUM CURVES RELATING COMBUSTION TEMPERATURE

TO CAKE CONCENTRATION

SLUDGE INCINERATION SYSTEMS

System Components and Make Up

Sludge incineration systems include the following components, in general:

1. Sludge thickener

2. A disintegrating or macerating system

3. Polymer handling and feeding system or other pretreatment schemes

4. Centrifuge or vacuum filter or any mechanical dewatering system

5. Incinerator feed system

6. Air pollution control devices

7. Ash handling facilities

8. Complete set of automatic controls such as fail-safe devices, stack temperature regulator and interlocks to permit positive control of excess air.

Incineration processes involve two steps: 1) drying, and 2) combustion. In addition to fuel and air, time, temperature and turbulence are necessary for a complete reaction. The drying step is different from preliminary dewatering. The drying is achieved by mechanical means and precedes the incineration process. Sludges having a solids content of 25% and more are delivered to the most common types of incinerators. Because of the high moisture content, the heat required to evaporate the water nearly balances the heat available from combustion of the dry solids[44].

Drying and combustion is done in separate pieces of equipment or successively in the same unit. Manufacturers have developed widely varying types of sludge drying and combustion equipment. But the principle variation between manufacturers is in the requirement for heating excess air and the efficiency of utilizing the waste gases.

The principal types of sludge incineration systems are as follows:

1. Multiple hearth furnace

2. Fluidized bed

3. Flash drying with incineration

4. Wet oxidation (Zimpro Process)

5. Atomized suspension technique

Multiple Hearth Furnaces

The most widely used type of incineration system is multiple hearth furnace. The multiple hearth type of incineration is very popular in large cities where alternate final sludge disposal techniques are inconvenient or too expensive. There are about 120 of these units installed[45]. The types of solids incinerated were very varied and are as follows:

Raw primary sludge	Scum
Grit	Ground refuse
Grease	Activated sludge
Screenings	Trickling filter sludge
Skimmings	

Multiple hearth units are popular because they are simple, durable and have the flexibility of burning a wide variety of materials even with fluctuations in the feed rate.

A cross section of a typical multiple hearth incinerator is shown in Figure 24, and a typical flow diagram for a plant incorporating such a system is shown in Figure 25. Multiple hearth units are available in sizes to handle from 5 to 1250 tons/24 hr. These units are designed with varying diameters from 6 ft-0 in. to 22 ft-3 in., and a varying number of hearths--usually between four and twelve[1]. Multiple units are often used as it allows flexibility of operation. The units are capable of burning grit, screenings, grease and sludge.

The design and operation of multiple hearth units are made simple so that they cost less compared to the other types of incinerators. The multiple hearth furnace consists of a circular steel shell surrounding a number of solid refractory hearths (See Figure 24) and a central rotating shaft to which rabble arms are attached. Each hearth has openings that allow the sludge to be dropped to the

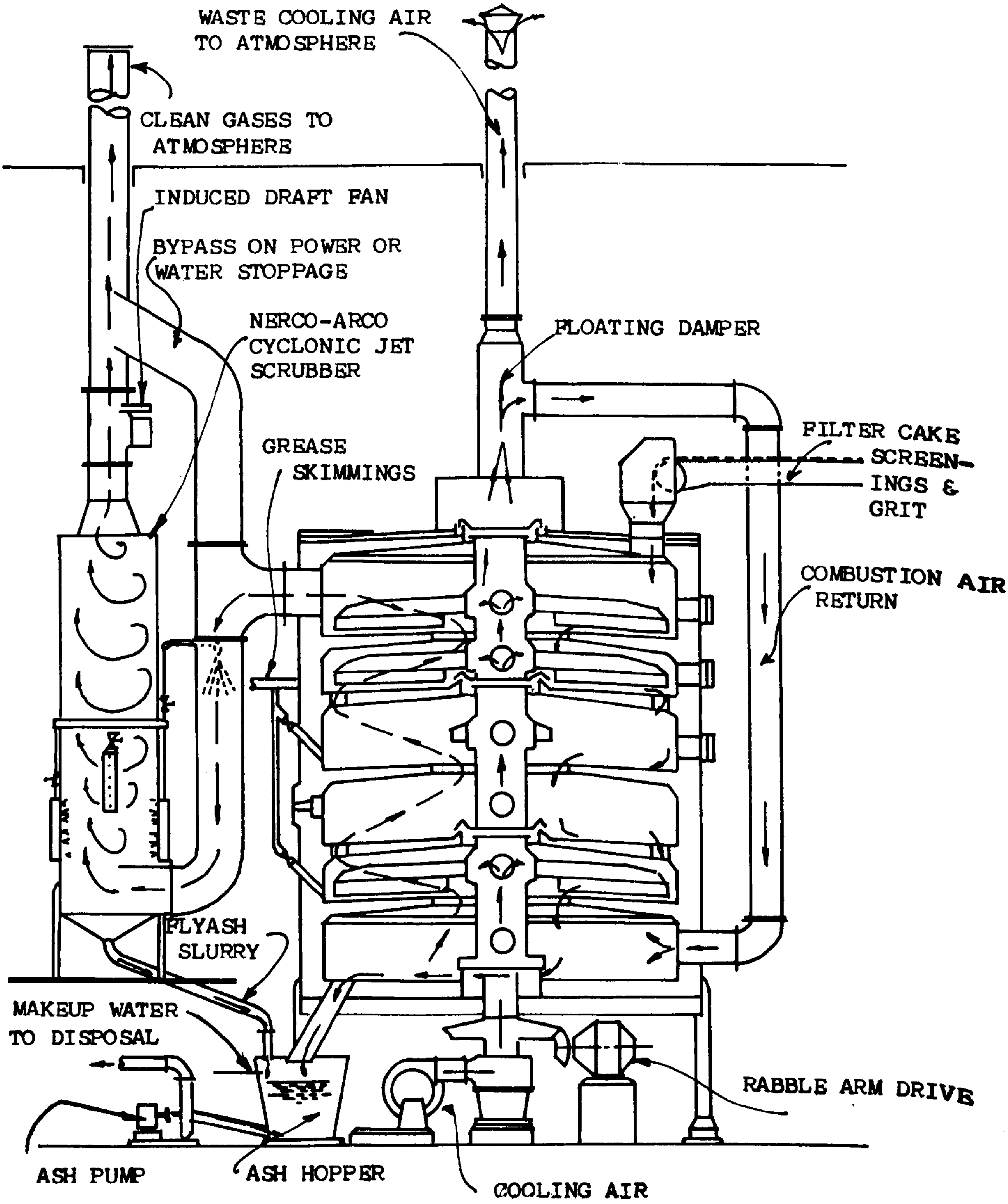


FIGURE 24

TYPICAL SECTION OF MULTIPLE HEARTH INCINERATOR

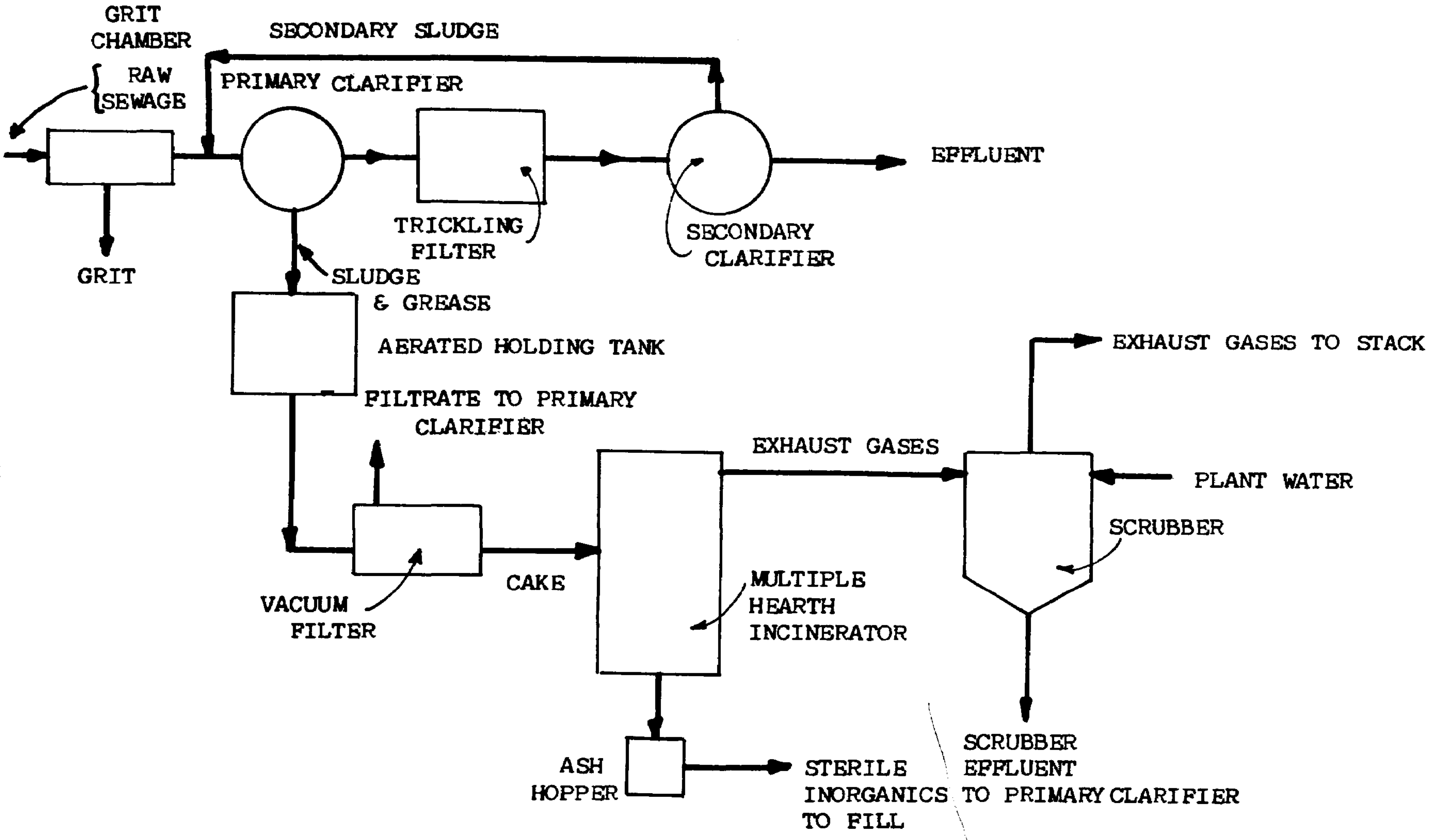


FIGURE 25

FLOW SHEET OF A TYPICAL PLANT WITH MULTIPLE HEARTH INCINERATOR next lower hearth. The central shaft and rabble arms are cooled by air supplied in regulated quantity and pressure from a blower discharging air into a housing at the bottom of the shaft. Rabbling is very important to combustion because it breaks up large sludge particles, thereby exposing more surface area to the hot furnace gases that induce rapid and complete combustion.

Partially dewatered sludge is continuously fed to the upper hearths which form a drying and cooling zone. In the drying zone, vaporization of some free moisture and cooling of exhaust gases occur by transfer of heat from the hot gases to the sludge. Intermediate hearths form a high temperature burning zone where all volatile gases and solids are burned. The lowest hearth of the combustion zone is the place where most of the total fixed carbon is burned. The bottom hearth of the furnace functions as a cooling and air preheating zone where ash is cooled by giving up heat to the shaft cooling air which is returned to the furnace in this zone. The temperatures range from 600° F at the bottom, 1600 - 1800° F in the middle hearths, and 1000° F on the top hearths. The waste gases from combustion are heated to deodorizing temperature so as to guard against odor nuisance. Exhaust gases leaving the incinerator at the top are scrubbed in a wet scrubber to remove flyash.

Auxiliary fuel is invariably used to heat the waste gases before venting to the atmosphere and the operating cost becomes expensive due to the fuel cost. A heat recovery device may be suggested to improve the economy of high temperature deodorization but this requires expensive deodorization and combustion air preheating equipment.

Incineration of sludge is generally considered to be more expensive than other sludge disposal processes. However, with the increase in the population served, the economics are favorable expecially for large size communities. This could be noted in the Figure 26, developed from the data of Bartlett-Snow-Pacific, Inc.[46]. The cost figures include vacuum filtration equipment, chemicals, power, fuel and maintenance.

McLaren, in his evaluation of sludge treatment and disposal systems for Canadian municipalities[27] estimated that the capital cost of incinerators was between $5 to $10 per ton of dry solids based on a 30-year amortization at 5% interest. He also estimated the operating costs to be between $4 to $7 per ton and, thus, the total annual cost varies from $9 to $17 per ton of dry solids.

Quirk estimated the cost for digested sewage sludge incineration[47] for a city of about 100,000 contributing 2,530 tons of solids per year. The total annual operating cost of solids with and without deodorization is summarized in Table IX.

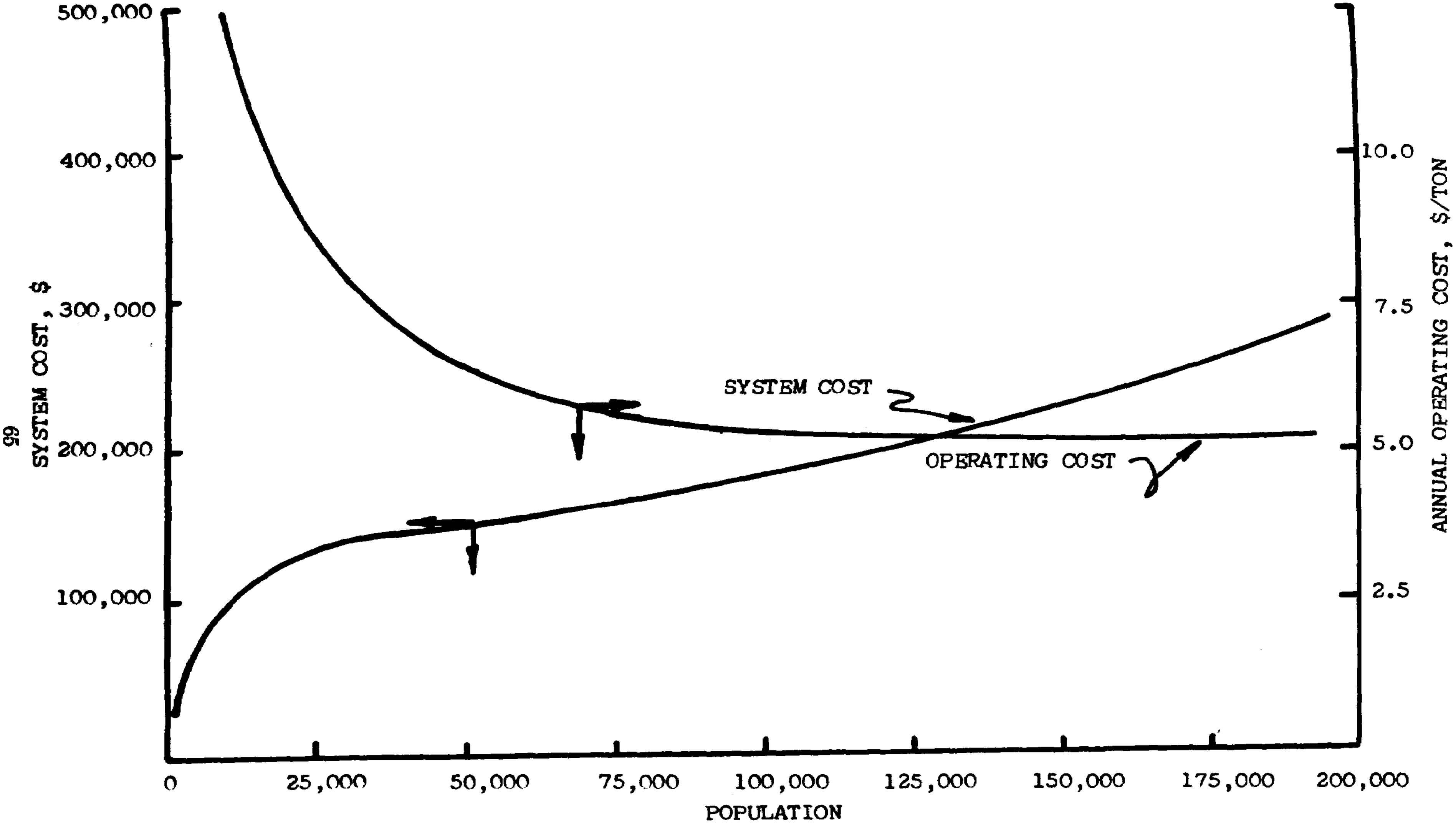


FIGURE 26

RELATIONSHIP BETWEEN POPULATION SYSTEM COST AND ANNUAL OPERATING COST

TABLE IX

TOTAL ANNUAL OPERATING COST FOR SLUDGE INCINERATION

WITH AND WITHOUT DEODORIZATION

(FOR DORR-OLIVER F/S UNIT)

1. Total annual cost without deordorization

A. Capital cost (includes vacuum filtration but excludes ash disposal facilities)	$11.75/ton
B. Operating cost	
1) vacuum filtration	7.91/ton
2) incineration	6.36/ton
Total	$26.02/ton

2. Total annual cost with deodorization

A. Capital cost (includes vacuum filtration but excludes ash disposal facilities)	$12.07/ton
B. Operating cost	
1) vacuum filtration	7.91/ton
2) incineration	9.50/ton
Total	$29.48/ton

There is a wide variation in operating costs found in the literature and this variation could be attributed to the variation in supplemental fuel requirements. A wide difference between the fuel required for raw sludge incineration and digested sludge incineration was reported by Schroepfer[48] and the additional heat requirements for raw sludge and digested sludge were found to be 1.75 and 17.9%, respectively. This variation in fuel requirements accounts for a difference in operating cost of $1.06 per ton.

Multiple hearth furnaces may also be operated as sludge dryers. The flow of sludge and the rabbling action in multiple hearth furnaces are identical to incineration procedures. Modifications to the basic furnace design include fuel burners at the top and bottom hearths plus down-drafting of the gases. As the solids moved downward through the furnace, the gases became cooler and the solids became drier. At the point of exit from the furnace, the gas temperature was about 325° F and the solids temperature about 100° F.

Incineration of sewage sludge in multiple hearth units is progressively increasing and, therefore, some improvements in the design and operation would be desirable even though the present units operate quite satisfactorily. Recovery and reuse of heat offers one important potential way of improving the economy of incineration. Recovered heat could be used to condition the sludge to be incinerated. Other areas of improvements could be the development of additional instrumentation to control the combustion process and the development of some beneficial uses for ash, such as the use of ash as an aid to sludge conditioning.

Fluidized Bed Furnaces

Fluidized bed technology, developed for catalyst recovery in oil refining by the Standard Oil Development Company, has been applied to metallurgical roasting, lime mud reburning, spent sulfite liquor combustion, the incineration of municipal and industrial sludges and a host of other industrial applications.

A typical section of the fluid-bed reactor used for combustion of sewage sludges is shown in Figure 27. The bed material is composed of graded silica sand. When particles are suspended in an upward-moving stream of gases, the mixture of particles and gases behaves much like a fluid. Mixing is an important factor in combustion. The air is supplied as near the surface of the fuel as practical and thoroughly mixed with the combustible matter in order that the combustion may be completed in a short time and the combustion space used more effectively. Sufficient air is used to keep the sand in suspension but not to carry it out of the reactor. The

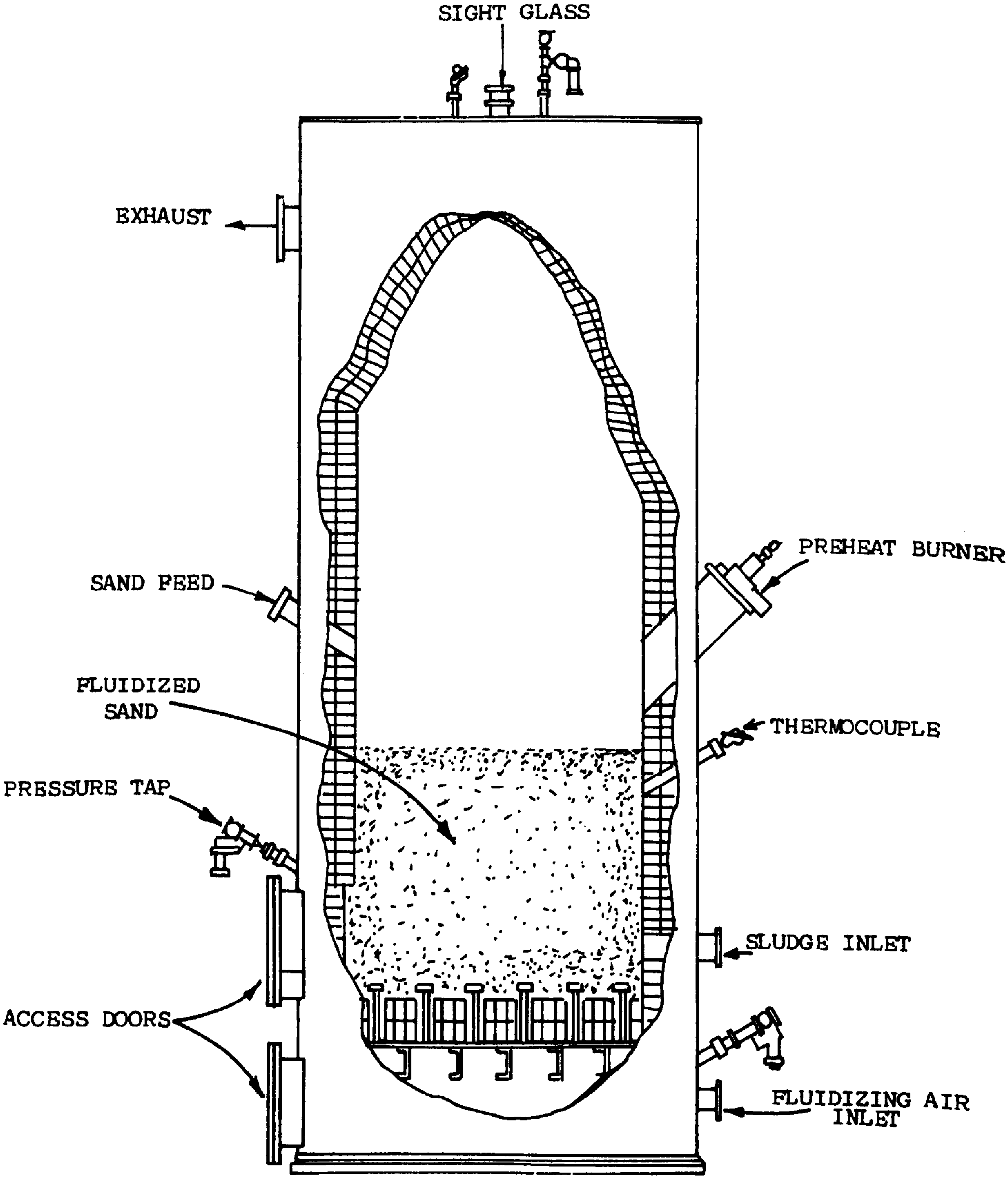


FIGURE 27

TYPICAL SECTION OF A FLUID BED REACTOR

(DORR-OLIVER, INC.)

intense and violent mixing of the solids and gases 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[42].

The heat required for raising the sludge to the kindling point must come from the combustion zone. While standard combustion units rely on the heat transfer from the hot gases which contain only 16 BTU/cu ft, the expanded bed of the fluid-bed reactor has 16,000 BTU/cu ft. Because of the enormous reservoir of heat in the bed and a rapid distribution of fuel and sludge throughout the bed, optimum contact between fuel and oxygen and rapid transfer of heat is insured. The sand bed retains the organic particles until they are reduced to mineral ash and the violent motion of the bed comminutes the ash material, preventing the build up of clinkers. The resulting fine ash is constantly stripped from the bed by the up-flowing gases.

The major advantages of using the fluid-bed reactor include:

1. Ideal mixing of the sludge and the combustion air is achieved.

2. Drying and combustion take place concurrently within the bed and, therefore, there is no air pollution problem.

3. The reactor has no moving parts.

4. There are no liquid heat-exchange surfaces to scale and the operating pressure is as low as 2 psig.

5. The unit can be operated four to eight hours a day with little reheating when restarting because of the fact that the sand bed serves as a heat reservoir.

6. Need for a mechanical system for ash removal is eliminated because ash removal from the reactor is accomplished by the up-flowing combustion gases.

The flow diagram of the Dorr-Oliver Fluo Solids disposal system is shown in Figure 28.

The major process steps involved are listed below:

1. solids preparation

2. solids dewatering

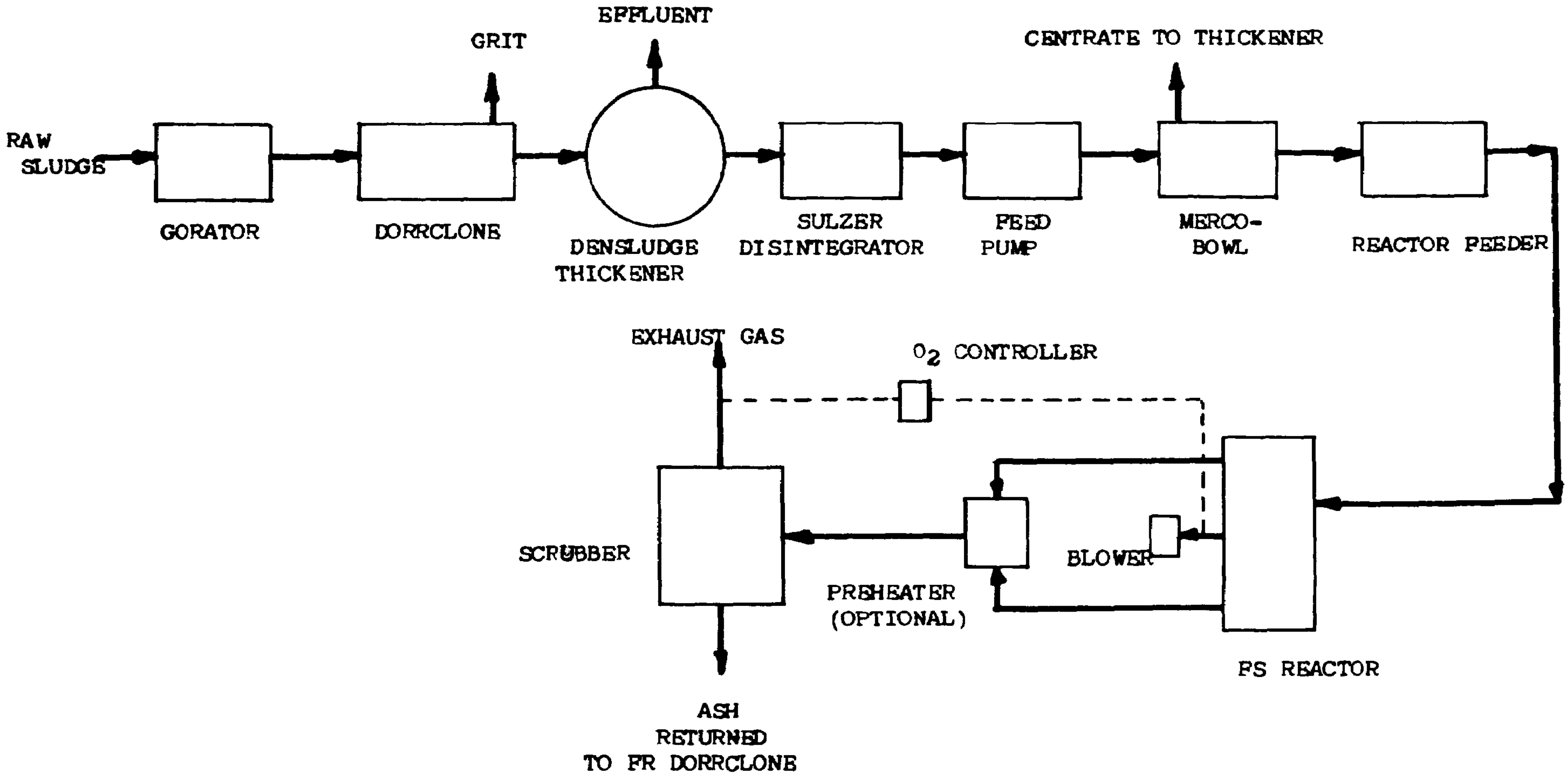


FIGURE 28

FLOW DIAGRAM OF DORR-OLIVER'S FS DISPOSAL SYSTEM

3. solids combustion

4. stack gas treatment.

The solids preparation starts with the degritting operation. Degritting is an important step in order to increase the heat value of the sludge and to protect the equipment from wear and tear. In the conventional design of grit chambers practiced in the United States, usually about 95% of the 48 - 65 mesh particles are removed. To achieve higher degree removal of about 95% of the 200+ mesh particles, hydrochlones* are installed and they represent only a fraction of the installed cost of a gravity unit. Sludge thickening is the next step for solids preparation as it equalizes the sludge flow and increases the solids concentration.

The second step is sludge dewatering and is preceded by a solids disintegrator or comminutor. Sludge dewatering is usually achieved by either a centrifuge or vacuum filter. Dewatering is a very important step as it improves the economics of combustion by reducing the amount of water fed to the reactor.

In the combustion step, the dewatered sludge solids are pumped into the reactor operating at a pressure of about 2 psi and a temperature of 1400 - 1500° F. Sludge has to be fed only when the bed temperature has been raised to 1400° F and this is necessary in order to insure odor control. Because of the high temperature, the sludge quickly dries and burns and, thus, helps maintain the bed temperature. The solids are reduced to inert ash and removed from the fluidized bed by the upward flowing combustion gases.

Exhaust gases are scrubbed usually in wet scrubbing equipment using the treatment plant effluent as the scrubbing medium. Ash solids are separated from the liquid in a Dorrclone and the liquid returned to the raw waste stream.

Following the laboratory test work, a complete pilot plant was installed at the New Rochelle, New York, sewage treatment plant[42]. The initial pilot plant installation consisted of a thickener, a sludge storage tank, a sludge transfer pump, a progressing cavity pump to feed the solids to concentration unit, a screening-type centrifuge, a fluid-bed reactor and a wet-impingement scrubber. The recoveries in the screening centrifuge were too low and, therefore, it was replaced by solid-bowl centrifuge which produced 30 to 40% solids and a recovery of 85 - 95% of the feed solids. The pilot plant tests showed that 10 to 15% excess air was adequate for complete

*Dorrclone is the registered trade mark of Dorr-Oliver, Inc., for hydrocyclones.

combustion of the carbon and hydrogen. It was also found that smoke and odor conditions were eliminated above 1100 - 1150° F, compared with the required 1350 - 1400° F for deodorization. However, the combustion capacity of the unit was reduced because of the reduced sludge combustion rate. Radiation losses were found to be less than 4% of the input BTU's when the operating temperature was 1600 - 1700° F.

The first commercial combustion system employing the fluid-bed technique was installed in the City of Lynnwood, Washington[42]. Raw primary sewage sludge was combusted in this unit following gravity thickening and centrifuge dewatering. The underflow from the thickener varied considerably and the average concentration was in the range of 10 to 12% total solids.

The scum removed from the primary clarifier is pumped to the thickener along with the settled solids. The floating material removed from the thickener is concentrated by removing the subnatant liquid and, then, by pumping the concentrated scum into the thickener sludge blanket via sludge withdrawal pipe. Pneumatic conveying of the low volatile sludge was found to be impractical and this system was replaced by a stainless steel lift conveyor and retractable extrusion screw.

The fluid-bed reactor was designed to receive 220 pounds dry solids per hour at 75% volatile sludge at about 35% solids. The reactor has been operated with 20% excess air or about 360 scfm at a sludge feed rate of about 210 lb dried solids/hr. No. 2 oil was used for daily reheating and as auxiliary fuel because the reactor has not been operated continuously. The reheat time and the fuel required for reheating is a function of the duration of shut down and this is shown in Figure 29 as observed in the Lynnwood plant.

The feed rate control was automatic and based on the oxygen content of the stack. It has worked very well. The auxiliary fuel system is controlled by the bed temperature, and fuel can be added automatically if the temperature falls below a preset minimum. The system was designed in such a way that it will shut down automatically in case of failure of an item of equipment or instrument.

The scrubber, using about 40 gpm final effluent, was able to cool the exhaust gases to about 160° F in addition to removing the ash. The total operating power for the complete disposal system has been estimated at 237 KWH/ton dry solids.

The annual operating cost per ton of dry solids varies, depending on the amount of solids, from about $25 to $50. The cost of operation is greatly reduced by the utilization of automatic

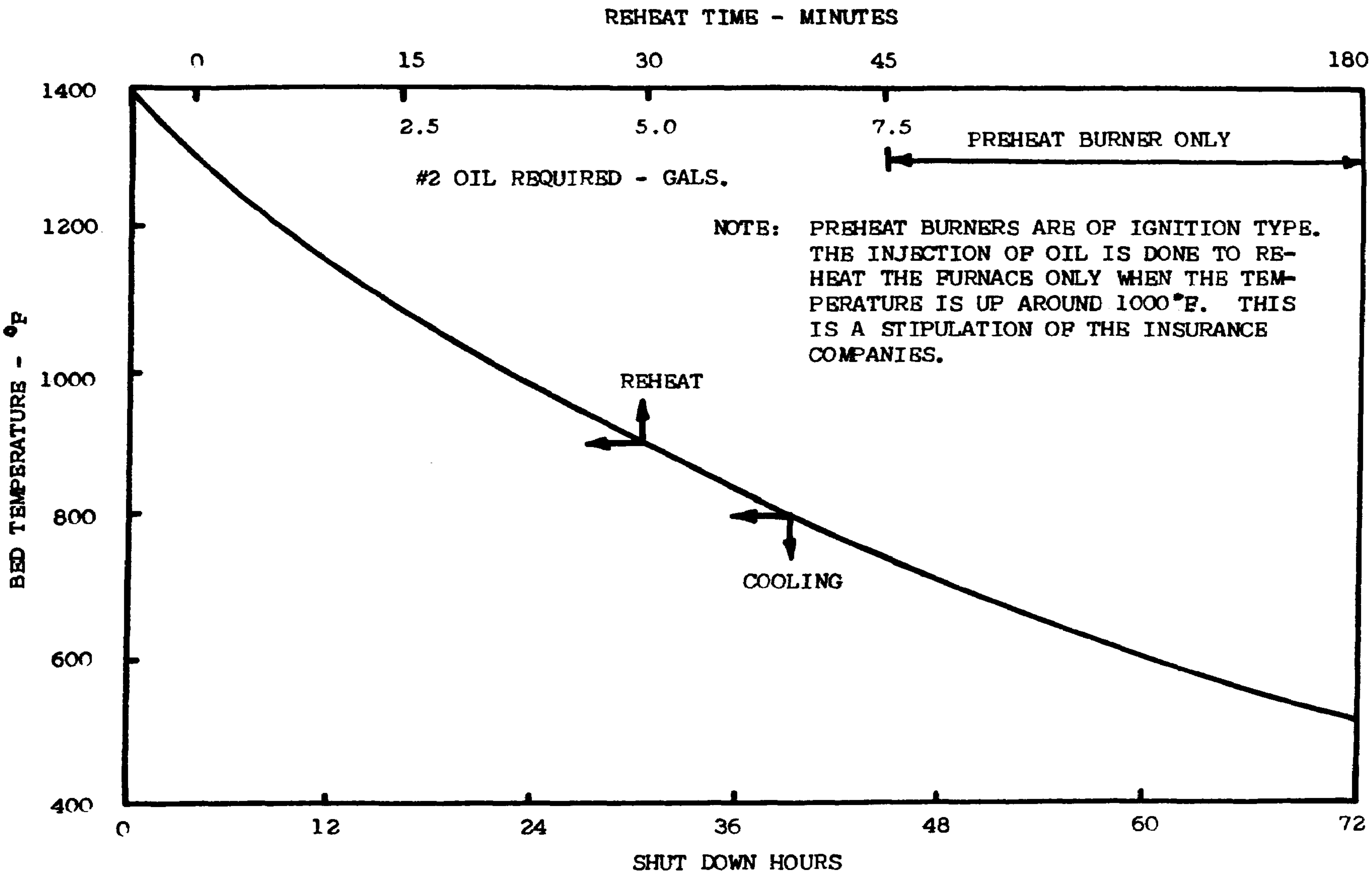


FIGURE 29

FUEL REQUIREMENTS FOR PREHEATING AND REHEATING THE LYNNWOOD FS REACTOR AFTER VARIOUS SHUT DOWN PERIODS controls to maintain optimum combustion conditions and, thus, freeing the plant operator for other duties. The results of the pilot plant at New Rochelle and the commercial installation at Lynnwood indicate that high speed centrifugation produces primary sludge concentrations that are economical to burn without heat recovery or the use of a sludge-drying stage.

The economy of the fluidized-bed system is a function of the percentage of the excess air. Therefore, control of the excess air is very necessary and this is achieved by automatic controls.

An air preheater is an optional piece of equipment which will reduce the auxiliary fuel cost[49]. The incoming air for fluidization and combustion is heated to 1000° F by the hot exhaust gases from the reactor. Even though preheating reduces the fuel cost considerably, the capital cost of preheat system is about 15% of the fluidized bed plant's investment. Further, maintenance cost of the preheating system is considerable compared to other auxiliary equipment.

Albertson reported[42] the following cost data (See Table X) on combustion based on the performance of the plant at Lynnwood, Washington, serving a population of 8,000. These cost figures were extrapolated to 22,000 population and it was assumed that volatile matter will not increase above 70%. As can be seen in the Table, power and fuel accounted for 21.7% of the operating cost at the 8,000-population level, and 38.6% at the 22,000-population level. However, based on the total operating cost, including amortization of the capital cost, the figures are more attractive for 22,000 population than 8,000 population.

The capital and operating cost for an alternative system--single-stage digestion system--has been estimated for the same plant and this is furnished in Table XI.

Sohr[50] has reported a total operating cost of $25.32 per ton of dry solids for the East Cliff Sanitary District Plant, California. This figure includes the following:

fuel cost:	$ 2.50 per ton
power cost:	$ 4.47 per ton
labor cost:	$18.35 per ton

Feed solids concentration and its volatile content are the other major factors in the economy of combustion. The higher the solids concentration from vacuum filtration or centrifugation, the lesser the cost of combustion and this is shown in Figure 30. The effect of per cent of volatile solids on the cost of auxiliary

TABLE X

COMBUSTION COSTS FOR DORR-OLIVER F/S UNIT

Details	$/Ton Dry Solids	
	8,000 Population	22,000 Population
Capital Costs		
Combustion system, amortized at 4% interest over 25 years, on basis of design tonnage capacity.	15.00	15.00
Operating Costs		
Power @ 1¢/KWH	2.37	2.37
Fuel @ 12¢/gal. start up	0.45	0.39
Fuel @ 12¢/gal. operating	1.62	1.62
Maintenance	NA	NA
Labor (3 man hr/day)	16.00	7.00
Total	35.44	26.38

TABLE XI

SLUDGE DIGESTION COST

Details	$/Ton Dry Solids 8,000 Population	$/Ton Dry Solids 22,000 Population
Capital Costs		
Digestion system*	7.50	7.50
Operating Costs		
Power	4.48	1.80
Maintenance	NA	NA
Labor (3 man hr/day)	16.00	7.00
Sludge haulage**	18.00	18.00
Total	45.98	34.30

*Capacity for years 1 through 10 only.
**Based on hauling 50% of the raw solids weight at 6% TS and a unit cost of 0.9¢/gallon.

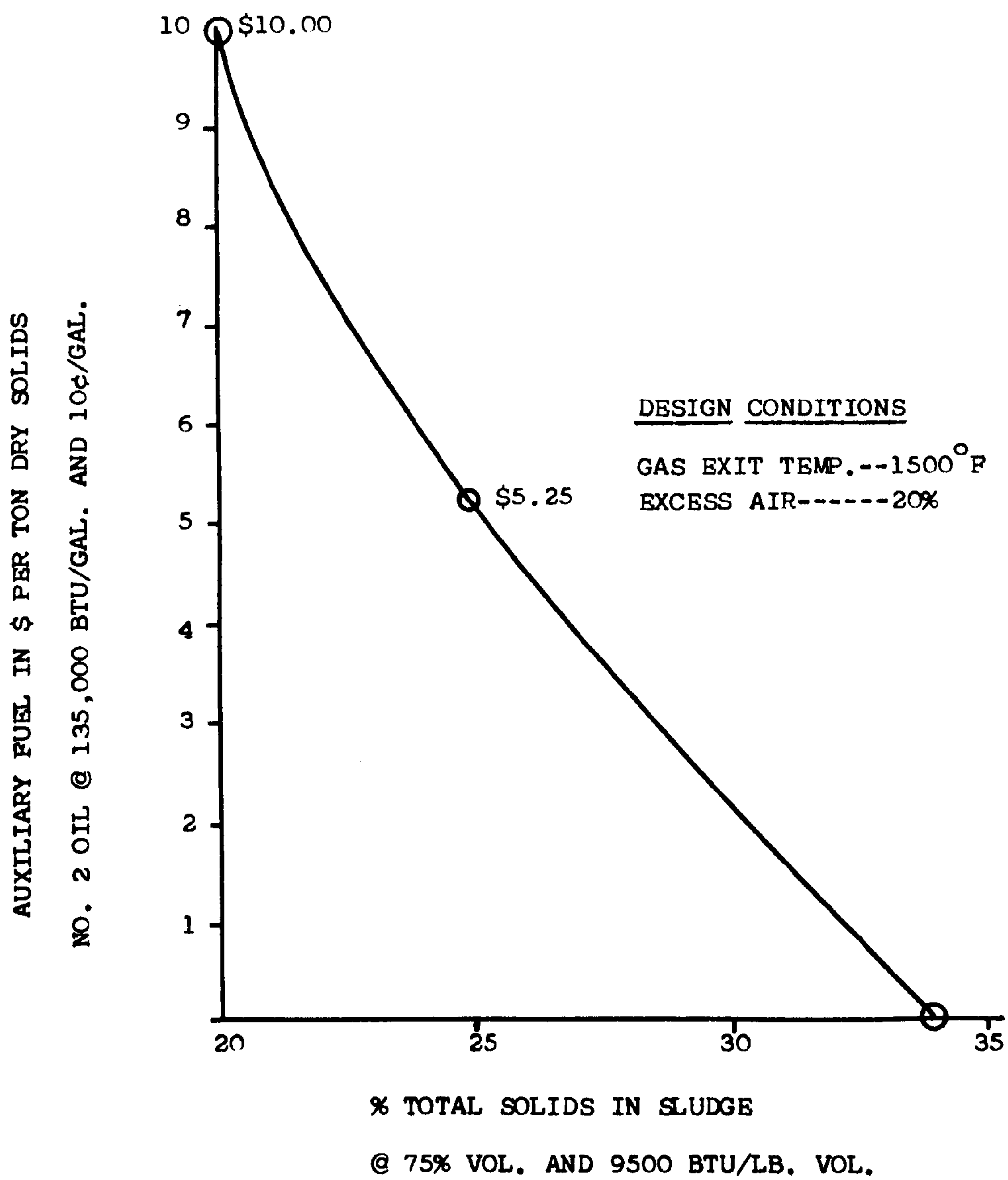


FIGURE 30

EFFECT OF FREE MOISTURE ON FUEL COST (NO. 2 OIL) fuel for sludge incineration is shown in Figures 15 and 16. The process steps, degritting, thickening, sludge dewatering, air preheating and close control of excess air, are very essential for optimizing the process efficiency.

Vacuum filtration always requires chemical conditioning whereas centrifugation does not. The operating cost for fuel, power and chemicals for fluidized-bed systems handling raw primary and secondary sludge is $15 - $18 per ton whereas it is $5 per ton for those handling primary raw sludge alone[9].

The fluidized-bed systems have been operating satisfactorily and they are very competitive with other techniques, especially when the operation is continuous and deodorization is required. When deodorization steps are not required, fluidized-bed systems are more expensive than multiple hearth furnaces.

Flash Drying and/or Incineration

Flash drying is the instantaneous removal of moisture from solids by introducing them into a hot gas stream. This process was first applied to the drying of sewage sludge at the Chicago Sanitary District in 1932 by the Raymond Division of Combustion Engineering, Inc.[51].

The pictorial flow diagram of the C-E Raymond Flash Drying and Incineration System is shown in Figure 31. This system is composed of four distinct cycles which can be combined in different arrangements to give the system maximum flexibility to meet specific requirements. The first cycle is the flash drying cycle, consisting of the hot gas duct, cage mill, mixer, uptake duct, cyclone, air lock, dry divider, and vapor fan. The wet filter cake is blended with some previously dried sludge in a mixer to make it fit for pneumatic conveyance. The blended sludge and the hot gases from the furnace at 1300° F meet ahead of the cage mill and flashing of the water vapor begins. The cage mill mechanically agitates the mixture of sludge and gas and the drying is virtually complete by the time the sludge leaves the cage mill. The sludge, at this stage, is dry at a moisture content of 8 to 10% and the dry sludge is separated from the spent drying gases in a cyclone. The dried sludge can be sent either to fertilizer storage or to the furnace for incineration.

The second cycle is the fuel-burning cycle. Combustion of fuel is essential to provide heat for drying the sludge and the fuel consists of gas, oil, coal or sewage sludge, itself. Primary combustion air, provided by the combustion air fan, is preheated and introduced

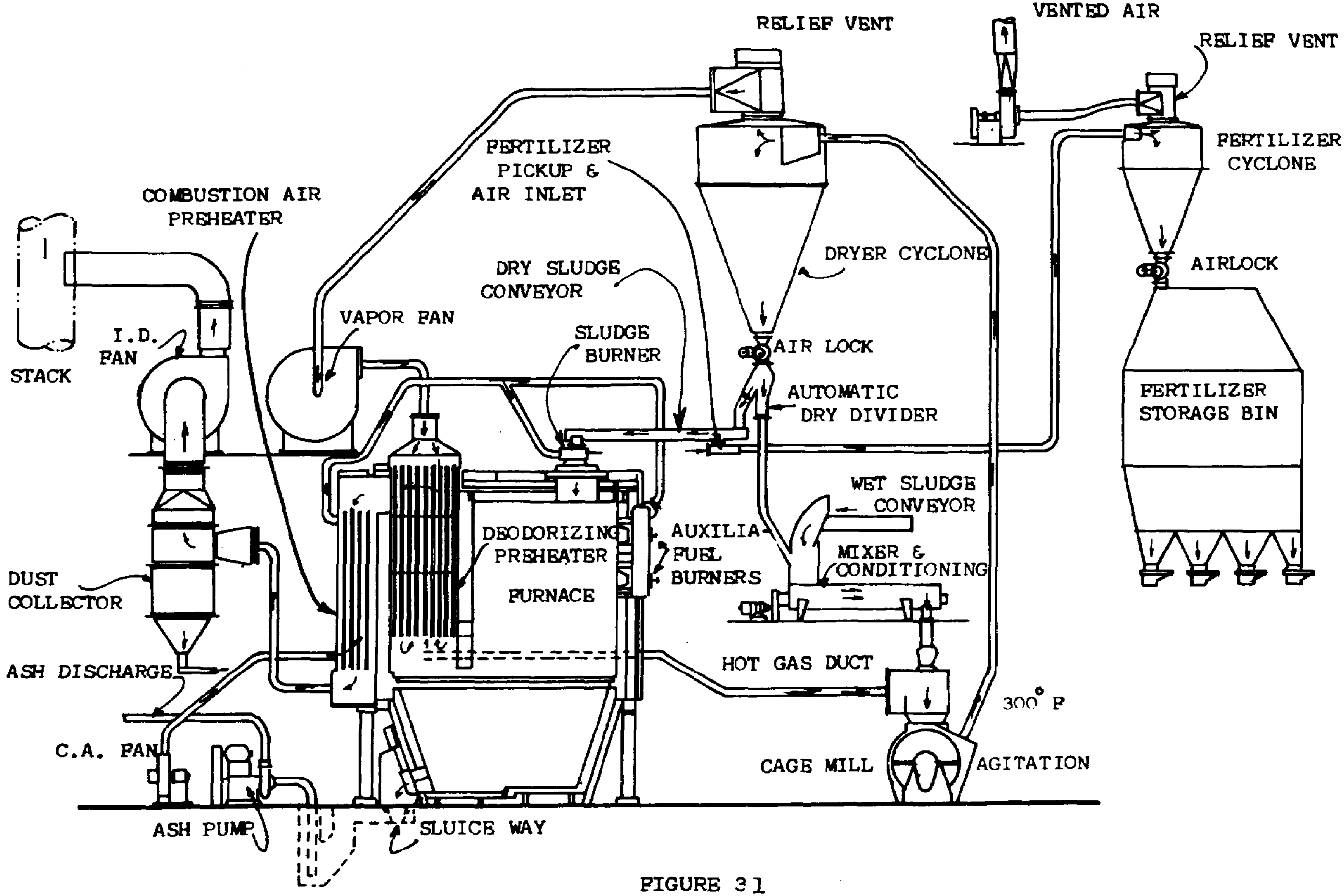


FIGURE 31

PICTORIAL FLOW DIAGRAM OF THE C-E RAYMOND FLASH DRYING AND INCINERATION SYSTEM at a high velocity to promote complete sludge combustion. The sludge ash accumulates in the furnace bottom and is removed periodically by a hydraulic sluicing system to an ash lagoon or other disposal area.

The third cycle is the effluent gas cycle or induced draft cycle consisting of the deodorizing and combustion air preheaters, dust collector, induced draft fan, and stack. Heat recovery is practiced to improve the economy of operation. The effluent gases then pass through a dust collector (dry centrifuge or wet scrubber) and the induced fan discharges the effluent gases through a stack into the atmosphere.

The fourth cycle is the fertilizer-handling cycle. Some of the advantages arising out of flexibility in operation are listed below:

1. Sludge can be dried or incinerated to suit the plant's immediate requirements.

2. The final moisture content can be automatically very closely controlled since a relatively small amount of sludge is in the system at one time.

3. The system can be started and shut down in a short period of time and no standby fuel is required when sludge is not being processed.

The lack of fertilizer market for dried sewage has eliminated the major advantage of this system, the flexibility of drying or burning. As an incineration unit, the flash drying system has the major disadvantages of complexity, potential for explosions and potential for air pollution by fine particles. Even though air pollution controls are readily applicable to the flash drying and incineration systems, in comparative situations it is not equal to other furnace designs.

Cyclonic Reactors

Cyclonic reactors are ideally suited for effective and economical sludge disposal in the smaller sewage treatment plants because of their simplicity in installation and flexibility in operation. The mechanism in cyclonic reactors is that high velocity air, preheated with combustion gases, from a burner is introduced tangentially into the cylindrical combustion chamber. Concentrated sludge solids are sprayed radially towards the intensely heated walls of the combustion chamber. This feed is immediately caught up in the rapid cyclonic flow of hot gases and combustion takes place so rapidly that no material adheres to the walls. The ash residue is carried off in the cyclonic flow and passes out of the reactor. Basically, the performance of the cyclonic reactor depends on 1) the cyclonic flow pattern, 2) the dispersion of the feed, and 3) the temperature of the combustion chamber walls.

Cyclonic reactors have high efficiency operation and this is achieved by the cyclonic action. Cyclonic reactors, manufactured by Dorr-Oliver[52], are quite compact and occupy a space of about 3.5 ft x six feet with a height of about 6 ft. The reactor is brick-lined steel and weighs less than 2 tons. Sargent (Zurn Industries) also produces a cyclonic incinerator.

An atomizing-type oil burner serves as the primary heat source and the hot gases from this burner enter the cyclonic reactor at high temperature and maintain the reactor walls at a high temperature to prevent sludge from sticking while burning on the walls. The sludge is fed into the reactor by a progressive cavity pump and the dispersed sludge particles burn as soon as they hit the wall of the reactor.

These reactors process combined primary plus secondary sludge at a nominal rate of 100 to 130 pounds of dry solids per hour or 500 to 650 pounds of wet sludge per hour. The detention time for the sludge within the reactor is less than 10 seconds. The cyclonic reactor oxidizes the sludge, producing inert ash, water and carbon dioxide (CO_2). The trace amounts of sulfur in the sludge and in the fuel oil are oxidized to sulfur dioxide (SO_2) but this amount is negligible after efficient scrubbing. The temperature is kept above 1400° F so that the organic matter is burned above the odor producing level.

Wet Oxidation

The wet oxidation process is based on the discovery that any substance capable of burning can be oxidized in the presence of liquid water at temperatures between 250° F and 700° F. The process is uniquely suited to the treatment of difficult-to-dewater waste liquors and sludges where the solids are but a few percent of the water streams. In general, given the proper temperature, pressure, reaction time and sufficient compressed air or oxygen, any degree of oxidation desired can be accomplished.

This process has been commercialized and patented as "Zimpro" process. This process has also been known as wet incineration, wet combustion and wet air oxidation processes. Wet air oxidation does not require preliminary dewatering or drying when compared to the conventional flash combustion. Water can be present up to 99% in this process whereas in conventional combustion it must be reduced to about 75% or auxiliary fuel must be added. Far from "quenching" the reaction, water is essential to wet air oxidation.

Another significant difference is the flameless oxidation of the organics at low temperatures of 300° F to 400° F when compared to 1500° F to 2700° F in the conventional combustion processes. Air pollution is controlled because the oxidation takes place in water at low temperatures and no flyash, dust, sulfur dioxide or nitrogen oxides are formed.

The general flow diagram of Zimpro continuous wet air oxidation system is shown in Figure 32. In the continuous process, the sludge is passed through a grinder which reduces any particles greater than 1/4 in. to about 1/4 in. size. Sludge and air are then pumped into the system and the mixture is passed through heat exchangers and brought to the initiating reaction temperature. As oxidation takes place in the reactor, the temperature increases. The oxidized products leaving the reactor are cooled in the heat exchangers against the entering cold sludge and air. The gases are separated from the liquid carrying the residual oxidized solids and released through a pressure control valve to a catalytic oxidation unit for complete odor control. Where economic conditions make it attractive, the gases may be expanded in power recovery equipment before being discharged. The oxidized liquid and remaining suspended solids are released through a level control valve and the solids may be separated by settling and drainage in lagoons or beds, or other methods depending upon project requirements.

For startup, heat is obtained from an outside source, usually a small steam generator. With high degree oxidations and high fuel value sludges, no external heat is needed once the process is started. Whenever the process is not thermally self-sustaining, steam may be injected continuously to sustain the reaction temperature.

This process may be applied to any type of sewage sludge--raw or digested, primary or secondary, plus scum and screenings. No special thickening beyond conventional settling is needed for application of the process. The choice of the degree of organic matter destruction, of COD reduction, depends on economic factors such as availability and cost of land, size of plant, power rates, etc. Typical cost relationships for various degrees of COD reduction are shown in Figure 33. This process can provide a wide range of oxidation end products depending upon the requirements of the application. It can be designed for high oxidation to produce a minimum volume of inert ash or for low oxidation to produce a residue containing stabilized organic matter with soil conditioning value.

The chemical oxygen demand (COD) of the waste serves as a valuable parameter for the design of the wet air oxidation process

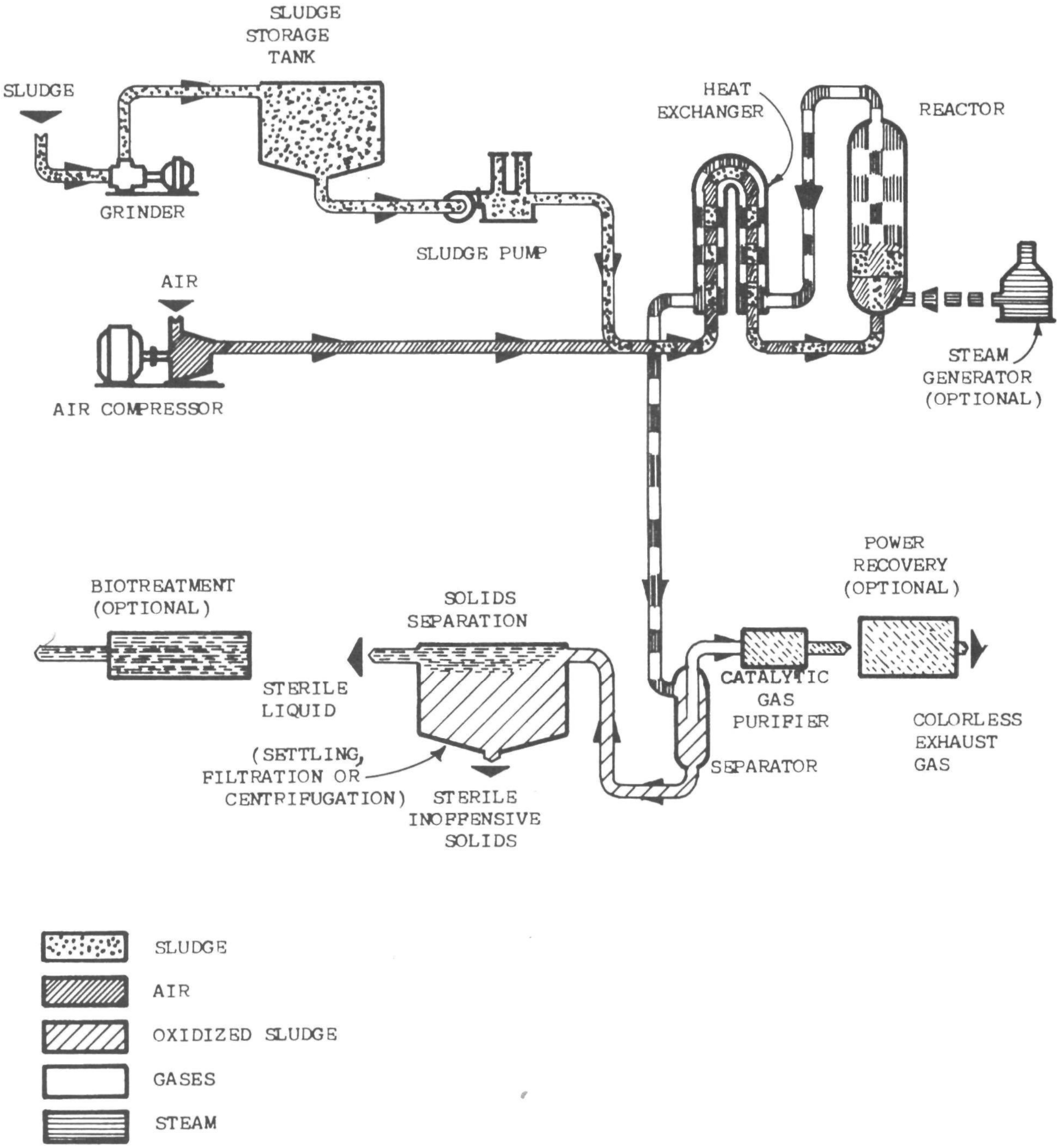
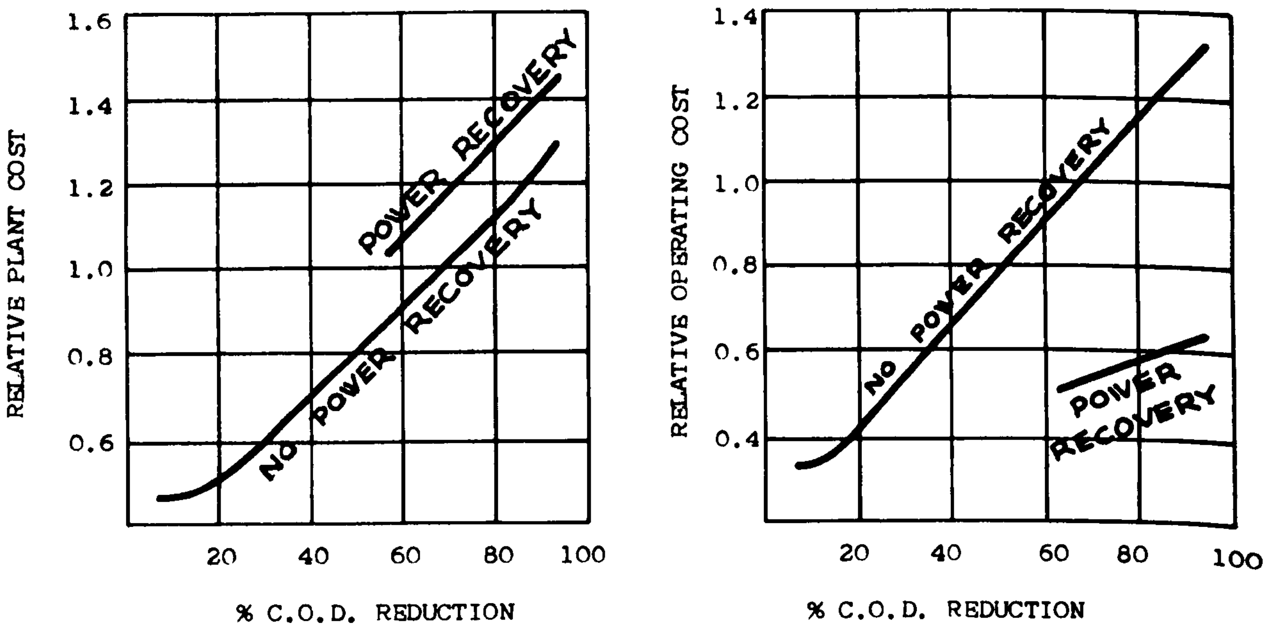


FIGURE 32

FLOW DIAGRAM FOR CONTINUOUS WET AIR OXIDATION



SLUDGE ASSUMED TO BE 5% SOLIDS

FIGURE 33

TYPICAL COST RELATIONSHIPS FOR

VARIOUS DEGREES OF C.O.D. REDUCTION

and waste sludges most applicable to the process have COD values between 25 and 100 grams per liter (25,000 to 100,000 mg/l). "Zimpro" units are operated either on a continuous or batch operation basis. In either case, the basic principles of oxidation are the same and the oxidation achieved depends on the temperature, pressure, holding time in the reactor, and the solids concentration of the sludge entering the process.

The degree and rate of sludge solids oxidation are significantly influenced by the reactor temperature. With increased temperature, a higher degree of oxidation is possible with shorter reaction times. The relative COD reduction with increase in temperature from 100° C to 300° C for a number of different sludges as reported by Hurwitz and co-workers[53] is shown in Figure 34.

Oxidation in an aqueous system requires sufficient pressure in the reactor to prevent water vaporization because temperatures are above 212° F. Operating pressures varied from 150 to 3000 psi, depending on the size of the plant and the degree of oxidation required.

The effect of feed solids concentration on capacity and costs of wet air oxidation process as observed in the Chicago Sanitary District[54] is shown in Figure 35. As can be seen from the Figure, the cost can be reduced considerably by increasing the feed sludge solids concentrations to about 6% and future modifications of the heat exchangers and pump capacity may reduce the cost further.

The operating costs of the high pressure Zimpro plant, including labor and maintenance, are about $15.00 per ton of solids processed. The installed and operating cost[45] for high pressure and low pressure operating units is shown in Figures 36 and 37, respectively. The building area requirements for the Zimpro units are shown in Figure 38.

The wet air oxidation process has many advantages in sewage sludge disposal and they are as follows:

1. Sterile end products low in volume and of special value as a soil amendment are produced.

2. Flyash or dust are not produced as the oxidation takes place in the presence of water. Sulfur dioxide and nitrogen oxides are not formed and odor control is assured by use of gas incineration devices.

3. Wet air oxidation renders sewage sludge easily dewaterable by filtration or settling without chemical conditioning.

4. This system permits a clean, sanitary plant without exposure of operating personnel to obnoxious unsterilized sludge solids.

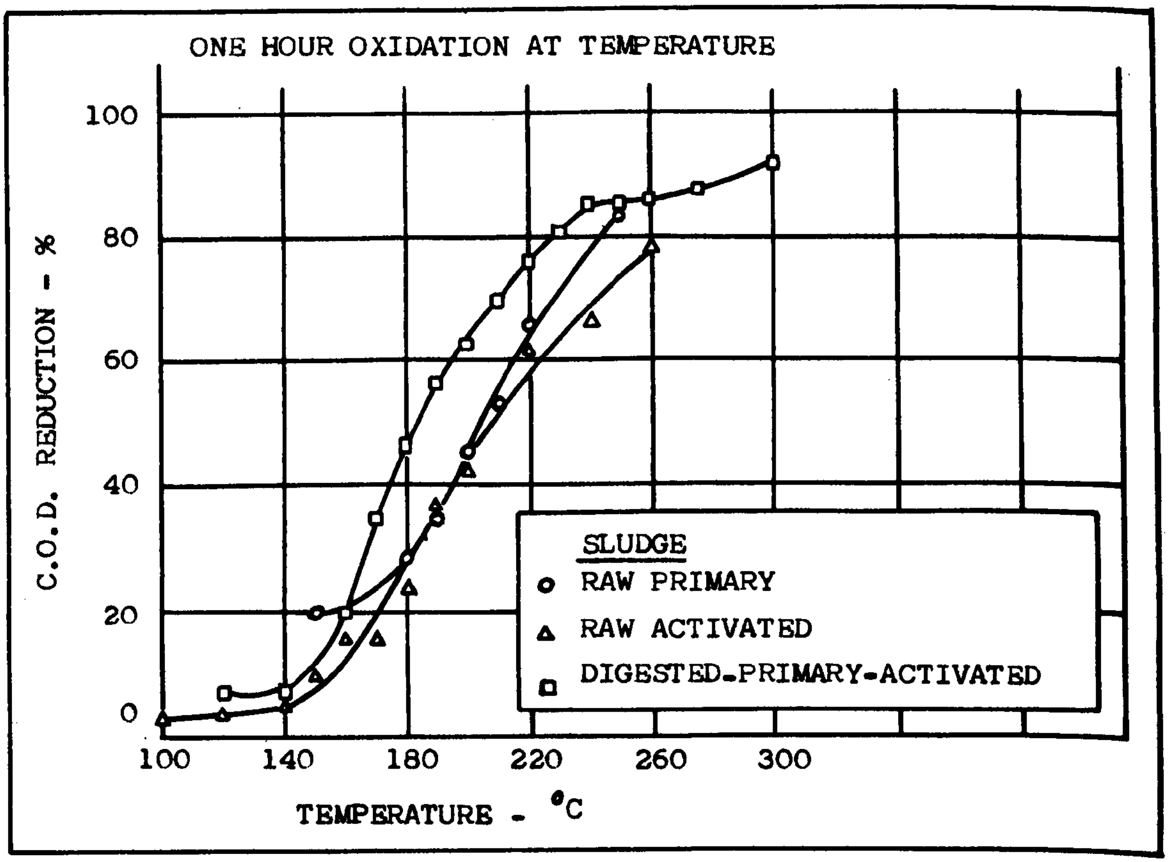


FIGURE 34

C.O.D. REDUCTION Vs TEMPERATURE

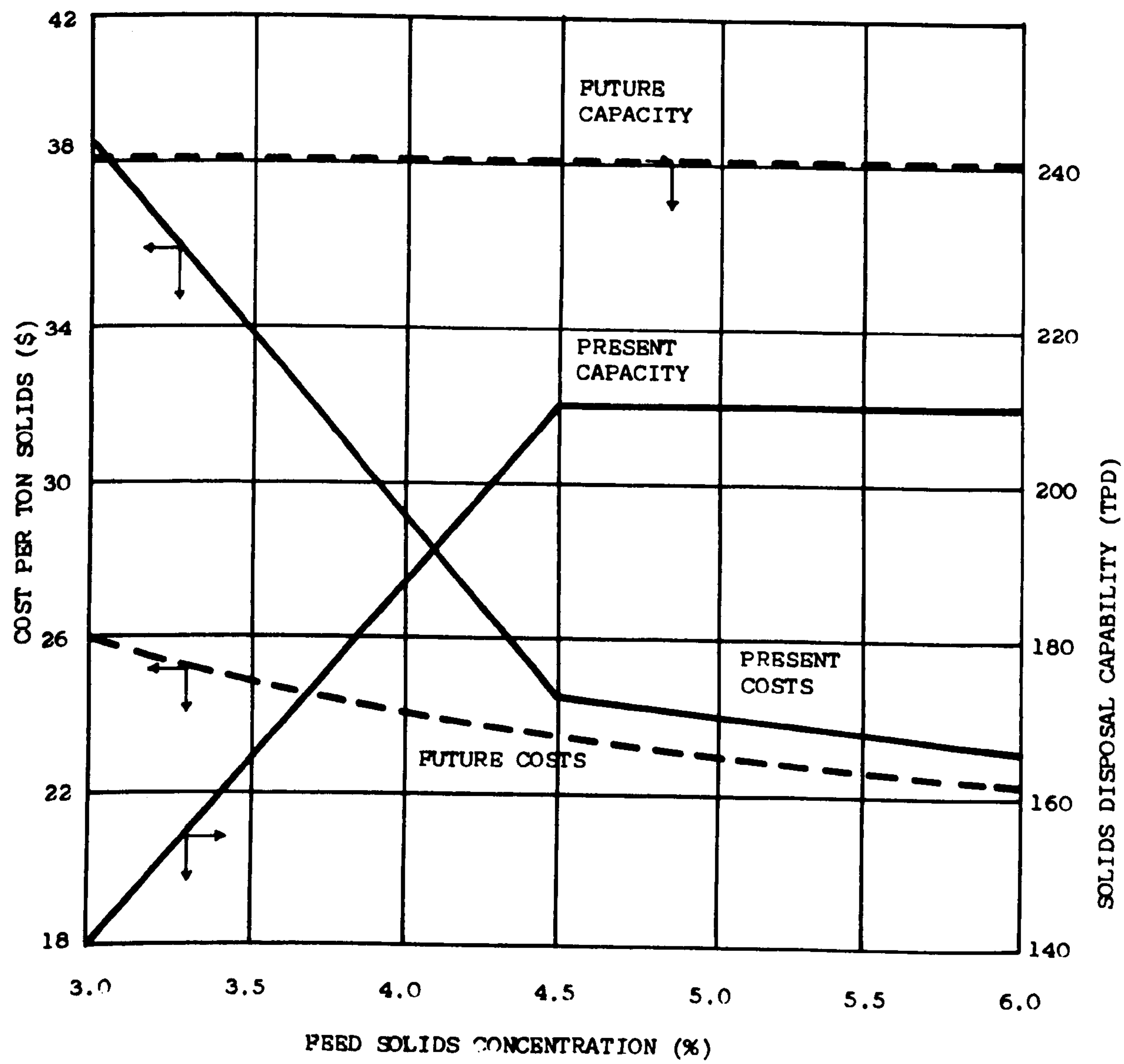


FIGURE 35

EFFECT OF FEED SOLIDS CONCENTRATION ON CAPACITY AND COSTS OF WET AIR OXIDATION PROCESS AT CHICAGO

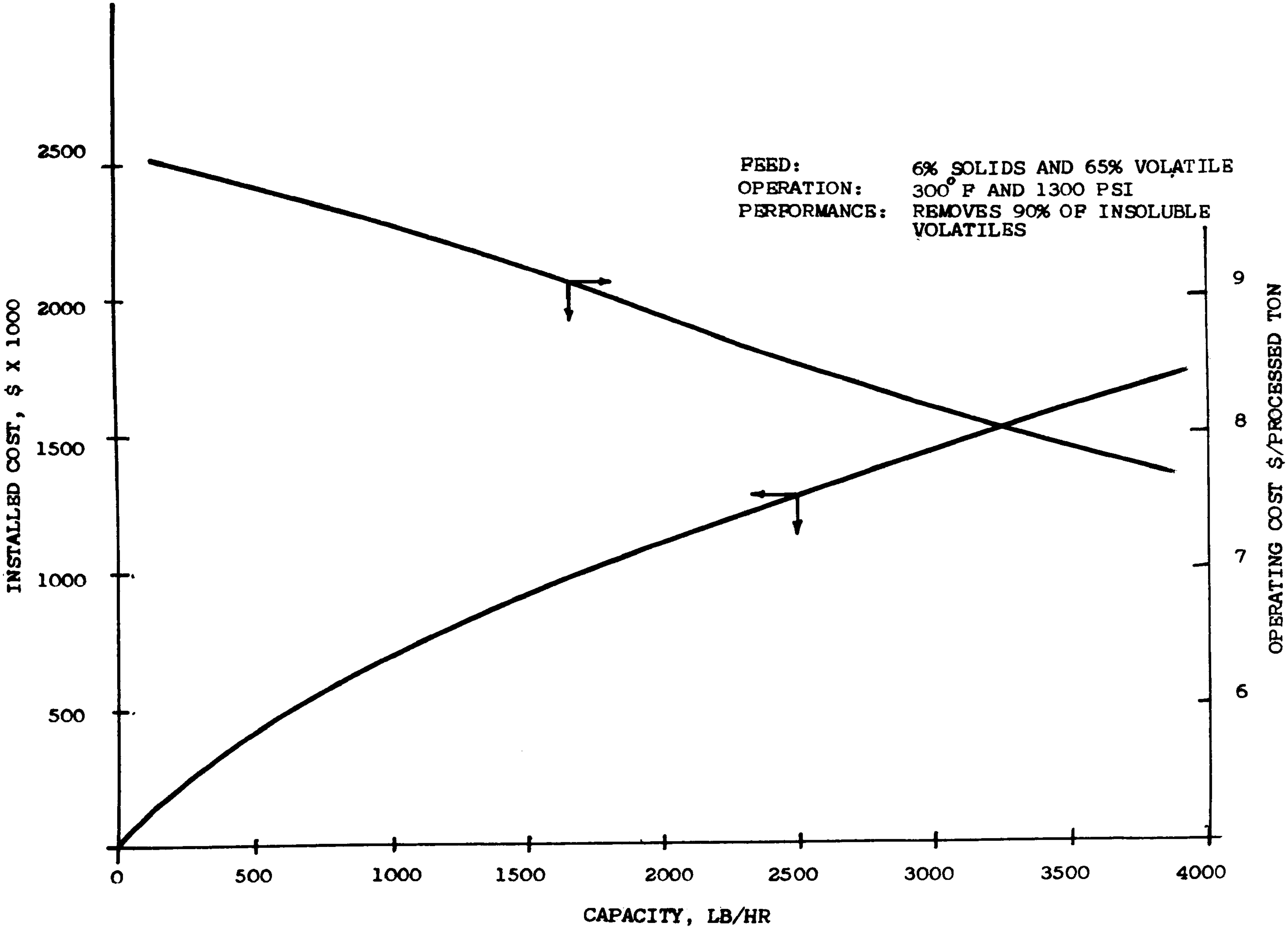


FIGURE 36 ZIMPRO, HPO - INSTALLED AND OPERATING COST

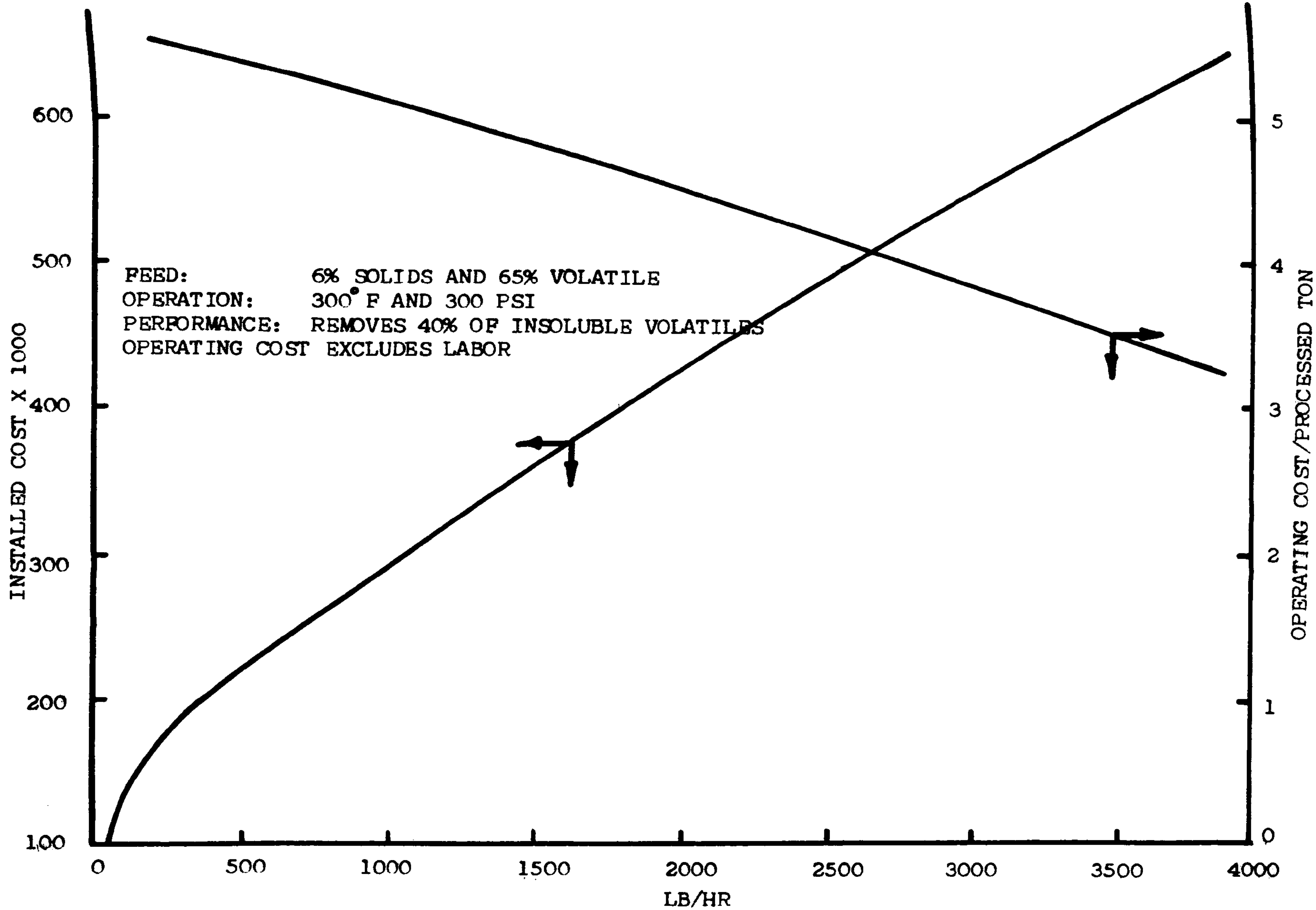


FIGURE 37 ZIMPRO LPO-INSTALLED AND OPERATING COST

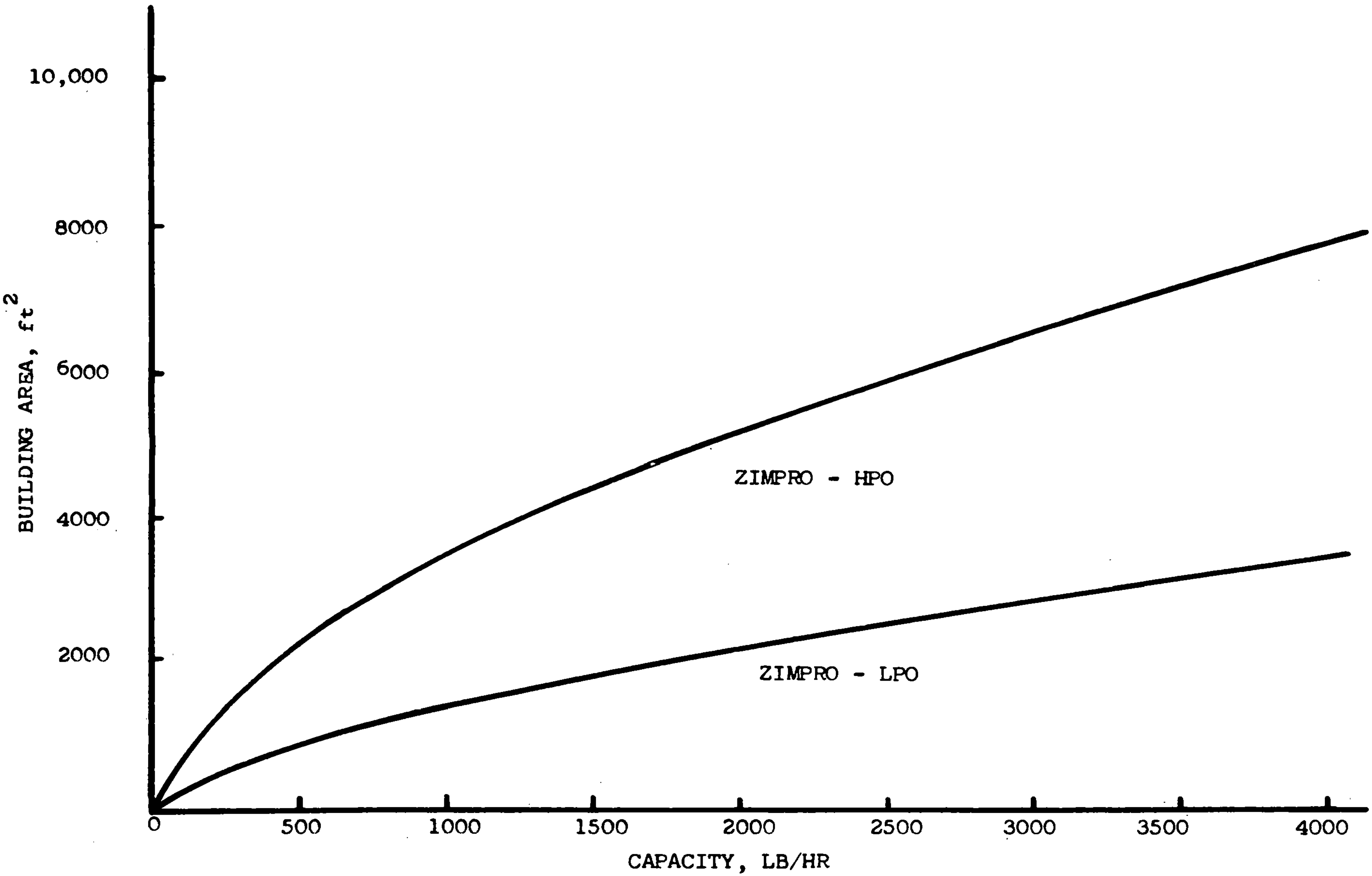


FIGURE 38

ZIMPRO - BUILDING AREA REQUIREMENTS

5. Wet air oxidation has the flexibility of handling any type of sludge and a wide range of oxidation conditions and end products is possible.

6. Land and building area requirements are minimal and the Zimpro units can be easily integrated into existing facilities with digesters, vacuum filters or incinerators to increase the sludge-handling capacity.

There are disadvantages associated with the wet oxidation process and the major one is the cost of construction and operation. This system is generally the most expensive of the processes considered in the design of sewage treatment plants and the specific cost depends on the required degree of oxidation which, in turn, depends on factors unique to a local situation such as the size of plant, the availability of land and the cost of power[53].

Odor problems can develop from the off-gases and from lagooning of the ash-containing effluent. Though air pollution caused by the stack gases can be controlled by catalytic burning at high temperatures, this is an unknown added expense. Another suggested disadvantage of wet combustion systems is the need for high quality supervision and frequent maintenance due to the use of sophisticated equipment and controls. A major operational disadvantage is the need to recycle wet oxidation liquors back through the wastewater treatment processes. This may represent a considerable organic load on the system and the fine ash could plug air diffusion plates and sludge vacuum filter media. Therefore, the effluent requires further treatment before final disposal. It should also be realized here that the wet oxidation cannot approach the degree of destruction of organic matter as is achieved in a true incineration process.

It is possible that wet air oxidation has the potential of being the best method for ultimate sludge disposal and further research and development of this technique could bring down the capital and operating cost.

Atomized Suspension Technique (AST)

The atomized suspension technique is designed for high temperature-low pressure thermal processing of wastewater sludges. In this system, sludges are reduced to an innocuous ash and bacteria and odors are destroyed. This system is known under different names such as spray evaporation, and thermosonic reactor system.

Figure 39 shows the basic components of the system and the unique features of the atomized sludge incineration process start with a sonic atomizer that produces a mist and fine particle spray at the top of

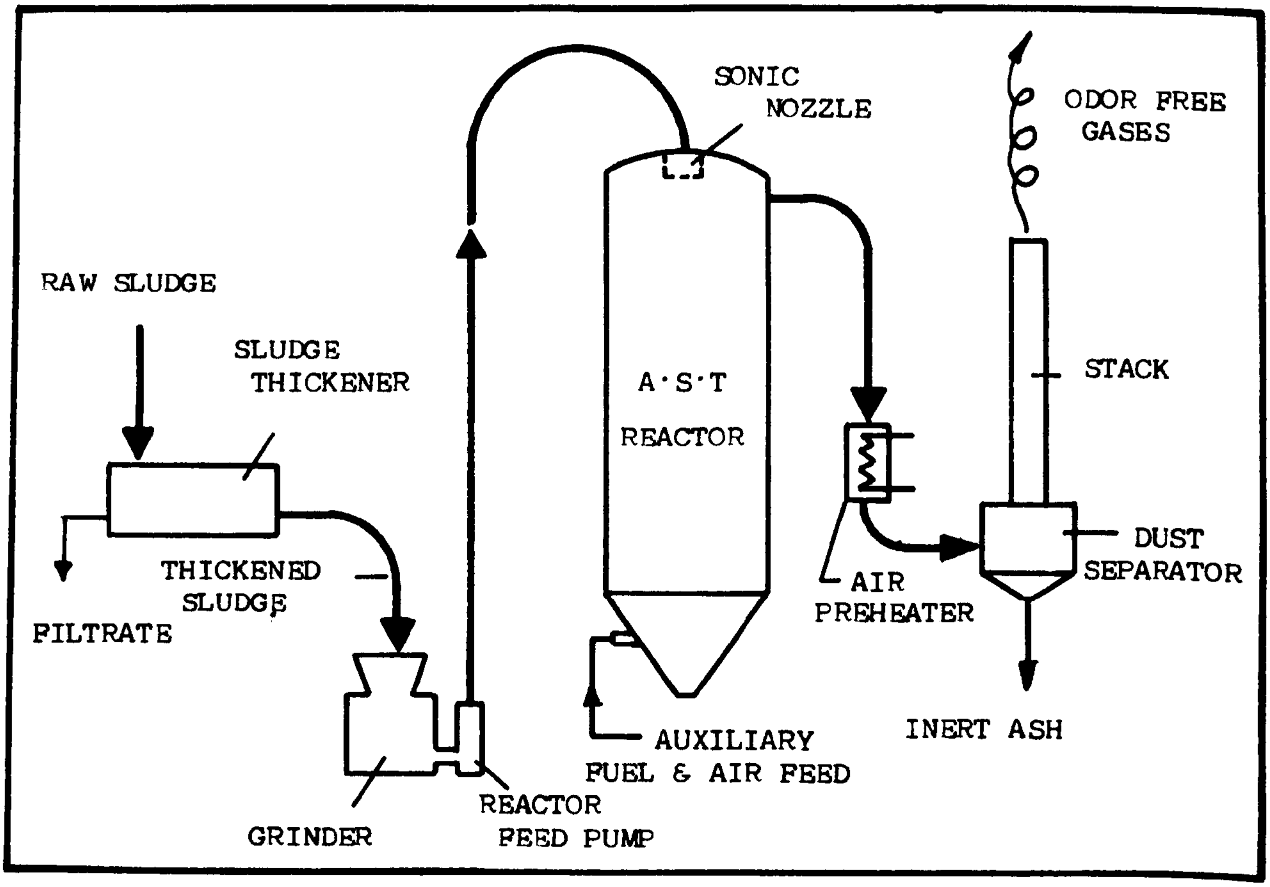


FIGURE 39

THERMOSONIC REACTOR SYSTEM FOR TREATMENT AND

DISPOSAL OF RAW SLUDGE

the reactor. The process generally includes the following steps:

1. Thickening of the feed sludge to 8% and higher.

2. Grinding the sludge to reduce the particle size to less than 25 microns.

3. Spraying the sludge into the top of a reactor to form an "atomized suspension."

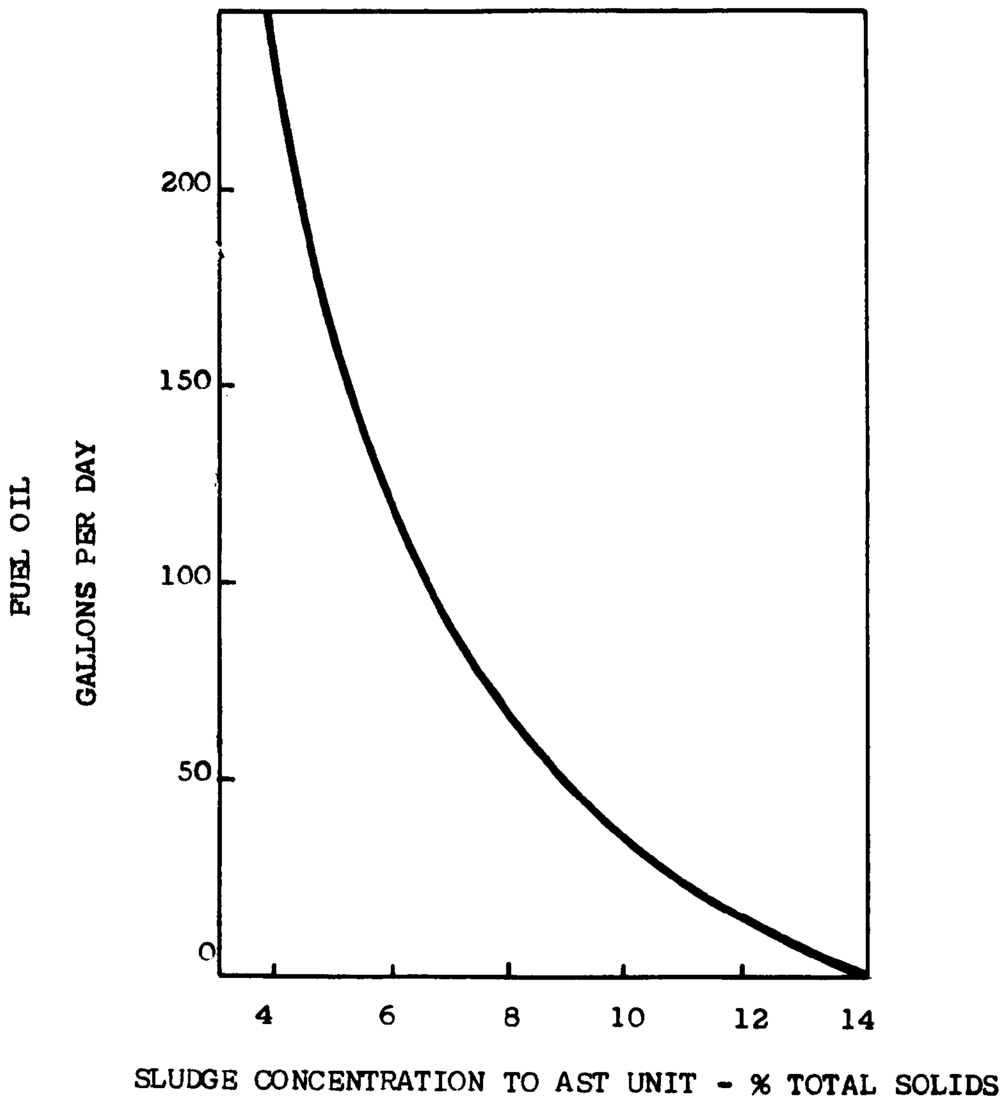
4. Drying and burning the sludge in the reactor.

5. Collecting and separating the ash from the hot gases.

The important parameters in the design and performance of atomized suspension incineration include: sludge type, sludge solids concentration, amount of excess air used, pressure in the reactor and sludge particle size. Sewage sludges, in general, are thermally not self-sufficient unless first dewatered in mechanical equipment. It has been estimated that a raw sludge having a heating value of 8,780 BTU per pound of dry solids would have to be thickened to 14% to be thermally self-sufficient. Fuel consumption has been related to the raw sewage sludge solids concentration[55] as shown in Figure 40.

Particle size distribution is an important factor to be considered to prevent sludge stoppages in lines and in the atomizing nozzles, and to improve the combustion. With the increase in the particle volume, the rates of evaporation and heat transfer in the reactor are increased directly proportional to particle volume. The operating pressure is kept under 30 inches of water to prevent leakage from the equipment and to insure no inhibition of evaporation and gasification.

This sytem has the following advantages: versatility in sludge handled, small space requirement, rapid conversion of raw sludge to innocuous ash, steam and CO_2, and no nuisance conditions. This system is very new and it has been estimated that the cost will be somewhat higher than conventional incineration processes due to maintenance and the need for supplemental fuel oil or gas. Capital costs do not also appear to be less than for other incineration techniques. The AST process has an advantage over the Zimpro process in that the operating pressures are much lower. The possibility of incinerating a dilute sludge, thereby eliminating costly dewatering steps, is very attractive.



SLUDGE FLOW = 4 GPM

FIGURE 40

FUEL CONSUMPTION AS A FUNCTION OF SLUDGE CONCENTRATION

CONSIDERATIONS IN INCINERATOR DESIGN

Plant Size and Capacity

Determining the actual continuous burning capacity of a proposed plant is vital to its ability to satisfy community needs - both present and future. The usual method of applying a nominal rating based on theoretical capacity can be misleading and may provide a plant too small and inflexible for those needs. It is considered good design to plan for multiple units in the event of operational failure of one unit. While it costs more to build two plants than a single plant of the same total capacity, the benefit derived from having seperate units may outweigh the cost, particularly when rating is based on a continuous burning operation. By borrowing from the power industry the concept of "firm power"--that capacity remaining for operation when the largest of multiple units is off the line--the incinerator plant can be designed with an assured actual continuous burning capacity so that there will always be enough available capacity to prevent sludge accumulation.

The required incinerator size as a function of population served and degree of treatment is shown in Table XII.

Aesthetics and Location of Plant

The quality of aesthetic design of the plant is a vital factor in community acceptance. Incinerator plants can be housed in attractive buildings with pleasing proportions, colorful or textured facades and surrounding landscaping. The only element that need distinguish an incinerator plant is the chimney, and the height of the stack can be visually minimized. Any unsightly activities or areas such as storage pits can be screened from view by trees and shrubbery, by placing them within buildings or by placing them in the lower areas of the natural configuration of the landscape.

Good design, both outside and inside the plant, can have the added advantage of creating the kind of environment that will attract more competent employees to the municipal incinerator. Currently, employment in an incinerator plant is not considered a desirable occupation and more desirable competing fields get first choice of skilled or technically trained people. To attract those with adequate training to handle increasingly sophisticated equipment and operations, the entire concept of working in an incinerator needs upgrading in the public mind.

The problems of heat, odor and insects could be avoided by separating the incinerator from other parts of the plant and air

TABLE XII

REQUIRED INCINERATOR SIZE AS A FUNCTION

OF POPULATION SERVED AND DEGREE OF TREATMENT

Population	Lb/hour Dry Solids (8-hour operation) Primary	Secondary
250	9	14*
750	28	42*
1,750	66	99*
3,750	141	210*
7,500	283	420
17,500	660	985
37,500	1,410	2,110
75,000	2,810	4,220
175,000	6,260	9,850
250,000	9,400	14,100

*Small cities, probably under 5,000 population, will not burn sludge 7 days a week under normal circumstances. Therefore, the size of unit required for design populations under 5,000 will be between 1.5 and 2 times the sludge quantity mentioned here.

conditioning the offices; and wherever possible, inclusion of showers and lockers for employees so that work clothes can be left at the plant is a great boon to those who must work in the sludge-handling areas. It should be noted that none of these features add materially to the cost of a modern plant but they can have a considerable effect on the efficiency of operation.

Careful operation and maintenance of the plant and surrounding areas are prerequisites to continued aesthetic quality, but any additional costs incurred in these areas will be more than offset by the maintenance of the land values not only of the site itself but in the vicinity. More modern plants burn better and operate better and the improvement cannot enitrely be credited to technological improvement in the incineration process.

Economic Factors

The lack of clarity in the economic picture presents a considerable challenge to the designer. For against comparatively small return in costs, the designer must weigh the costs of installing and maintaining equipment over the plant's useful period of life. It must also be decided how far to go in selecting automated equipment. Also, careful consideration must be given not only to initial costs of such sophisticated installations but to the costs involved in the use of relatively untested equipment by personnel oftentimes untrained to the degree necessary to handle the complexity of the job they are called upon to do[56]. Each plant currently designed must be given sufficient flexibility to encompass not only the community's existing needs and to take into consideration already existing facilities, but also the community's future need for additional facilities.

Air Pollution Standards and Control

Incineration offers the opportunity to reduce sludge to a sterile land fill and remove offensive odors, but it can be a significant contributor to the air pollution problem in an urban community. The quantity and size of particulate emission leaving the furnace of an incinerator varies widely, depending on such factors as the sludge being fired, operating procedures and completeness of combustion.

Complete combustion to produce the principal end products of CO_2, H_2O and SO_2 is costly but too much of SO_2 emission is not permissible due to its toxic and corrosive nature. Incomplete combustion can be disastrous because the intermediate products formed, such as hydrocarbon and carbon monoxide, are more objectionable. Smoke and gases contribute to overall air pollution through reduction in visibility and through their ability to enter into smog-forming photochemical reactions in the air.

The emission standards for particulate matter vary from state to state. Previous practice usually attempted to control these emissions to 0.85 lb of flyash per 1000 lb of flue gas, adjusted to 50% excess air (1 lb per 10^6 BTU), as suggested in the "1949 ASME Example for a Smoke Regulation Ordinance." The ASME published a new suggested regulation in 1966 entitled "Recommended Guide for the Control of Dust Emission - Combustion for Indirect Heat Exchangers." It seems reasonable to assume that this document will receive the same widespread acceptance that the earlier ordinance did. Thus, future codes can be expected to lower the allowable emission from 1.0 to 0.80 lb of flyash per million BTU, or to 0.68 lb of dust per 1000 lb of gas corrected to 50% excess air. More congested metropolitan areas or areas with adverse topography, such as the Los Angeles Basin, may adopt the recent regulations that limit emissions to 0.10 - 0.20 grains per standard cubic foot at 50% excess air (0.22 - 0.44 lb of dust per million BTU fired) for incinerator capacities of 200 lb per hour and larger. The lower standards have been adopted not only in California but in many parts of the Northeast and Midwest. It is expected to become the standard.

Most incinerator manufacturers advertise to limit the particulate matter to 0.20 to 0.28 lb per 1000 lb of stack gas at 50% excess air. However, in the event of increased air pollution standards, electrostatic precipitation or high efficiency scrubbing may be required. Such systems are expensive and, hence, the less excess air used, the lower the cost will be for electrostatic equipment.

It is also important to observe that suggested criteria for particulate matter in the ambient air as developed by the Department of Health, Education and Welfare and adopted by various jurisdictions may effect these discharge limits.

The stack gases must be cooled so that the plume produced will dissipate upon entry into the atmosphere. Temperatures of up to 160° F have proven to be quite satisfactory. Care must be taken to prevent plume condensation which would violate equivalent opacity regulations even though the plume may be white in color.

Particulate matter can be effectively controlled by centrifugal dust collectors or wet scrubbers[57]. Centrifugal collectors remove 75 to 80% of the particles and are suitable for exhaust gas temperatures of 650 - 700° F. Water scrubbers are at least equally effective; they are less sensitive to loadings and gas temperatures and they collect the condensable portion of the exit gases. In general, the nature of the emitted particulate matter from sludge incinerators does not lend itself to centrifugal collection and most systems utilize wet scrubbers of a variety of types including venturi, baffle plate, packed tower and impingement models. These scrubbers have the added advantage of absorbing significant amounts of gases including sulfur oxides and odorous organics.

Air pollution control has assumed enormous importance in all waste management fields due to public awareness and the expansion of urban areas. Generally, environmental problems are interrelated and the solution of a water pollution and land use problem may cause an odorous air pollution problem in poorly designed and/or operated sludge incinerators. Odors generally emanate from raw sludge thickening or storage tanks, vacuum filtration units, sludge incinerators and dryers.

Odors can be eliminated at their source or can be prevented from reaching the atmosphere by control. The basic requirements for preventing odor are good plant design and operation. Septicity of sludge can be prevented by providing adequate sludge hoppers and flexibility in pumping schedules. Odors, when emitted, can be controlled by any one of the following five methods with certain limitations:

1. Combustion

2. Chemical oxidation

3. Adsorption

4. Dilution

5. Masking

Chemical oxidation can be achieved in two ways[58]: 1) oxidizing the gases in a dry environment, or 2) scrubbing the gases with a liquid-containing oxidant. Ozone is commonly used for odor control as it is relatively inexpensive. Its effectiveness is open to considerable question. Chemical oxidants such as chlorine (Cl_2), hydrogen peroxide (H_2O_2) and hypochlorite (HoCl) have been used in absorption processes to control odors. Their efficiency depends upon the chemistry of the situation. Packed scrubbing towers are usually used for gradual oxidation of the gases.

Odor control can be achieved through the use of adsorption towers packed with activated carbon. The technique is relatively expensive and usually limited to cases where organics may be recovered.

Tall stacks are frequently used (especially with chemical or thermal combustion) to dilute odorous gases and particulates with the outside atmosphere and reduce their concentration but this route has not been a satisfactory odor control technique due to the existence of downwind problems. Normal diffusion equations have not been satisfactory in predicting the necessary dilution to prevent odor detection. Frequently, odors have been observed 10 - 50 miles downwind of an incinerator.

Use of masking agents (often quaternary amines) is not a very satisfactory odor control measure and, therefore, should be limited to temporary emergency situations. Sometimes odor masking may produce intolerable combinations of sludge odors plus masking agent odors; and masking prevents recognition of a serious community problem. However, masking agents are perhaps the most frequently utilized for masking the odor.

While the above methods have some usefulness in the control of odors, the control of odors from sludge incinerators is generally limited to two techniques. The main and most successful approach is to incorporate a means of ensuring that all gases arising from the system are raised to and held at a sufficiently high temperature and for a sufficient time period to ensure complete oxidation of all organics. It is generally considered that if the gases are held at 1400° F, oxidation will occur in a matter of seconds. Thus, if the gases are held at 1400° F for the usual gas phase detention time (10 - 60 seconds), no odors should be present in the gas exhaust. However, through poor design, operation and/or maintenance, these conditions are frequently not achieved and a serious odor problem can and does arise. As sewage treatment plants become surrounded by valuable real estate (homes, etc.) and as society becomes more aware of olfactory insults, pressures will increase to ensure non-odorous operation.

A less frequently utilized control technique is to take the off gases to a secondary incineration chamber. This may be of the flame type in which the gases are passed through a natural gas or oil (usually the former) flame to ensure complete organic destruction. As an alternative, the gases may be passed over a catalytic system where the same oxidation takes place but at a lower temperature since the catalytic surface lowers the oxidation energy "hump." In both cases, the chemistry is identical to that described relative to incineration and additional air may be added to ensure complete combustion.

The detection of odors is generally dependent upon complaints and control is usually by means of the nuisance clause of most air pollution codes (or Common Law). However, many communities have developed trained odor panels to detect odors from a variety of sources on a regular basis.

In contrast, the emission of particulate matter from incinerators is controlled by many air pollution regulatory agencies by the application of precise technically measurable (See this section above) limits. Techniques to sample incinerator effluents for particulate matter are well established although considerable controversy exists concerning the methodology. The variation in operational conditions cause additional problems to the tester.

The variation of control approach between odors and particulate matter means that incinerator operators must have an unusually broad outlook when dealing with the general public and regulatory agencies relative to air pollution regulations.

Safety Standards

It is advantageous to control the entire system from a single instrument panel and to protect against oil burner flame failure, high and low exhaust temperatures, blower failure and high and low oil burner inlet temperature. An alarm should ring and shut down the operation in all these failure modes. The complete instrument and control package allows the system to be run semi-automatically after startup. However, periodic checking on sludge level in the hopper is required to ensure constant feed to the incinerator.

Explosions that damage equipment may occur from the combustion of grease. For this reason, seperate feed openings in the furnace are to be provided for grease and screenings. In cases where a unit is used for the incineration of grease and skimmings only, a parallel flow of feed solids and hot gases is desirable.

OPERATIONAL ASPECTS

Dust Collection and Ash Handling

Following the deodorization step, the particulate matter is removed from the cooled gases before they pass up the stack and into the atmosphere. If a centrifugal dust collector is used, the cooled gases are drawn through the dust collector by the induced draft fan. The flyash settles out by the centrifugal action and is discharged automatically into the furnace bottom. The deodorized and ash-free gases, along with the moisture from the drying operation, are vented to the atmosphere without nuisance.

Ash assumes a fine, granular form resembling sand, free from clinker and unburned organic matter. Any convenient method of disposal may be used but a preferred method involves discharging the total ash into a water-filled sump and pumping the mixture to land fill.

A sewage sludge combustion unit does not dispose of the solids completely. It produces an end product that requires further handling but by virtue of greater solids destruction, the handling procedures are greatly simplified.

Ash handling can be performed by either "dry" or wet methods. Dry handling is never absolutely dry since water sprays are utilized to prevent dust from scattering. Such systems are generally used at smaller installations (less than 30,000 populations).

The problem is quite different if wet scrubbers are used. The ash from the underflow of the scrubbing unit can be handled by various means. Among these are the following:

1. Settling Basins

   Ash has a high settling rate and clarification tests on a typical ash indicate that 99.9% plus will settle in less than two hours. The quantity of ash removed from the scrubber for the purpose of sizing the settling basin need not be uniform.

2. Mechanical Concentration

   If settling basins are not practical for a given application, the ash can be concentrated in hydrocyclones. Tests have indicated that underflow concentrations in the range of 20 - 25% total solids can be expected. If further dewatering is desired, the underflow of the hydrocyclone is fed to a rake classifier or small settling tanks where concentrations of 70 - 80% total solids can be achieved.

Flexibility and Controls

Sludge incineration systems should be designed in such a way that they could have utmost flexibility in operation. Some of the advantages accruing from this flexibility are as follows:

1. Sludge can be dried or incinerated to suit the plant's immediate requirements.

2. The final moisture can be very closely controlled during the sludge-drying operation.

3. The system can be started and shut down in a short period of time and no standby fuel is required when sludge is not being processed.

While designing facilities for sludge incineration, flexibility should be built in so that increasing demands due to the population growth can be met.

A full set of instruments and controls must be provided to the operator in order to ensure operation at maximum efficiency at all times. Recording instruments are generally preferred so that a permanent record may be kept. Devices such as deodorizing air preheater must be protected against overheating by an automatic air damper. When the gas temperature entering the preheater exceeds a safe figure, this damper automatically opens and permits room air to enter and reduce the temperature.

Production of sludge of low and uniform moisture is important in either drying or incineration of sludge and this could be achieved only by automatic controls. Because of the variations in the moisture and heat content of the incoming wet filter cake, continuous attention to auxiliary fuel burners is required with manual controls and this could be avoided by automatic controls.

CAPITAL AND OPERATING COSTS

Sludge incineration is generally more expensive than other sludge disposal methods. The approximate pricing information on incineration systems is presented in Table XIII. The capital outlay required for incinerator systems by population group is presented in Table XIV. The capital cost of incineration systems depends on the type of incinerator and whether deodorization, dust collection and disposal are included. There are many factors that affect the cost of sludge incineration and the major ones include:

1. Size and design of incinerator
2. Nature of waste sludge
3. Amount and type of chemicals used for sludge conditioning
4. Extent of standby facilities
5. Cost of utilities (fuel, water, power)
6. Air pollution control requirements

The operating costs have been reported to have wide variations and these variations are partly due to the fluctuations in supplemental fuel requirements. A survey on supplemental fuel[48] showed a variation from less than 1% to 35% of the heat value supplied by the sludge cake itself. There was a wide difference observed between the fuel required for raw sludge incineration and for digested sludge incineration. In general, raw sludge units required an average of 1.75% additional heat in the form of fuel, while digested sludge required 17.9% and this variation means a difference in operating costs of $1.00 per ton[48].

TABLE XIII

PRICING INFORMATION ON INCINERATION SYSTEMS[1]

Type	Manufacturer	Size (lb/hr)	1968 Dollars	
Fluid Solid	Dorr-Oliver	200	180,000	
		400	300,000	
		1,000	550,000	
		2,000	825,000	
Multiple Hearth	Nichols	500	300,000	
	Bartlett-Snow-Pacific	2,000	550,000	
		4,000	700,000	
		6,000	850,000	
Cyclonic Reactor	Dorr-Oliver	100	85,000	
		200	120,000	
Wet Oxidation	Sterling Drug	1,000	300,000	(Oxidation unknown)
	Zimpro Division	470	284,000	(High oxidation)
Flash Dryer and Incinerator	Combustion Engineering Raymond Division	400	300,000*	
		600	330,000	
		1,000	375,000	
		2,000	460,000	
		5,000	700,000	
Cyclo-Burner	Sargent - Zurn	130	70,000	

*Prices included drying but not dewatering equipment. Delete 20% for special equipment and add 25% for dewatering.

1. Obtained from the manufacturer's estimating price and bids.

TABLE XIV

CAPITAL OUTLAY REQUIRED FOR INCINERATOR SYSTEMS BY POPULATION GROUP *

Population	Average Incinerator System Capital Cost - (1968 Dollars)
250	Not applicable
750	50,000[1]
1,750	70,000[1]
3,750	120,000[1]
7,500	130,000[2]
17,500	345,000[2]

[1] Based on one shift operation

[2] Based on two shift operation

* Derived from a composite of estimates and bids.

INCINERATION OF MATERIALS OTHER THAN MUNICIPAL SLUDGES

The general opinion obtained from the consulting engineer questionnaire (See Section on "Attitudes of the Consulting Engineer") and other data is that waste materials other than sewage sludge may be disposed of through incineration. The three classes of non-sludge materials which could be incinerated in the same type of burner, either in place of or with pumpable sewage sludge, are:

1. Screenings - the materials removed at the sewage treatment plant headworks by screens.

2. Waste oils, greases and other skimmed material.

3. Industrial waste solids - waste materials from the fruit and vegetable processing industry.

In larger plants where digestion is still employed, a separate incinerator for skimmings and screenings may be desirable. However, it is not likely that smaller plants with two-stage digestion will purchase a second solids disposal system where incineration of screening is practical. A separate macerator and pump are needed to move the screenings to the incinerators. It is generally desirable to mix the ground screenings with the sludge prior to centrifugation.

While handling skimmings in incinerators, special care should be taken to avoid slugging of high BTU material. This problem is solved by mixing the skimmings directly into the thickener sludge blanket. This has been patented by Dorr-Oliver. This system, however, has a major disadvantage in that if the sludge is held long or if the temperature of the sewage is high under normal detention conditions, substantial breakdown and solubilization of the greases occur which results in the loss of the high caloric value fuel. A satisfactory solution is to bleed the scum into the system on a continuous basis from a mixed holding tank and the system would be operated when the sludge incinerator is functioning. The grease adds 10 to 15% to the gross BTU value of the sludge and is very desirable from this standpoint.

Other waste oils constitute a potential market of great magnitude. The total waste oil disposal requirements of the gasoline stations in the United States is 350 x 10^6 gallons per year. The total number of stations is 210,000 and the average annual disposal burden is 140 gallons per month per station. This oil is now being disposed of in a highly haphazard manner of much concern to both federal and state officials. For example, in the Westport-Norwalk, Connecticut, area, there are in excess of 300 gasoline stations;

about half of these are served by sewers, the remainder by other means of waste disposal. Assuming these are of average size, 32,000 gallons of waste oil a month needs to be handled.

The waste oil constitutes an enormous pollution problem and it is not possible at this point in time to identify a customer. It is also not to be a municipal chore to pick up waste oils. However, it is clear that the 20 to 25 cent differential between buying BTU's at roughly 15 cents per gallon and picking up the oil at 5 to 10 cents per gallon is sufficient to make it a satisfactory adjunct to the municipal incineration of sludge.

It is important to note that in the President's special report[59], "A Report on Pollution of the Nation's Waters by Oil and Other Hazardous Substances," the proposed action program indicates a complete lack of understanding of the problem of assigning or finding a responsible party or legal entity to deal with waste oils from service stations. Therefore, it would appear that little can be expected in terms of federal pressures in the near future.

A thorough analysis of the waste sludges from the fruit and vegetable processing industries indicates that while the problem is large, there appears to be insufficient fiscal pressure to make incineration attractive. The National Canners Association states[60] that waste solids cannot be incinerated at costs comparable to their present method of disposal. Waste disposal from the food industry, which amounts to 500,000 to 700,000 tons of wet waste during the four month campaign in the 13 county delta area surrounding the California Bay area, is currently barged to sea. This waste cannot be dried much further than 12 to 18% solids, depending on which fruit or vegetable has been processed. The operating costs of incineration would exceed $30 - $40 per ton which is more than $25--the industry's total investment for barge disposal at this time.

Another area of interest is the marine waste disposal. The disposal of concentrated sewage from the containment vessels at the marina pierhead by incineration will be a substantial service business which can be correlated with fueling and dewatering. Water from dockside could be employed for scrubbing with direct ash discharge or cyclonic ash separation.

A similar business is possible in connection with the disposal of septic tank or pit toilet wastes at camps of the United States Park Service and the United States Forest Service. The device for such service would have to be mobile but could be operated in many instances with dry rather than wet stack quality control devices.

DISPOSAL OF REFUSE WITH SEWAGE SLUDGE

A number of municipalities are reaching the capacity of their land fill areas to receive their refuse. The value of land surrounding municipalities is increasing at a rapid rate for residential and industrial development making new land areas very expensive and often unattainable. Furthermore, people are becoming sensitive to the existence of a dumping or land fill area in close proximity to the residential areas. These factors are giving impetus to the ever growing popularity of the mixed refuse incinerator for the incineration of sewage sludge and refuse.

Whenever the location of the sewage treatment plant will permit reasonable hauls, the installation of a mixed refuse incinerator at the sewage treatment plant site will permit disposal of the municipal garbage, refuse and sewage sludge at the same plant site. Such an installation permits drying or incineration of the sewage sludge with no auxiliary fuel requirements due to the heat in the waste gases from the burning of the mixed refuse.

Heat for drying the sewage sludge filter cake is supplied by the mixed refuse incinerator and the flash dried sludge may be marketed as fertilizer or incinerated at will. The dual disposal of mixed refuse and sewage sludge at the same plant site affects economics in both first cost and operating costs of the disposal equipment. For smaller communities, this system provides modern disposal facilities whereas the first cost or operational cost of the separate disposal facilities will be prohibitive. The following cities have this system in use:

Watervliet, New York	Bloomsburg, Pennsylvania
Stamford, Connecticut	Louisville, Kentucky
Waterbury, Connecticut	Neenah-Menasha, Wisconsin
Fond du Lac, Wisconsin	

The success of burning the sludge with refuse depends on the type of sludge, hauling cost for refuse, etc. However, in all cases, it is important to give consideration to combined use and sludge incineration. This system may be particularly useful in small cities where hauling costs could be reasonable. For larger cities, centrally located refuse collection and sewage treatment could make this system very conducive. Improved mechanical design of incinerators and development of inexpensive refuse collection technique would encourage combined incineration.

EFFECT OF INCINERATION ON OTHER RESOURCE MANAGEMENT

The incineration of sewage sludge is usually cited as a prime example of the interrelationship between the management of land, air and water resources. It is unfortunate that many sludge disposal systems (starting at the clarifier) have not, during their concept, been designed with an eye towards total resource management. Among the factors which need to be considered in any evaluation of a sludge disposal system with respect to total resource management are:

1. Effect of the return of recovered liquors from sludge dewatering steps to the wastewater treatment system.

2. Availability of land for solids disposal.

3. Impact of solids disposal upon land use and ground and surface waters.

4. Impact of treatment facility upon adjacent land use and value.

5. Extent of odor problems.

6. Effect of sludge disposal upon ambient air quality.

7. Interrelation between sludge disposal and the potential disposal of other community solid and high-caloric liquid wastes.

Only when the total resource management picture is seen can the municipality be satisfied that an optimum solution be found to the sludge disposal problem.

ATTITUDES OF STATE AGENCIES TOWARD INCINERATION

As a result of the clean water legislation in the United States Congress, the state regulatory agencies have increased the tempo of their regulatory activities. As of now, all fifty states have had their water quality criteria approved by the United States Department of the Interior, at least in part. This implies obligatory secondary treatment and in most states the deadline is prior to 1973.

The results available to Resource Engineering Associates from a survey[61] conducted on sludge incineration earlier to the initiation of this project are analyzed and presented in the following paragraphs.

About half the states in the United States contain plants which practice some form of sludge incineration. The bulk of these serve population groups over 10,000 in size. However, six states--Nevada, Missouri, New Jersey, Colorado, Washington and California--have incinerators serving population groups under 10,000 people. The states generally not employing incinerators are located in the deep South, Southwest, Rocky Mountain area, upper New England and the Great Plains. Incineration appears to go with urban thinking and planning and not with the rural community.

States reporting no incineration are the following:

Alaska[1]	New Hampshire
Arizona	New Mexico
Delaware	North Dakota
Florida	Oklahoma
Georgia	Oregon
Idaho[2]	South Carolina
Iowa	South Dakota
Maine	Utah
Mississippi	Vermont
Montana	Wyoming

[1]Abandoned one

[2]Boise is installing twin type C/R Reactors (Dorr-Oliver)

Most states indicated that they could foresee an increase in the use of incineration. Fifty-four per cent saw an increase, 29% saw no increase and 17% had no opinion.

From an operational viewpoint, there were comments from only fourteen states. The most common concerns were: 1) ash disposal, 2) thickening and dewatering, and 3) odors; although others commented on 4) capacity, 5) temperature control (related normally to grease incineration), 6) sludge conveyance problems, and 7) smoke. Only in Texas did 8) vector control also appear to be a problem.

Most states indicated that they felt no reluctance to approve incineration facilities. Seventy-seven per cent indicated no reluctance, 17% some reluctance and 6% had no opinion.

Very little incinerator type preference was reported from the states. Those reporting were split between multiple hearth and fluid bed reactors at 6 - 10. Only one state, Florida, appeared to favor cyclonic-type reactors.

In response to the question concerning size and applicability, the states responded in the following ratios:

Greatest use over 50,000 persons	10
Greatest use from 10,000 - 50,000	5
Greatest use from 5,000 - 10,000	1
Greatest use from 2,000 - 5,000	0
Greatest use from 1,000 - 2,000	0
Greatest use from 0 - 1,000	0

Generally speaking, the states responded to the questions concerning sludge disposal problems by saying at a ratio of 4 to 1 that they had no major problem disposing of sludge in their areas. Those states indicating a major problem were:

Georgia

Iowa

Maryland

Nevada

New Jersey

Oregon

Rhode Island

Those states indicating some acute, but localized problems were:

Idaho	New Jersey
Kentucky	Rhode Island
Maryland	South Dakota
Massachusetts	Tennessee
Nevada	Washington

It should be pointed out that often cost is not considered a major problem by state officials. Therefore, there probably are more true problem areas than are reflected in that answer.

ATTITUDES OF THE CONSULTING ENGINEER TOWARD INCINERATION

The following paragraphs are presented based on a survey[61] conducted in the latter part of 1968 on the attitudes of consulting engineers on sludge incineration.

As might be expected, only a portion of the firms questioned have constructed incinerators; about 35% indicated that they have built incinerators. Nonetheless, a large majority, 65%, believe incinerator use is increasing, only 6% believe it is decreasing and 29% had no opinion. Almost all of the units constructed, over 90%, were above 500 lb/hr, as might be expected.

The bulk of the engineers, or 80%, reported that the operators prefer to burn sludge less than 8 hours a day. The remaining few that answered were evenly scattered up to 24 hours of burning.

Roughly half of the consultants had no type preference. In the larger size - over 15,000 population - 25% preferred the multiple hearth, 25% the fluid bed, 8% the travelling grate and 42% had no opinion. Under 15,000 population, 24% preferred the fluid bed, 12% multiple hearth, 8% cyclonic type, 2% travelling grate, and 54% had no opinion.

When asked if two-stage digestion would disappear, 39% said yes, 27% said no, and 34% had no opinion.

A good response was obtained to the question dealing with the factors mitigating against incineration. The response was as follows:

High operating cost	39%
High capital cost	35%
Thickening and dewatering problems	26%
Air pollution	22%
Required operator expertise	18%
General increase of operating problems	12%
Safety	0

Forty-three per cent favor packaged system, 16% built-up, and 41% had no opinion.

Only four consultants have experienced problems in getting incineration approval. These were located in California and Illinois.

Three of the four are in sensitive air pollution areas.

Forty-three per cent indicated that some of their clients have a history of sludge disposal problems. Sixteen per cent indicated no problem and 41% did not respond.

The consultants felt almost universally that greases, oils and screenings could best be disposed of by incineration. A substantial fraction also favor disposal of organic industrial wastes by this technique.

In summary, the overall attitude appears to be one of acceptance and even eagerness to employ incineration. Certainly there is little evidence of genuine emotional bias against this mode of sludge disposal.

THE SLUDGE INCINERATION MARKET - CURRENT STATUS

The incineration of sewage sludge has been practiced in this country since 1934. The vast bulk of the incinerators that have been installed have been of the multiple hearth or flash drying and incineration types. However, since the beginning of this decade, two new incinerator concepts have cut into the commercial lead of the other manufacturers; these are the wet oxidation and fluid-bed reactors. The major incinerator manufacturers are shown in Table XV.

The time of construction and related pertinent information concerning these incinerators are shown in Tables XVI through XX.

The two manufacturers of systems incinerating pumpable sludges in small sizes are both employing cyclonic-type reactors. On the cost basis, multiple hearth, flash drying and fluid-bed reactors are very expensive in the smaller sizes.

TABLE XV

MAJOR MANUFACTURERS OF SLUDGE INCINERATORS

Manufacturer	Type Constructed	Year of Entry	System	Other Remarks
Nichols	Multiple hearth	1934	No	81 Constructed
Bartlett-Snow-Pacific	Multiple hearth	1963	No	24 Constructed
Dorr-Oliver	Fluid-bed	1962	Yes	38 Constructed
Dorr-Oliver	Cyclonic-reactor	1966	Yes	1 Constructed 4 Under construction
Raymond (Combustion Engineering)	Open furnace with drying column	1935	Optional	50 Constructed 19 Drying only
Sterling Drug Zimpro Division	Wet oxidation	1961	Yes	17 Constructed 1 Under construction

TABLE XVI

MULTIPLE HEARTH INSTALLATIONS

BY MAJOR UNITED STATES MANUFACTURERS

Year	Capacity lb/hr Dry Solids	Dewatering Technique if Known	Remarks
1934	1,000		
1936	500		
1936	1,000		
1937	2,000		
1938	11,000		
1938	7,000		
1938	500		
1938	1,000		
1939	1,600		
1939	23,000		
1939	700		
1939	700		
1939	900		
1941	900		
1945	1,600		
1948	1,300		
1948	7,000		
1949	5,000		
1949	1,000		
1949	3,900		
1949	2,000		
1949	1,600		
1950	2,000		
1950	4,000		
1952	1,000		
1952	1,500		
1952	1,000		
1952	500		
1952	1,000		
1953	1,000		
1953	1,000		
1954	800		
1954	400		
1954	3,000		
1955	14,000		
1955	12,000		
1956	3,000		
1956	2,000		
1956	1,600		
1957	6,000		
1958	800		
1958	300		
1959	2,000		
1959	1,400		

TABLE XVI (Continued)

Year	Capacity lb/hr Dry Solids	Dewatering Technique if Known	Remarks
1960	1,500		
1960	800		
1961	1,500		
1961	3,000		
1961	500		
1962	6,100		
1962	4,000		
1962	2,000		
1962	2,700		
1962	1,300		
1962	6,600		
1962	6,600		
1963	1,400		
1963	400		
1963	6,000		
1963	11,500		
1963	800		
1963	5,000		
1963	5,400	Vacuum Filter	
1963	600	Vacuum Filter	
1963	900	None	Grease and skimmings only
1964	100		
1964	150		
1964	5,000		
1964	700		
1964	5,000		
1964	3,600	Centrifuge	
1964	2,030	Vacuum Filter	
1964	1,700	Vacuum Filter	
1965	15,000		
1965	25,000		
1965	400		
1965	2,000		
1965	3,000		
1965	7,150	Vacuum Filter	
1965	500	Vacuum Filter	
1965	6,600	Vacuum Filter	
1966	7,000		
1966	2,200	Vacuum Filter	
1966	4,000	Vacuum Filter	
1966	25	Vacuum Filter (Centrifuge)	Pilot plant
1966	1,750	Vacuum Filter	
1967	3,000		
1967	3,000		
1967	2,600		
1967	8,000		
1967	300		
1967	1,100	Centrifuge	

TABLE XVI (Continued)

Year	Capacity lb/hr Dry Solids	Dewatering Technique if Known	Remarks
1967	900	Centrifuge	
1967	1,500	Centrifuge	
1967	1,500	Centrifuge	
1967	3,250	Vacuum Filter	
1967	450	Vacuum Filter	
1967	1,000	Vacuum Filter	
1968	5,000		
1968	1,500		
1968	3,600		
1968	1,200		
1968	2,500		
1968	1,800	Vacuum Filter	
1968	2,000	Centrifuge	
1968	2,100	Vacuum Filter	(Porteous Plant)

TABLE XVII

FLASH DRYING AND INCINERATION SYSTEMS

Year	Capacity lb/hr Dry Solids	Dewatering Technique	Remarks
1935	1,667	Vacuum Filter	
1938	2,500		
1939	5,250		
1940	878		
1940	420		
1941	1,060		
1943	1,570		Drying only
1944	1,500		
1946	1,353		Drying only
1950	2,250		Drying only
1950	3,210		Drying only
1950	7,740		
1951	1,000		Drying only
1951	785		
1952	1,170		
1953	2,083		Drying only
Unknown	420		Drying only
1953	2,100		
1953	890		
1953	3,000		Drying only
1954	1,500		
1954	5,025		
1954	750		Drying only
1955	5,250		Drying only
1955	4,370		
1955	1,400		Drying only
1956	3,000		
1956	1,000		
1957	2,190		
1957	1,075		Drying only
1957	630		Drying only
1958	2,000		
1958	862		Drying only
1958	1,224		Drying only
1958	354		Drying only
1958	4,000		Drying only
1959	4,610		
1959	2,671		
1959	2,694		
1959	3,710		
1959	1,490		
1960	4,300		
1960	1,714		
1962	2,520		Drying only

TABLE XVII (Continued)

Year	Capacity lb/hr Dry Solids	Dewatering Technique	Remarks
1963	3,100		
1964	700		
Unknown	1,820		Drying only
Unknown	5,178	Vacuum Filter	
Unknown	4,830		
Unknown	3,460		

TABLE XVIII

WET OXIDATION INSTALLATION LIST

Year	Capacity lb/hr Dry Solids	Dewatering Technique	Remarks
1961	25,000	Sedimentation and/or Thickening	
1961	960		
1963	125		
1964	175		
1967	400		
1967	330		
1967	1,250		
1969	1,040		
1969	540		
1969	117		
1969	560		
1970	4,200		
1970	3,840		

TABLE XIX

FLUID-BED REACTORS INSTALLATION LIST

Year	Capacity lb/hr Dry Solids	Dewatering Technique if Known	Remarks
1962	220	Centrifuge	
1963	500	Centrifuge	
1963	1,000	Centrifuge	
1964	220	Centrifuge	
1964	420	Centrifuge	
1964	500	Vacuum Filter	
1964	5,000	Centrifuge	
1964	840	Vacuum Filter	
1965	490	Centrifuge	
1965	2,000	Vacuum Filter	
1965	500	Centrifuge	
1966	282	Centrifuge	
1966	470	Centrifuge	
1966	450	Centrifuge	
1967	500	Centrifuge	
1967	1,215		
1967	500	Centrifuge	
1967	1,000		
1967	350	Centrifuge	
1967	500	Centrifuge	
1967	875		
1967	1,100	Centrifuge	
1968	430	Centrifuge	
1968	860	Centrifuge	
1968	700		
1968	425	Centrifuge	
1968	700	Centrifuge	
1968	3,340	Centrifuge	
1968	950	Centrifuge	

TABLE XX

CYCLONIC-TYPE REACTORS INSTALLATION LIST

Year	Capacity lb/hr Dry Solids	Dewatering Technique	Remarks
1966	100	Centrifuge	
1968	350	Centrifuge	
1968	400	Centrifuge	

AN ANALYSIS OF NEEDS

A number of system needs have come to light either directly or indirectly from the analysis of the state of the art on sludge incineration. Some of these, such as the need for cost reduction for sludge conditioning and the need for a greater ability to concentrate waste activated sludge have been derived in a driect fashion from the data and observations contained in this document. However, there are a number of other items which, because of their absence from existing systems, the need can only be deduced from an analysis of processes which might be considered desirable or to be good engineering practice. Each of the individual items with the pertinent details will be considered in turn in the following paragraphs.

Cost of Conditioning

A number of figures for the cost of conditioning the sludge have been presented. It is obvious from these data and from more casual references to this particular problem that the cost of conditioning mixed activated and primary sludges can vary from as little as ten or twelve dollars a ton of dry solids to as much as fifty or one hundred dollars a ton of dry solids.

Much of the high cost for sludge conditioning derives from the condition of anaerobiosis of the sludges when they reach the sludge conditioning portion of the system. Anaerobiosis results from the fact that most operators do not like to burn on a twenty-four hour basis. Hence, there is a necessity to store sludge, probably in the thickener for some period of time. If the plant is small, sludge may be stored for as long as 16 or 18 hours and sometimes it may be stored over an entire weekend.

Storage has some additional undesirable features in that many of the items of high BTU fuel in the sludge may be sufficiently hydrolyzed so they result in the filtrate or centrate at the dewatering device and are returned to the system. They then appear as new biological material rather than being incinerated directly as a high BTU fuel. Therefore, storage has two significant disadvantages.

Obviously, the heat treatment sludge conditioning concepts reported on in this document in an extensive fashion are one answer to the problem of reducing the cost of sludge conditioning. Depending on the plant size, the overall cost of sludge conditioning can be reduced to less than ten to fifteen dollars per ton including the amortization of equipment.

In a very special way, heat conditioning of the sludges is also an answer to the second problem--the one of sludge hold over and the resulting anaerobiosis and loss of high BTU fuels. That is, that the normal impact of waste activated sludge on the solids concentration of the filter or centrifuge cake going to the incinerator is altered. The cell rupturing effects of heat treatment with the resulting loss of internally bound water obviously permits a much higher cake concentration. Therefore, although additional biological material may be produced as a result of sludge holding, its total impact on the entire sludge-handling process is much reduced.

It can be concluded that there is a very real need for an inexpensive sludge conditioning system which can be incorporated in small incineration packages. There are some rather obvious features or attributes which should be included in such a system which can be drawn by inference from this document. These are as follows:

1. The impact of sludge hold over on both solids content and the loss of high BTU fuel should be eliminated.

2. Should the system involve heat conditioning maximum use of waste heat, which is substantial in quantity because of the need for deodorization, should be included.

3. The impact of the physical or physical-chemical characteristics of the conditioned sludge on the entire system should be evaluated. For example, it is becoming increasingly obvious that the physical characteristics of heat-treated sludge are dramatically different from those which have not received heat treatment.

Redundant Systems

Because of the basic characteristics employed in the design of conventional sludge incineration systems, it has not been economically feasible to provide redundant or multiple incinerators within the entire solids disposal facility. There is a need for overlapping capacity to permit the continuous, albeit lowered, rate of sludge disposal during the time an incinerator is out of service. Experience has shown that the overall effect of long-term storage is undesirable. Experience has also shown that the cost of alternate means of disposal such as trucking, emergency lagooning, and so forth, is excessive.

Extremely large systems have employed the redundant or multiple unit concept. There is an equal need to provide or include such facilities in systems of smaller size, for example, in most systems for populations under 50,000.

Dorr-Oliver, Inc., has, in part, applied this concept in the design of the multiple Type C/R sludge incineration system. The most recent unit placed in operation is at Laguna Beach, California. This plant contains two Type C/R incinerators which will provide some of the redundant capacity which is believed to be desirable.

Sludge Conveyance

In all of the systems examined, there have been reports of problems of sludge conveyance particularly associated with either lack of or improper internal system capacitance. It is believed that these two problems--that is, conveyance and capacitance--must be considered together. It appears from the results of the analysis that the ideal sludge storage and conveyance system would embody the following characteristics:

1. A strong capability or provision for internal capacitance. This implies the need for short-term storage of conditioned sludge between the sludge dewatering device and the incinerator. There are several reasons as to why system capacitance at this point is desirable and perhaps necessary.

    a) The incinerator can be run for short periods of time without the sludge dewatering unit.

    b) With internal capacitance, there is no need to balance the output of the sludge dewatering unit on a continuous basis with the incinerator burning rate.

    c) If the sludge dewatering unit goes off the line for a short period of time, the incinerator need not be shut down.

As indicated, it appears necessary to concurrently evaluate means of conveyance with techniques for providing system capacitance. A number of conveying methods have been employed. The selection has been more or less based on the general characteristics of the sludge cake itself and the methods of sludge injection into the incinerator. For example, dewatered raw sludge is frequently conveyed to the incinerator with a screw-type device. Mixed, raw and activated sludge varying in solids concentration between 20 and 25% frequently has been conveyed from the point of dewatering to the incinerator with a positive displacement pumping device. It has generally been considered impractical to attempt to design into the sludge conveying system a modulating or variable feed property. At the present time, and this applies usually to fluid bed system, when the fuel tends to run much higher than autogenous in its net BTU content, the system is cooled with water sprays. The net result is effective loss of fuel whether it happens to be derived from material to be burned or auxiliary fuel. Therefore, in a way this is a self defeating approach. There will be also an increase in the average velocities above the bed due to the steam resulting from the added water.

As heat conditioning becomes a more significant factor in terms of the number of applications, fuels will tend to be, in general, more nearly autogenous in character. Therefore, a system for temperature control within the reactor would appear to be substantial. While, in a physical sense there would appear to be nothing wrong with the water cooling as the fuels become increasingly high in net or effective BTU value, the need for temperature control by other means will become more acute. It would appear, therefore, to minimize the reactor size and also provide for the optimum or desirable temperature controls that a means of varying the feed rate should be included. It may be necessary to control the varying rate feed device from the stack temperature sensing system. Considering current practice, it would appear this should be controlled between 1200 or 1300° F and perhaps up to 1600 or 1700° F. While in some cases it may be possible to employ on/off sludge feeding mechanisms, those systems (such as the Dorr-Oliver Type C/R incinerator) which have a fairly high system capacity in terms of pounds of solids burned per unit volume per unit time will cool quite rapidly should sludge not be fed. Therefore, a varying rate feed system would appear to be more desirable than the one based on the on/off concept.

A number of other points which should be considered are the following:

1. Better techniques for handling skimmings and screenings in the incinerator need to be evolved. Conveyance of these materials to the incinerator is also a problem.

2. Continued considerations need to be given to coincineration of solid wastes and sludges because of the high net BTU content of the former.

3. Based on the operator complaints, better odor control around the conditioning and dewatering subsystems needs to be practiced.

4. Better means of ash removal, and scrubber water recycle need to be evolved.

5. Where applicable better techniques for fuel conservation through the heating of the secondary air need to be practiced.

Summary

To summarize briefly, the following system needs have been noted:

1. The need for better and more economical sludge conditioning techniques particularly applied to those cases where substantial quantities of waste activated sludge are encountered and in those instances where sludge storage for periods of hours or days is a necessary part of the operation.

2. A need for system redundancy has been noted. It has been further noted that the Dorr-Oliver Type C/R system, as it is currently being marketed, to a degree meets the need for system redundancy. However, further research and development would appear to be desirable in this particular area.

3. A need has been noted for system capacitance and a variable feed sludge conveyance system as sludge conditioing techniques improve and more nearly autogenous sludges are burned. The conditions make it desirable to control the reactor temperature by the use of a modulating or variable feed system. System capacitance between the sludge dewatering device and the incinerator will aid in the development of a varying type feed system and also provide for short periods of sludge incineration during a period that the sludge dewatering facility may be out of service.

4. Several secondary considerations have been noted such as coincineration, internal odor control, detritus incineration, secondary air heating, and ash handling.

REFERENCES

1. Owen, M.B., "Sludge Incineration," Proc. of the ASCE, San. Engr. Div., Proc. Paper No. 1172, 1957.

2. Millward, R.S., Booth, P.B., "Incorporating Sludge Combustion into a Sewage Treatment Plant," Paper presented at the 39th Annual Meeting of the New York Water Pollution Control Association at New York, 1967.

3. Babbitt, H.E., Sewerage and Sewage Treatment, John Wiley & Sons, Inc., London, 7th Edition, 1952.

4. Mancini, J.L., "Gravity Clarifier and Thickener Design," Proc. of the 17th Purdue Industrial Waste Conference, pp. 267-277, 1962.

5. Kynch, G.J., "A Theory of Sedimentation," Trans. the Faraday Society, Vol. 48, pp. 166-176, 1952.

6. Fitch, E.B., "Sedimentation Process Fundamentals," Trans. Society of Mining Engineers, Vol. 223, pp. 129-137, 1962.

7. Fitch, E.B., Talmage, W.P., "Determining Thickening Unit Areas," Industrial and Engr. Chemistry, Vol. 47, No. 1, pp. 38-41, 1955.

8. Rudolfs, W., "Concentration of Activated Sludge by Compacting and Flotation," Sewage Works Journal, Vol. 15, No. 4, pp. 642-657, 1943.

9. Burd, R.S., "A Study of Sludge Handling and Disposal," Publication No. WP-20-4, Federal Water Pollution Control Administration, U.S. Department of the Interior, p. 29, 1968.

10. Comings, E.W., "Continuous Settling and Thickening," Industrial and Engr. Chemistry, Vol. 46, No. 6, pp. 1164-1172, 1954.

11. Ettelt, G.A., "Activated Sludge Thickening by Dissolved Air Flotation," Proc. of the 19th Purdue Industrial Waste Conf., pp. 210-244, 1964.

12. Eckenfelder, W.W., McCabe, B.J., Biological Treatment of Sewage and Industrial Wastes, Vol. II, pp. 222-258, Reinhold Publishing Corporation, New York, 1958.

13. Mayo, E., "Industrial Applications of Air Flotation," Paper presented at the 38th WPCF Conference, 1965.

14. Laboon, J.F., "Pittsburgh Plans Unique Project to Abate Stream Pollution," Civil Engr., Vol. 24, No. 1, pp. 44-45, 100, 1954.

15. Committee on Sewerage and Sewage Treatment, "Advances in Sludge Disposal in the Period from October 1, 1954, to February 1, 1960," A Progress Report of the ASCE - San. Engr. Div., Vol. 88, No. SA2, pp. 13-51, 1962.

16. Evans, S.C., Roberts, F.W., "Heat Treatment of Sewage Sludge," The Surveyor, Vol. 106, No. 2867, 1947.

17. Lumb, C., "Heat Treatment as an Aid to Sludge Dewatering - Ten Year's Full Scale Operation," Jour. of the Institute of Sewage Purification, Part I, pp. 5-15, 1951

18. Evans, S.C., "Metropolitan and Southern Branch - Sludge Treatment at Luton," Jour. of the Institute of Sewage Purification, Part V, 1961.

19. Lancord, F., "Utilisation de Nouvelles Techniques dans les Installations D'Assainissment du Canto de Geneve," Bulletin Technique de la Swisse Romando, Vol. 91, No. 14, 1965.

20. Lumb, C., "Heat Treatment as an Aid to Sludge Dewatering - Ten Month's Full Scale Operation," The Surveyor, Vol. 98, No. 2550, 1940.

21. Harrison, J., "Aspects of the Heat Treatment of Domestic Sewage Sludge," M.S. Thesis, Virginia Polytechnic Institute, 1964.

22. Lumb, C., Hirst, J., "Experiments on Dewatering Humus and Activated Sludge," The Surveyor, Vol. 92, No. 2371, 1937.

23. BSP Corporation, "The Porteous Process," U.S. Patent 3,155,611.

24. White, W. F., Burns, T.E., "Continuous Centrifugal Treatment of Sewage Sludge," Water and Sewage Works, Vol. 109, pp. 384-386, 1962.

25. Jones, W.H., "Sewage Sludge Dewatering - Selection/Sizing and Application of Equipment," A Paper Presented at the 9th Great Plains Sewage Works Design Conf., 1965.

26. Schempman, B.A., Cornell, C.F., "Fundamental Operating Variables in Sewage Sludge Filtration," Sewage and Industrial Wastes, Vol. 28, No. 12, pp. 1443-1460, 1956.

27. McLaren, J.W., "Evaluation of Sludge Treatment and Disposal," Canadian Municipal Utilities, pp. 23-33, 51-59, 1961.

28. Simpson, G.D., Sutton, S.H., "Performance of Vacuum Filters" in "Sludge Concentration Filtration and Incineration," Continued Education Series 113, U. of Mich., Ann Arbor, pp. 126-138, 1964.

29. Dietz, J.C., "Some Factors Influencing the Selection of Sludge Handling and Disposal Methods for Municipal Sewage Treatment Plants," Proc. of the 13th Purdue Industrial Waste Conference, pp. 555-565, 1958.

30. "Nichols-Roto-Plug Sludge Concentrator," Bulletin No. 254, Nichols Engr. and Research Corp., New York, 1963.

31. Smith, E.G., "Features of a Mechanical Sludge Concentrator for Dewatering Sludge," Sewage and Industrial Wastes, Vol. 29, No. 5, pp. 601-606, 1957.

32. Thompson, J.T., Proctor, J.W., "Filter Pressing of Sludge," The Surveyor, Vol. 93, pp. 235-236, 1938.

33. Slagle, E.A., Roberts, L.M., "Treatment of Sewage and Sewage Sludge by Electrodialysis," Sewage Works Jour. Vol. 14, No. 5, pp. 1021-1029, 1942.

34. Beaudoin, R.E., "Reduction of Moisture in Activated Sludge Filter Cake by Electro-Osmosis," Sewage Works Jour. Vol. 15, No. 6, pp. 1153-1163, 1943.

35. Cooling, L.F., and others, "Dewatering of Sewage Sludge by Electro-Osmosis," Water and San. Engr., Vol. 3, No. 7, p. 246, 1952.

36. Stallery, R.H., Eauth, E.H., "Treatment of Sewage Sludge by the McDonald Process," Public Works, Vol. 88, p. 111, 1957.

37. Bruce, A., and others, "Further Work of the Sludge Freezing Process," The Surveyor, Vol. 112, p. 849, 1953.

38. Clements, G.S., and others, "Sludge Dewatering by Freezing with Added Chemicals," Jour. Inst. of Sew. Purif., Part 4, pp. 318-337, 1950.

39. Doe, P.W., Beys, L.R., Benn, D., "Sludge Concentration by Freezing," Water and Sewage Works, Vol. 112, pp. 401-406, 1965.

40. "Sludge Concentration by Freezing," Editors, Water and Sewage Works, November, 1965.

41. Coackley, P., "Research on Sewage Sludge Carried Out in the Civil Engr. Dept. of University College," Jour. Inst. of Sew. Purif., Part I, pp. 59-72, 1955.

42. Albertson, O.E., "Low Cost Combustion of Sewage Sludges," Paper presented at the 1963 Annual Meeting of the Water Pollution Control Federation in Seattle, Washington, Oct. 8, 1963.

43. Chasick, A.H., Burger, T.B., "Using Graded Sand to Test Grit Removal Apparatus," Vol. 36, No. 7, p. 884, Jour. Water Pollution Control Federation, July, 1964.

44. Russel, R.A., "Theory of Combustion of Sludge," in "Sludge Concentration - Filtration and Incineration," Continued Education Series No. 113, U. of Mich., Ann Arbor, pp. 380-382, 1964.

45. Albertson, O.E., Personal Communication, Dorr-Oliver, Inc., Stamford, Connecticut, 1969.

46. Bartlett-Snow-Pacific, Inc., Bulletin No. HI-2M-1-65, 1964.

47. Quirk, T.P., "Economic Aspects of Incineration Versus Incineration-Drying," in "Sludge Concentration - Filtration and Incineration," Continued Education Series No. 113, U. of Mich., Ann Arbor, pp. 389, 1964.

48. Schroepfer, G.J., "Incinerator Problems," Sewage Works Journal, Vol. 19, No. 4, pp. 559-579, 1946.

49. Walter, L.H., Millward, R.S., "Sludge Disposal by the F/S System," A Paper presented at the 16th U. of Kansas San. Engr. Conf., 1966.

50. Sohr, W.H., et al., "Fluidized Sewage Sludge Combustion," Water Works and Wastes Engineer, Vol. 2, No. 9, pp. 90-93, 1965.

51. "The C-E Raymond Flash Drying and Incineration System for Sewage Sludge Disposal," Bulletin No. FD-60, Combustion Engineering, Inc., Chicago, Ill.

52. Hubbard, P.J., Albertson, O.E., "The Type CR FS Disposal System," Dorr-Oliver Technical Reprint No. 607-P, 1967.

53. Hurwitz, E., et al., "Wet Air Oxidation of Sewage Sludge," Water and Sewage Works, Vol. 112, No. 8, pp. 298-305, Aug., 1965.

54. Ettelt, G.A., Kennedy, T.J., "Research and Operation Experience in Sludge Dewatering," Jour. Water Pollution Control Federation, Vol. 38, No. 2, p. 250, 1966.

55. Pinder, K.L., Gauvin, W.H., "Applications of the Atomized Suspension Technique to the Treatment of Waste Effluents," Proc. of the 12th Purdue Industrial Waste Conference, pp. 217-249, 1957.

56. Campbell, H.J., "The Changing Pattern of Municipal Incinerator Design," Consulting Engineer Magazine, November, 1965.

57. Nickerson, R.D., "Sludge Drying and Incineration," Jour. Water Pollution Control Federation, Vol. 32, No. 1, pp. 90-98, 1960.

58. Jaffe, T., "Odor Control in Sewage Treatment," Water and Sewage Works, Vol. 104, No. 4, pp. 175-178, 1957.

59. A Report on Pollution of the Nation's Waters by Oil and Other Hazardous Substances, Department of the Interior and Secretary of Transportation, 1968.

60. "The Canning Industry," National Canners Association Publication, 1963.

61. Balakrishnan, S., Personal Communication, Resource Engineering Associates, Wilton, Conn., 1968.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1970 O - 405-436