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Laboratory
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EPA

Handbook

Estimating Sludge Management Costs

NOTICE

EPA/625/6-85/010

HANDBOOK

ESTIMATING SLUDGE MANAGEMENT COSTS

U.S. ENVIRONMENTAL PROTECTION AGENCY

Office of Research and Development
Water Engineering Research Laboratory
Cincinnati, Ohio 45268

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FOREWORD

The formation of the U.S. Environmental Protection Agency (EPA) marked a new era of environmental awareness in America. This Agency's goals are national in scope and encompass broad responsibilities in the areas of air and water pollution, solid and hazardous wastes, pesticides and toxic substances, and radiation. A vital part of EPA's national pollution control effort is the constant development and dissemination of new information.

The purpose of this Handbook is to provide information on estimating costs for management of the sludge residue that results from municipal wastewater treatment. The cost for sludge management represents as much as half of the total cost of wastewater treatment.

The information in this Handbook should make it possible to obtain rapid cost comparisons between different sludge management alternatives. This, in turn, should result in choosing more cost-effective combinations of processes and help decrease the nationwide cost of sludge management.

At some time in the future, we may consider updating this Handbook if interest seems to justify such an effort. With that goal in mind, comments that would aid in issuing a revised and improved version are earnestly solicited.

We sincerely hope that this document will be of value to those interested in municipal sludge management.

ABSTRACT

This manual provides preliminary cost estimating curves, covering both capital costs and annual operating and maintenance (O&M) costs, for commonly used processes in municipal wastewater sludge treatment, storage, transport, use, or disposal. In addition, annual O&M component curves, which provide additional user flexibility, are also included. Curves are based on the cost algorithms contained in Appendix A. The processes can be readily arranged into various sludge management chains and preliminary costs estimated for each sludge management chain to be evaluated. Costs presented are based on the last quarter of 1984, and can be updated to later years by use of appropriate cost indexes.

An annotated bibliography of selected literature containing sludge management cost estimating information is included in Appendix B. Appendix C provides commonly used English to metric conversion factors.

The cost curves provided generally cover a range up to 100 million gallons of sludge per year, which is roughly equivalent to a wastewater treatment plant capacity of at least 50 mgd. The range selected includes plant sizes where it was considered that supplemental cost information might be the most useful. By using the cost curves, the user may obtain approximate capital and annual O&M costs rapidly. Where applicable, a family of curves is presented showing cost differentials as a function of a significant sludge quality variable (e.g., sludge suspended solids) or operational variable (e.g., dry solids application rate).

The cost estimating algorithms, on the other hand, present a logical series of calculations for inputting site-specific data for deriving base capital and base annual operation and maintenance costs.

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Dr. Joseph B. Farrell and Dr. Harry E. Bostian of EPA's WERL* were responsible for overall project direction. Other EPA staff contributing to project management were R. V. Villiers, WERL, and Orville E. Macomber and Dr. James E. Smith, CERI.

EPA staff who provided review comments on drafts of the handbook were the following:

- Robert K. Bastian, OMPC.
- Dr. Harry E. Bostian, WERL.
- Dr. Carl A. Brunner, WERL.
- Ben Chen, Region IV.
- Alden G. Christianson, WERL.
- Dr. Robert M. Clark, WERL.
- Richard G. Eilers, WERL.
- Dr. Joseph B. Farrell.
- Gilbert M. Gigliotti, CERI.
- Dr. James A. Heidman, WERL.
- Orville E. Macomber, CERI.
- Steven Poloncsik, Region V.
- Dr. Lewis A. Rossman, WERL.
- Dr. James A. Ryan, WERL.
- Dr. James E. Smith, CERI.
- Charles S. Spooner, OWP.
- Dr. John M. Walker, OMPC.
- James Wheeler, OMPC.

Other individuals who provided review comments on drafts of the handbook were:

- Gordon L. Culp, Culp, Wesner, Culp, Inc., Consulting Engineers.
- Dr. Richard I. Dick, Cornell University.
- Dr. Cecil Lue-Hing, Chicago MSD.
- J. Robert Nicholson, Zimpro, Inc.
- Sherwood C. Reed, U.S. Army Corps of Engineers.
- Thomas K. Walsh, Metcalf and Eddy, Inc.

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* EPA organizational abbreviations are as follows:

WERL - Water Engineering Research Laboratory, Cincinnati, Ohio.
CERI - Center for Environmental Research Information, Cincinnati, Ohio.
OMPC - Office of Municipal Pollution Control, Washington, D.C.
OWP - Office of Water Policy, Washington, D.C.

SCS Engineers staff making major contributions were:

- Kenneth V. LaConde, Project Director.
- Curtis J. Schmidt, Senior Project Engineer.
- Julio A. Nuno, Project Engineer.
- Richard Taylor, Computer Programming.
- Steven R. Davidson, Computer Programming.
- Ilknur Erbas, Researcher.
- Robert W. Black, Word Processing.
- Jane E. Humphrey, Word Processing.
- K. J. Lee, Graphics.

Other major contributers were:

- Dr. Robert Gumerman and Bruce Burris, Culp, Wesner, Culp, Inc., Consulting Engineers, Santa Ana, California.
- Ms. Berrin Tansel, University of Wisconsin, CAPDET Programming.
- Robert A. Witzgall, Gregory R. Heath, Jeffrey R. Pinnette, and Elliot Crafts, Metcalf & Eddy, Inc., Wakefield, Massachusetts.

Contract Administrator for ICF, Inc., Washington, D.C., was Ms. Nan F. Darack, Contracts Supervisor.

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SECTION 1

INTRODUCTION

1.1 General

This cost handbook is designed for use by municipal wastewater treatment and sludge management authorities, program and project planners, government regulatory officers, designers, and consulting engineers to assist in obtaining preliminary cost estimates for 34 common municipal wastewater sludge management processes. A review of the table of contents shows the sludge management processes included.

Preliminary base capital costs and base annual operation and maintenance (O&M) costs are obtained in this manual through the use of curves developed for each of the 34 sludge management processes. These curves are based on the cost algorithms contained in Appendix A. The cost curves allow the user to rapidly obtain approximate cost estimates for sludge management processes based on only one or two process variables (e.g., annual sludge volume and distance hauled from treatment plant). In preparing the cost curves, average default values were assumed for most of the variables contained in the Appendix A cost algorithms. The majority of the cost algorithms are quite complex, having more process variables than the curves, allowing the user greater flexibility to adjust to site-specific characteristics. Therefore, while the curves are helpful for rapidly obtaining approximate costs for preliminary evaluation, it is recommended that the cost algorithms in Appendix A be used when more accurate site-specific cost estimates are desired.

The cost curves and algorithms for each process generally cover a range up to 100 million gallons of sludge per year. This range is approximately equivalent to a wastewater treatment plant of at least 50 mgd. The range was selected to include plants where supplemental cost information might be most useful.

For each sludge management process in this manual, a base capital cost curve and a total base annual O&M curve are presented. In addition, annual O&M component curves are presented for most processes. Base capital cost curves include mechanical equipment, concrete, steel, electrical and instrumentation, and installation labor. Specific items included in base capital costs are detailed in the process descriptions which accompany the algorithms in Appendix A. Annual O&M component curves provided for each process include the following, where applicable:

- Annual labor hours required.
- Annual electrical energy required.
- Annual fuel required.
- Annual chemical requirements.

- Annual maintenance material costs.
- Other annual O&M requirements, as needed.

These curves allow the user flexibility to specify costs for these components, which may vary significantly with geographic region. In addition, the user can easily identify the cost components which have a major impact on overall O&M costs.

All cost curves are based on fourth quarter 1984 costs; Engineering News Record Construction Cost Index (ENRCCI) equals 4,171. Appropriate cost indices should be used to adjust cost estimates for future years, as discussed in Section 2 of this manual.

Appendix A contains cost algorithms which require site-specific and process design input. The degree of detail varies among the algorithms; however, cost estimates based on direct use of the algorithms should be sufficiently accurate for Step 1 Construction Grant Planning purposes, as defined by Appendix A to Subpart E of 40 CFR, Part 35. Most of the algorithms can be hand-calculated in less than 20 minutes per trial.

The main emphasis of this manual is in obtaining preliminary cost estimates for various sludge management processes. Design parameters presented are "typical values" intended to guide the user in this pursuit. Obviously, the more accurate design information to which a user has access, the more accurate the resulting costs. A large amount of literature is available from which supplementary design information can be obtained. These manuals are:

- Process Design Manual - Sludge Treatment and Disposal (EPA-625/1-79-011), Reference 1.

- Process Design Manual - Dewatering Municipal Wastewater Sludge (EPA-625/1-82-014), Reference 2.

- Process Design Manual - Land Application of Municipal Sludge (EPA-625/1-83-016), Reference 3.

- Process Design Manual - Municipal Sludge Landfills (EPA 625/1-78-010), Reference 4.

Before attempting to use the cost curves provided in this manual or the algorithms in Appendix A, it is very important to read and understand Section 2 (User's Guide). Failure to do so may result in inaccuracies in cost estimating. This section also provides several example calculations.

1.2 Project Development History

The process cost algorithms for lime stabilization (Section 4.4), composting (Section 8), transport (Section 9), land application/disposal (Section 10), and storage (Section 11) were developed by SCS Engineers for addition to and enhancement of the existing Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems (CAPDET). Cost algorithms for the remaining processes covered in this manual were already contained in the CAPDET program.

The CAPDET program was originally developed in 1973 by the U.S. Army Corps of Engineers to provide wastewater treatment system planners with a tool for rapidly generating planning-level cost estimates for alternative wastewater treatment systems, using limited user-specified input (i.e., the types of design and cost input which are readily available during a project planning phase). Subsequent CAPDET revisions were made with assistance from the U.S. Environmental Protection Agency (EPA). CAPDET is currently (1985) available on the NCC/IBM system at EPA in Research Triangle Park, North Carolina.

1.3 Development of the Algorithms and Cost Curves

Cost algorithms and curves for 17 processes covering lime stabilization, composting, transport, land application/disposal, and storage were derived as follows:

1. Processes were broken down into significant component parts. For example, the truck haul of liquid sludge algorithm includes 23 component parts ranging from distance hauled to driver salary.

2. Formulas were developed to relate each of the component parts of the algorithm to the capital and annual O&M costs for the sludge management process being estimated.

3. Fourth quarter 1983 average costs were developed for purchased and constructed items such as equipment, vehicles, and sludge-loading facilities, and these were integrated into the algorithms.

4. The cost algorithms were applied to actual projects which have been implemented in various U.S. locales, and the algorithm cost outputs compared with actual reported capital and O&M costs. Where significant differences were found, the cost algorithms were reviewed and revised as necessary to conform more closely to actual project costs.

5. Cost curves were generated through use of each algorithm by inputting the parameters listed under the assumptions section for the corresponding curve (usually algorithm default values). Costs were updated to last quarter 1984 values by inputting appropriate cost indices. The resulting cost curves were compared with a variety of other cost curves in the literature developed by EPA and others. Where signficant differences were found, the cost curves were reviewed and corrected, as necessary.

The remaining sludge management processes are contained in the CAPDET program. Costs were derived using the program by varying sludge volume and solids concentration, and utilizing CAPDET default values. Where the CAPDET program requires additional user input, parameters listed in Table 1-1 (last quarter 1983 values) and in the algorithm development subsection of each algorithm were used. The resulting costs were compared with a variety of other costs in the literature developed by EPA and others. Where significant differences were found, appropriate changes were made. Curve costs were subsequently updated to last quarter 1984 values during the latter stages of this project, so that the curves would be as current as possible.

TABLE 1-1

INPUT PARAMETERS USED WHEN UTILIZING THE CAPDET PROGRAM*

Parameter	Value ($)
Engineering News Record Construction Cost Index (ENRCCI)	4,006.00
Marshall and Swift Equipment Cost Index (MSECI)	751.00
EPA Construction Cost Index	224.00
Pipe Cost Index	410.00
Labor Rate ($/hr)	18.00
Operator Class II ($/hr)	13.00
Electricity ($/kWhr)	0.09
Chemical Costs:	
Lime ($/lb)	0.05
Alum ($/lb)	0.23
Iron Salts ($/lb)	0.19
Polymer ($/lb)	2.80
Building ($/ft^2)	70.00
Excavation ($/yd^3)	2.50
Wall Concrete ($/yd^3)	250.00
Slab Concrete ($/yd^3)	130.00
Canopy Roof ($/ft^2)	15.75
Handrail ($/ft)	33.00
Pipe Installation Labor Rate ($/hr)	18.00
8-inch Pipe ($/ft)	15.00
8-inch Pipe Bend ($/unit)	106.00
8-inch Pipe Tee ($/unit)	159.00
8-inch Pipe Valve ($/unit)	1,200.00
Crane Rental ($/hr)	100.00

* Basis is fourth quarter 1983.

During draft handbook review, costs obtained using the CAPDET program were determined to have substantial errors. For the following processes, new cost algorithms were generated based on cost information obtained from the literature:

- Thermal conditioning.
- Centrifuge dewatering.
- Belt filter dewatering.
- Recessed plate filter press dewatering.
- Sludge drying bed dewatering.

Costs generated using a combination of some CAPDET costs along with other costs obtained in the literature were:

- Vacuum filter dewatering.
- Sludge drying bed dewatering.
- Chemical conditioning with lime.
- Chemical conditioning with ferric chloride.
- Chemical conditioning with polymers.
- Fluidized bed incineration.
- Multiple hearth incineration.

Costs for the remaining sludge management processes were derived wholly from the CAPDET program.

Base capital costs and O&M component requirements obtained using both the CAPDET program and cost information from the literature were fit to equations using a multiple regression program. These equations appear in the cost algorithms located in Appendix A. Costs and requirements were expressed as functions of the parameter most closely related to costs or requirements. Equations were developed to provide user flexibility in terms of site-specific parameters without overcomplicating the algorithm. In some cases, this resulted in an algorithm that is more limited than the more complex ones. However, the costs obtained are reasonable for estimating purposes. Specific information on algorithm development and references used to correct costs are presented in the introductory descriptions for each process in Appendix A.

1.4 Relative Accuracy of the Costs Presented

In preparing cost algorithms and cost curves for the processes covered in the manual, the authors had access to a wealth of existing technical and cost information for some processes (e.g., truck hauling of sludge), and virtually no existing full-scale operation information for other processes which are rarely used (e.g., rail hauling of sludge). In addition, some processes included in the manual (e.g., sludge storage facilities) are relatively straightforward, while others (e.g., ocean outfall sludge disposal) are very complex and difficult to generalize because of site-specific variables. For these reasons, the authors' level of confidence in the accuracy of the cost algorithms and cost curves presented varies between the different processes.

This level of confidence is expressed subjectively in the following listing:

1. Sludge management processes with a low level of accuracy confidence:

   - Pipeline transport of liquid sludge.
   - Ocean disposal by submarine outfall.
   - Rail hauling of liquid sludge.
   - Barge hauling of liquid sludge.
   - Disposal in sludge landfill.

2. Sludge management processes with a medium level of accuracy confidence:

   - Land application to cropland.
   - Land application to marginal or disturbed land for reclamation.
   - Land application to forest land.
   - Land application to dedicated disposal site.
   - Lime stabilization.
   - Thermal conditioning (also known as Zimpro Process, low-pressure oxidation, and heat treatment).

3. Sludge management processes with a high level of accuracy confidence:

   - All other processes contained in this manual.

An approximate quantitative value may be assigned to the low, medium, and high levels of accuracy confidence. By comparison with levels given for similar cost estimates on pages H-3 and H-4 in Reference 5, low may approximate ± 50 percent; medium, ± 30 percent; and high, ± 15 percent. It must be emphasized, however, that levels of confidence which have statistical significance could only be established by numerous comparisons of predicted costs with actual project costs.

Accuracy of curves with respect to the specific calculation methods has likely been affected by smoothing employed when drawing curves through the plotted points. The curves should actually have discontinuities due to two different factors. First, some items of equipment, e.g., earth-moving equipment, are only available in a limited number of sizes. Also, several separate functions have been used in many cases to cover different sections of the entire range of some of the parameters. The discontinuities caused by these factors are somewhat arbitrary, however, since different sizes of equipment are available at different times from different manufacturers, and the way a cost function is broken into several segments would be dependent on choices made by a specific cost estimator. For these reasons, it was decided to smooth the curves in the Handbook to better represent an "average" cost.

1.5 Other Sludge Management Processes Not Included in This Manual

There are a number of other processes applicable to municipal sludge management which have not been included in this manual, since a sufficient cost data base has not been firmly established. These other processes include:

- Vacuum-Assisted Drying Beds - This process is a modification of drying bed dewatering, in which a vacuum is applied to an underdrain system, thereby increasing the drainage rate significantly. Disadvantages of the system result from cracking of the cake and breakthrough of the vacuum before thorough drying occurs.

- In-Vessel Composting - In this process, composting is accomplished in an enclosed system which permits controlled mixing and aeration, along with containment of odorous gases that can be treated prior to release.

- Carver-Greenfield Sludge Drying Process - This process utilizes multiple effect evaporation with an oil carrier to increase fluidity at high solids concentrations. Units are currently being installed in Los Angeles, and are under consideration at several other locations.

- Staged Digestion - Various combinations have been investigated using several stages of digestion with both mesophilic (low temperature, around 35 °C) and thermophilic (higher temperature, around 55 °C) units.

- Advanced Membrane Technology - Includes hyperfiltration units which have a membrane deposited on porous stainless steel tubes. Initial sludge studies have demonstrated that elimination of chemical conditioning may pay back increased capital costs when compared to belt filtration.

- Freeze Conditioning - For cold climates, natural freezing can be used to advantage to make sludge dewatering easier on sand drying beds. This process has been investigated by the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

- Conversion of Sludge to Gas and Oil - Processes similar to those suggested for fossil fuel gasification and liquefaction have also been investigated for sludge, and look promising.

- Irradiation of Sludge - Disinfection has been studied using gamma radiation from radioactive isotopes, electron beams, and microwaves.

- Additional Processes - Alternative sludge management processes that have been investigated include: enzyme addition to digestion, ultrasonics, combined oxygen and ozone contacting, and clathrate freezing using a liquid refrigerant to form separate crystals with water to effect dewatering.

1.6 Other Sludge Management Process Cost Information in the Technical Literature

Appendix B of this manual contains an annotated bibliography and reference chart of other sources of sludge management process cost information in the technical literature.

1.7 English to Metric Conversion Factors

Appendix C of this manual contains metric equivalents and conversion factors from U.S. customary to metric units for commonly used units of expression in sludge management.

1.8 References

1. Process Design Manual: Sludge Treatment and Disposal. Technology Transfer Series. EPA-625/1-79-011, Center for Environmental Research Information, Cincinnati, Ohio, September 1979. 1135 pp.

2. Process Design Manual: Dewatering Municipal Wastewater Sludges. EPA-625/1-82-014, Center for Environmental Research Information, Cincinnati, Ohio, October 1982. 222 pp.

3. Process Design Manual: Land Application of Municipal Sludge. Technology Transfer, EPA-625/1-83-016, Center for Environmental Research Information, Cincinnati, Ohio, October 1983. 436 pp.

4. Process Design Manual: Municipal Sludge Landfills. EPA-625/1-78-010, Environmental Research Information Center, Cincinnati, Ohio, October 1978.

5. Areawide Assessment Procedures Manual. EPA-600/9-76-014. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio, July 1976. (Available from NTIS as PB271863/Set.)

SECTION 2

USER'S GUIDE

2.1 General

Users should read and understand this section prior to estimating costs with the cost curves or cost algorithms contained in this manual. If the user goes directly to the cost curves or algorithms without performing the preliminary steps required by this section, the resulting sludge management cost estimates may be over- or underestimated.

2.2 Developing the Sludge Management Process Chain

The user should develop a sludge management process chain (and/or alternate chains). This will usually consist of a figure (or figures) which shows the sequence of processes to be used in the entire sludge management chain, starting with the raw sludge and ending with final disposal or recycling. Figure 2-1 shows the sludge management processes for which costs are included in this manual. Many feasible processing combinations are possible, as shown in Figure 2-1. It is assumed that the user will develop a rational sludge management process scheme (and/or alternate schemes) prior to beginning cost estimating.

2.3 Developing the Mass Balance of Sludge Volume and Sludge Concentration Entering and Leaving Each Process

Most cost algorithms for sludge management processes in this manual have, as necessary input data, the volume of sludge entering the process (not necessarily the entire raw sludge flow), and the suspended solids content of the sludge entering the process (not necessarily the raw sludge solids concentration). It is essential, therefore, in using this manual to compute an approximate mass balance to obtain the sludge volume and sludge solids concentration entering and leaving each process in the entire sludge management scheme.

The inexperienced cost estimator might mistakenly believe that the volume of raw sludge is the same as the volume of final treated sludge leaving the management scheme. This is virtually never the case because each successive sludge treatment process normally tends to reduce the mass and volume of sludge. Therefore, the mass and volume of the final treated sludge leaving the management scheme is typically only a fraction of the initial raw sludge volume. Similarly, the sludge solids concentration changes as the sludge proceeds through a series of treatment processes.

FIGURE 2-1

SLUDGE MANAGEMENT PROCESSES INCLUDED IN THIS MANUAL

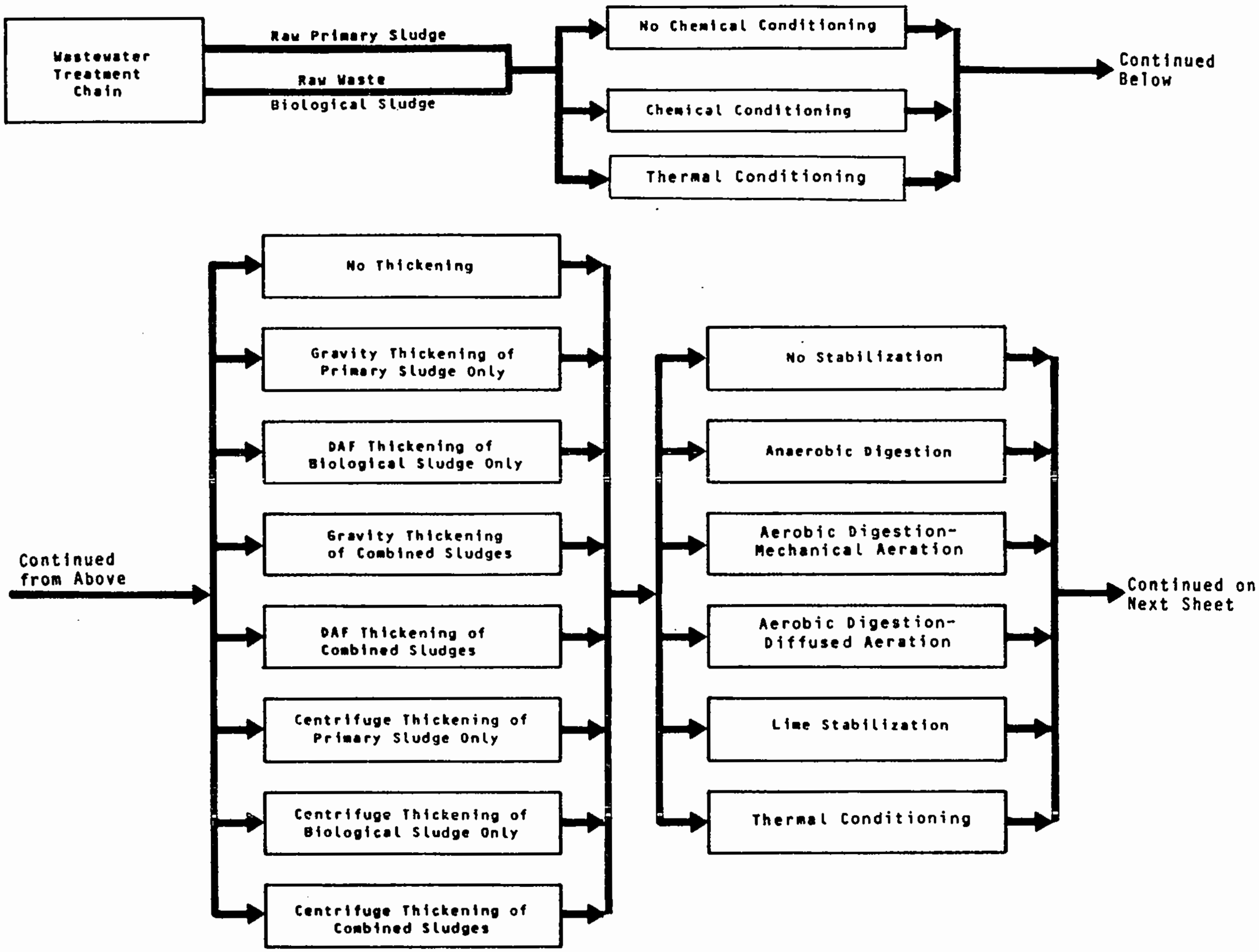


FIGURE 2-1 (CONTINUED)

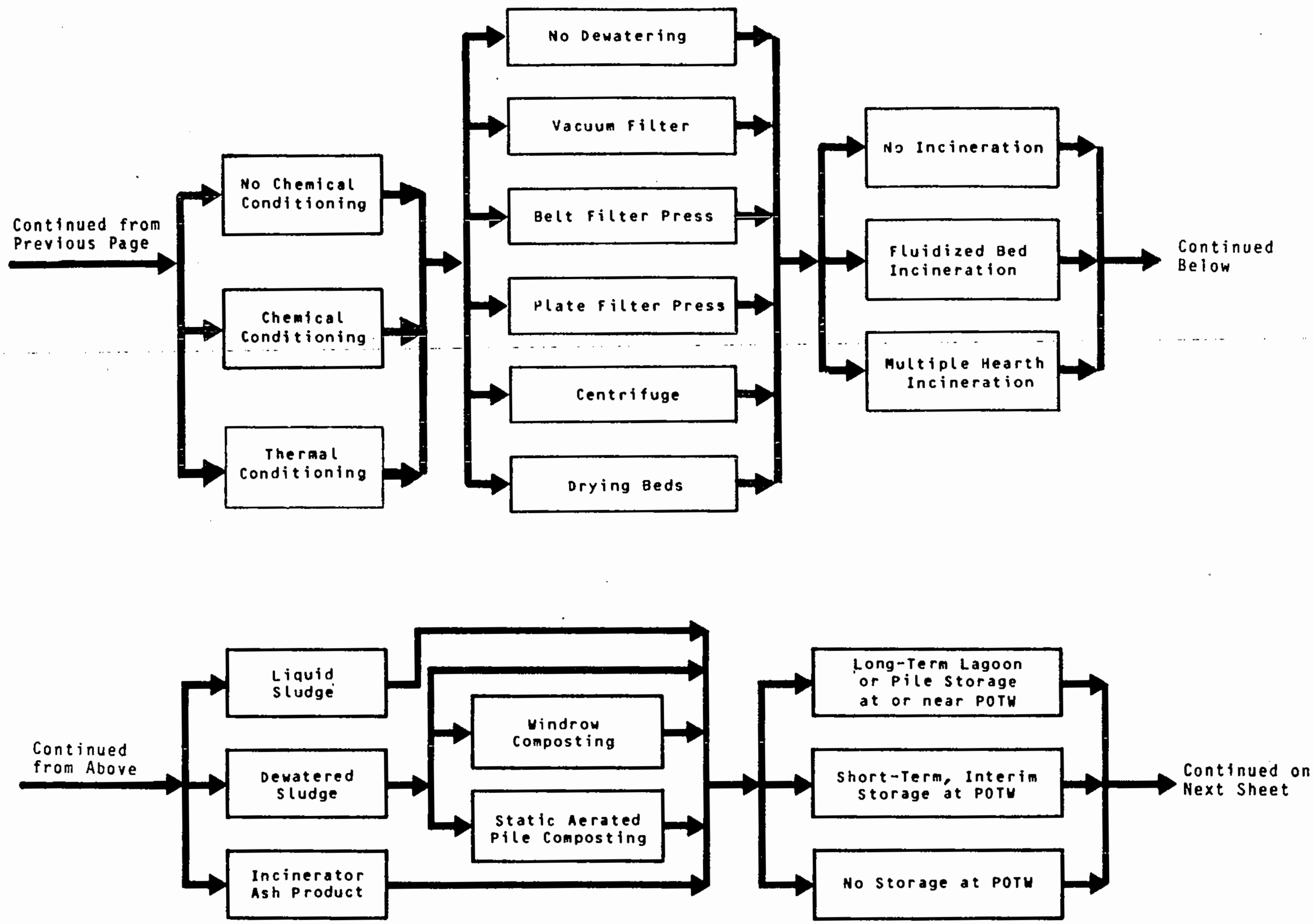
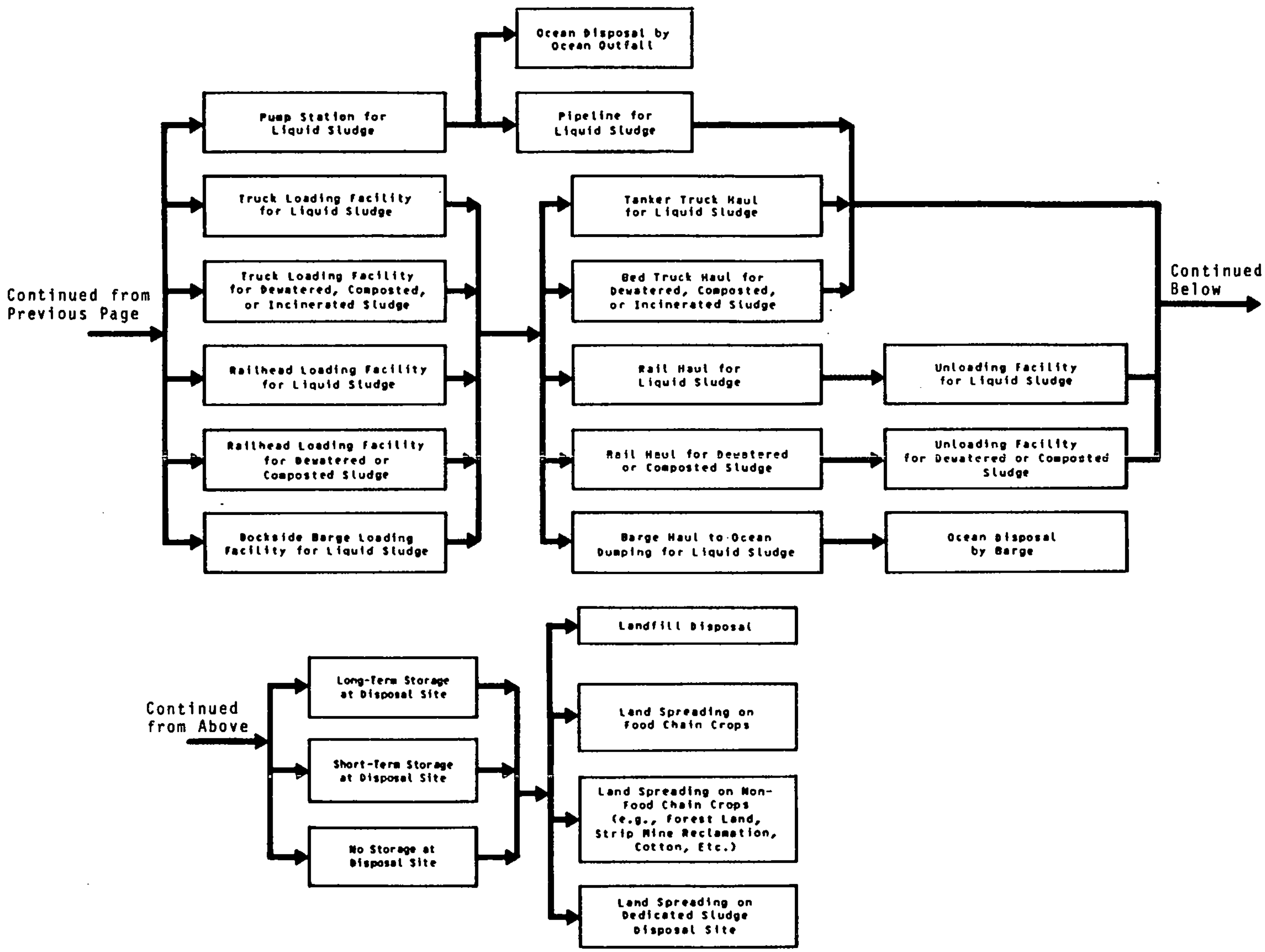


FIGURE 2-1 (CONTINUED)



In order to estimate the sludge volume and solids concentration entering each successive treatment process, the cost estimator should perform the following steps:

1. Calculate the volume, solids concentration, and weight of dry sludge solids produced by the wastewater treatment chain.

2. Draw a flowsheet of the proposed sludge treatment process chain.

3. Identify all streams entering and leaving each sludge management process. The streams would generally consist of the influent, effluent, and recycle streams.

4. For each process, identify and calculate the relationship of entering and leaving streams to one another in terms of mass, volume, and solids concentration. To do this requires knowledge of the approximate solids capture capabilities and conversion parameters for each management process. Table 2-1 provides typical solids capture capabilities and expected sludge concentrations from various treatment processes. Table 2-2 provides typical parameters required for calculating a mass balance for the conversion processes. These tables can serve as guides, unless more accurate design information is available for the specific sludge and sludge processes under consideration. Solids capture and conversion parameters for each sludge management process depend on a number of factors, including but not limited to the following:

   - Type of sludge treated, particularly the percentage of waste-activated sludge.

   - Whether the sludge has been stabilized.

   - Type and amount of conditioning chemicals used.

   - Hydraulic and mass loading rates to process.

5. Tabulate sludge volume and solids concentration for each stream identified in Step 3.

2.4 Mass Balance Example

The steps involved in computing a mass balance are detailed in the following example for a treatment plant with a design capacity of 20 mgd. The proposed sludge treatment process chain is shown on Figure 2-2. Letter designations are provided for each stream entering and leaving the process. For example, Stream A is the incoming raw primary sludge to the gravity thickener; Stream M is the decant return from the gravity thickener to the wastewater treatment chain; Stream B is the subnatant from the gravity thickener, etc. These letter designations are cross-referenced on the table of sludge volume and solids concentration identified in Step 5 above. A completed version of this table is shown on Table 2-3 for the mass balance developed in this subsection.

FIGURE 2-2

EXAMPLE FLOWSHEET FOR SLUDGE TREATMENT PROCESS CHAIN SHOWING FLOW STREAMS ENTERING AND LEAVING EACH SLUDGE MANAGEMENT CHAIN UNIT PROCESS

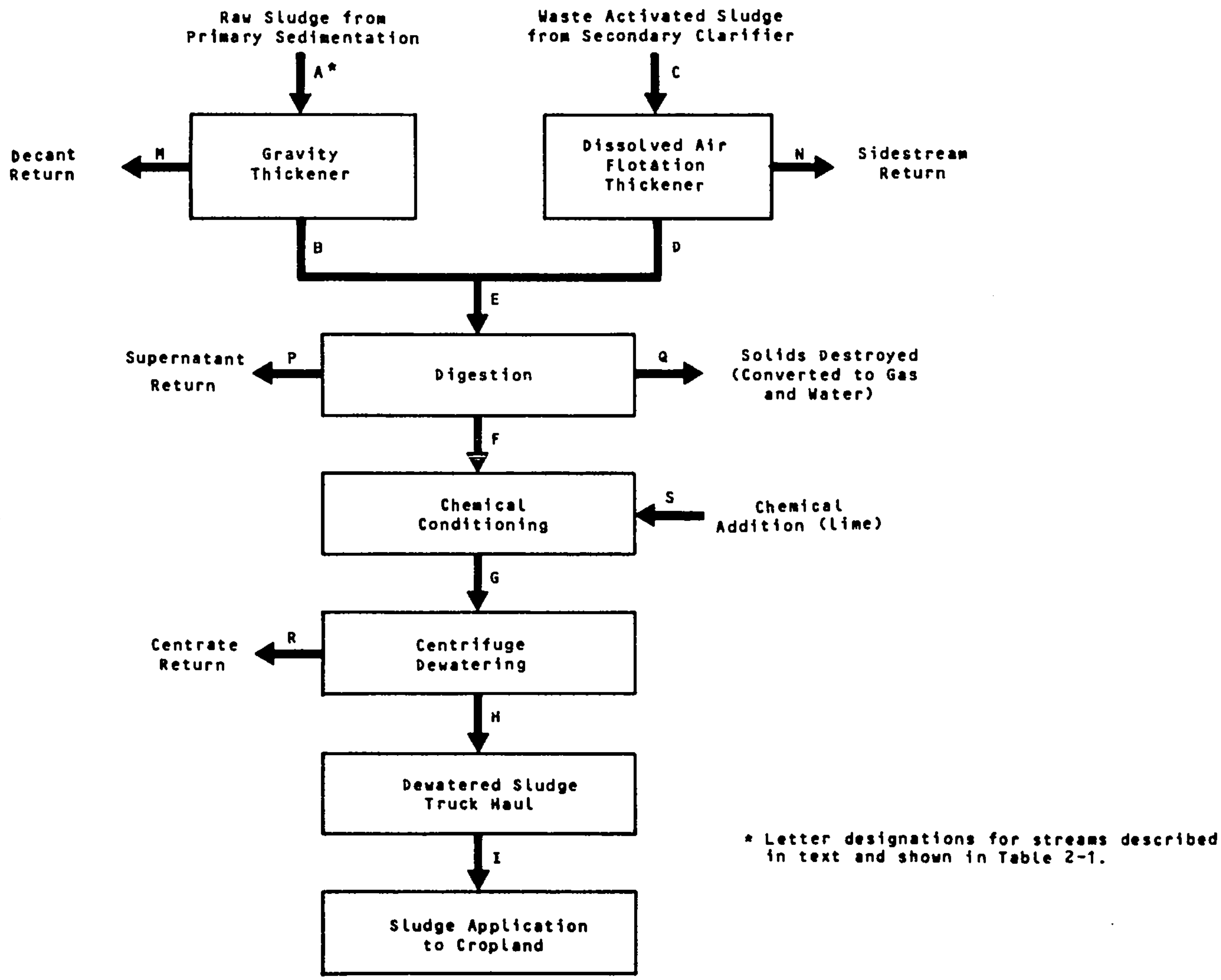


TABLE 2-1

TYPICAL INFLUENT SOLIDS CONCENTRATIONS, CAPTURE VALUES, AND EXPECTED EFFLUENT SOLIDS CONCENTRATIONS FROM VARIOUS TREATMENT PROCESSES

Process	Typical Influent Solids Concentration (%)	Process Solids Capture (%)	Effluent Solids Concentration (%)	Reference
Gravity Thickeners				
Primary Only	2-7	85-92	4-10	1,2
Primary and Waste-Activated	1.5-6	80-90	3-7	
Primary and Trickling Filter Humus	3-6	80-90	7-10	
Flotation Thickener				
Waste-Activated Only	0.4-1.5	80-95	2-7	3
Anaerobic Digester				
Primary Only	2-10		3-12	
Primary and Waste-Activated	1.5-6		2-8	
Primary and Trickling Filter Humus	2-6		3-8	
Aerobic Digester				
Primary Only	2-6		2.5-7	3
Primary and Waste-Activated	1.5-4		2-5	
Waste-Activated Only	0.3-2		0.8-2.5	
Thermal Conditioning				
Primary Only	1-6	90-92	1.5-8	3, 5
Primary and Waste-Activated	1-6	90	1.5-12	
Centrifuge Dewatering				
Primary Only	4-8	90-97	20-40	3
Primary and Waste-Activated	0.5-3	85-90	16-25	
Primary and Trickling Filter Humus	2-5	90-97	20-30	
Anaerobically Digested Primary and Waste-Activated	1-8	85-99	12-30	
Thermally Conditioned Primary and Waste-Activated	4-8	85-99	38-50	

Table 2-1 (continued)

Process	Typical Influent Solids Concentration (%)	Process Solids Capture (%)	Effluent Solids Concentration (%)	Reference
Belt Filter Press				
Primary Only	3-10	85-99	28-44	3, 6
Primary and Waste-Activated	3-6	85-99	20-40	
Primary and Trickling Filter Humus	3-6	85-99	20-40	
Anaerobically Digested Primary and Waste-Activated	1-8	85-99	38-50	
Thermally Conditioned Primary and Waste-Activated	4-8	85-99	38-50	
Pressure Filtration				
Primary Only	5-10	85-99	45-50	3, 6
Waste-Activated Only	3-5	85-99	37-45	
Primary and Waste-Activated	3-6	85-99	35-50	
Primary and Trickling Filter Humus	3-6	85-99	35-50	
Anaerobically Digested Primary and Waste-Activated	2-10	85-99	40-50	
Thermally Conditioned Primary and Waste-Activated	3-7	85-99	30-48	
Vacuum Filtration				
Primary Only	3-8	90-98	25-30	3, 6
Waste-Activated Only	3-5	75-80	12-18	
Primary and Waste-Activated	2-4	85-99	15-30	
Primary and Trickling Filter Humus	2-4	85-99	15-30	
Anaerobically Digested Primary and Waste-Activated	2-8	70-80	15-28	
Thermally Conditioned Primary and Waste-Activated	3-7	70-95	30-50	
Drying Beds				
Primary Only	2-9	>99	20-40	3, 4
Waste-Activated Only	0.7-4	87	10-20	
Primary and Waste-Activated	2-5	85-100	10-30	
Primary and Trickling Filter Humus	2-5	85-100	10-30	
Anaerobically Digested Primary and Waste-Activated	3-8	86	10-45	
Thermally Conditioned Primary and Waste-Activated	3-7	99	15-45	

Table 2-1 (continued)

Process	Typical Influent Solids Concentration (%)	Process Solids Capture (%)	Effluent Solids Concentration (%)	Reference
Multiple Hearth Incineration	16-40			7
Fluidized Bed Incineration	15-60			7
Windrow Composting	15-40		45-65	7
Static Aerated Pile Composting	30-50		40-65	7

TABLE 2-2

TYPICAL PARAMETERS REQUIRED FOR CALCULATING A MASS BALANCE FOR THE CONVERSION PROCESSES

Process	Parameter	Range
Anaerobic Digestion	Influent volatile solids	50-80%
	Volatile solids destroyed	40-60%
	Return stream suspended solids concentration	3,000-15,000 mg/l
Aerobic Digestion	Influent volatile solids	50-80%
	Volatile solids destroyed	33-70%
	Return stream suspended solids concentration	5,000-30,000 mg/l
Lime Stabilization	Dosage - Primary sludge	0.10-0.15 lb/lb dry solids
	Dosage - Activated sludge	0.30-0.50 lb/lb dry solids
	Dosage - Combined sludge	0.20-0.40 lb/lb dry solids
Thermal Conditioning	Raw solids concentration	1.5-15%
	Influent volatile solids	50-80%
	Volatile solids destroyed	30-40%
	Return stream suspended solids concentration	1,000-5,000 mg/l
Chemical Conditioning:		
- Lime	Raw primary and waste activated	110-300 lb/ton dry solids
	Digested primary and waste activated	160-370 lb/ton dry solids
- Ferric Chloride	Primary	40-120 lb/ton dry solids
	Waste activated	120-200 lb/ton dry solids
	Digested combined	60-200 lb/ton dry solids
- Polymers	Primary	0.5-1.0 lb/ton dry solids
	Waste activated	8-15 lb/ton dry solids
	Digested combined	5-12 lb/ton dry solids

Table 2-2 (continued)

Process	Parameter	Range
Composting	Solids concentration of sludge cake	20-50%
	Solids concentration of recycle	60-75%
	Solids concentration of bulking agent	50-85%
	Solids concentration of compost mixture	40-50%
	Volatile solids concentration of sludge cake - Digested sludge	40-60%
	Volatile solids concentration of sludge cake - Raw sludge	60-80%
	Volatile solids concentration of recycle	0-90%
	Volatile solids concentration of bulking agent	55-90%
	Volatile solids concentration of compost mixture	40-80%
	Volatile solids destroyed in sludge cake	33-56%
	Volatile solids destroyed in recycle	0-20%
	Volatile solids destroyed in bulking agent	0-40%
	Volatile solids destroyed in compost product	20-60%

TABLE 2-3

SUMMARY OF CALCULATED SLUDGE VOLUME AND SOLIDS CONCENTRATION FOR EACH FLOW STREAM SHOWN IN FIGURE 2-2 AND DESCRIBED IN MASS BALANCE EXAMPLE*

Flow Stream Letter Designation in Figure 2-2 and Brief Description	Calculated Average Solids, DSS (lb/day)	Calculated Average Volume, SV (gal/day)	Calculated Average Volume, SV (million gal/yr)	Estimated Average Solids Concentration, SS
A. Primary Sludge	26,000	156,000	57	2%
B. Thickened Primary Sludge	23,400	70,100	25	4%
C. Waste Activated Sludge	10,400	250,000	91	0.5%
D. Thickened Waste Activated Sludge	9,400	38,000	14	3.0%
E. Combined Sludge to Digestion	32,800	108,100	39	3.6%
F. Digested Sludge Withdrawal	21,600	51,300	19	5%
G. Chemically Conditioned Sludge	24,800	57,700	21	5%
H. Dewatered Sludge	22,800	14,500	5	18%
I. Hauled Dewatered Sludge	22,800	14,500	5	18%
M. Gravity Thickener Sidestream	2,600	85,900	--	3,600 mg/l
N. DAF Thickener Sidestream	1,000	212,000	--	560 mg/l
P. Digester Supernatant Return	1,400	56,000	--	3,000 mg/l
Q. Solids Destroyed in Digester	9,800	--	--	--
R. Dewatering Centrate Return	2,000	43,200	--	5,500 mg/l
S. Conditioning Chemical Added	3,200	6,400	--	

* Example is developed for a treatment plant with a wastewater flow of 20 mgd.

The following three equations will be useful for estimating a mass balance:

Dry sludge solids produced per day:

$$DSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{100} \qquad \text{(Eq. 2-1)}$$

where

DSS = Dry sludge solids produced per day, lb/day.
SV = Daily sludge volume, gal/day.
SS = Sludge suspended solids concentration, percent.
SSG = Sludge specific gravity, unitless.
8.34 = Conversion factor, lb/gal (for water).

Specific gravity of combined sludge solids after mixing two sludge streams:

$$SPG = \frac{1}{\frac{(PSA)}{(100)\ (SPA)} + \frac{(100 - PSA)}{(100)\ (SPB)}} \qquad \text{(Eq. 2-2)}$$

where

SPG = Combined sludge solids specific gravity, unitless.
PSA = Percentage of Sludge A solids in combined sludge solids, percent.
SPA = Specific gravity of Sludge A solids, unitless.
SPB = Specific gravity of Sludge B solids, unitless.

Sludge specific gravity:

$$SSG = \frac{1}{\frac{(SS)}{(100)\ (SPG)} + \frac{(100) - (SS)}{(100)}} \qquad \text{(Eq. 2-3)}$$

where

SSG = Sludge specific gravity, unitless.
SS = Sludge suspended solids concentration, percent.
SPG = Sludge solids specific gravity, unitless.

Sludge volume and sludge concentrations determined in this mass balance example (Table 2-3) were calculated using the assumptions listed with the individual process calculations.

2.4.1 Raw Primary Sludge (Stream A).

Assumptions:

- Sludge volume = 156,000 gal/day.
- Solids concentration = 2 percent.
- Primary sludge specific gravity = 1.0 (from Eq. 2-3).

2.4.1.1 Dry solids produced per day (Eq. 2-1).

$$DSS = \frac{(156{,}000)\ (2)\ (1.0)\ (8.34)}{(100)} = 26{,}000 \text{ lb/day}$$

2.4.2 Gravity Thickening.

Assumptions:

- Solids capture = 90 percent.
- Effluent solids = 4 percent.
- Influent sludge specific gravity = 1.0 (from Eq. 2-3).

2.4.2.1 Solids Captured (Stream B), DSS.

$$DSS = \frac{(26{,}000)\ (90)}{(100)} = 23{,}400 \text{ lb/day}$$

2.4.2.2 Sludge Volume (Stream B) (Eq. 2-1).

$$SV = \frac{(23{,}400)\ (100)}{(8.34)\ (4)\ (1.0)} = 70{,}100 \text{ gal/day}$$

$$= 25 \times 10^6 \text{ gal/yr}$$

2.4.2.3 Side Stream Return (Stream M).

Assumptions:

- Solids = 26,000 - 23,400 = 2,600 lb/day.
- Flow rate = 156,000 - 70,100 = 85,900 gal/day.

$$\text{Solids Concentration in side stream return} = \frac{(2{,}600)\ (100)}{(85{,}900)\ (8.34)} = 0.36 \text{ percent}$$

$$= 3{,}600 \text{ mg/l}$$

2.4.3 Waste Activated Sludge (Stream C).

Assumptions:

- Sludge volume = 250,000 gal/day.
- Sludge solids concentration = 0.5 percent.
- Specific gravity of dry sludge solids = 1.25.
- Influent sludge specific gravity = 1.0 (from Eq. 2-3).

2.4.3.1 Total Dry Solids (Eq. 2-1).

$$DSS = \frac{(250{,}000)\ (0.5)\ (1.0)\ (8.34)}{(100)} = 10{,}400 \text{ lb/day}$$

2.4.4 Dissolved Air Flotation Thickening.

Assumptions:

- Solids capture = 90 percent.
- Effluent solids = 3 percent.
- Waste activated sludge specific gravity = 1.0 (from Eq. 2-3).

2.4.4.1 Solids Captured (Stream D).

$$DSS = \frac{(10,400)\ (90)}{(100)} = 9,400 \text{ lb/day}$$

2.4.4.2 Sludge Volume (Stream D) (Eq. 2-1).

$$SV = \frac{(9,400)\ (100)}{(8.34)\ (3)\ (1.0)} = 38,000 \text{ gal/day}$$
$$= 14 \times 10^6 \text{ gal/yr}$$

2.4.4.3 Side Stream Return (Stream N).

Assumptions:

- Solids = 10,400 - 9,400 = 1,000 lb/day.
- Flow rate = 250,000 - 38,000 = 212,000 gal/day.

$$\text{Percent Solids} = \frac{(1,000)\ (100)}{(212,000)\ (8.34)} = 0.056\%$$
$$= 560 \text{ mg/l}$$

2.4.5 Combined Sludge (Stream E).

2.4.5.1 TDSS = 23,400 + 9,400 = 32,800 lb/day.

2.4.5.2 SV = 70,100 + 38,000 = 108,100 gal/day
= 39×10^6 gal/yr.

2.4.5.3 Solids concentration.

$$SS = \frac{(32,800)\ (100)}{(108,100)\ (8.34)} = 3.6\%$$

2.4.5.4 Determine specific gravity of sludge solids.

Assumptions:

- Specific gravity of primary sludge solids, SPA = 1.4.
- Specific gravity of waste-activated sludge solids, SPB = 1.25.

$$PSA = \frac{(23,400)\ (100)}{(32,800)} = 71.3$$

Using Eq. 2-2:

$$SPG = \frac{1}{\frac{71.3}{(100)\ (1.4)} + \frac{(100 - 71.3)}{(100)\ (1.25)}} = 1.35$$

where

PSA = Percentage of primary solids in combined sludge solids, percent.
SPG = Specific gravity of sludge solids, unitless.

2.4.5.5 Determine specific gravity of sludge.

$$SSG = \frac{1}{\frac{(3.6)}{(1.35)\ (100)} + \frac{(100 - 3.6)}{(100)}} = 1.01$$

where

SSG = Sludge specific gravity, unitless.

2.4.6 Anaerobic Digestion.

Assumptions:

- Volatile solids = 60 percent.
- Volatile solids destroyed = 50 percent.
- Digested sludge solids concentration = 5 percent.
- Supernatant solids = 0.3 percent (3,000 mg/l).
- Specific gravity of digested sludge solids = 1.4.

2.4.6.1 Solids destroyed (Stream Q) = (32,800) (0.60) (0.50)
= 9,800 lb/day.

Remaining solids = 32,800 - 9,800 = 23,000 lb/day.

2.4.6.2 Calculate total mass input to digester (solids + water).

(108,100) (1.01) (8.34) = 910,600 lb/day

2.4.6.3 Mass output less solids destroyed.

910,600 - 9,800 = 900,800 lb/day

2.4.6.4 Determine the flow rate distribution between the supernatant at 0.3 percent solids and digested sludge at 5 percent solids. Let S = lb/day of supernatant suspended solids (Stream P).

$$\frac{S\ (100)}{0.3} + \frac{(23{,}000 - S)\ (100)}{5} = 900{,}800$$

$$333S + 460{,}000 - 20S = 900{,}800$$

$$313S = 440{,}800$$

$$S = 1{,}400\ \text{lb/day}$$

2.4.6.5 Supernatant flow rate (Stream P).

$$Q = \frac{(1{,}400)\ (100)}{(8.34)\ (0.3)\ (1)} = 56{,}000\ \text{gal/day}$$

where

Q = Flow rate, gal/day.

2.4.6.6 Digested sludge withdrawal (Stream F).

$$DSS = 23{,}000 - 1{,}400 = 21{,}600\ \text{lb/day}$$

2.4.6.7 Digested sludge specific gravity (Eq. 2-3).

$$SSG = \frac{1}{\frac{(5)}{(100)\ (1.4)} + \frac{(100) - (5)}{(100)}} = 1.01$$

2.4.6.8 Digested sludge volume (Stream F).

$$SV = \frac{(21{,}600)\ (100)}{(8.34)\ (5)\ (1.01)} = 51{,}300\ \text{gal/day}$$

$$= 19 \times 10^6\ \text{gal/yr}$$

2.4.7 Chemical Conditioning (Stream S).

Assumptions:

- Lime dosage = 300 lb/ton of dry sludge.
- Lime feed solution contains 0.5 lb lime/gal.

2.4.7.1 Daily lime requirement.

$$\text{Lime} = \frac{(21{,}600)\ (300)}{(2{,}000)} = 3{,}200 \text{ lb/day}$$

TDSS = 21,600 + 3,200 = 24,800 lb/day (Stream G)

2.4.7.2 Flow rate of liquid lime feed system.

$$Q = \frac{3{,}200}{0.5} = 6{,}400 \text{ gal/day}$$

$$SV = 51{,}300 + 6{,}400 = 57{,}700 \text{ gal/day (Stream G)}$$
$$= 21 \times 10^6 \text{ gal/yr}$$

2.4.7.3 Solids concentration.

$$SS = \frac{(24{,}800)\ (100)}{(57{,}700)\ (8.34)} = 5.2\%$$

2.4.8 Centrifuge dewatering.

Assumptions:

- Solids capture = 92 percent.
- Effluent solids = 18 percent.

2.4.8.1 Solids captured (Stream H).

$$(24{,}800)\ (0.92) = 22{,}800 \text{ lb/day}$$

2.4.8.2 Sludge specific gravity (Eq. 2-3).

$$SGS = \frac{1}{\frac{(18)}{(1.40)\ (100)} + \frac{(100 - 18)}{(100)}} = 1.05$$

2.4.8.3 Sludge volume (Stream H), SV.

$$SV = \frac{(22{,}800)\ (100)}{(8.34)\ (18)\ (1.05)} = 14{,}500 \text{ gal/day}$$

$$= 5 \times 10^6 \text{ gal/yr}$$

2.4.8.4 Dewatering centrate return volume (Stream R).

$$\text{Volume} = 57{,}700 - 14{,}500 = 43{,}200 \text{ gal/day}$$

2.4.8.5 Dewatering centrate return solids (Stream R).

$$24{,}800 - 22{,}800 = 2{,}000 \text{ lb/day}$$

2.4.8.6 Solids concentration (Stream R).

$$\frac{(2{,}000)\ (100)}{(43{,}200)\ (8.34)} = 0.55 \text{ percent, or } 5{,}500 \text{ mg/l}$$

2.4.9 Hauled dewatered sludge.

One hundred percent of dewatered sludge from the centrifuge process will be truck-hauled and disposed by application to cropland. Stream I = Stream H.

Flow volumes and sludge solids estimated above are tabulated in Table 2-3. Note how the sludge volume and solids concentration changes entering successive treatment process steps.

After completing a table similar to Table 2-3, the manual user may go to the cost curves or algorithms and estimate the base capital cost and base annual O&M cost of each process in the sludge management chain, as exemplified in Section 2.8 of this user's guide.

2.5 Importance of Assumptions Listed on Cost Curves

2.5.1 Capital cost curves.

The user should pay close attention to the assumptions listed on the cost curves. In the base capital cost curves particularly, note the assumptions for hours per day and days per week of operation which for many processes are 8 hr/day and 7 days/week. Larger treatment plants often operate processes 16 or 24 hr/day. If the process for which cost estimates are being made will operate more hours per day than the assumption shown on the cost curve, the capital cost must be adjusted accordingly. This adjustment is made by moving down on the curve by calculating an annual sludge volume for a process operating under the conditions noted on the curve at an equivalent design capacity.

For example, Figure 5-4 shows the base capital cost for a belt filter press dewatering process which is operating a total of 56 hr/week (8 hr/day, 7 days/week). The base capital cost for a belt filter press with an annual sludge volume of 50 million gal/yr at 2 percent solids under this operating schedule is $0.95 million. If, instead, it is planned to operate the dewatering process a total of 140 hr/week (20 hr/day, 7 days/week), the capital cost derived from the curve using the annual sludge volume directly is too high.

An equivalent design capacity is obtained by lowering the sludge volume by a ratio of 8:20 (i.e., multiply the annual sludge volume, 50, by 0.4 = 20 million gal/yr). The base capital cost is then estimated using the cost curves. In this example, the base capital cost would then be $0.46 million.

For processes operating on a 24-hr/day schedule, costs include standby equipment and tankage necessary for safe operation during shutdown for cleaning and maintenance. However, for processes assuming 8-hr/day operation such as dewatering, little or no standby equipment is included, since two-shift operation following a shutdown can effectively compensate for a unit out of service. Standby equipment required is highly variable depending on site-specific operating conditions, reliability of process considered, storage availability, operating capability, and operating philosophy of the owner. Therefore, the user should include standby capacity or storage (Section 11) when adjusting costs from processes assuming an 8-hr/day operation to 24-hr/day operation.

Land costs are included in the base capital cost curves for those processes for which land is a major capital cost element. Process capital cost curves which include land costs (as noted in the assumptions section of each curve) are:

- Sludge Drying Beds.
- Composting - Aerated Static Pile Method.
- Composting - Windrow Method.
- Land Application to Dedicated Disposal Sites.
- Land Disposal to Sludge Landfill.
- Sludge Storage - Facultative Lagoons.
- Storage of Dewatered Sludge in Unconfined Piles.

For these processes, capital costs include land at $3,120 per acre. Adjustments to capital costs for locations which have actual land costs different from those assumed can be accomplished using the procedures presented in each respective cost curve section.

Land costs are not included in the curve capital costs for the remaining processes. However, the cost algorithms for some processes do contain provisions for calculating the cost of land if it is applicable to the specific case being examined. These processes are:

- Land Application to Cropland.
- Land Application to Forest Land Site.
- Land Application to Marginal Land for Land Reclamation.

If desired, the cost of land for these unit processes may be added to the curve capital costs by using the procedure presented in Section 10.

2.5.2 O&M cost curves.

For each process covered in this manual, there is a total O&M cost curve as well as O&M requirement curves for each component (labor hours, electrical energy, fuel, and chemicals) included in the O&M cost. The <u>total base annual</u>

O&M curve is based on the assumptions noted with each curve. The assumptions consistently use these unit costs:

- Labor rate = $13.50/hr.
- Electrical energy cost = $0.094/kWhr.
- Fuel = $1.35/gal.

If the locale where the cost estimates are being made has unit costs substantially different from the assumed costs, the user may utilize the individual component curves to estimate total O&M costs. In order to obtain the annual O&M component cost, the requirements obtained when using the curve must be multiplied by the appropriate local unit cost. Note that some components such as annual replacement parts and materials are given directly in annual cost. Total base annual O&M cost for each process is obtained by summing the individual annual O&M component costs.

For instance, the base annual O&M cost shown in Figure 5-5 for a belt filter which processes 80 million gal/yr at 6 percent solids is $180,000/yr, based on a labor cost of $13.50/hr and an electrical energy cost of $0.094/kWhr. However, if the local labor rate is $12.00/hr and electrical energy is $0.05/kWhr, the total base annual O&M cost is obtained using the component curves (Figure 5-6) as follows:

- Annual cost of labor = 7,500 hr/yr x $12.00/hr = $90,000.

- Annual cost of electrical energy = 3.4 x 100,000 kWhr/yr x $0.06/kWhr = $20,400.

- Annual cost of replacement parts and materials = $50,000.

- Total base annual O&M cost = $160,400.

However, to arrive at total project costs and total O&M costs, certain costs should be added as described in Section 2.6.

2.6 Total Project Cost

2.6.1 Adjusting costs to account for inflation.

Costs obtained with the base capital and base annual O&M cost curves in this manual are based on last quarter 1984 costs, and must be adjusted for inflation for use in later years. Note that costs obtained using the algorithms in Appendix A are internally adjusted for inflation. Moreover, when using the annual O&M component curves described in Subsection 2.5.2, only those components given directly in dollars per year (such as annual replacement parts and materials) need to be adjusted for inflation, assuming that current unit costs are used.

Costs are adjusted for inflation using the Engineering News Record Construction Cost Index (ENRCCI), as shown in Table 2-4 for total base capital costs and Table 2-5 for total base annual O&M costs. Costs derived with the algorithms are updated internally using a combination of the ENRCCI and the Marshall and Swift Equipment Cost Index (MSECI). The ENRCCI appears weekly in Engineering News Record, McGraw Hill, Inc. The MSECI is available from

TABLE 2-4

DEVELOPMENT OF TOTAL CAPITAL COSTS

A. Sludge management process TBCC costs derived in this manual.

Process 1	$________________
Process 2	$________________
Process 3	$________________
Process 4	$________________
Subtotal A	$________________

B. Conversion of Subtotal A from fourth quarter 1984 values to inflated costs at midpoint of construction period using the Engineering News Record (ENR) Construction Cost Index. Not necessary when using algorithms to calculate TBCC costs (Subtotal A = Subtotal B).

Estimated ENR construction cost index at midpoint of construction period = current ENR index = ______________.

Divide current ENR index above by 4,171 = ENR index ratio = __________.

Multiply ENR index ratio x Subtotal A = Subtotal B = ________________.

C. Add nonconstruction costs to Subtotal B

Engineering design @ 10%* of Subtotal B =	$____________
Construction supervision @ 5%† of Subtotal B =	$____________
Legal and administrative costs @ 20%* of Subtotal B =	$____________
Contingencies @ 15% of Subtotal B =	$____________
Subtotal C =	$____________
Interest during construction @ current annual interest = decimal rate x years of estimated construction period x 1/2 =_____ x Subtotal C =	$____________
Total estimated capital cost (Subtotal C + Interest)	$____________

* Engineering design costs normally range from 7 to 15%.

† Construction supervision costs normally range from 3 to 8%.

TABLE 2-5

DEVELOPMENT OF TOTAL ANNUAL O&M COSTS

A. Fourth quarter 1984 sludge management process O&M costs derived from the cost curves or algorithms in this manual.

Process 1	$__________
Process 2	$__________
Process 3	$__________
Process 4	$__________
Subtotal A	$__________

B. Conversion of Subtotal A to inflated O&M costs during the first year of system operation using the ENR index. Conversion not necessary when obtaining costs from the component curves and algorithms (Subtotal A = Subtotal B).

Estimated ENR construction cost index at midpoint of first year of system operation = current ENR index = __________

Divide current ENR index above by 4,171 = O&M index ratio = __________

Multiply O&M index ratio x Subtotal A = Subtotal B = __________

C. Add administrative and laboratory costs to Subtotal B

Administrative costs @ 20%* of Subtotal B =	$__________
Laboratory costs @ 10%† of Subtotal B =	$__________
Total estimated annual O&M costs for first year of system operation	$__________

---

* Administrative costs normally vary from 10 to 30%.

† Laboratory costs vary widely depending on the sludge processes used. Can be 0% to over 30%.

Chemical Engineering magazine. The Marshall and Swift Index is used to adjust equipment costs or combined costs in which equipment is the major cost component. The remainder of costs are adjusted using the ENRCCI. When developing total project costs using the algorithms in Appendix A, adjustment for inflation (Step B, Tables 2-4 and 2-5) is not necessary, since the adjustment is made in the algorithm.

When using the O&M component curves, the user can specify unit costs for most O&M components, thus eliminating the need for inflation adjustment if current unit costs are used. However, components presented in terms of annual cost, such as annual replacement parts and maintenance materials, must be adjusted for inflation using the appropriate index. This adjustment should be done prior to obtaining a process total O&M cost using an equation such as:

$$\text{COSTOM} = (\text{L})\ (\text{COSTL}) + (\text{E})\ (\text{COSTE}) + (\text{COSTM})\ \frac{\text{ENRCCI}}{4{,}171}$$

where

COSTOM = Annual cost of operation and maintenance, $/yr.
L = Annual labor requirement, hr/yr, from component curve.
COSTL = User-specified cost of labor, $/hr.
E = Annual energy requirement, kWhr/yr, from component curve.
COSTE = User-specified cost of energy, $/kWhr.
COSTM = Annual cost of maintenance, $/yr, from component curve.

When using the O&M component curves and the cost algorithms, inflation adjustment is not necessary (Step B, Table 2-5); therefore, Subtotal A = Subtotal B.

2.6.2 Development of total base capital cost estimates.

Total base capital costs (TBCC) for sludge management processes in this manual include structural, mechanical, equipment, electrical, and instrumentation costs. They do not include costs for engineering design, construction supervision, legal and administration, interest during construction, and contingencies. These nonconstruction costs must be estimated and added to the process TBCC costs derived from the cost curves or cost algorithms in order to estimate the total project construction cost as shown on Table 2-4.

2.6.3 Development of total annual O&M cost estimates.

The annual O&M cost for sludge management processes in this handbook do not include costs for administration and laboratory sampling/analysis. These costs must be estimated and added to the process O&M costs derived from the cost curves and cost algorithms in order to obtain the total estimated annual O&M cost, as shown on Table 2-5. Total annual O&M costs will normally be about 30 percent higher than the O&M costs shown in the cost curves adjusted for inflation.

The total estimated O&M cost calculated above does not include revenues generated through the sale and/or use of sludge, composting products, or sludge by-products (i.e., methane produced in anaerobic digestion). If the user has information available on revenues generated through usage or sale, O&M costs may be decreased by subtracting any revenues generated on an annual basis from the fixed annual O&M cost for that process.

2.6.4 Development of total project cost.

Total project cost is obtained by combining the total base capital cost from Table 2-4 and the total annual O&M cost from Table 2-5. Two approaches are possible: use of total annual cost or use of present worth. If the total annual cost concept is to be used, the total base capital cost must be amortized using the appropriate interest rate and time period.

The annual amortized capital cost is calculated as follows:

1. Calculate the capital recovery factor.

$$CRF = \frac{i\ (1 + i)^{pp}}{(1 + i)^{pp} - 1} \qquad \text{(Eq. 2-4)}$$

where

CRF = Capital recovery factor, decimal percent/yr.
i = Interest rate, annual percentage (decimal).
pp = Planning period, yr.

2. Calculate the annual amortized capital cost.

$$ACC = (CRF)\ (PC) \qquad \text{(Eq. 2-5)}$$

where

ACC = Annual amortized capital cost, \$/yr.
PC = Total base capital cost, \$ (from Table 2-4).

The annual amortized capital cost is added to the total annual O&M cost (from Table 2-5) to obtain a total annual project cost. For example, assume a \$5,000,000 project, a \$129,000 O&M cost in year 1, 5 percent/yr escalation in O&M, amortization at a 10 percent interest rate over 20 years (capital recovery factor = 0.11746). The total annual project cost in any year is calculated as follows:

Year	Amortized Capital Cost (\$/yr)	O&M Cost (\$/yr)	Total Annual Cost (\$/yr)
1	587,300	129,000	716,300
2	587,300	135,500	722,800
3	587,300	142,200	729,500
4	587,300	149,300	736,600
etc.	etc.	etc.	etc.

The second method of comparing projects is to use the present worth concept, which brings the annual expenditures for O&M back to present worth. For the example shown previously, it is necessary to determine the present worth of the O&M expenditures (increasing at 5 percent annually) over the period of time under consideration, and to add this to the capital cost. For a 10-year period of time, the present worth of the annual O&M expenditures, which are assumed to increase at a rate of 5 percent, is:

Year	Amortized O&M Cost ($/yr)	Present Worth Factor* (10% Interest Rate)	Present Worth on Annual O&M ($)
1	129,000	1.000	129,000
2	135,500	0.9091	123,200
3	142,200	0.8264	117,500
4	149,300	0.7513	112,200
5	156,800	0.6830	107,100
6	164,600	0.6209	102,200
7	172,900	0.5645	97,600
8	181,500	0.5132	93,200
9	190,600	0.4665	88,900
10	200,100	0.4241	84,900
			1,055,800

* Present worth factor = $1/(1 + i)^n$

where
i = Interest rate, decimal percent.
n = Year - 1.

The total base capital cost (obtained from Table 2-4) is then added to the present worth of the annual O&M expenditures to obtain a total estimated project present worth. Thus, in this example, the total estimated project present worth for a 10-year period would be $6,055,800.

The total estimated project cost calculated above does not include salvage values and other items usually considered when performing a present worth analysis. The user should be aware that the structural and equipment components with lives greater than the planning period have a salvage value calculated using a uniform depreciation over the service life of the equipment. Land is unique in terms of salvage value in that its value has escalated at a compounded annual rate of 3 percent. Therefore, the salvage value of land at the end of the planning period is assumed to be higher than its initial cost.

The total estimated project cost does not include a number of items which relate to the entire treatment plant. These items include:

- Inter-process piping.
- Standby power.

- Roads, landscaping, and lighting.

- Special subsurface or geological conditions which may require dewatering or piles.

- Administration, laboratory, and maintenance buildings/facilities.

While costs obtained with this manual are suitable for alternative comparisons, it is possible that these components vary between alternatives. Under these circumstances, it is essential that the cost of these items be included in the total project cost estimate.

2.7 Calculating Cost Per Dry Ton

In sludge processing, it is often desirable to express costs in terms of annual cost per dry ton. This cost is obtained by summing the amortized capital cost and base annual O&M costs (as discussed in Subsection 2.6.4) and dividing by the annual dry sludge solids processed.

1. Calculate the annual process rate of sludge in dry tons per year.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{(100)\ (2{,}000)}$$

where

TDSS = Annual dry solids processed, tons/yr.
SV = Sludge volume, gal/yr.
SS = Suspended solids, percent.
SSG = Sludge specific gravity, unitless.
8.34 = Conversion factor, lb/gal.
2,000 = Conversion factor, lb/ton.

2. Determine the cost per dry ton.

$$CPDT = \frac{ACC + COSTOM}{TDSS}$$

where

CPDT = Cost per dry ton, $/ton.
ACC = Annual amortized capital cost, $/yr.
COSTOM = Base annual O&M cost, $/yr.

If information on salvage values and revenues generated from sludge usage is available, it can be subtracted from the numerator in the above equation.

2.8 Example Using Cost Curves

This subsection presents an example in which the cost curves are utilized to estimate costs for a proposed sludge management system. Total project cost is obtained for the same 20-mgd treatment plant for which the mass balance was developed in Subsection 2.4. This sludge management scheme, shown schematically on Figure 2-2, consists of gravity thickening of primary sludge, dissolved air flotation thickening of secondary sludge, anaerobic digestion of combined thickened sludge, centrifuge dewatering of conditioned sludge, dewatered truck haul, and sludge application to cropland. Refer to Table 2-3 for influent sludge volume and solids concentrations.

2.8.1 Gravity thickening of primary sludge.

- Influent sludge volume = 57 million gal/yr.
- Influent solids concentration = 2 percent.
- Base capital cost from Figure 3-1 = $280,000.
- Base annual O&M cost from Figure 3-2 = $40,000/yr.

2.8.2 Dissolved air flotation thickening of secondary sludge.

- Influent sludge volume = 91 million gal/yr.
- Influent solids concentration = 0.5 percent.
- Base capital cost from Figure 3-4 = $360,000.
- Base annual O&M cost from Figure 3-5 = $58,000/yr.

2.8.3 Anaerobic digestion of combined sludge.

- Influent sludge volume = 39 million gal/yr.
- Influent solids concentration = 3.6 percent.
- Base capital cost from Figure 4-1 = $1,760,000.
- Base annual O&M cost from Figure 4-2 = $140,000/yr.

2.8.4 Chemical conditioning with lime.

- Influent sludge volume = 19 million gal/yr.
- Influent solids concentration = 5 percent.
- Lime dosage = 300 lb/ton of dry sludge.
- Base capital cost interpolated from Figures 6-2 and 6-3 = $160,000.
- Base annual O&M cost interpolated from Figures 6-5 and 6-6 = $170,000/yr.

2.8.5 Centrifuge dewatering.

- Influent sludge volume = 21 million gal/yr.
- Influent solids concentration = 5 percent.
- Base capital cost from Figure 5-1 = $420,000.
- Base annual O&M cost from Figure 5-2 = $56,000/yr.

2.8.6 Dewatered sludge truck haul.

- Sludge volume = 5 million gal/yr.
- Solids concentration = 18 percent.
- Round trip haul distance = 200 miles.
- Base capital cost from Figure 9-4 = $900,000.
- Base annual O&M cost from Figure 9-5 = $200,000/yr.

2.8.7 Sludge application to cropland.

- Sludge volume = 5 million gal/yr.
- Solids concentration = 18 percent.
- Sludge application rate = 5 dry tons/acre (land is not purchased).
- Base capital cost from Figure 10-1 = $170,000.
- Base annual O&M cost from Figure 10-2 = $50,000/yr.

Annual sludge volume, solids concentration, base capital cost, and base annual O&M cost for each sludge management process in the proposed scheme are summarized on Table 2-6. The total capital cost is developed in Table 2-7, assuming a 1-year construction period in which the ENRCCI increases by 5 percent. Interest during construction is calculated at 10 percent per year. The total capital cost from Table 2-7 is estimated to be $6,699,000.

The total annual O&M cost for this example developed in Table 2-8 is estimated to be $1,002,000. It is assumed that the midpoint of the first year of system operation is 1 year after construction commences, during which inflation increases at a rate of 5 percent per year.

The total project cost for the first year of operation using the total annual cost concept, based on a capital cost amortization of 11 percent interest rate over 20 years, is calculated as follows:

1. Capital recovery factor, using Eq. 2-4.

$$\text{CRF} = \frac{(0.11)\ (1 + 0.11)^{20}}{(1 + 0.11)^{20} - 1} = 0.126$$

2. Annual amortized capital cost, using Eq. 2-5.

$$\text{ACC} = (0.126)\ (6{,}699{,}000) = \$844{,}000/\text{yr}$$

3. Total annual cost during first year.

$$844{,}000 + 1{,}002{,}000 = \$1{,}846{,}000/\text{yr}$$

2.9 References

1. Process Design Manual for Sludge Treatment and Disposal. Technology Transfer Series. EPA-625/1-79-011, Center for Environmental Research Information, Cincinnati, Ohio, September 1979. 1135 pp. (Available from NTIS as PB80-200546.)

2. Metcalf and Eddy, Inc. Wastewater Engineering: Treatment, Disposal, Reuse. Second Edition. McGraw-Hill Book Company, New York, New York, 1979. 920 pp.

TABLE 2-6

SUMMARY OF BASE CAPITAL AND BASE ANNUAL O&M COSTS DESCRIBED IN EXAMPLE

Sludge Management Process	Average Influent Sludge Volume, SV (million gal/yr)	Solids Concentration, SS (percent)	Base Capital* Cost from Curves ($)	Base Annual O&M Cost from Curves ($/yr)
Gravity Thickening	57	2	280,000	40,000
Flotation Thickening	91	0.5	360,000	58,000
Anaerobic Digestion	39	3.6	1,760,000	140,000
Chemical Conditioning with Lime	19	5	160,000	170,000
Centrifuge Dewatering	21	5	420,000	56,000
Dewatered Sludge Truck Haul	5	18	900,000	200,000
Sludge Application to Cropland	5	18	170,000	50,000
Total Cost			4,050,000	714,000

* Base capital and base annual O&M costs were obtained using the assumptions listed in the text.

TABLE 2-7

DEVELOPMENT OF TOTAL CAPITAL COSTS FOR EXAMPLE

A. Sludge management process TBCC costs derived in this manual.

Gravity Thickening	$ 280,000
Dissolved Air Flotation Thickening	$ 360,000
Anaerobic Digestion	$ 1,760,000
Chemical Conditioning	$ 160,000
Centrifuge Dewatering	$ 420,000
Dewatered Sludge Truck Haul	$ 900,000
Sludge Application to Cropland	$ 170,000
Subtotal A	$ 4,050,000

B. Conversion of Subtotal A from fourth quarter 1984 values to inflated costs at midpoint of construction period using the Engineering News Record (ENR) Construction Cost Index. Not necessary when using algorithms to calculate TBCC costs (Subtotal A = Subtotal B).

Estimated ENR construction cost index at midpoint of construction period = current ENR index = 4,380 .

Divide current ENR index above by 4,171 = ENR index ratio = 1.05

Multiply ENR index ratio x Subtotal A = Subtotal B = 4,253,000

C. Add nonconstruction costs to Subtotal B

Engineering design @ 10% of Subtotal B =	$ 425,000
Construction supervision @ 5% of Subtotal B =	$ 213,000
Legal and administrative costs @ 20% of Subtotal B =	$ 851,000
Contingencies @ 15% of Subtotal B =	$ 638,000
Subtotal C =	$ 6,380,000
Interest during construction @ current annual interest = decimal rate x years of estimated construction period x 1/2 = 0.05 x Subtotal C =	$ 319,000
Total estimated capital cost (Subtotal C + Interest)	$ 6,699,000

TABLE 2-8

DEVELOPMENT OF TOTAL ANNUAL O&M COSTS FOR EXAMPLE

A. Fourth quarter 1984 sludge management process O&M costs derived from the cost curves or algorithms in this manual.

Gravity Thickening	$ 40,000
Dissolved Air Flotation Thickening	$ 58,000
Anaerobic Digestion	$ 140,000
Chemical Conditioning	$ 170,000
Centrifuge Dewatering	$ 56,000
Dewatered Sludge Truck Haul	$ 200,000
Sludge Application to Cropland	$ 50,000
Subtotal A	$ 714,000

B. Conversion of Subtotal A to inflated O&M costs during the first year of system operation using the ENR index. Conversion not necessary when obtaining costs from the component curves and algorithms.

Estimated ENR construction cost index at midpoint of first year of system operation = current ENR index = 4,490 .

Divide current ENR index above by 4,171 = O&M index ratio = 1.08

Multiply O&M index ratio x Subtotal A = Subtotal B = 771,000

C. Add administrative and laboratory costs to Subtotal B

Administrative costs @ 20% of Subtotal B =	$ 154,000
Laboratory costs @ 10% of Subtotal B =	$ 77,000
Total estimated annual O&M costs for first year of system operation	$ 1,002,000

3. Process Design Manual: Sludge Treatment and Disposal. Technology Transfer, EPA-625/1-74-006, October 1974.

4. Eckenfelder, W. W., Jr., and J. S. Chakra, eds. Sludge Treatment. Marcel Dekker, New York, 1981. 591 pp.

5. Wet Air Oxidation of Chemical Sludges. Research Report No. 12. Environment Canada. Ottowa, Ontario. March 1973. 79 pp.

6. Water Pollution Control Federation. Sludge Dewatering. Manual of Practice No. 20. Washington, D.C. 1983. 164 pp.

7. Sludge Composting and Improved Incinerator Performance. Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1984. 158 pp.

SECTION 3

RAW SLUDGE THICKENING CURVES

3.1 Introduction

This section presents base capital and O&M curves for two thickening processes: gravity and dissolved air flotation (DAF) thickening. Thickening achieves sludge volume reduction by concentrating the solids at either the bottom (gravity) or the top (flotation) of the thickener. The residual liquid is normally returned to the treatment plant while the concentrated sludge is sent on for further processing and disposal. The principal purpose of thickening is to reduce sludge volume, thereby lowering the cost of subsequent treatment. Secondary benefits can include sludge blending, sludge flow equalization, and gas stripping.

For preparation of the cost curves, thickeners are assumed to receive sludge 24 hours/day, 7 days/week. Costs do not include equipment for the control of odor, often associated with gravity thickening operations.

3.2 Gravity Thickening

Gravity thickening utilizes the difference in specific gravity between the solids and water to achieve separation. Settling occurs in a tank similar to a clarifier under relatively quiescent conditions. The process is characterized by four basic settling zones: clarification zone, hindered settling zone, transition zone, and compression zone. The top layer, or clarification zone, contains the clear liquid. In the hindered settling zone, the suspended particles begin moving downward, forming a gradient of increased thickness. The transition zone is characterized by a decrease in the solids settling rate. The bottom, or compession zone, is where the thickening of sludge is a result of liquid being forced out due to the compression of the overlying solids.

Gravity thickening is commonly used to thicken primary sludge and combined primary and waste biological sludge. Waste biological sludge alone generally does not thicken well in a gravity thickener. Chemical conditioning of sludge (see Section 6) is often done prior to gravity thickening to enhance performance.

Capital and O&M cost and requirement curves presented in Figures 3-1 through 3-3 for gravity thickening were based on the CAPDET program. The CAPDET algorithm assumes the design of a circular, reinforced concrete tank equipped with a slowly revolving sludge collector. Assumptions and input parameters used in cost development are noted on the curves.

FIGURE 3-1

BASE CAPITAL COST OF GRAVITY THICKENING AS A FUNCTION OF ANNUAL VOLUME AND RAW SLUDGE SOLIDS CONCENTRATION

Assumptions: Solids loading = 12 lb/ft^2/day; operation = 24 hr/day; operation = 7 days/week; effluent solids concentration = influent solids concentration in percent plus 2 percent; chemical conditioning is not included.

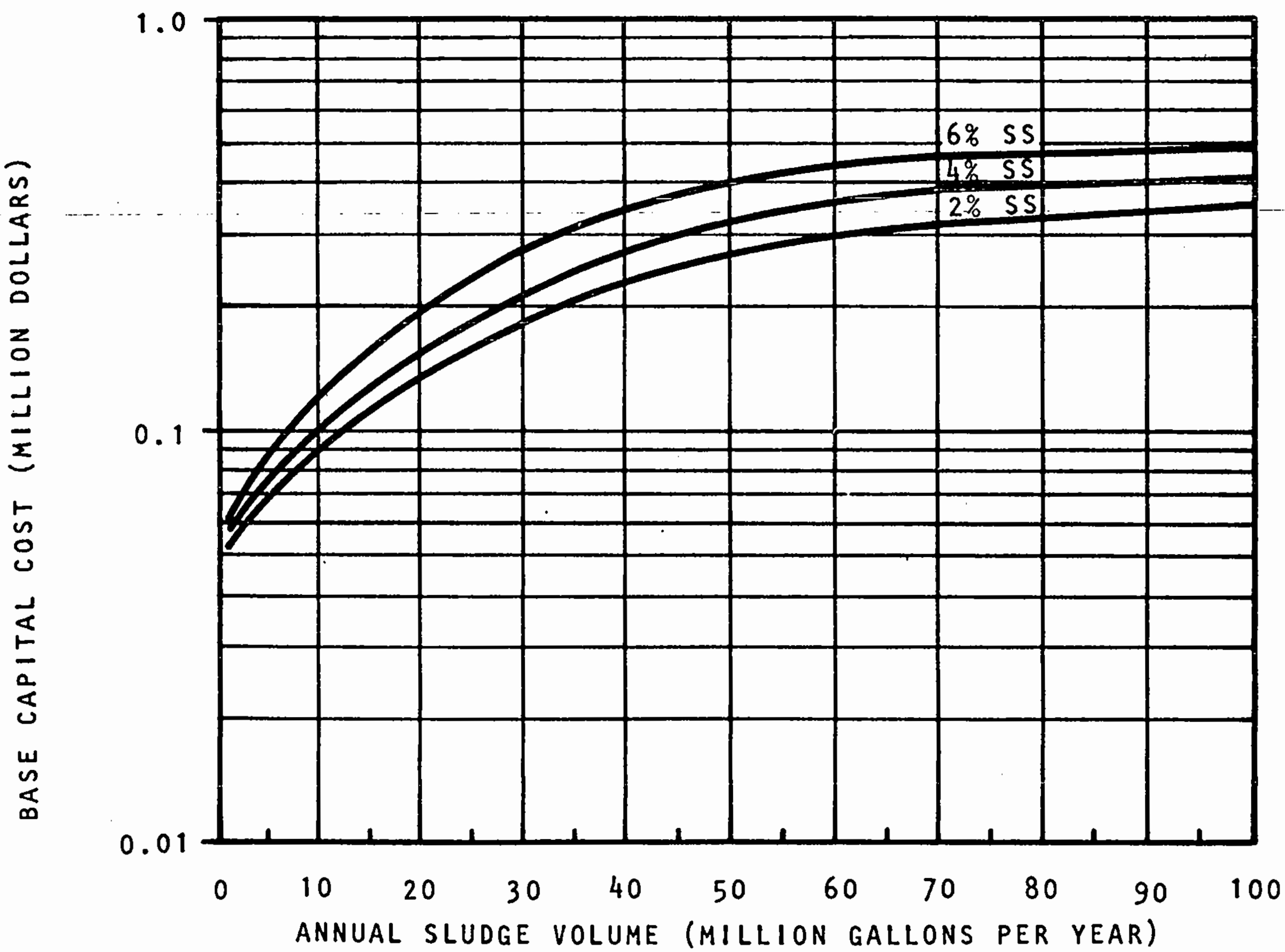


FIGURE 3-2

BASE ANNUAL O&M COST OF GRAVITY THICKENING AS A FUNCTION OF ANNUAL VOLUME AND RAW SLUDGE SOLIDS CONCENTRATION

Assumptions: Design assumptions are the same as for Figure 3-1; labor cost = \$13.50/hr; cost of electricity = \$0.094/kwhr.

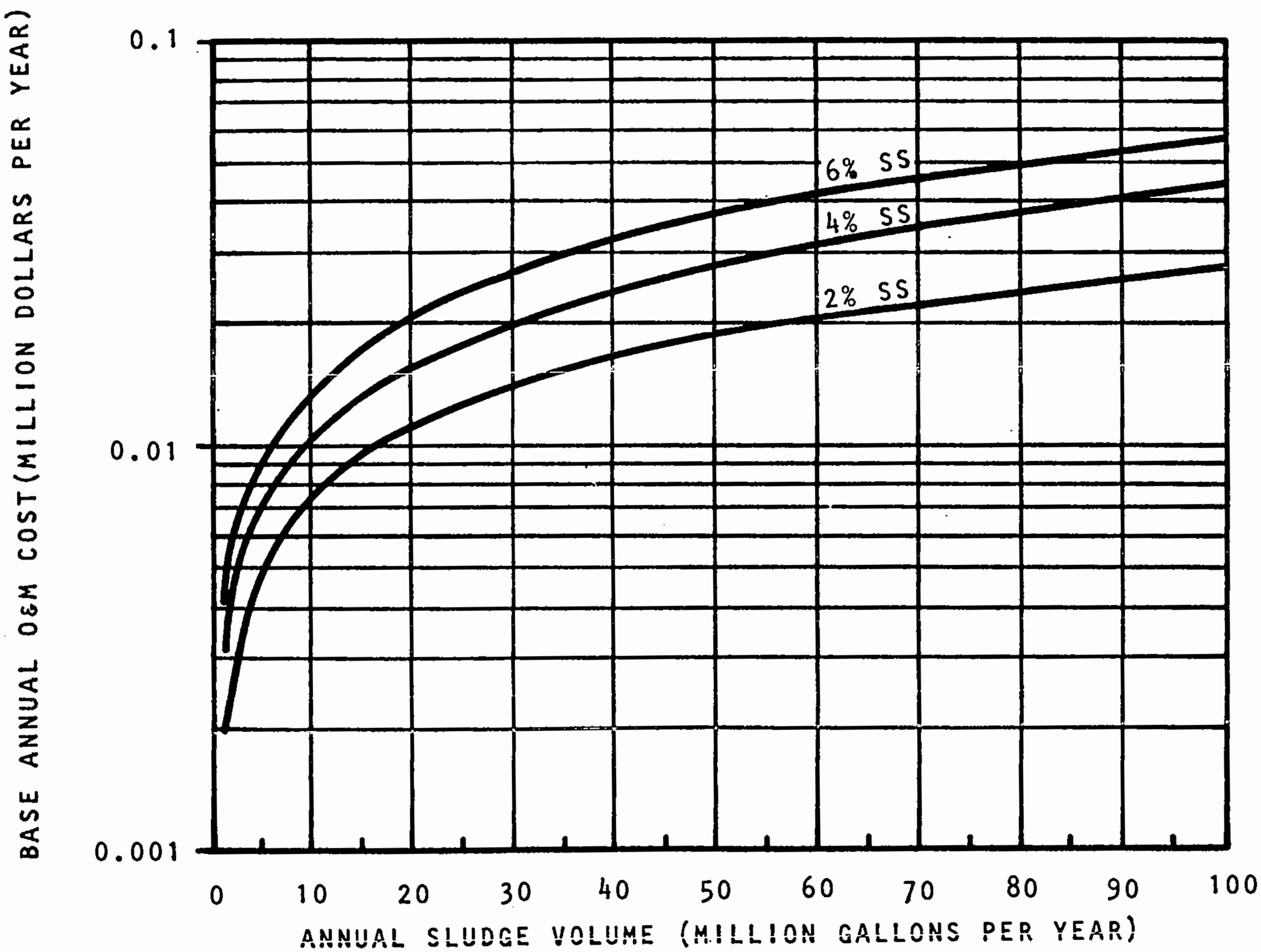
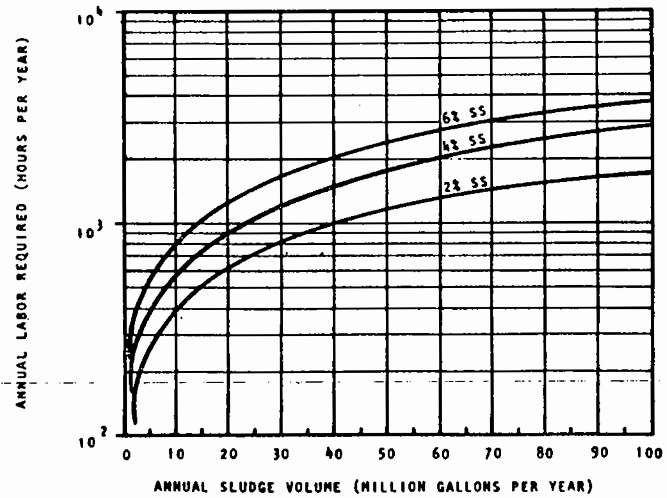
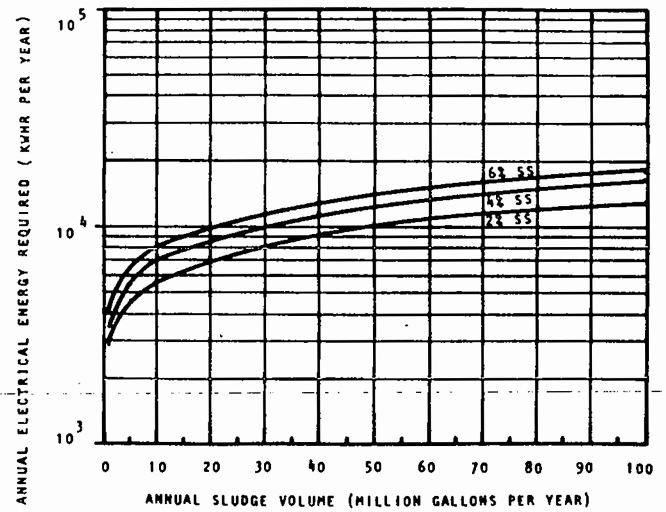
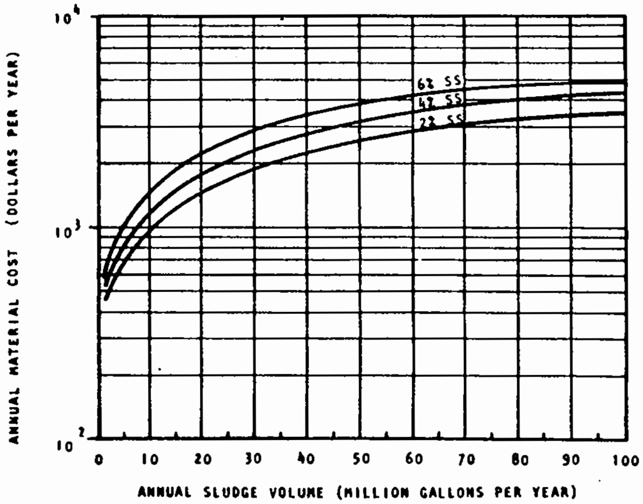


FIGURE 3-3

ANNUAL O&M REQUIREMENTS FOR GRAVITY THICKENING AS A FUNCTION OF ANNUAL VOLUME AND RAW SLUDGE SOLIDS CONCENTRATION







Assumptions: Design assumptions are the same as for Figure 3-1.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL REPAIR AND REPLACEMENT MATERIALS ESTIMATED AT 1% OF CAPITAL COST.

The cost algorithm for this process is presented in Appendix A-1. The user should consult Appendix A-1 for additional information on cost algorithm development, design parameters, and assumptions used in obtaining costs.

3.3 Dissolved Air Flotation Thickening (DAF)

In dissolved air flotation (DAF) thickening, air is introduced into a solution that is being held at an elevated pressure. Air can be added either to the incoming sludge stream, or more commonly, to a separate supernatant stream that is then combined with the sludge stream at atmospheric pressure. When the pressure is reduced, minute bubbles of air are formed which attach to the sludge particles and float to the surface. The sludge blanket is then removed using a skimmer mechanism.

DAF thickening is generally used for waste biological sludges and combined primary and waste biological sludges. Thickener performance is usually enhanced substantially by prior chemical conditioning of the sludge (see Section 6).

Capital and O&M cost and requirement curves presented in Figures 3-4 through 3-6 for flotation thickening were obtained using the CAPDET program. Costs assume the design of a circular reinforced concrete tank. Principal components included in the capital cost are pressurizing pump, air injection facilities, retention tank, back pressure regulating device, and the flotation unit. The flotation unit has a surface sludge collector to dispose of the floated particles, and a bottom sludge collector. Assumptions and input parameters used in cost development are noted on the curves.

A cost algorithm for flotation thickening is presented in Appendix A-2. The user should consult Appendix A-2 for additional information on cost algorithm development, design parameters, and assumptions used in obtaining costs.

FIGURE 3-4

BASE CAPITAL COST OF DISSOLVED AIR FLOTATION THICKENING AS A FUNCTION OF ANNUAL VOLUME AND RAW SLUDGE SOLIDS CONCENTRATION

Assumptions: Solids loading = 20 lb/ft^2/day; operation =24 hr/day; operation = 7 days/week; float solids concentration = 4 percent; chemical conditioning is not included.

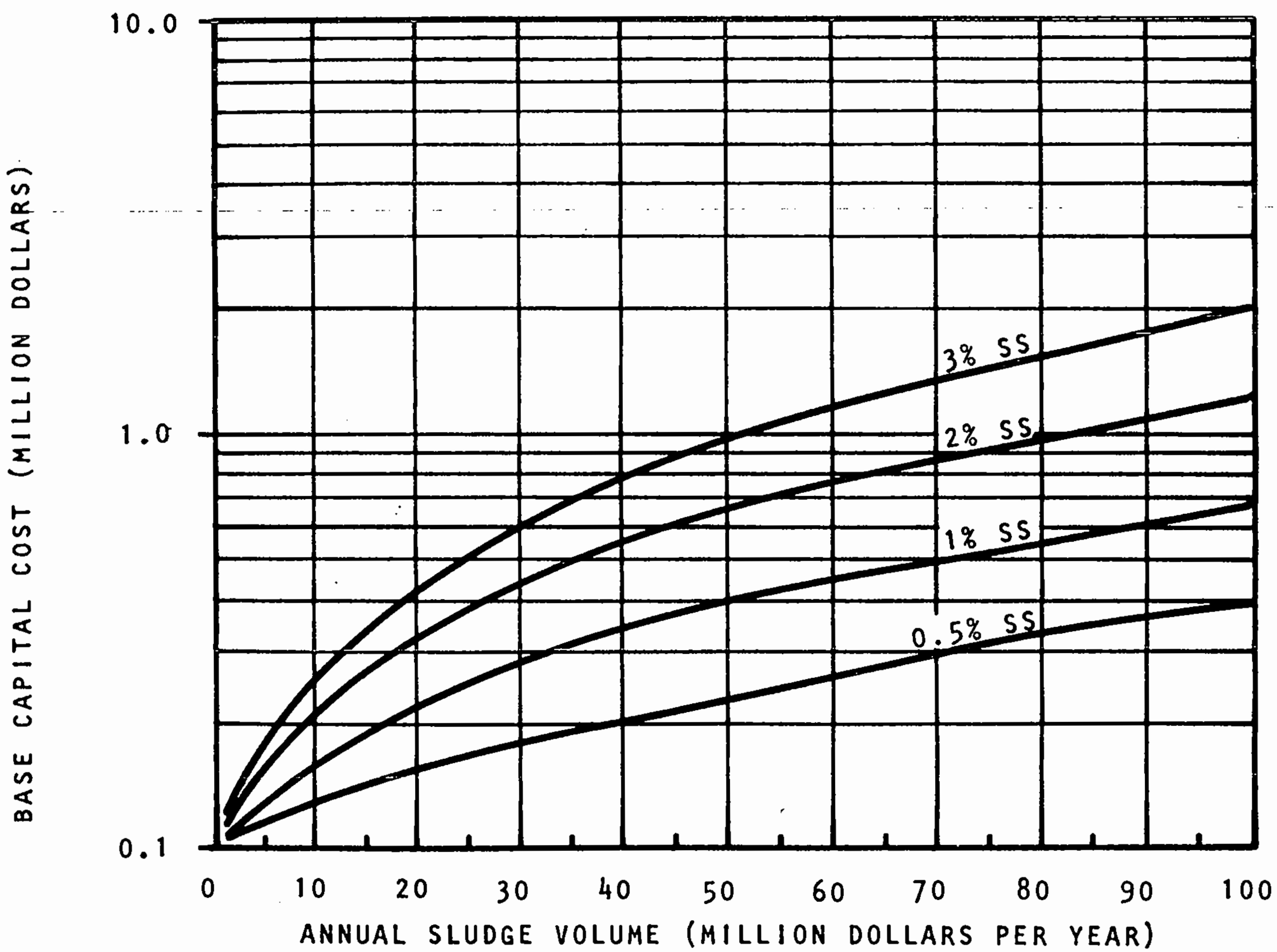


FIGURE 3-5

BASE ANNUAL O&M COST OF DISSOLVED AIR FLOTATION THICKENING AS A FUNCTION OF ANNUAL VOLUME AND RAW SLUDGE SOLIDS CONCENTRATIONS

Assumptions: Design assumptions are the same as for Figure 3-4; labor cost = $13.50/hr; cost of electricity = $0.094/kwhr.

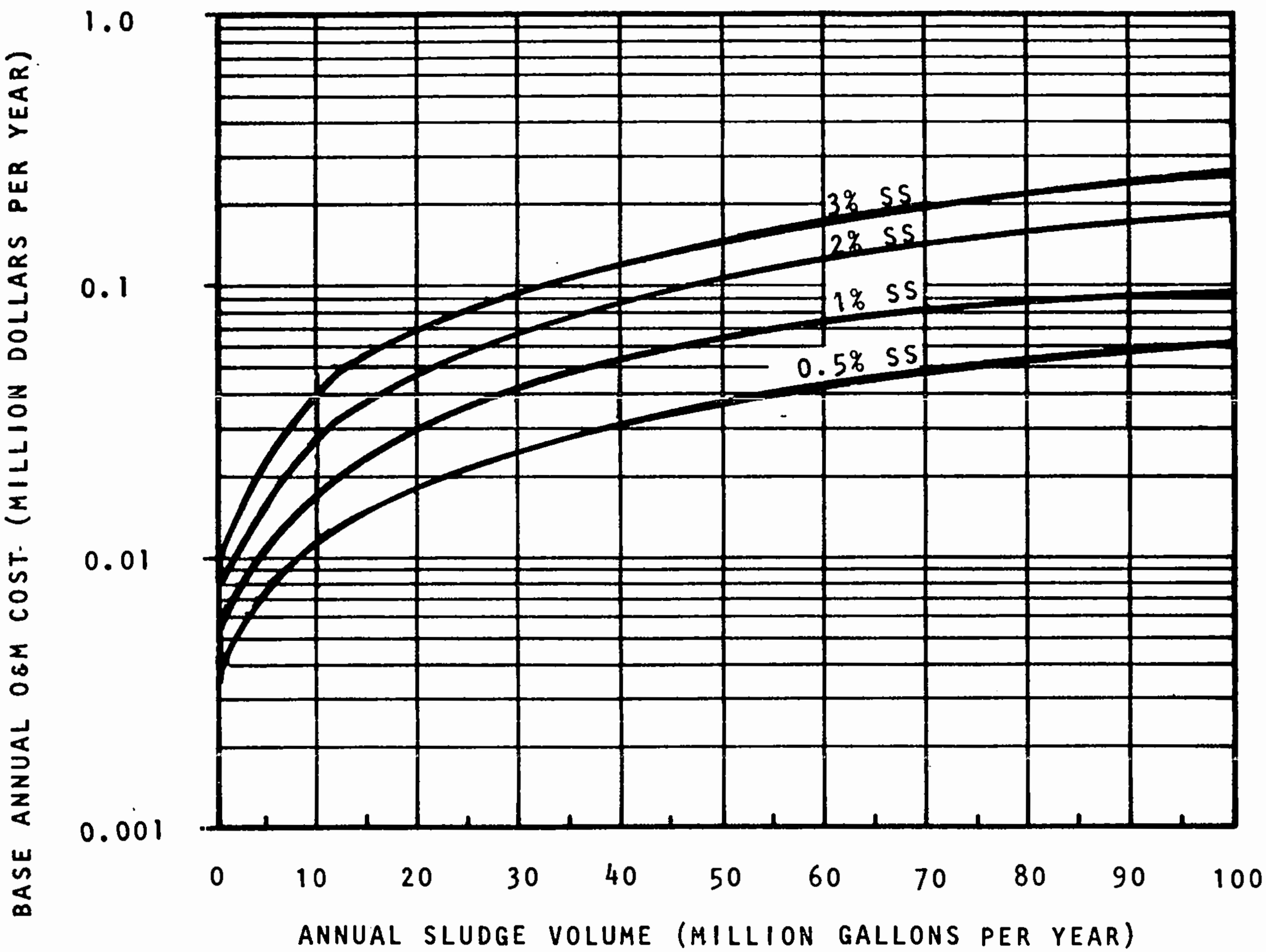
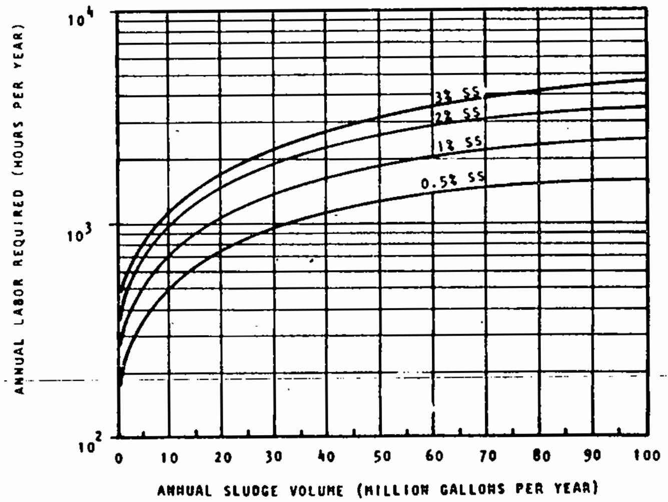
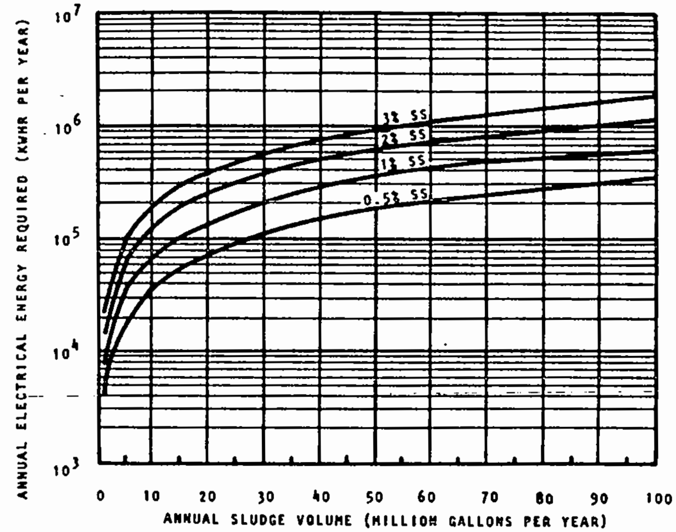
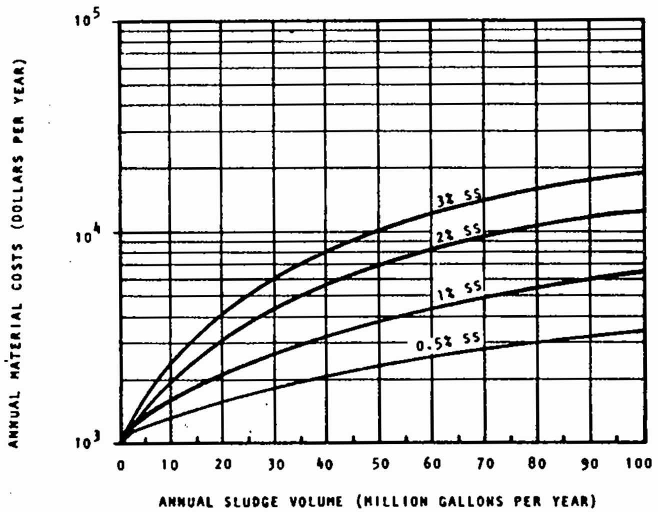


FIGURE 3-6

ANNUAL O&M REQUIREMENTS FOR FLOTATION THICKENING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design assumptions are the same as for Figure 3-4.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL REPAIR AND REPLACEMENT MATERIALS ESTIMATED AT 1% OF CAPITAL COST.

SECTION 4

SLUDGE STABILIZATION CURVES

4.1 Introduction

This section presents capital and annual operating and maintenance curves for five sludge stabilization processes: anaerobic digestion, aerobic digestion using mechanical aeration, aerobic digestion using diffused aeration, lime stabilization, and thermal conditioning. Thermal conditioning is unique in that it serves as both a stabilization process and a conditioning process.

Sludges are stabilized to render the sludge less odorous and putrescible, and to reduce the pathogenic organism content. In addition, anaerobic and aerobic digestion result in a substantial decrease in suspended solids concentration through the oxidation of the volatile or organic fraction of the sludge.

Operating conditions assumed when developing cost curves are listed on each respective curve. Generally, all stabilization processes, with the exception of lime stabilization and thermal conditioning, are assumed to operate continuously. Lime stabilization is assumed to operate 8 hours per day, 365 days per year, while thermal conditioning is assumed to operate 20 hours per day, 365 days per year. None of the processes include land costs, since they are generally minor compared to the capital cost of the equipment and structures required.

4.2 Anaerobic Digestion

Anaerobic digestion is a process in which biological degradation occurs in the absence of free oxygen. The degradation products under these conditions are methane, carbon dioxide, water, and partly degraded intermediate organics. The solids remaining after digestion are rendered stable, since little organic matter remains that can sustain further biological activity. Digested sludges are generally more readily dewatered than undigested sludges.

Capital costs and O&M costs and requirements presented in Figures 4-1 through 4-3 for anaerobic digestion are based on use of the CAPDET program. The CAPDET algorithm assumes the design of single-stage, low-rate cylindrical digesters constructed with reinforced concrete. Fuel energy for heating is supplied by the methane generated during digestion. Capital costs include excavation and construction of tanks, purchase and installation of floating cover, gas circulation equipment, external heater and heat exchanger, gas safety equipment, positive displacement pumps, internal piping, and ancillary equipment. In addition, capital costs include a two-story control building.

FIGURE 4-1

BASE CAPITAL COST OF ANAEROBIC DIGESTION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Incoming sludge temperature = 70° F; digestion temperature = 95° F; average ambient air temperature = 40° F; volatile solids = 60 percent; percent volatile solids destroyed = 50 percent; 24-hour continuous operation; effluent solids concentration = influent solids concentration plus 2 percent.

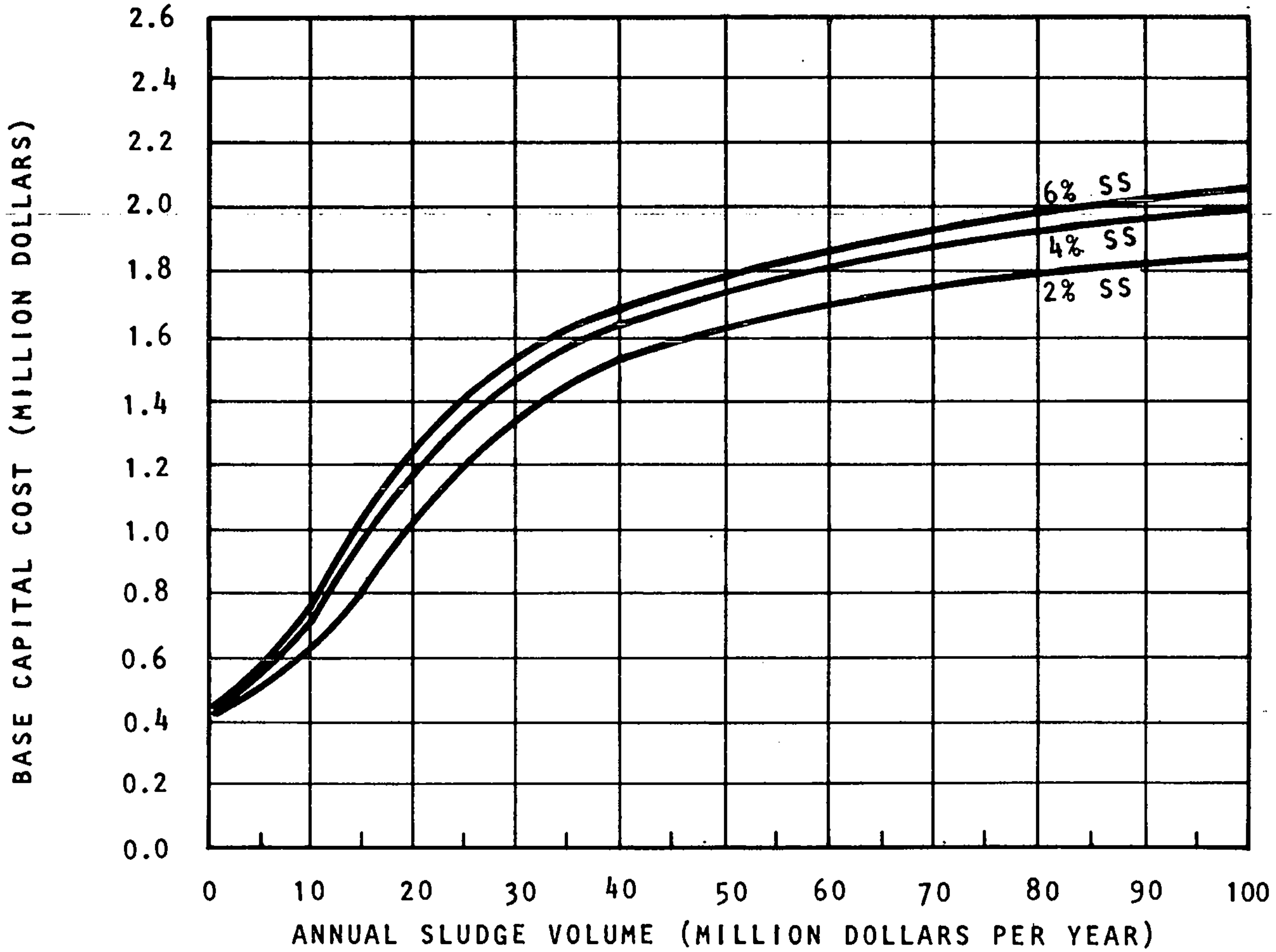


FIGURE 4-2

BASE ANNUAL O&M COST OF ANAEROBIC DIGESTION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design assumptions are the same as for Figure 4-1; labor cost = \$13.50/hr; cost of electricity = \$0.094/kwhr.

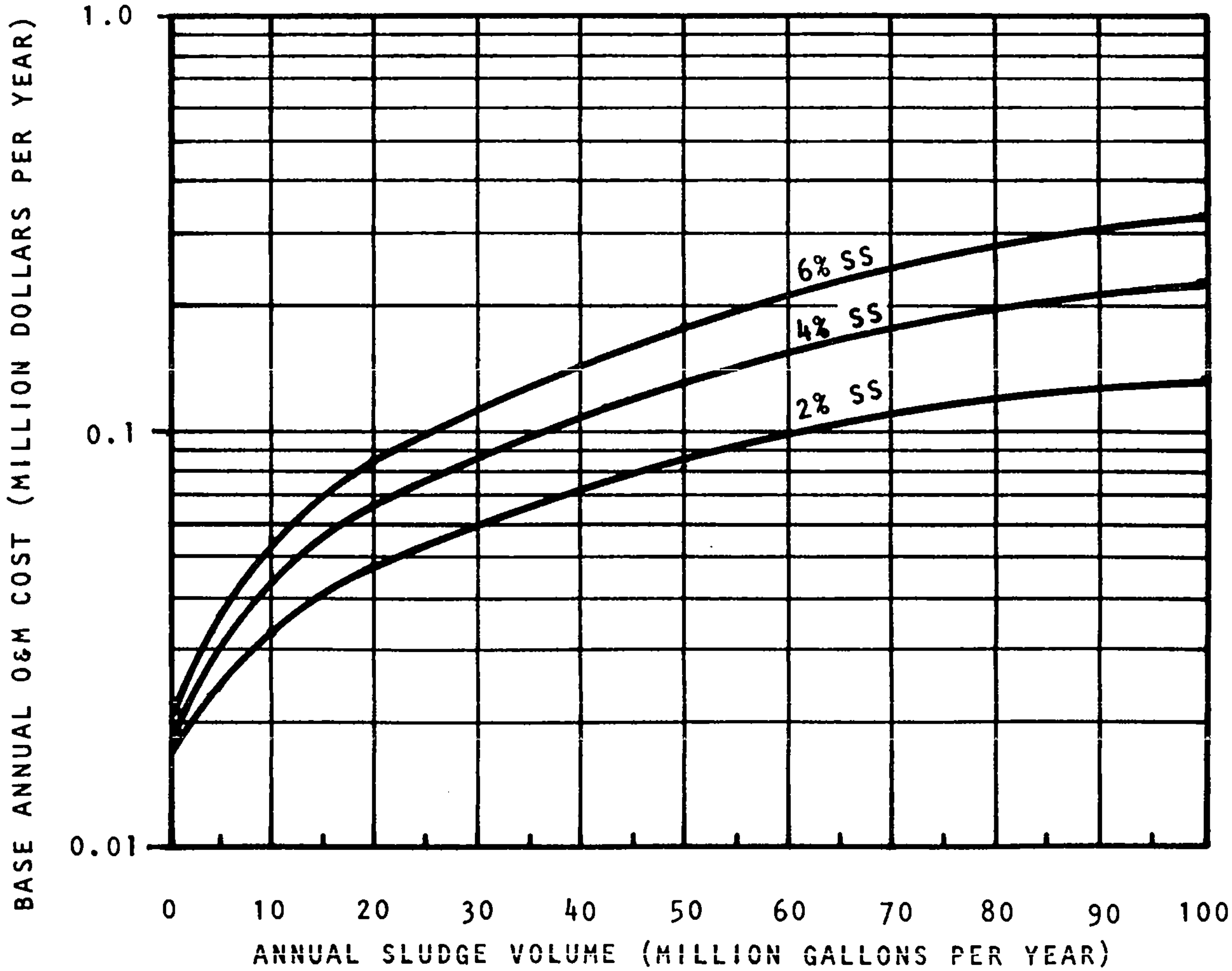
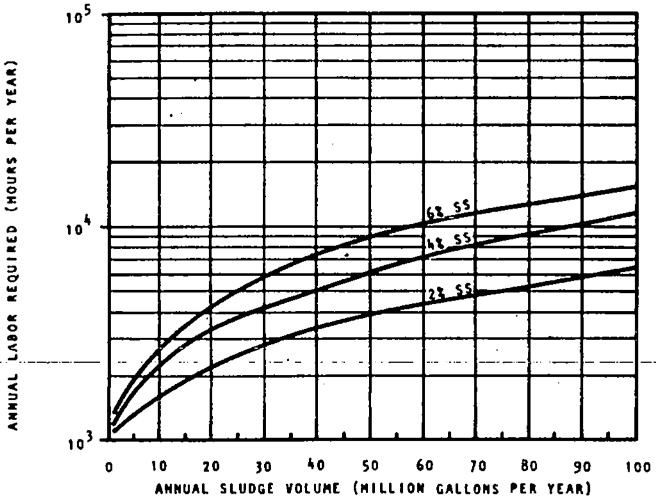
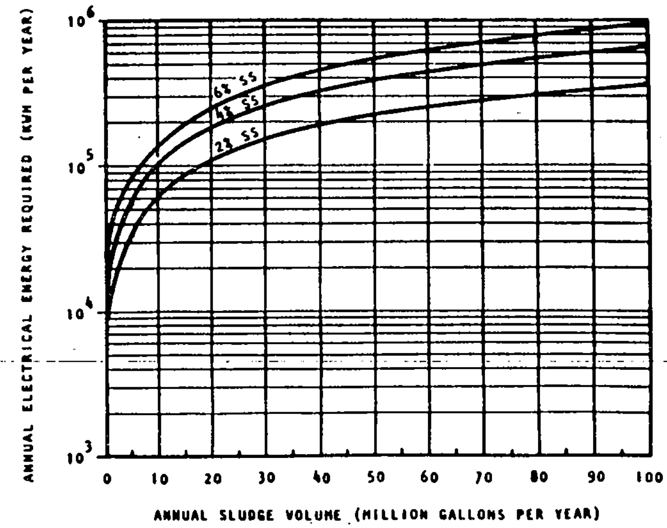
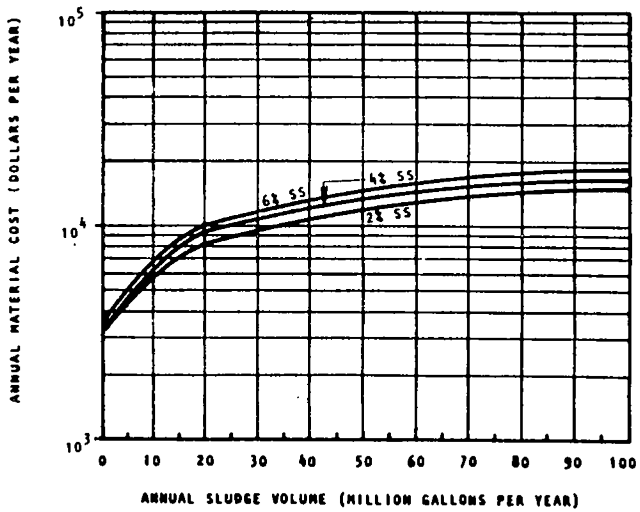


FIGURE 4-3

ANNUAL O&M REQUIREMENTS FOR ANAEROBIC DIGESTION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design assumptions are the same as for Figure 4-1.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL MATERIAL AND SUPPLIES REQUIRED FOR MAINTENANCES.

4.3 Aerobic Digestion

Aerobic digestion is the stabilization of raw sludge under aerobic conditions, similar in principle to the activated sludge process. Sludge solids are converted to carbon dioxide, water, and ammonia through the microbial degradation of sludge solids. Oxygen is supplied either by surface aerators (mechanical aeration) or by diffusers (diffused aeration). Aerobically digested sludges generally have poor mechanical dewatering characteristics.

Capital costs and O&M cost and requirement curves are presented in Figures 4-4 through 4-6 for aerobic digestion using mechanical aerators, and in Figures 4-7 through 4-9 for aerobic digestion using diffused aerators. Cost curves are based on use of the CAPDET program. CAPDET algorithms assume the design of cylindrical digesters constructed with reinforced concrete. Capital costs include excavation, construction, and installation of all equipment. Capital costs for aerobic digestion using mechanical aerators include purchase and installation of aerators. Capital costs for aerobic digestion using diffused aerators include purchase of diffusers and headers. However, capital costs do not include the cost of blowers, associated equipment, and blower building. It is assumed that the air capacity required for digestion would be provided by a common blower facility serving both the activated sludge process and diffused aerobic digestion.

4.4 Lime Stabilization

The addition of lime to stabilize sludge (pH >12) results in the destruction of pathogens and reduction of odor potential. Lime-stabilized sludges are easily dewatered, and are suitable for application on land (providing the high pH is not a problem). The process may be used on both raw and digested sludges. The primary disadvantage of lime stabilization is that no organic oxidation occurs. If the pH drops below 10, bacteria regrowth may occur, resulting in the production of noxious odors. A second disadvantage is that lime addition increases the sludge volume, often resulting in higher transportation and disposal costs.

Capital costs and O&M cost and requirement curves are presented in Figures 4-10 through 4-12 for lime stabilization. Curves are based on the use of hydrated lime ($Ca(OH)_2$). Capital costs include a lime storage silo sized for 30 days lime storage, dual batch mixing tanks (each having the capacity to hold 0.5 hours of plant design sludge flow), and a lime feeding system.

4.5 Thermal Conditioning

Thermal conditioning is both a stabilization and conditioning process which prepares sludge for dewatering without the use of chemicals. The sludge is heated to temperatures between 290 °F and 410 °F under pressures of 150 to 400 lb/in^2 with the addition of steam and sometimes air. Sludge is stabilized due to the hydrolysis of proteinaceous materials and destruction of cells. In addition, the high temperatures and pressures to which the sludge is subjected result in the release of bound water, enhancing dewatering.

Capital costs and O&M cost and requirement curves are presented in Figures 4-13 through 4-15 for thermal conditioning. Capital costs include purchase and installation of the following equipment: sludge feed pumps, sludge

FIGURE 4-4

CAPITAL COST OF AEROBIC DIGESTION USING MECHANICAL AERATORS AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Detention time = 20 days; volatile solids = 60 percent; volatile solids destroyed = 45 percent; digestion temperature = 73° F; 24-hour continuous operation; effluent solids concentration = 4 percent.

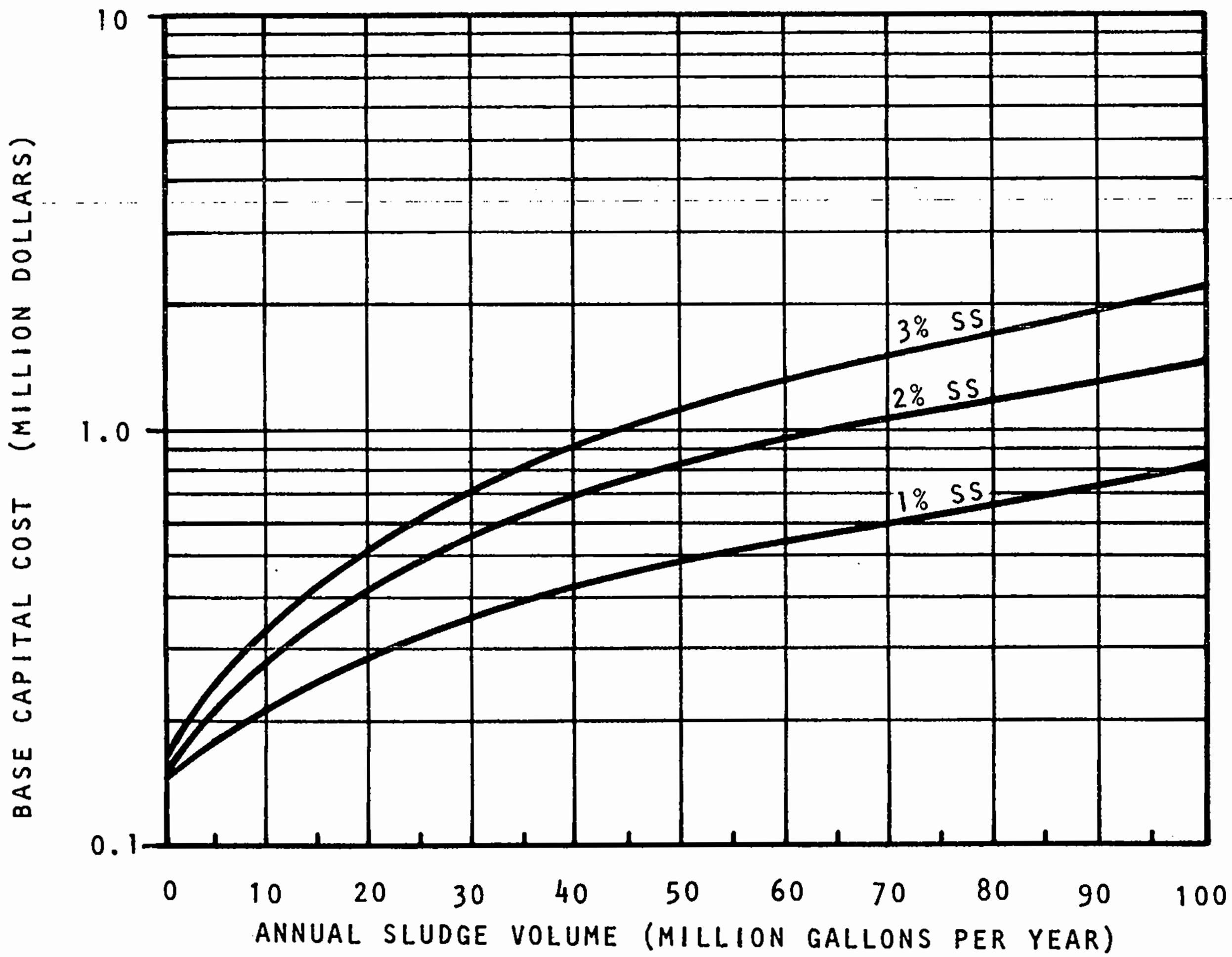


FIGURE 4-5

BASE ANNUAL O&M COST OF AEROBIC DIGESTION USING MECHANICAL AERATORS AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design assumptions are the same as for Figure 4-4; labor cost = $13.50/hr; cost of electricity = $0.094/kWhr.

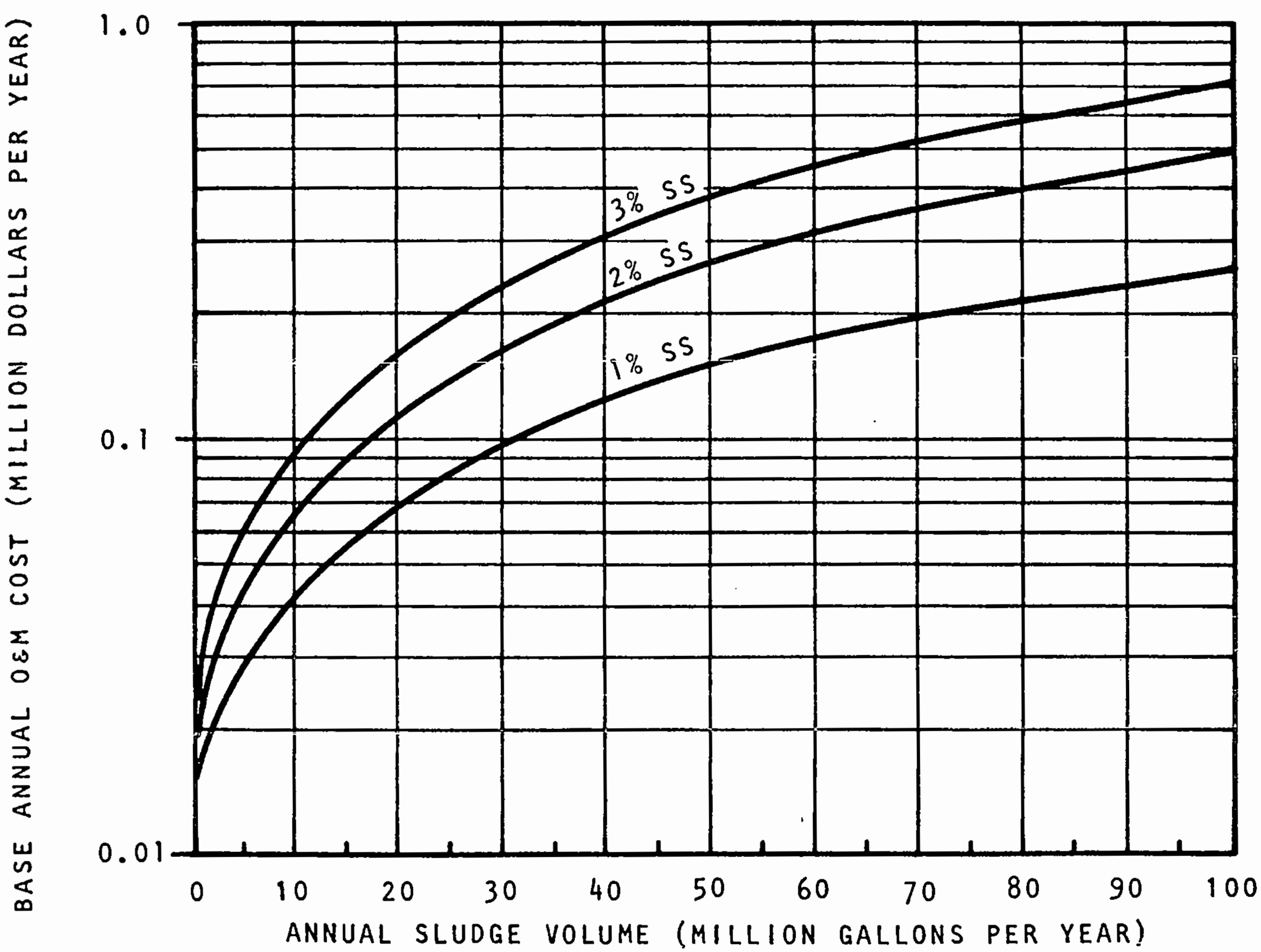
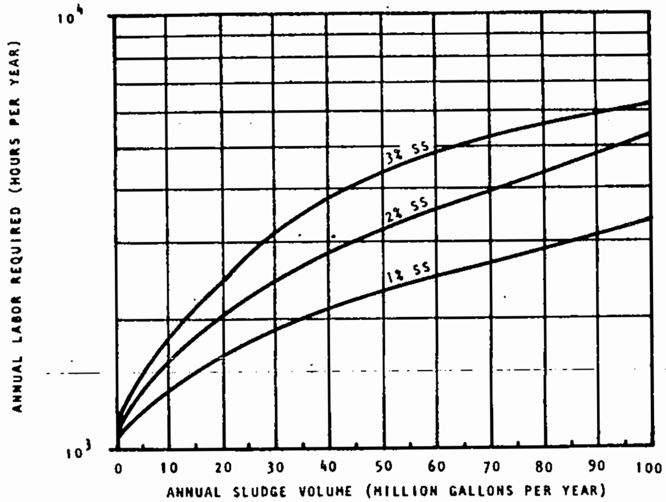
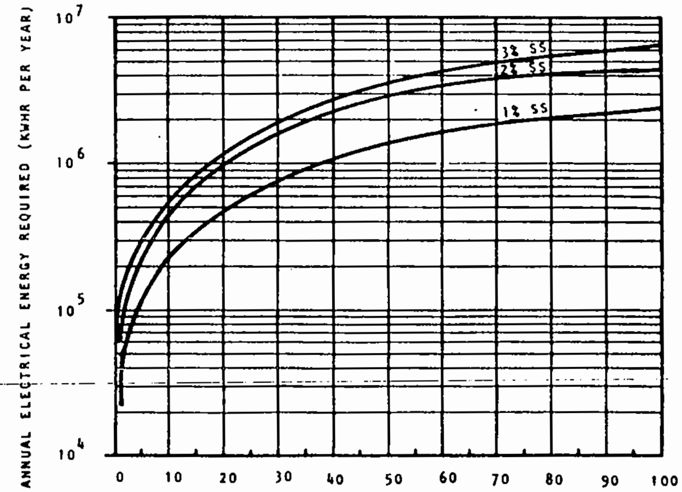
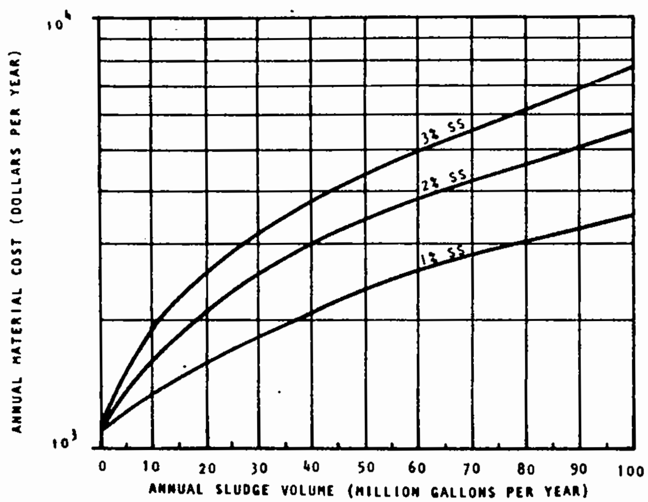


FIGURE 4-6

ANNUAL O&M REQUIREMENTS FOR AEROBIC DIGESTION USING MECHANICAL AERATORS AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design assumptions are the same as for Figure 4-4.

NOTE : THE MATERIAL COST CURVE IS FOR MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 4-7

BASE CAPITAL COST OF AEROBIC DIGESTION USING DIFFUSED AERATION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Detention time = 20 days; volatile solids = 60 percent; volatile solids destroyed = 45 percent; digestion temperature = 73° F; 24-hour continuous operation; effluent solids concentration = 4 percent.

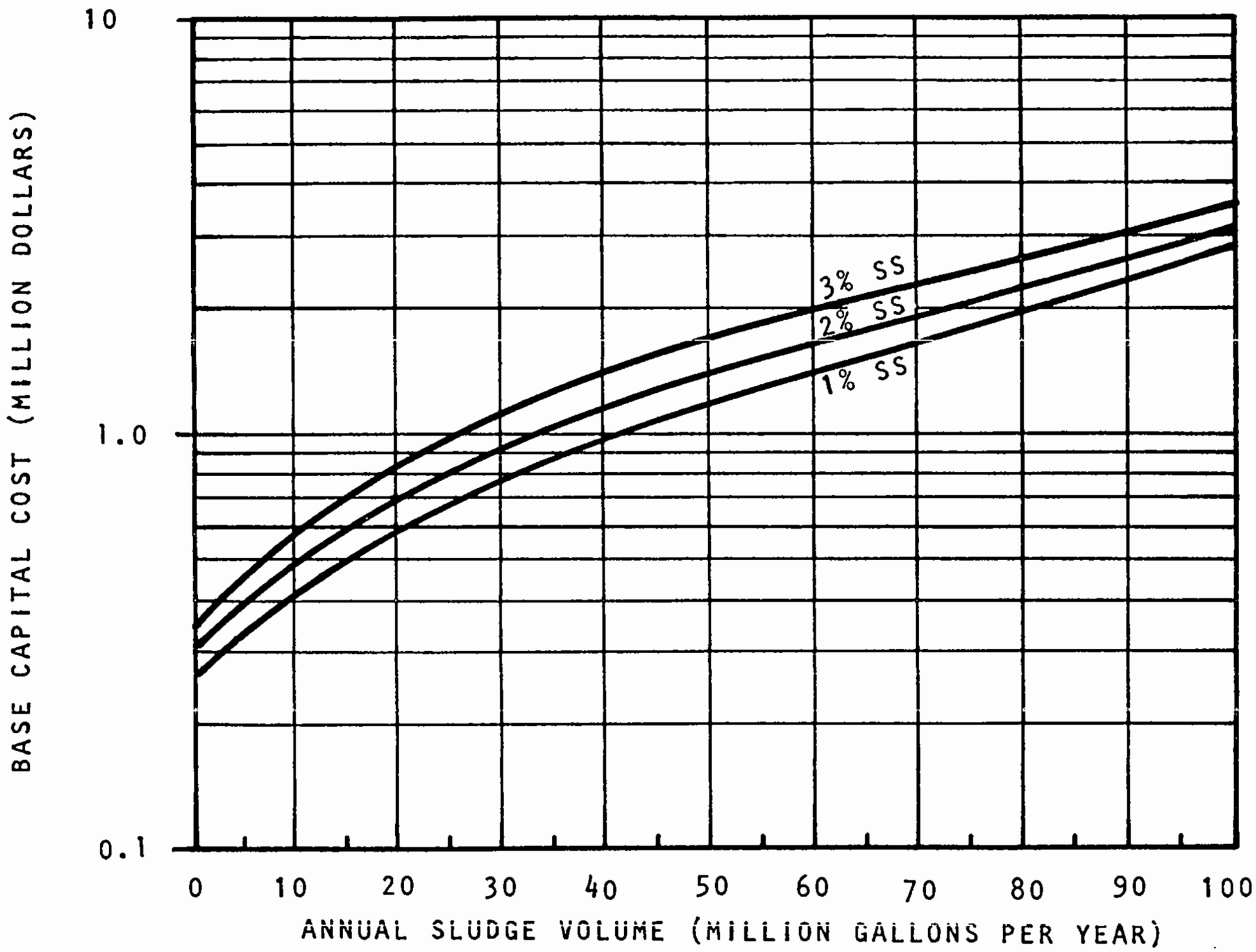


FIGURE 4-8

BASE ANNUAL O&M COST OF AEROBIC DIGESTION USING DIFFUSED AERATION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 4-7; labor cost = $13.50/hr; cost of electricity = $0.094/kWhr.

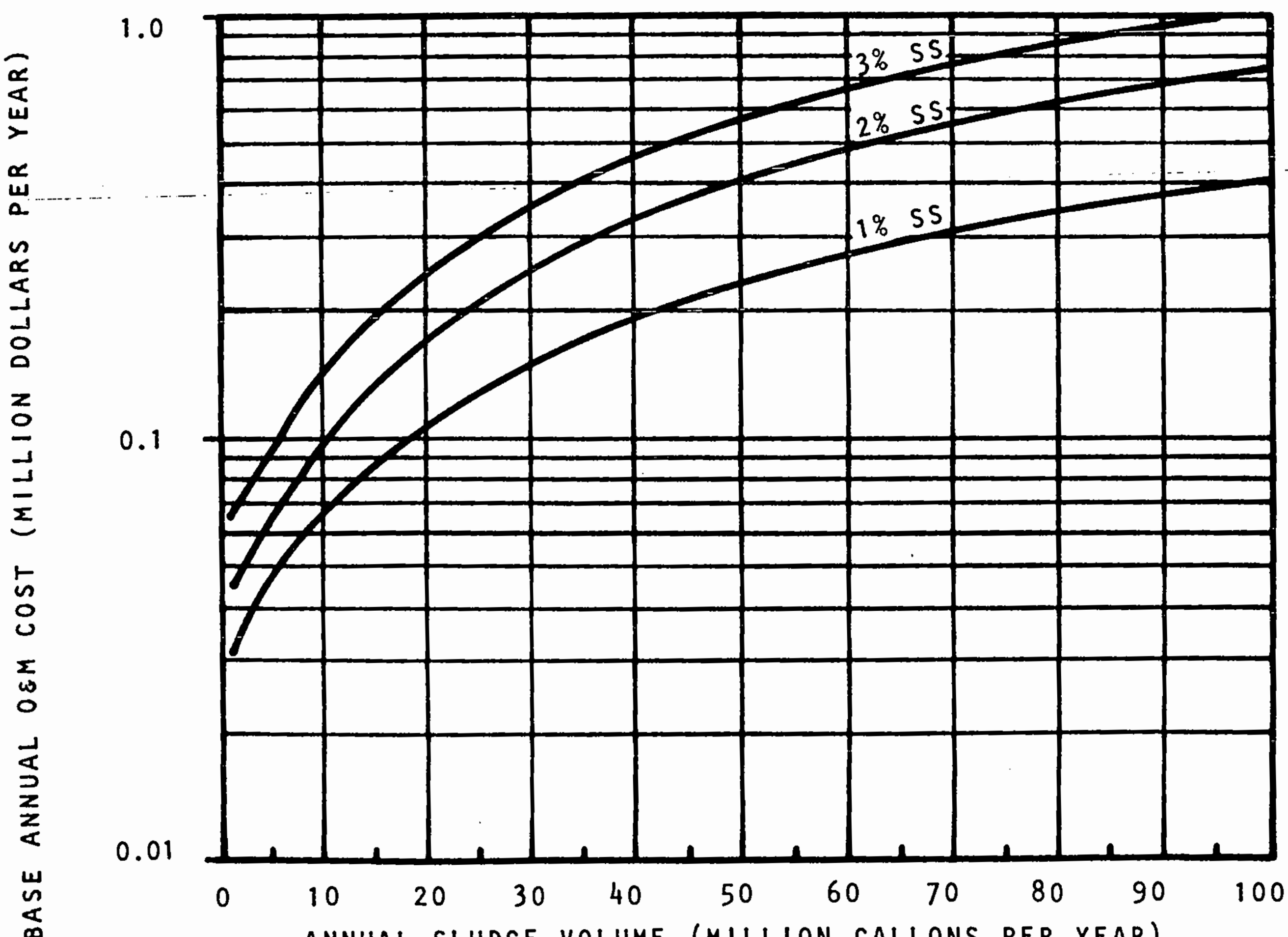
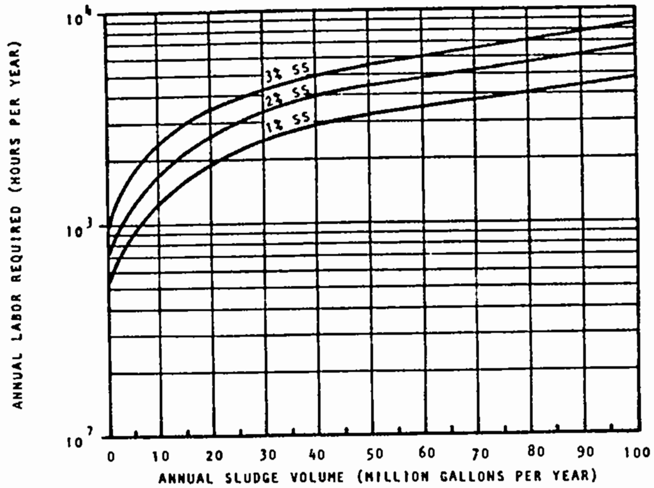
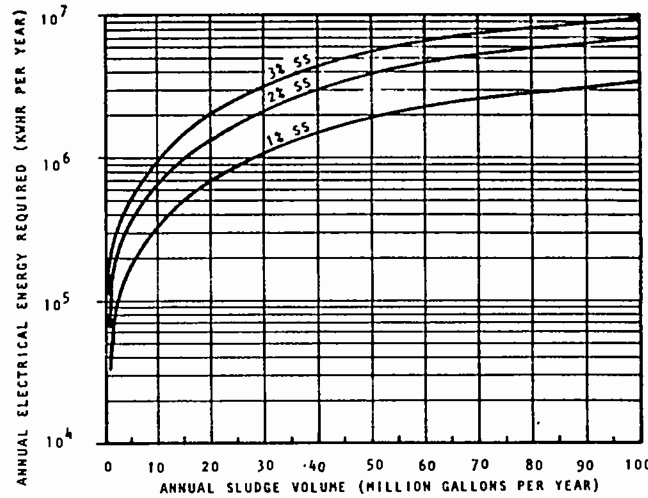
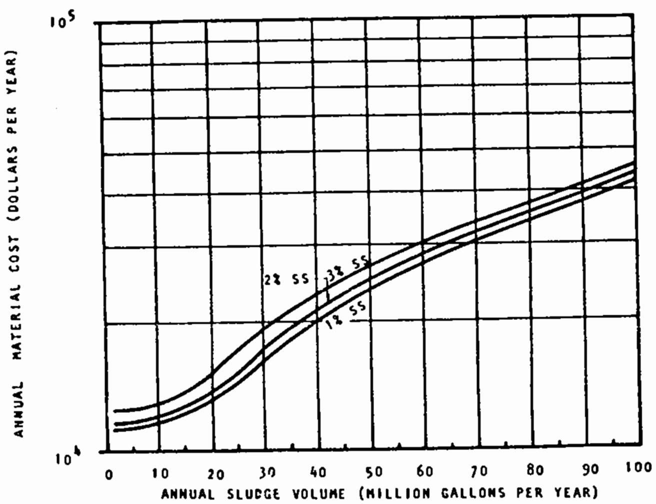


FIGURE 4-9

ANNUAL O&M REQUIREMENTS FOR AEROBIC DIGESTION USING DIFFUSED AERATION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design parameters are the same as for Figure 4-7.

NOTE : THE MATERIAL COST CURVE IS FOR MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 4-10

BASE CAPITAL COST OF LIME STABILIZATION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Daily operation period = 8 hr/day; annual operation period = 365 days/yr; sludge detention time in mixing tank = 0.5 hr/batch; hydrated lime content of lime product used = 90 percent; cost of storage silos = $7.70/cu ft; cost of mixing tanks = $0.83/gal of capacity; cost of lime feed system = $15.60/lb of feed capacity/hr; lime dosage = 0.2 lb lime/lb dry solids.

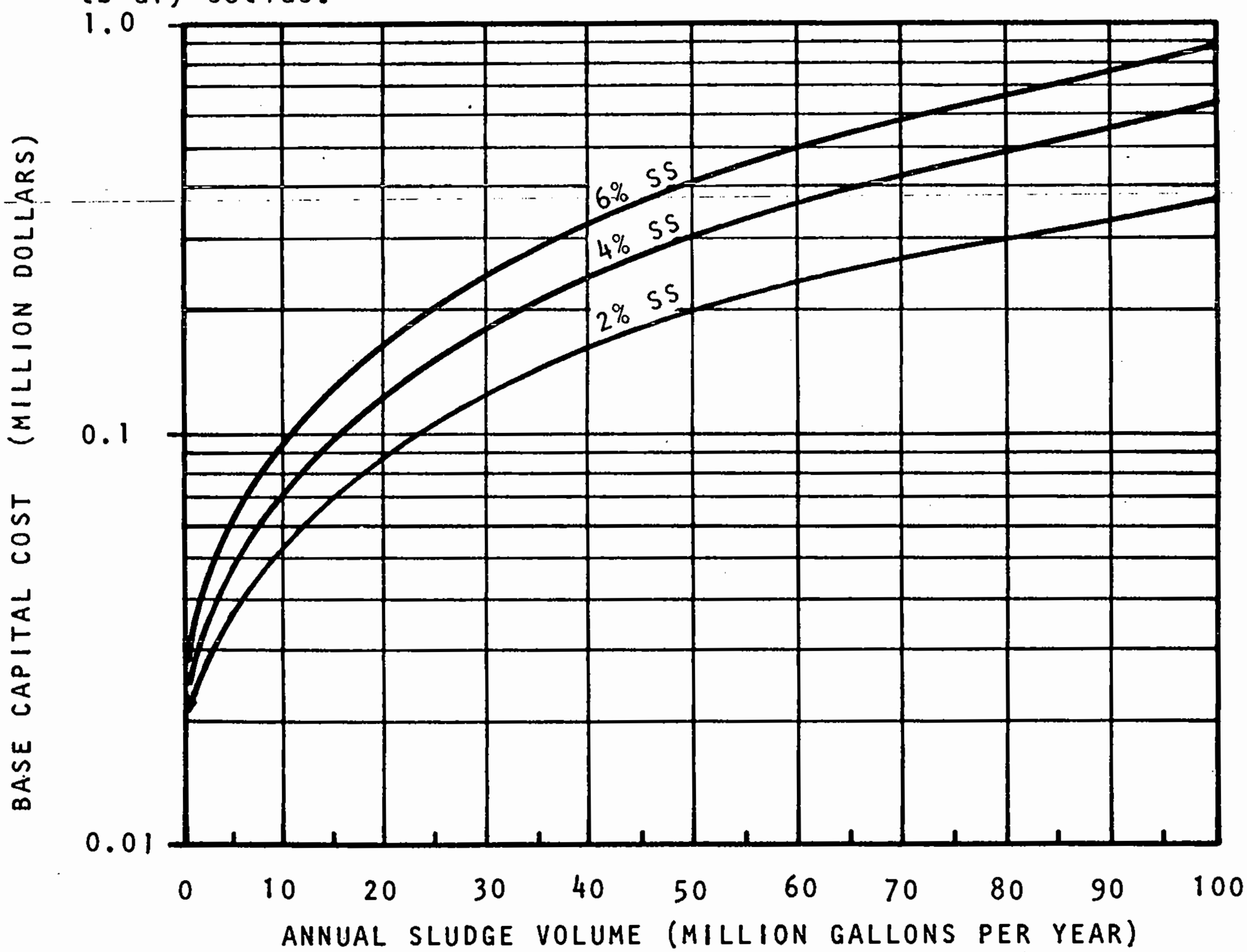


FIGURE 4-11

BASE ANNUAL O&M COST OF LIME STABILIZATION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 4-10; cost of lime = $104.00/ton; cost of electricity = $0.094/kWhr; cost of labor = $13.50/hr.

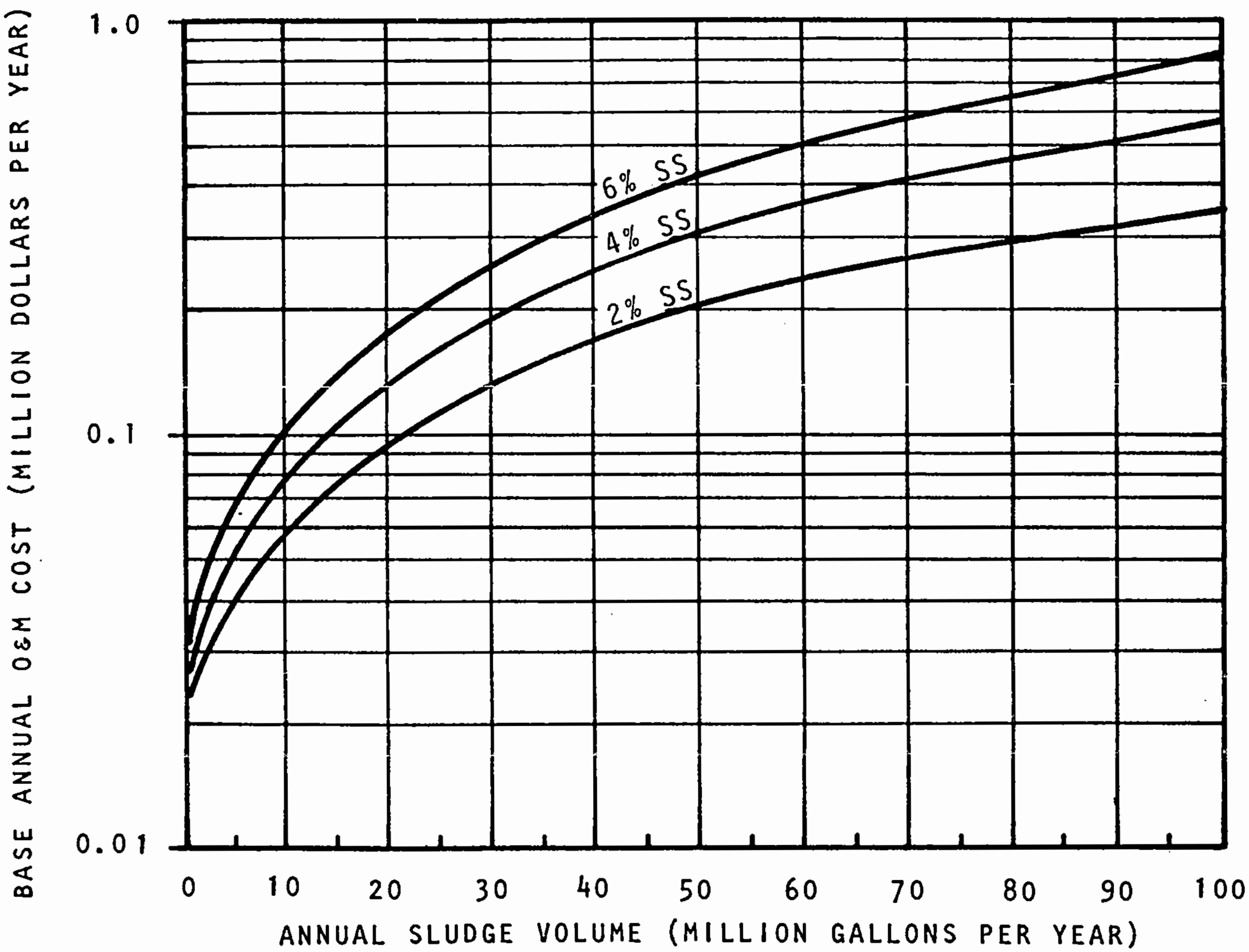


FIGURE 4-12

ANNUAL O&M REQUIREMENTS FOR LIME STABILIZATION AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 4-10.

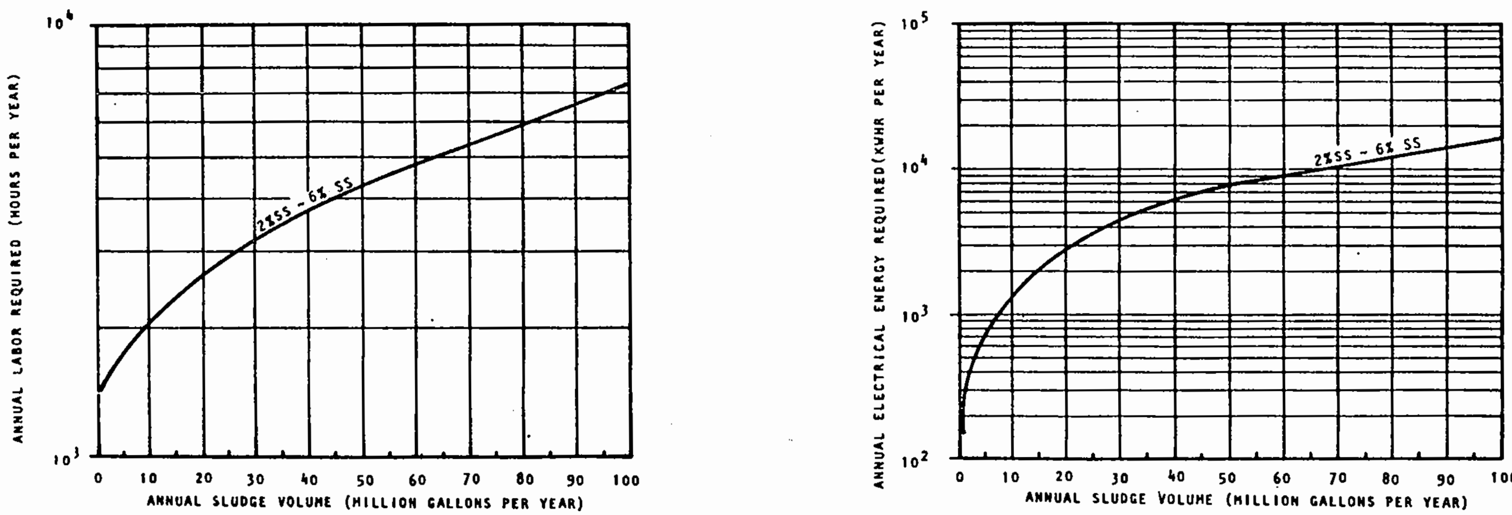
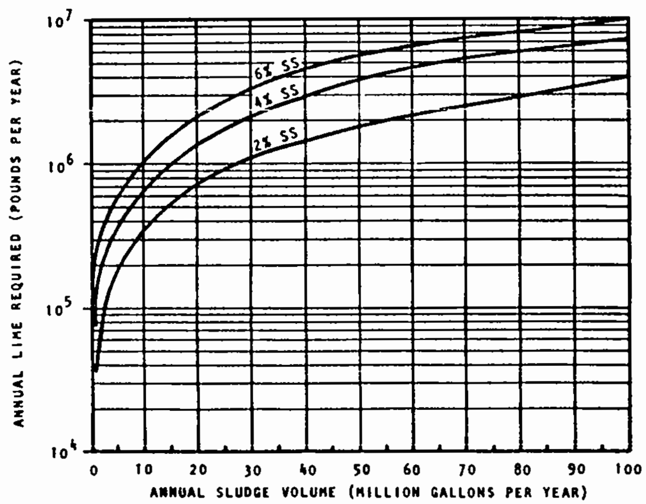


FIGURE 4-12 (CONTINUED)

Assumptions: Design assumptions are the same as for Figure 4-10.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL MAINTENANCE MATERIALS AND SUPPLIES, ASSUMED TO BE 1.5% OF THE BASE CAPITAL COST.



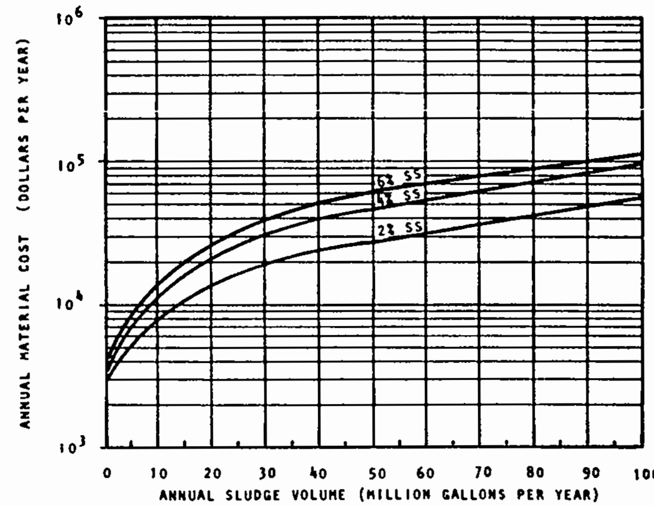


FIGURE 4-13

BASE CAPITAL COST OF SLUDGE THERMAL CONDITIONING AS A FUNCTION OF ANNUAL VOLUME

Assumptions: Daily operation period = 20 hr/day; reactor pressure = 300 lb/in^2 g; reactor temperature = 350° F; detention time in reactor = 15 minutes; system includes all grinding, pumping, air compression, and heating.

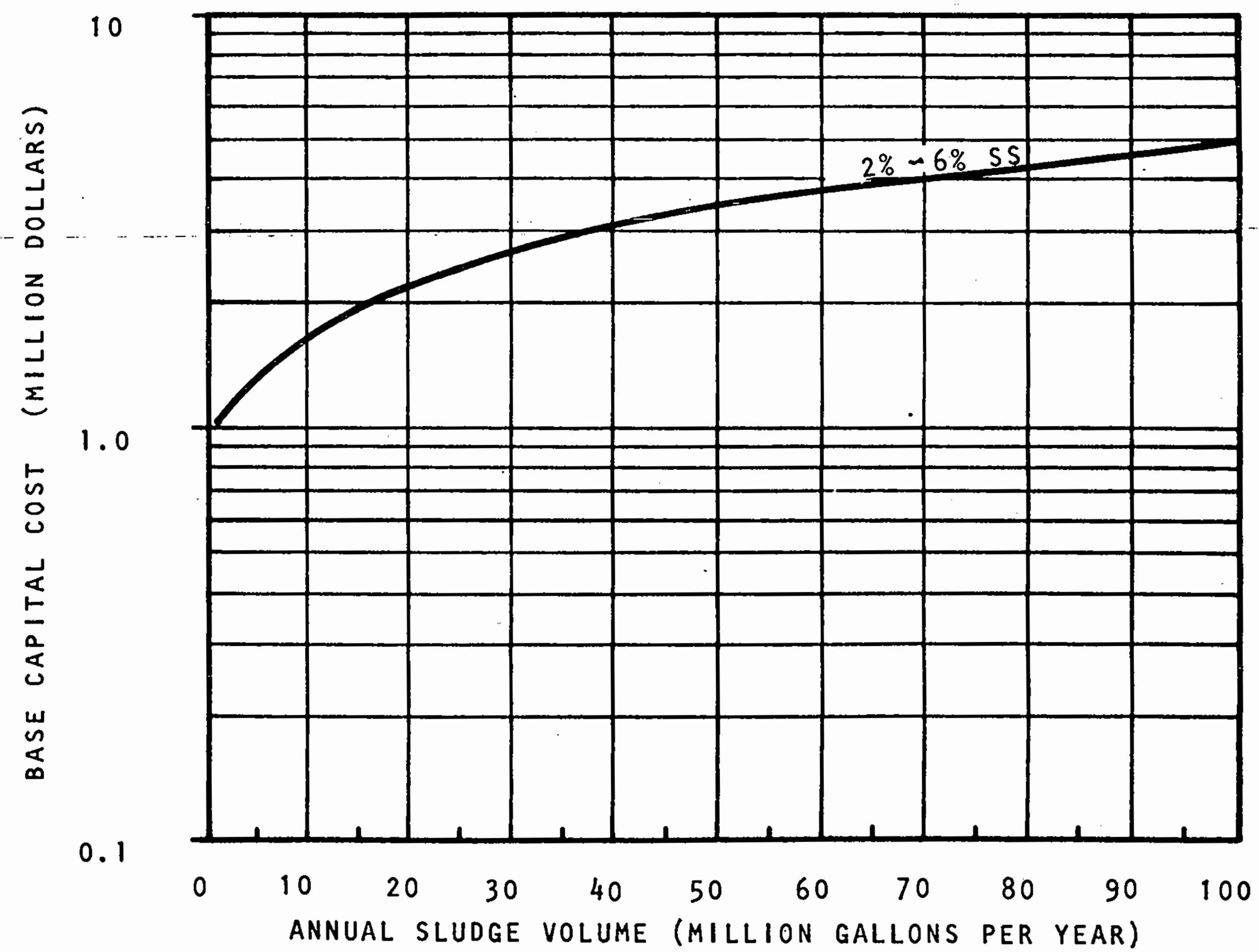


FIGURE 4-14

BASE ANNUAL O&M COST OF SLUDGE THERMAL CONDITIONING AS A FUNCTION OF ANNUAL VOLUME

Assumptions: Design assumptions are the same as for Figure 4-13; labor cost = $13.50/hr; cost of electricity = $0.094/kWhr; cost of diesel fuel = $1.35/gal.

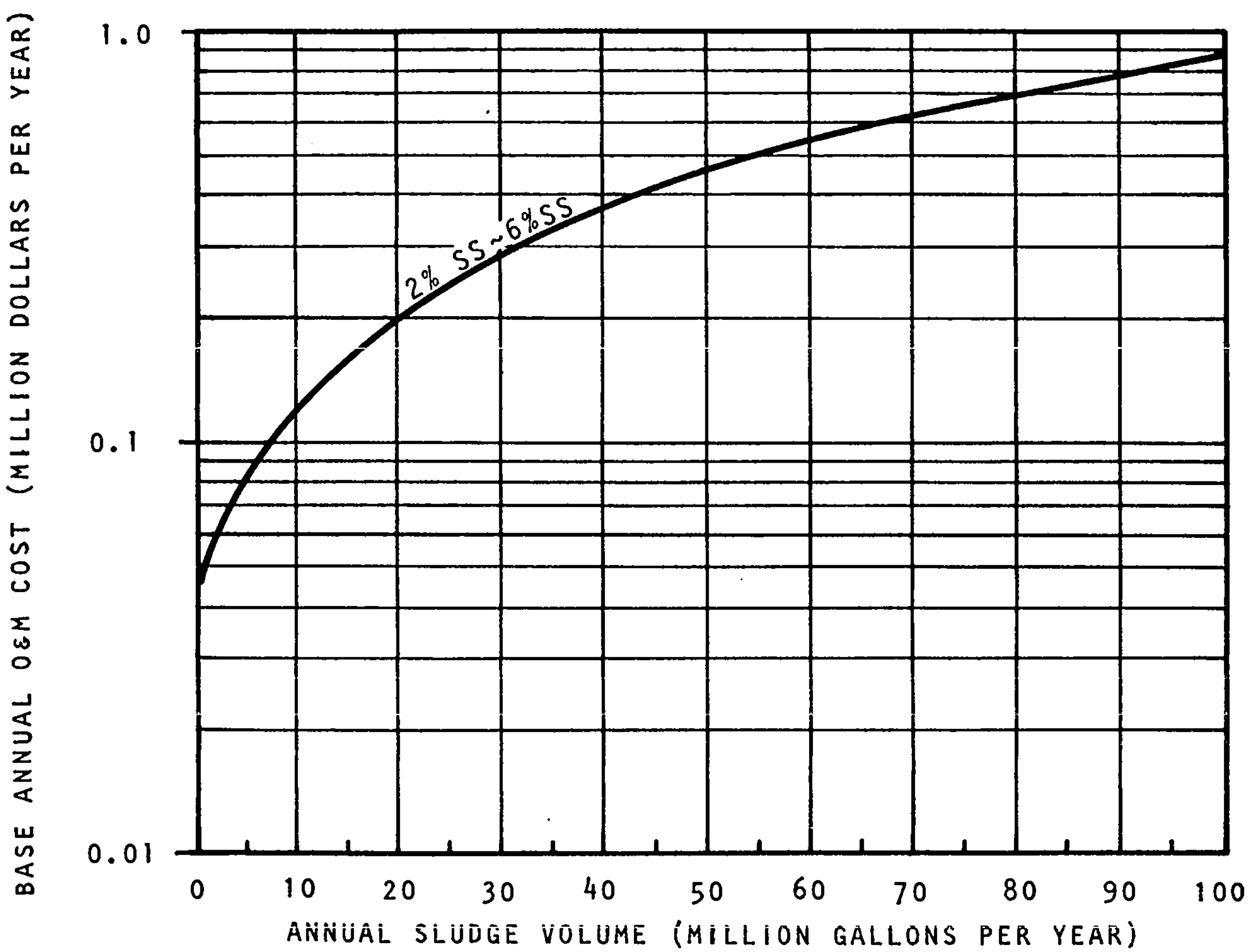
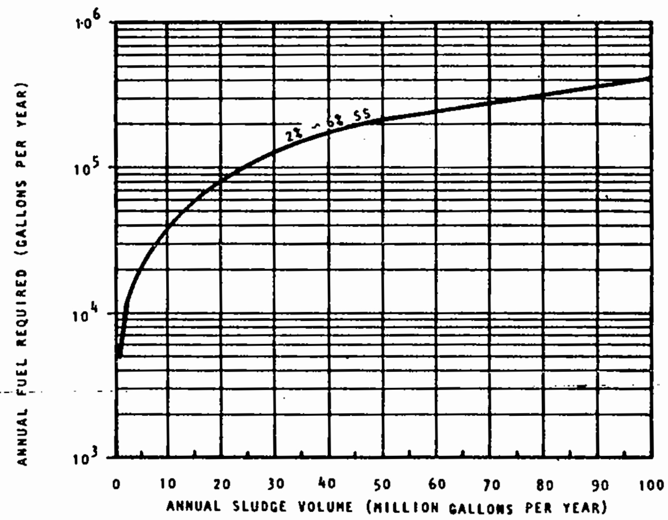
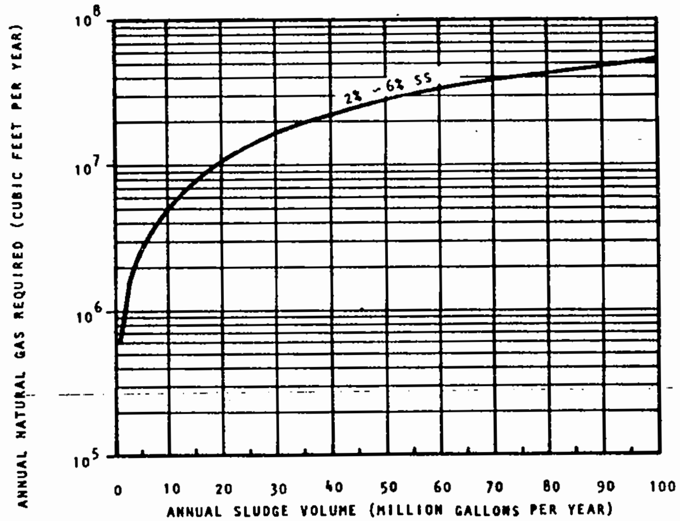
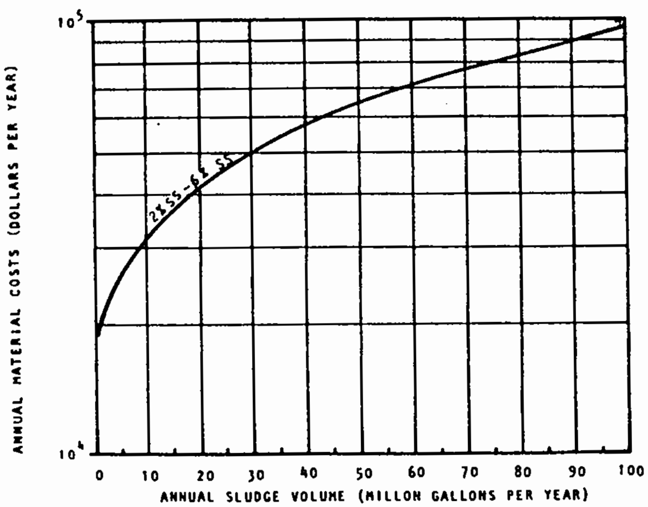


FIGURE 4-15

ANNUAL O&M REQUIREMENTS FOR SLUDGE THERMAL CONDITIONING AS A FUNCTION OF ANNUAL VOLUME





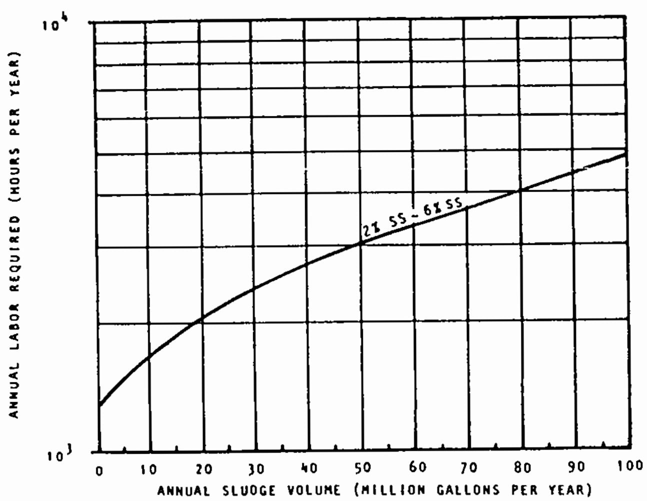


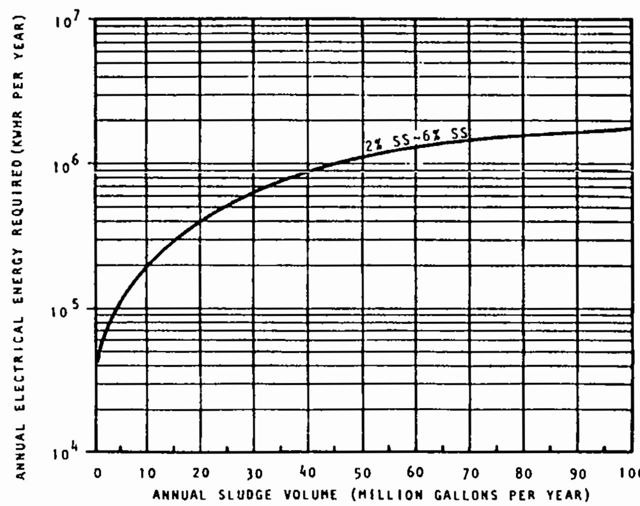
Assumptions: Design assumptions are the same as for Figure 4-13.

FIGURE 4-15 (CONTINUED)

Assumptions: Design assumptions are the same as for Figure 4-13.

NOTE : A CHOICE IS NECESSARY BETWEEN FUEL OIL OR NATURAL GAS AS A FUEL.
THE MATERIAL COST CURVE IS FOR ANNUAL MAINTENANCE MATERIALS
AND SUPPLIES, ASSUMED TO BE 2% OF THE BASE CAPITAL COST.





grinders, heat exchangers, reactors, boiler, gas separators, air compressors (if required), decanting tank, piping, and controls. Costs also include a single-story building and odor control systems. Systems for treatment of the supernatant and filtrate recycle streams are not included. These streams are normally returned to the main treatment plant after preliminary treatment.

SECTION 5

SLUDGE DEWATERING CURVES

5.1 Introduction

This section presents base capital and annual operation and maintenance curves for five sludge dewatering processes: centrifuge, belt filter, recessed plate filter press, vacuum filter, and sludge drying beds. The cost of land (at an assumed $3,000/acre) is included only in the sludge drying beds capital cost. The other sludge dewatering processes listed are not land-intensive, and land costs are negligible. All dewatering process costs except sludge drying beds include the cost of a building to house equipment.

As previously discussed in Section 2.5, the user should carefully note the "hours per day of operation" in the assumptions noted on the curves. All dewatering curves in this section assume 8 hr/day operation except sludge drying beds, which are used continuously. Many treatment plants operate dewatering equipment for two or three shifts daily. If the dewatering unit will be operated more than 8 hr/day, the annual sludge volume from which the capital cost is derived should be adjusted downward proportionately, as was described in Section 2.5.1.

At present (1985), belt filters and solid bowl centrifuges are the mechanical devices most commonly selected for dewatering municipal wastewater sludges. Vacuum filters are rarely installed at new treatment plants today. Recessed plate filter presses are seldom selected due to their high capital and operating costs, yet in those cases where a very dry cake (e.g., solids over 30 percent) is desired or necessary, a filter press can be cost-effective. Sludge drying beds have been commonly used at small treatment plants which have land available, and in large treatment plants which have both high evaporation rates and available land.

5.2 Dewatered Sludge Cake Generated by Various Dewatering Devices

It is beyond the scope of this manual to discuss in detail the dewatering capabilities of various mechanical dewatering processes acting upon different types of sludges. As a very general guide, however, the following dewatered sludge cake percent total dry solids ranges are typical for each dewatering device acting upon a typical digested mixture of 70 percent waste activated sludge and 30 percent primary sludge:

- Solid bowl centrifuge: 13 to 18 percent.
- Vacuum filter: 12 to 17 percent.
- Belt filter: 15 to 23 percent.
- Recessed plate filter press: 32 to 40 percent.

Sludge drying beds vary widely in their dewatering capabilities, with sludge cake total dry solids generally ranging from 15 percent up to 45 percent. Sludge type, adequacy of digestor, climate, presence of underdrains, and time on the beds are some of the factors which affect performance.

5.3 Chemical Conditioning

Proper chemical conditioning prior to dewatering is extremely important. Chemical conditioning costs are not included in the cost curves presented in this section, but are covered in Section 6.

5.4 Centrifuge Dewatering

Centrifuge dewatering is a process whereby centrifugal force is applied to promote the separation of solids from the liquid in sludge. The most common type of centrifuge is the solid bowl; cost curves are based on the use of this type. The process is energy-intensive, but has the advantage of requiring little space.

Capital and O&M costs for centrifuge dewatering are presented in Figures 5-1 and 5-2, respectively. O&M requirements are given in Figure 5-3. Curves are based on the algorithm in Appendix A-8 using the assumptions noted on the curves.

5.5 Belt Filter Dewatering

Belt filtration is accomplished using two filter belts on rollers which run continuously in the same direction and at the same speed. Sludge is dewatered as it is conveyed between the belts, where the rollers exert increasing pressure on the sludge. Additional dewatering occurs as a result of shear pressure as the belts pass over an S-shaped roller configuration.

Capital and O&M costs for belt filter dewatering are presented in Figures 5-4 and 5-5, respectively. O&M requirements are given in Figure 5-6. Curves are based on the algorithm in Appendix A-9, using the assumptions noted on the curves.

5.6 Recessed Plate Filter Press Dewatering

Recessed plate pressure filters are constructed from a number of parallel plates. The plate surfaces, which are recessed on both sides of the plates, are covered with filter cloth. Sludge is pumped under high pressures into the void spaces between the plates where a sludge cake forms. Filtrate passes through the filter cloth, flows out between the cloth and plate surfaces, and is collected in a common drainage port. Sludge continues to be pumped into each recessed plate until they are filled and the filtrate flow approaches zero. The feed pump is then stopped, the plates are opened, and the sludge cake falls out. The cycle is then repeated.

Figures 5-7 and 5-8 present capital and O&M costs for recessed plate filter press dewatering. O&M requirements are given in Figure 5-9. Curves are based on the algorithm in Appendix A-10, using the assumptions noted on the curves.

FIGURE 5-1

BASE CAPITAL COST OF CENTRIFUGE DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Operation = 8 hr/day; operation = 365 days/year; costs do not include chemical conditioning; centrifuge h.p. = approximately 1.25 h.p. per gpm of sludge flow; discharge SS = approximately 10 to 14 percent.

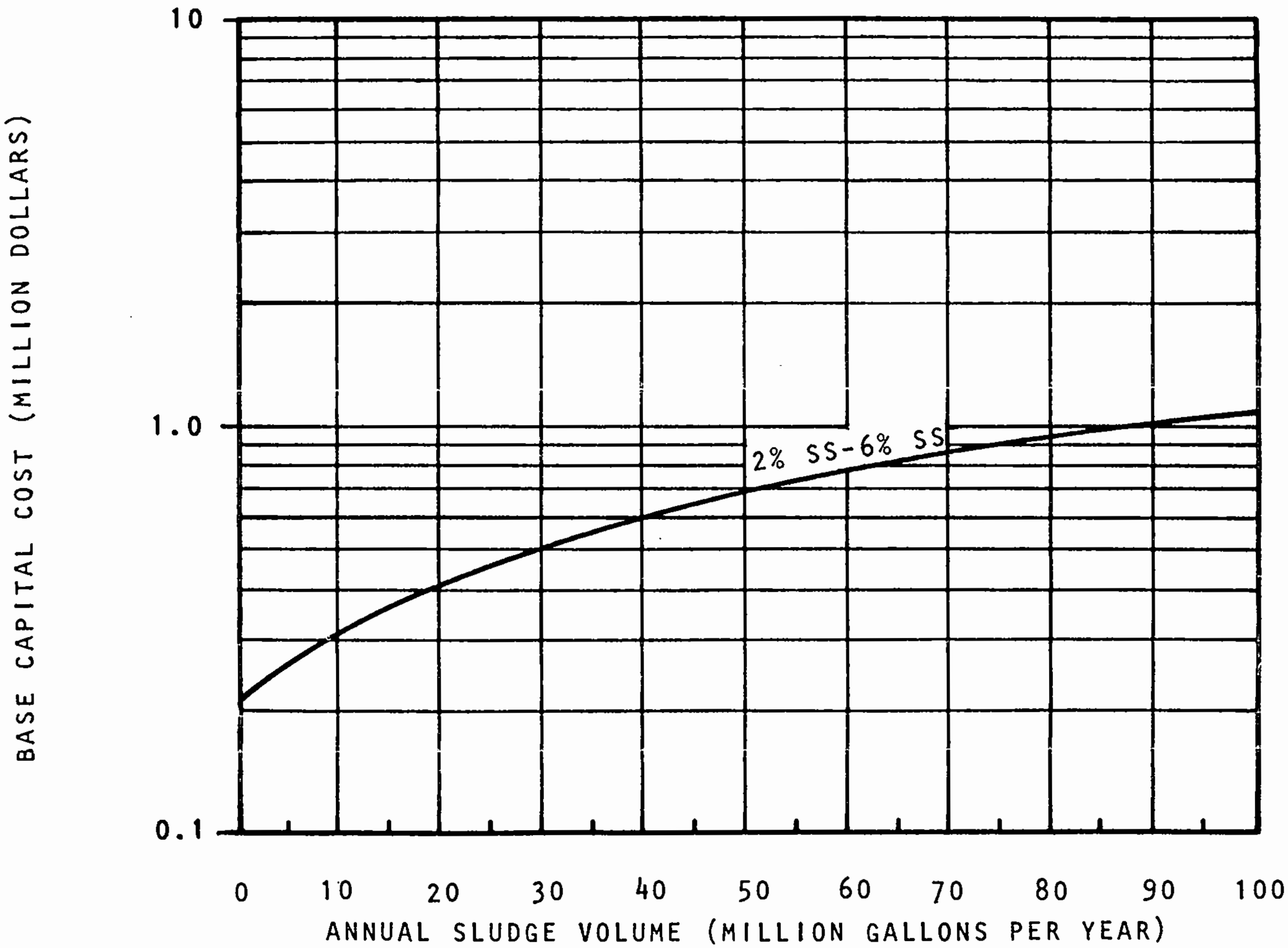


FIGURE 5-2

BASE ANNUAL O&M COST OF CENTRIFUGE DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 5-1; labor cost = $13.50/hr; cost of electricity = $0.094/kWhr.

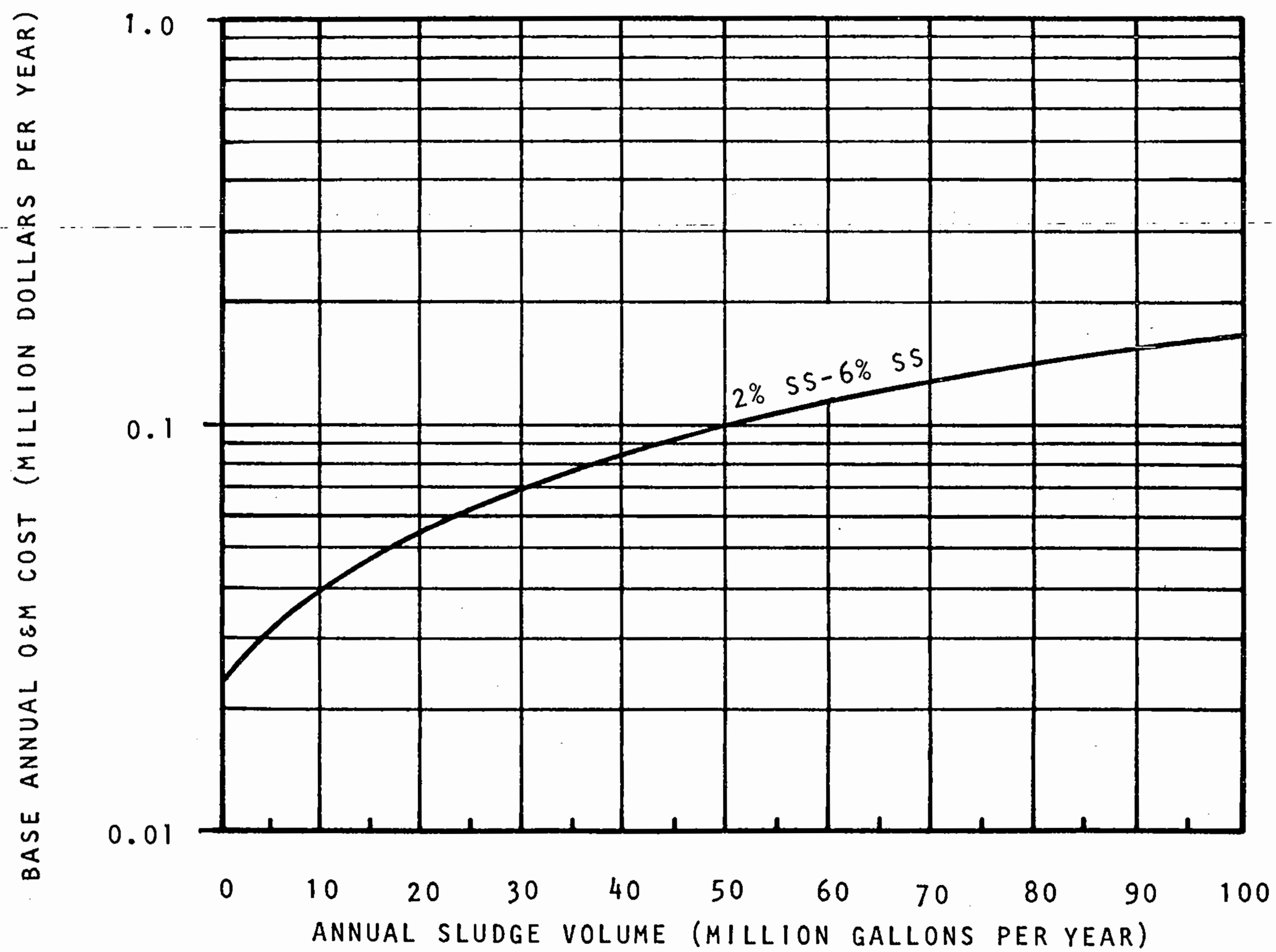
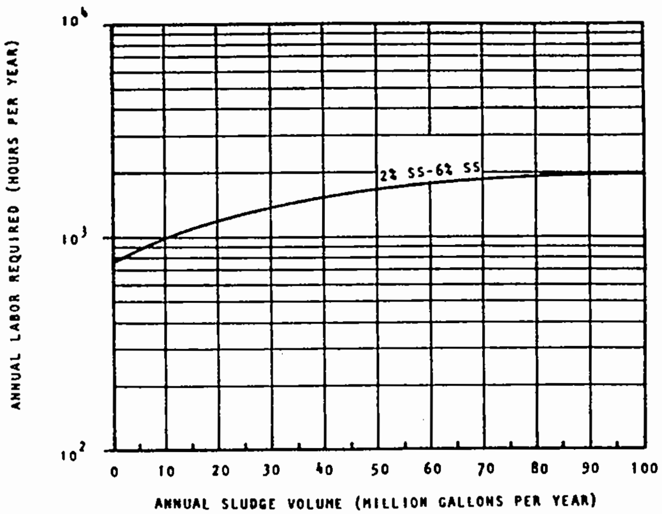
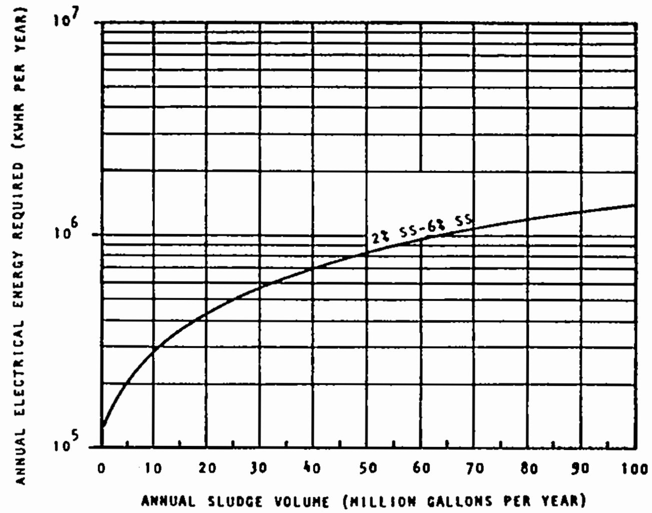
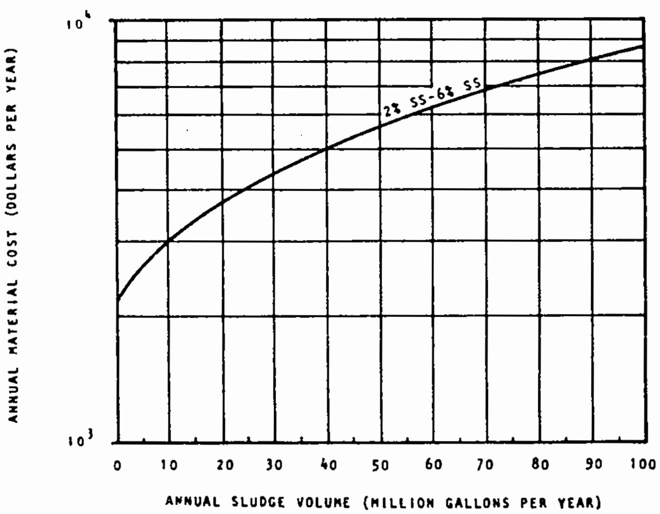


FIGURE 5-3

ANNUAL O&M REQUIREMENTS FOR CENTRIFUGE DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design parameters are the same as for Figure 5-1.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL MAINTENANCE PARTS AND MATERIALS.

FIGURE 5-4

BASE CAPITAL COST OF BELT FILTER PRESS DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Operation = 8 hr/day; operation = 365 days/year; costs do not include chemical conditioning; loading rate per meter of belt width is 500 lb/hr for 2 percent SS, 650 lb/hr for 4 percent SS, and 800 lb/hr for 6 percent SS; discharge SS is approximately 18 to 22 percent.

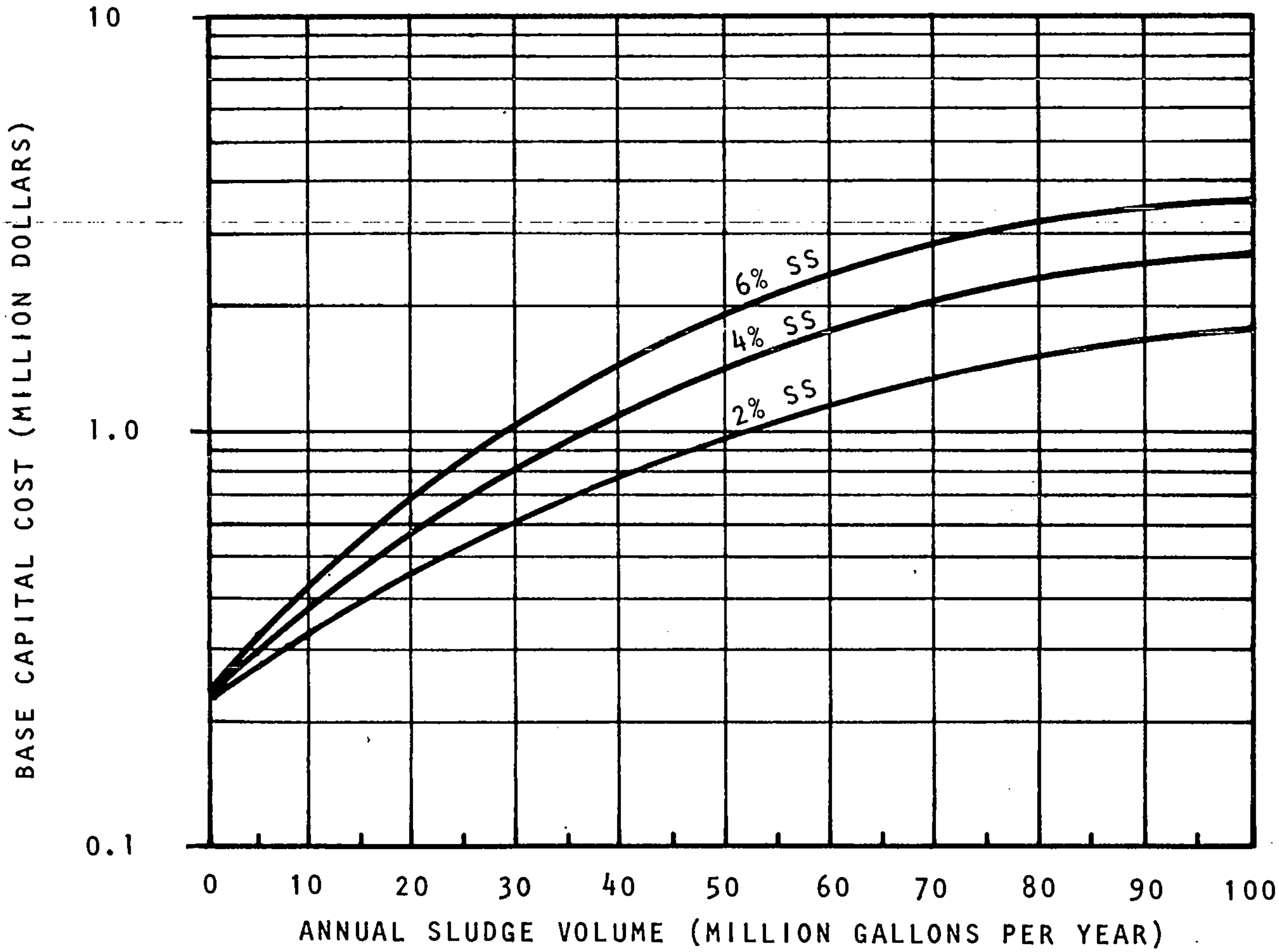


FIGURE 5-5

BASE ANNUAL O&M COST OF BELT FILTER PRESS DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 5-4; labor cost = $13.50/hr; cost of electricity = $0.094/kWhr.

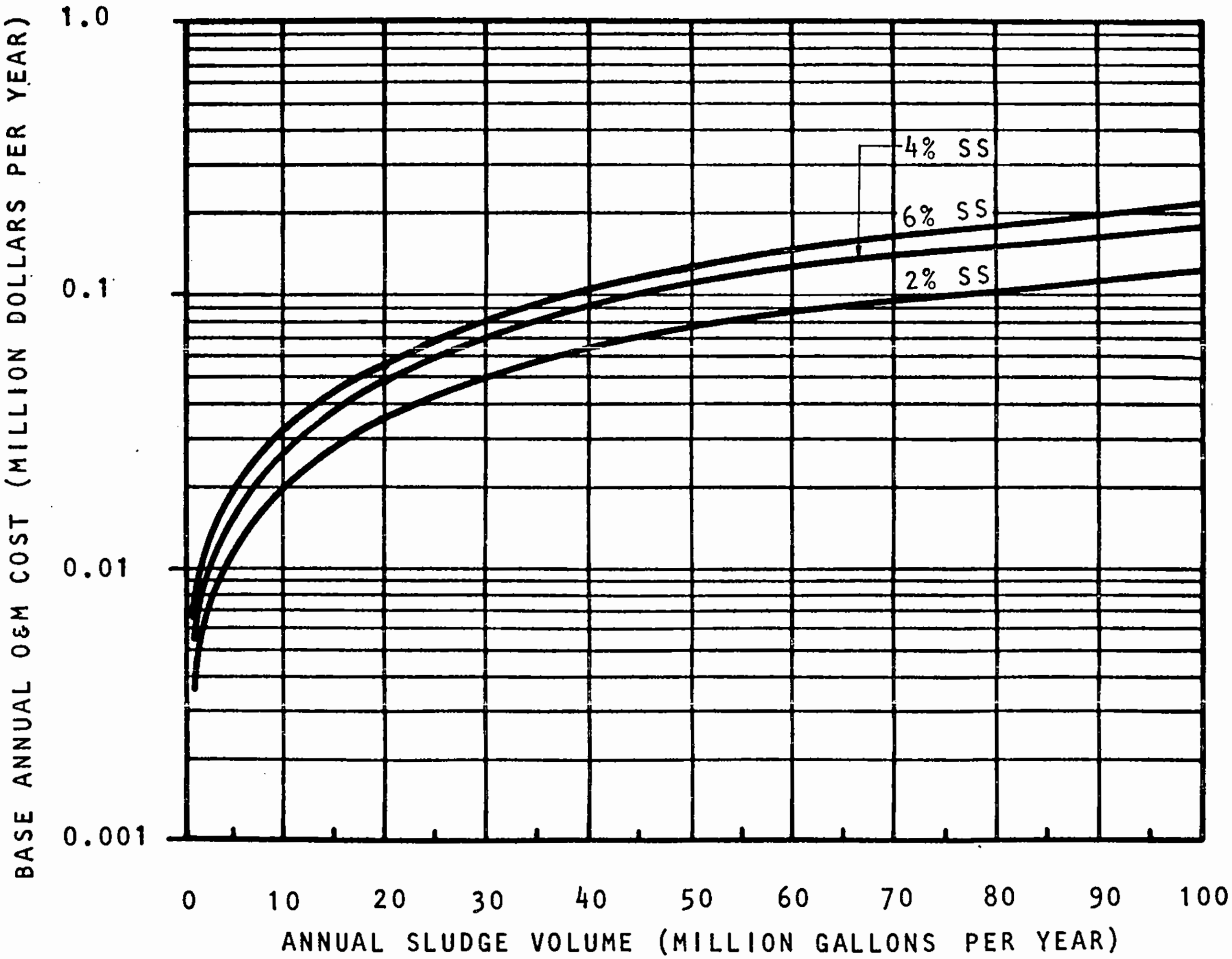
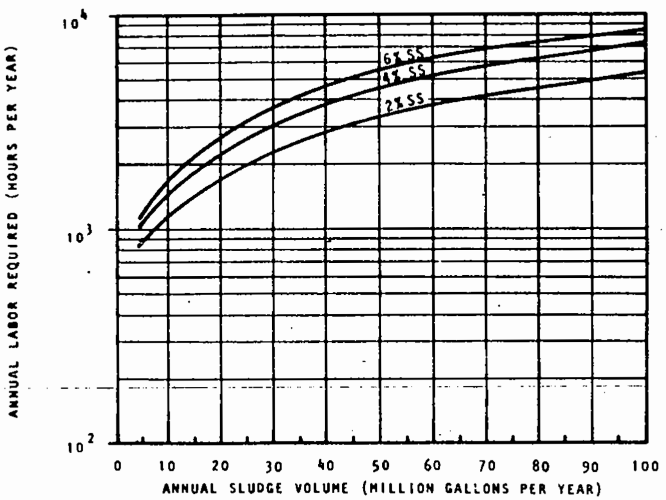
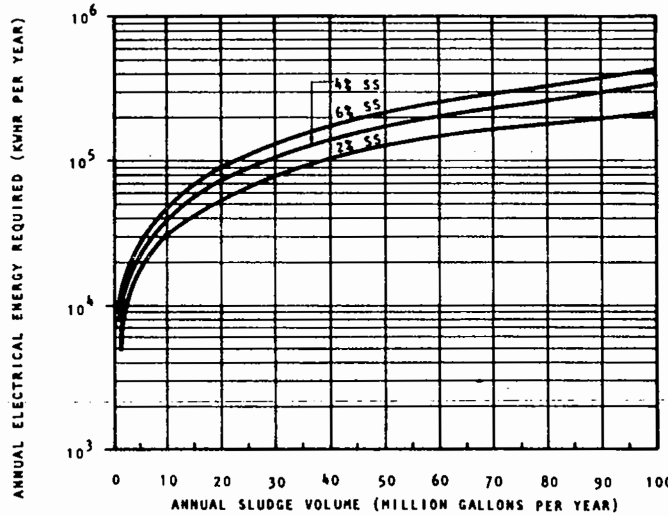
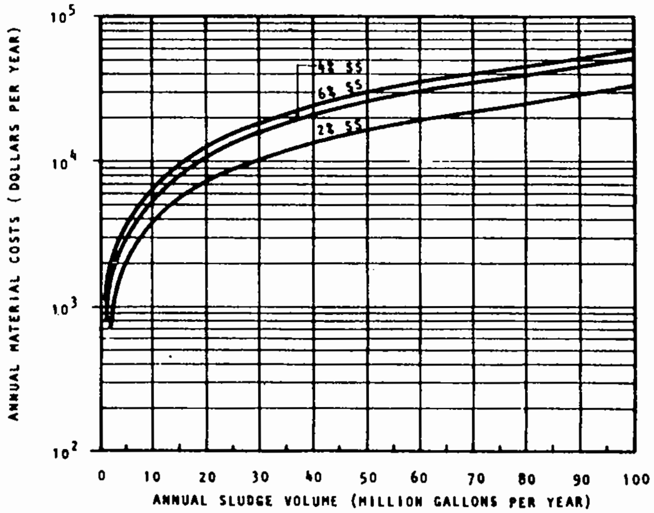


FIGURE 5-6

ANNUAL O&M REQUIREMENTS FOR BELT FILTER PRESS DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design parameters are the same as for Figure 5-4.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL PARTS AND MATERIALS.

FIGURE 5-7

BASE CAPITAL COST OF RECESSED PLATE FILTER PRESS DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Filter cake solids concentration = 40 percent; filter cake density = 71 lb/ft^3; filter chamber volume = 2 ft^3; operation = 8 hr/day; operation = 7 days/week; costs do not include chemical conditioning.

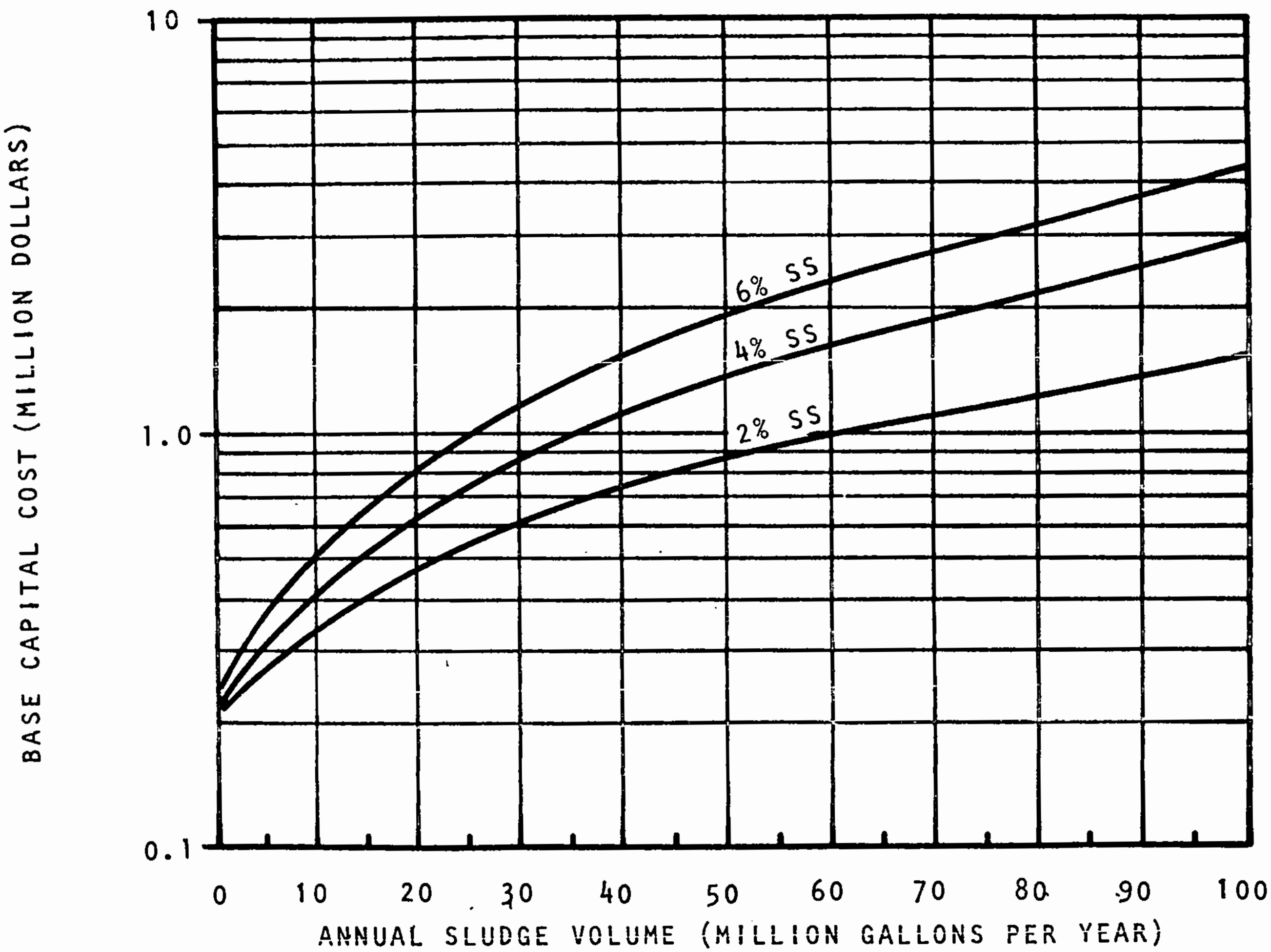


FIGURE 5-8

BASE ANNUAL O&M COST OF RECESSED PLATE FILTER PRESS DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 5-7; labor cost = $13.50/hr; cost of electricity = $0.094/kWhr.

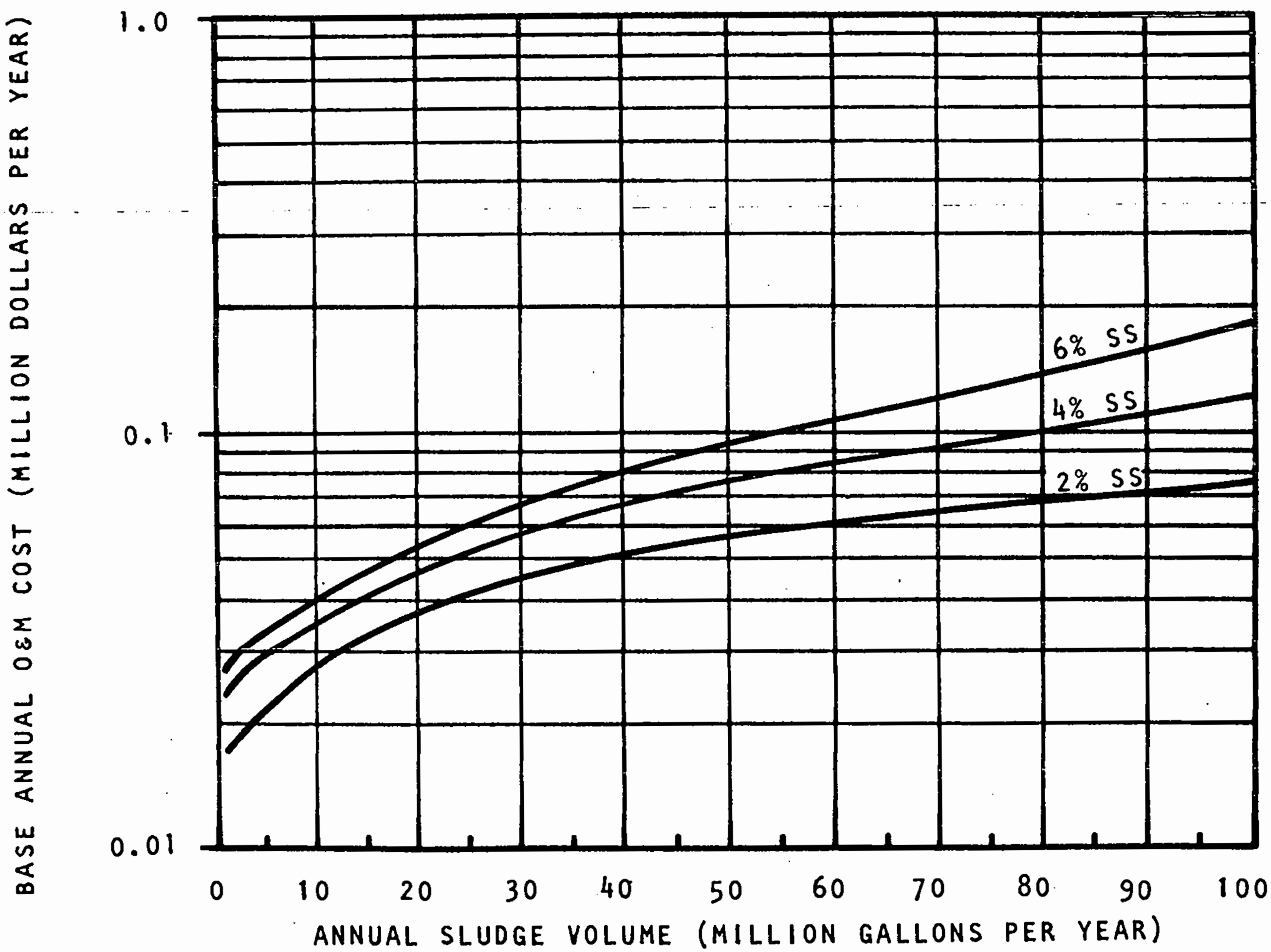
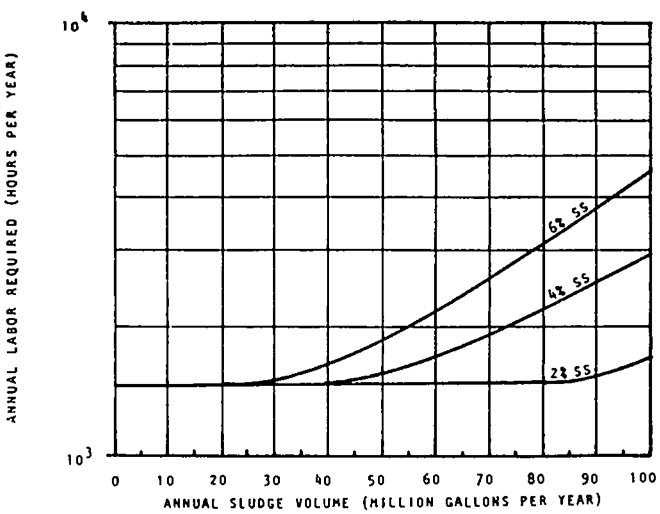
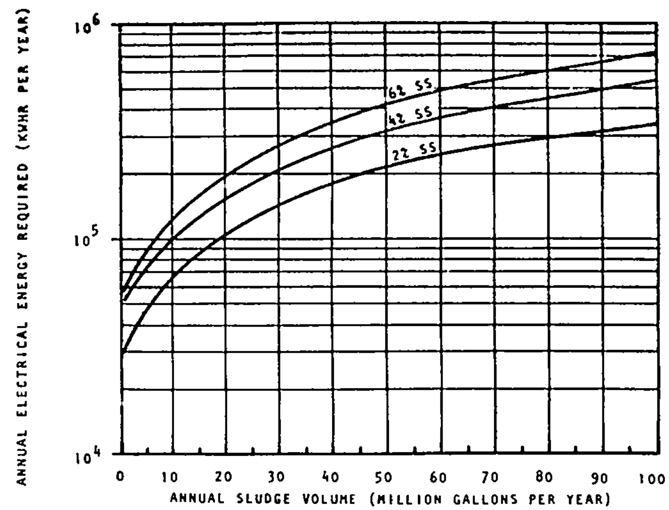
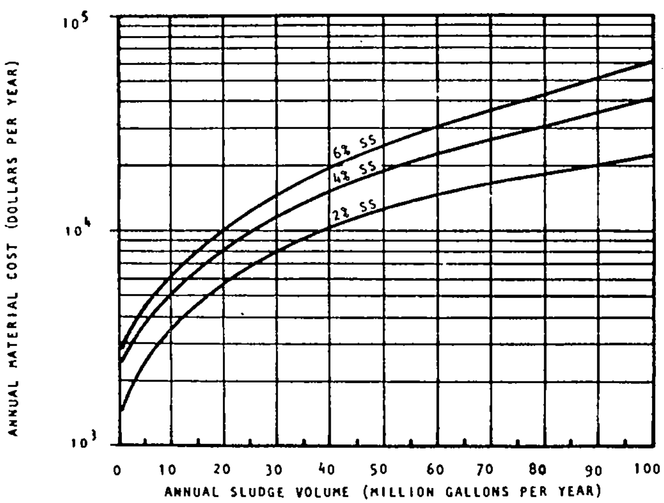


FIGURE 5-9

ANNUAL O&M REQUIREMENTS FOR RECESSED PLATE FILTER PRESS DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design parameters are the same as for Figure 5-7.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL MAINTENANCE PARTS AND MATERIALS.

5.7 Vacuum Filter Dewatering

In vacuum filtration, a vacuum is applied to a portion of the inside of a moving filter-medium covered drum, which is partially submerged in sludge. Solids adhere to the surface of the filter medium, and are removed with a mechanical scraper as the drum surface rotates and air pressure replaces the vacuum. Vacuum filters are seldom selected today for new treatment plants due to their high capital cost, high energy consumption, and inability to produce as dry a sludge cake as belt filters or centrifuges.

Base capital and O&M costs for vacuum filtration are presented on Figures 5-10 and 5-11, respectively. Figure 5-12 provides O&M requirements. Curves were obtained from the algorithm in Appendix A-11, using the assumptions noted on the curves.

5.8 Sludge Drying Beds

Sludge drying bed dewatering is perhaps the simplest dewatering process. Dewatering occurs by drainage through the sludge mass, and by evaporation from the surface exposed to air. Drying beds are commonly used in small plants, since they require little operator attention and skill, and use little energy. The limitations of this process are that it requires a large land area, requires stabilized sludge to prevent nuisance odors, is sensitive to climate, and is labor-intensive.

Base capital and O&M costs are presented in Figures 5-13 and 5-14, respectively. Figure 5-15 is used in adjusting capital costs to account for land costs different from those assumed in Figure 5-13. The procedure for adjusting capital costs is described in Subsection 5.8.1 below. O&M requirements are presented in Figure 5-16. Curves were obtained from the algorithm in Appendix A-12, using the assumptions noted on the curves.

5.8.1 Land Cost Adjustment

Land cost is a significant component of the base capital cost presented in the cost curves for sludge drying beds. Figure 5-13 includes the purchase of land at an assumed unit cost of $3,120/acre. Because land costs are highly variable, the user may wish to change this unit cost to more accurately estimate local costs. This may be accomplished using the following procedure:

Step 1. Calculate the cost of land assumed in the curve cost, CLC, from the following:

$$CLC = TLAR\ (3,120)$$

where

CLC = Curve land cost, $.
TLAR = Land area required, acres, obtained from Figure 5-15.

FIGURE 5-10

BASE CAPITAL COST OF VACUUM FILTER DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Dry solids loading = 5 lb/ft^2/hour; dewatered cake solids concentration = 19 percent; operation = 8 hr/day; operation = 7 days/week; chemical conditioning is not included.

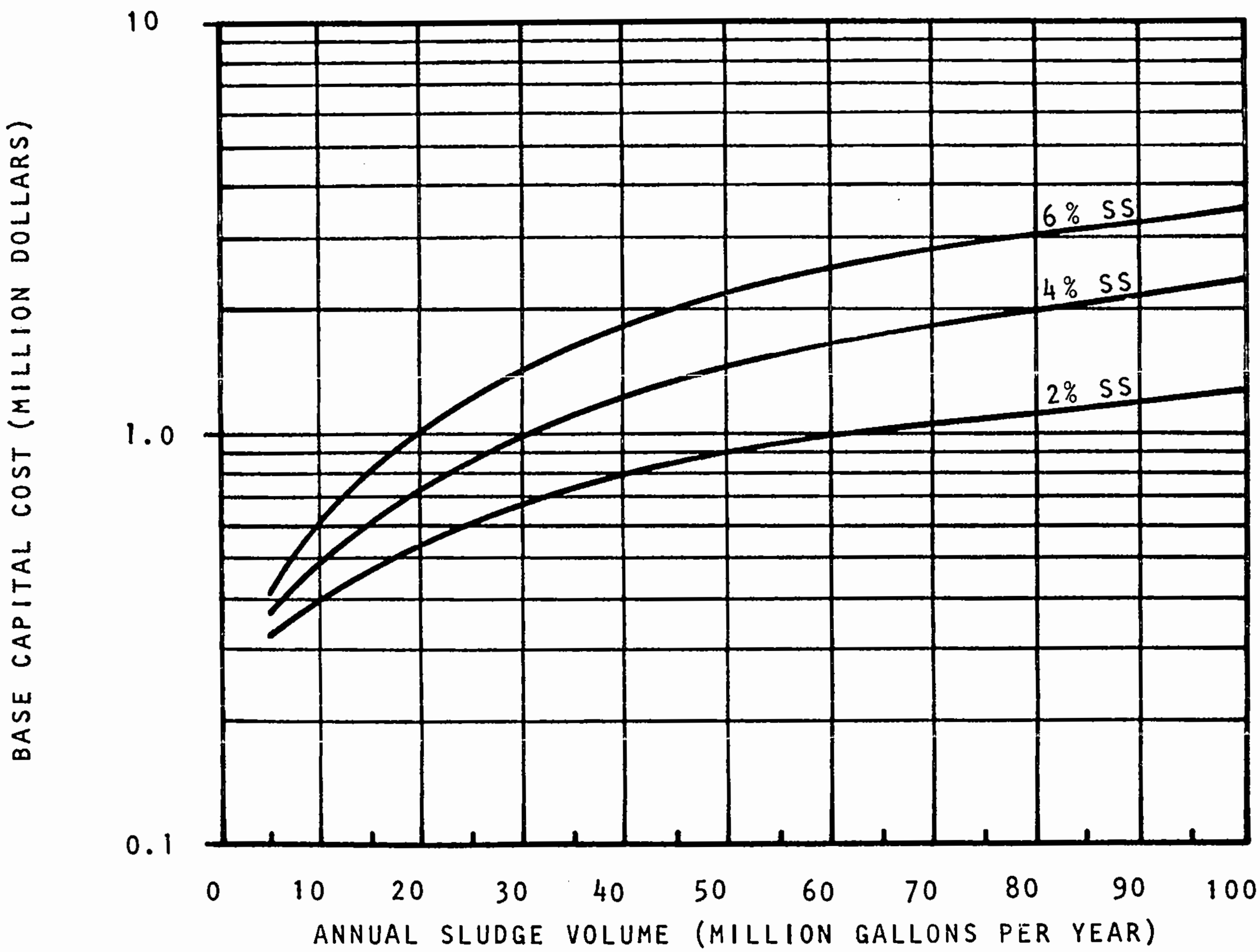


FIGURE 5-11

BASE ANNUAL O&M COST OF VACUUM FILTER DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 5-10; labor cost = \$13.50/hr; cost of electricity = \$0.094/kWhr.

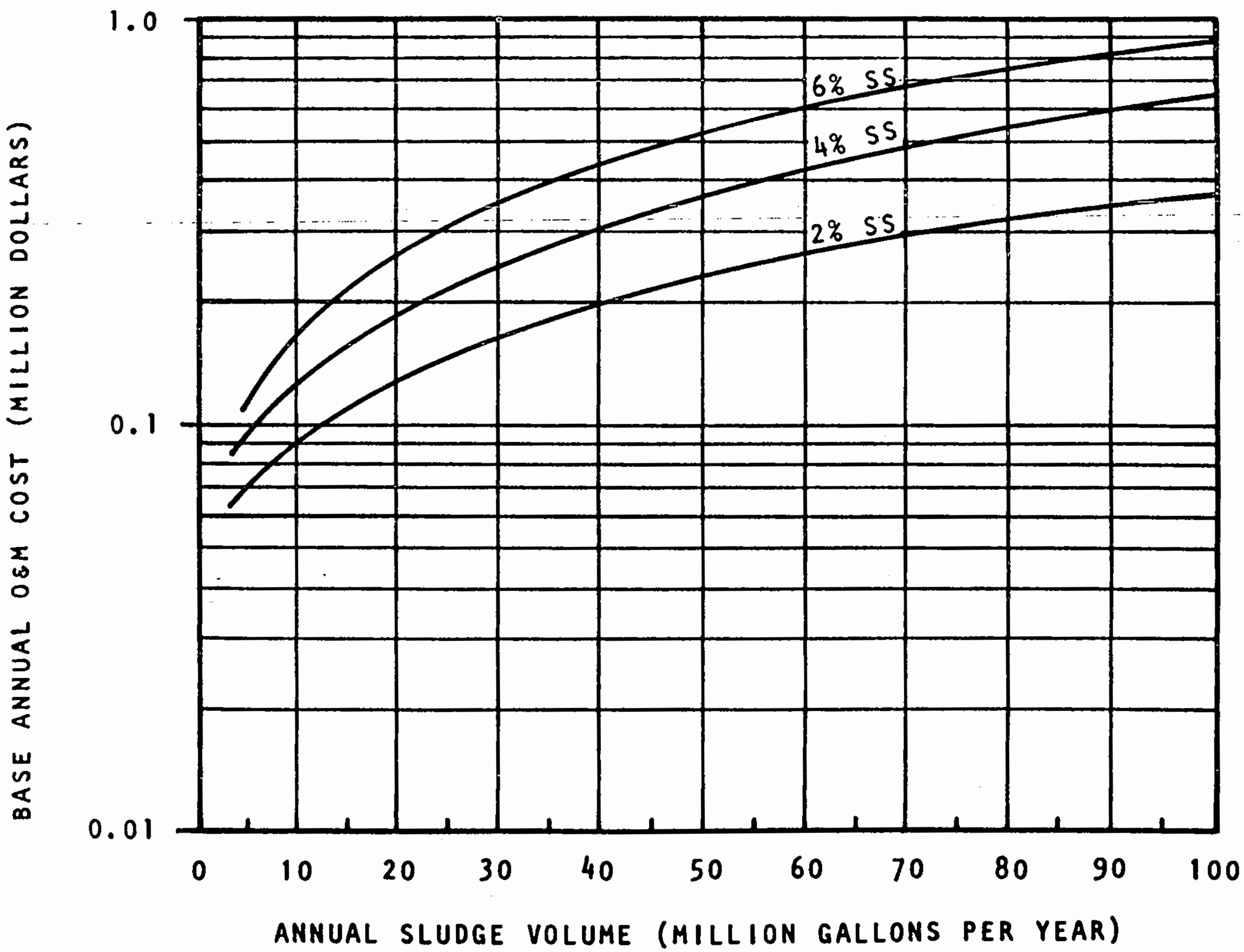
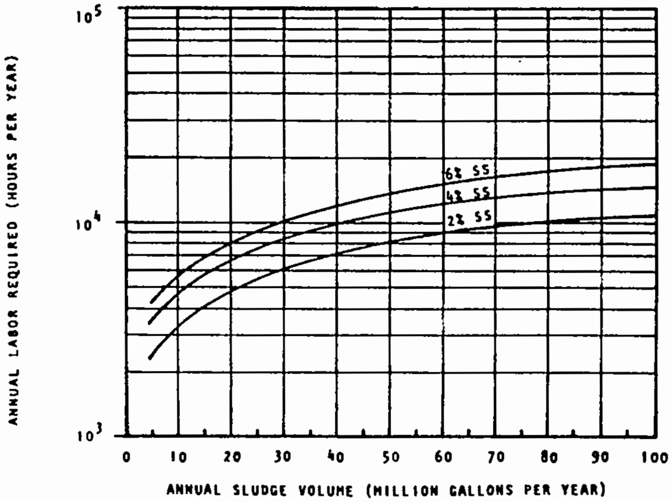
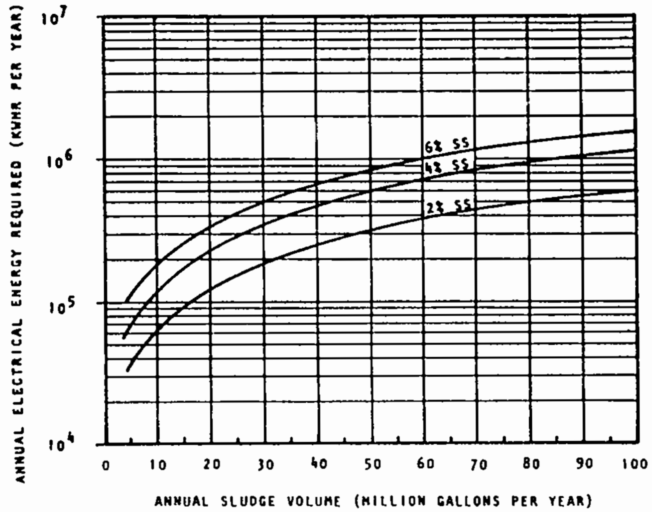
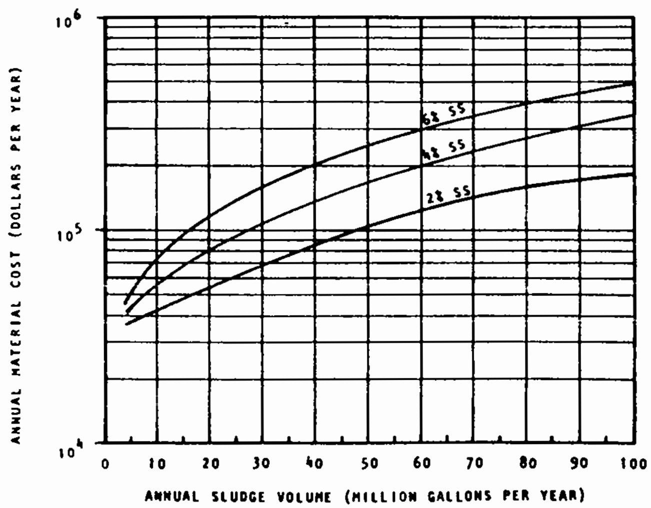


FIGURE 5-12

ANNUAL O&M REQUIREMENTS FOR VACUUM FILTER DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design parameters are the same as for Figure 5-10.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL PARTS AND MATERIALS.

FIGURE 5-13

BASE CAPITAL COST OF SLUDGE DRYING BED DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Drying beds are not covered; land cost = $3,120/acre; sludge loading rate = 15 lb dry solids/ft^2/yr at 2 percent SS, 22 lb dry solids/ft^2/yr at 4 percent SS, 28 lb dry solids/ft^2/yr at 6 percent SS, and 33 lb dry solids/ft^2/yr at 8 percent SS. Costs do not include chemical conditioning.

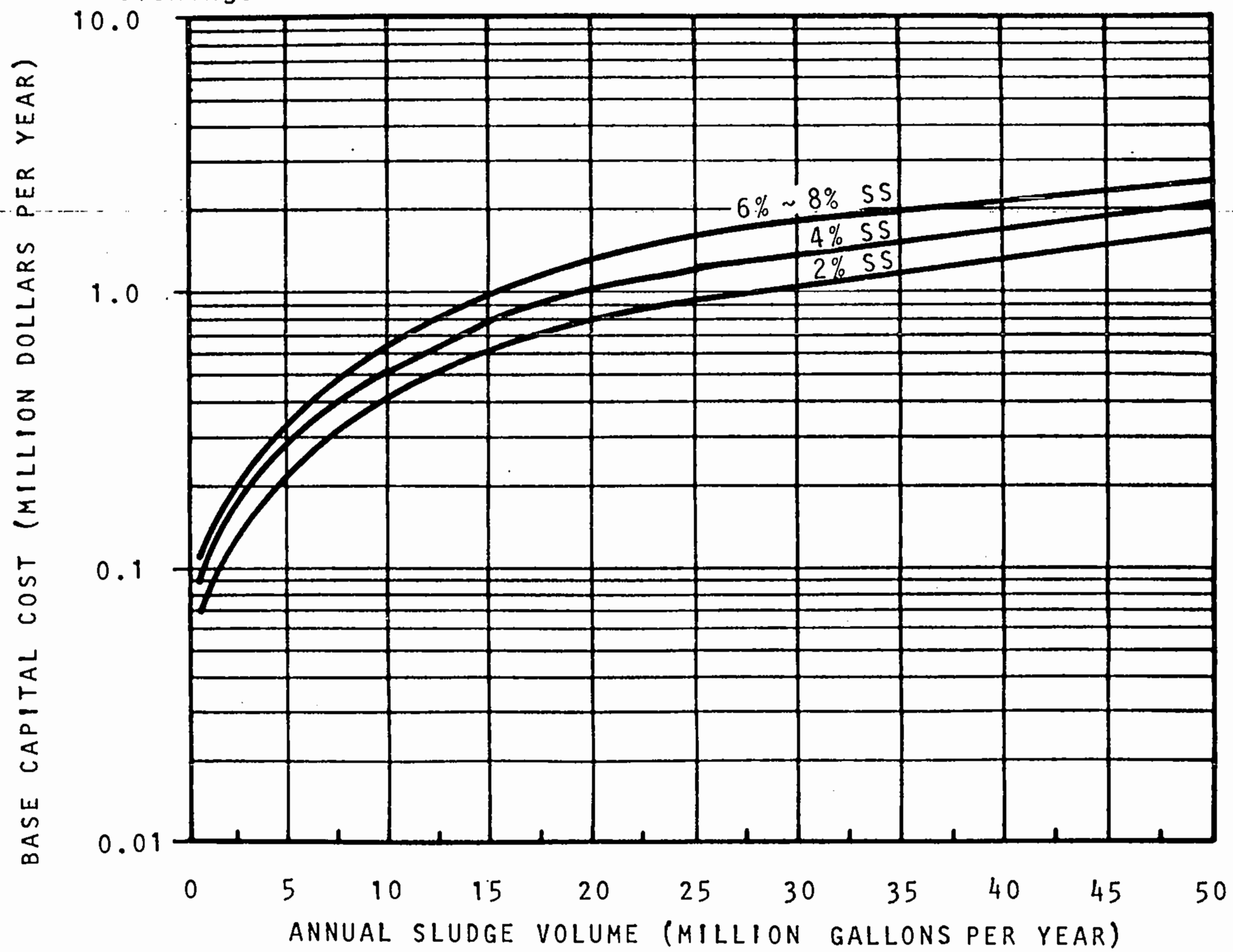


FIGURE 5-14

BASE ANNUAL O&M COST OF SLUDGE DRYING BED DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 5-13; cost of labor = \$13.50/hr; cost of electricity = \$0.094/kWhr; cost of diesel = \$1.35/gal.

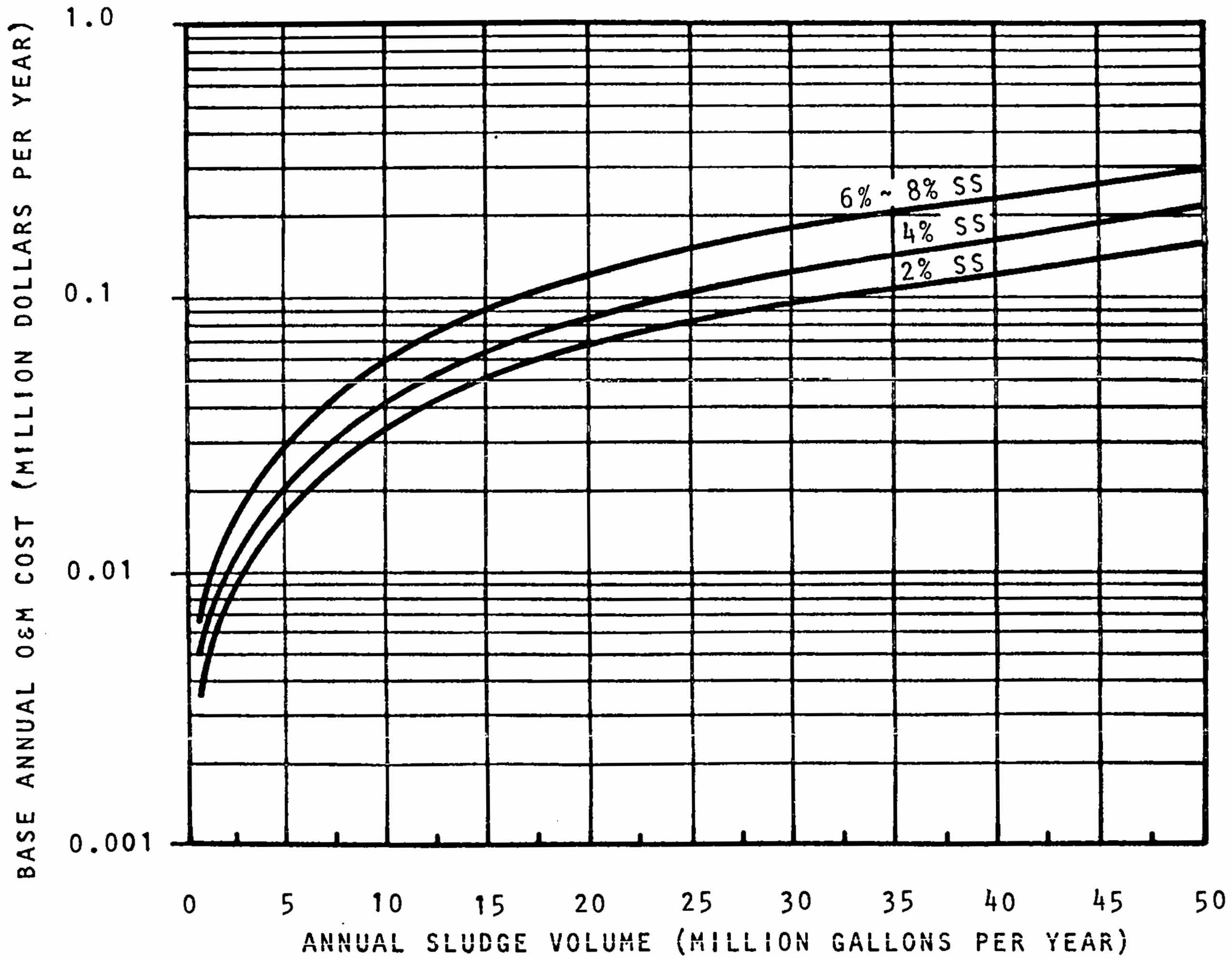


FIGURE 5-15

AREA REQUIRED FOR SLUDGE DRYING BED DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 5-13.

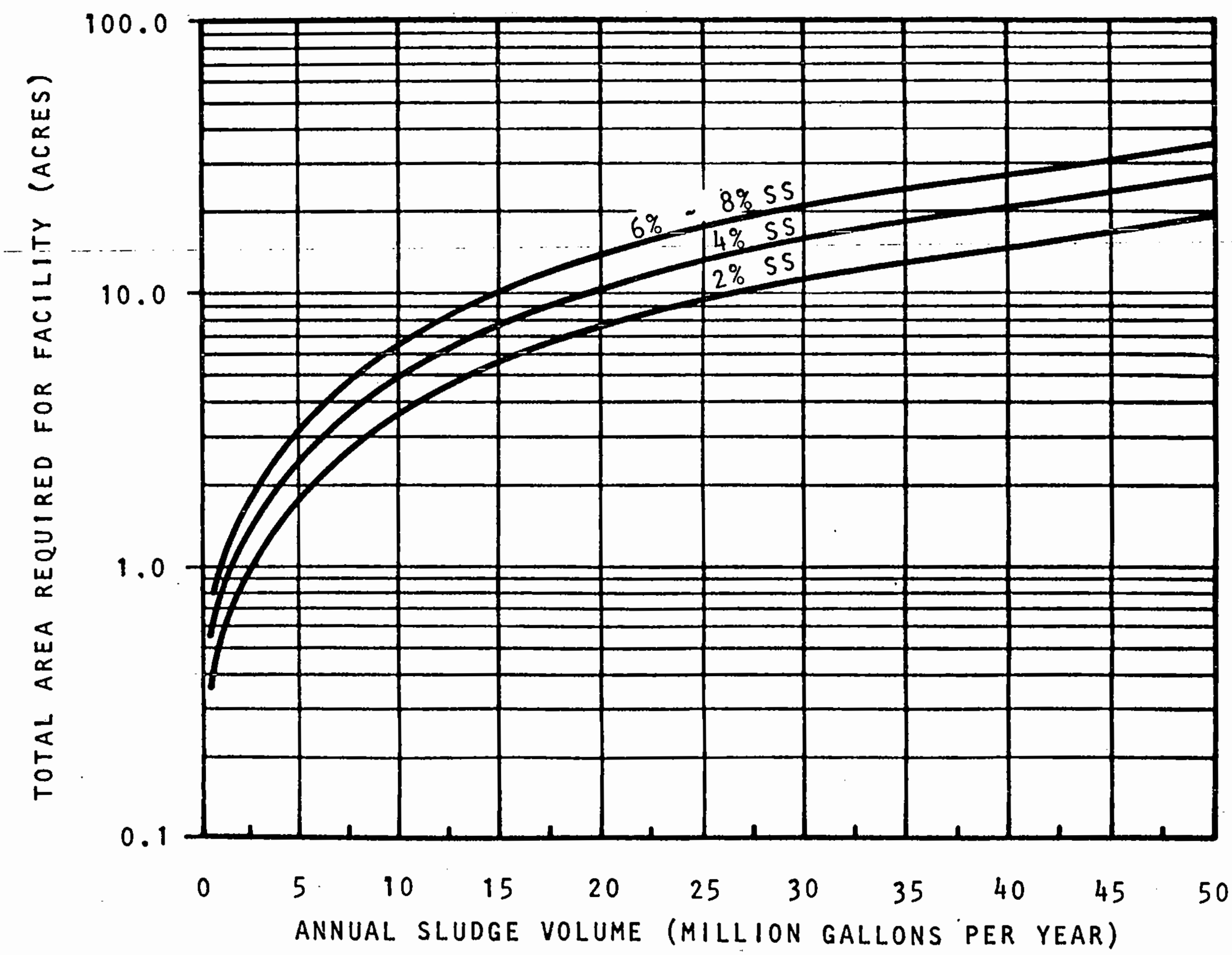
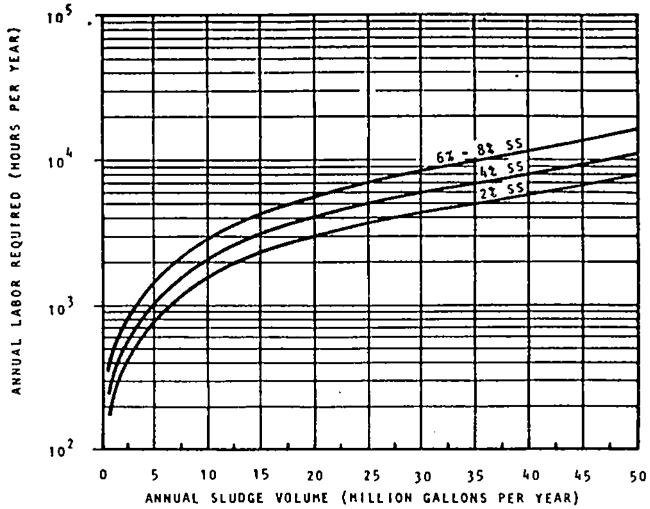
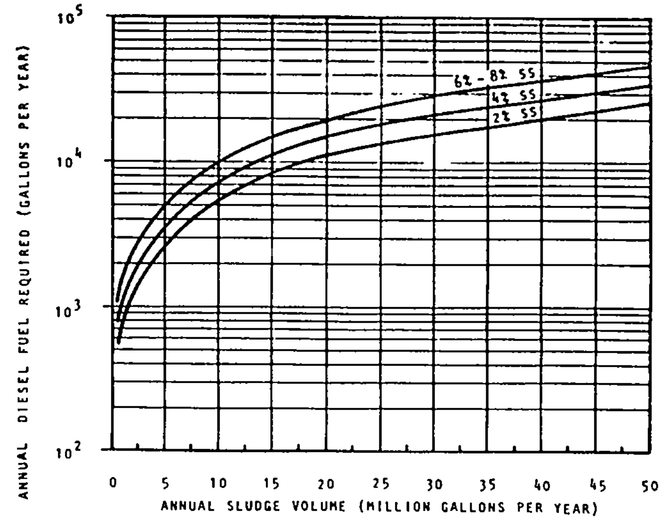
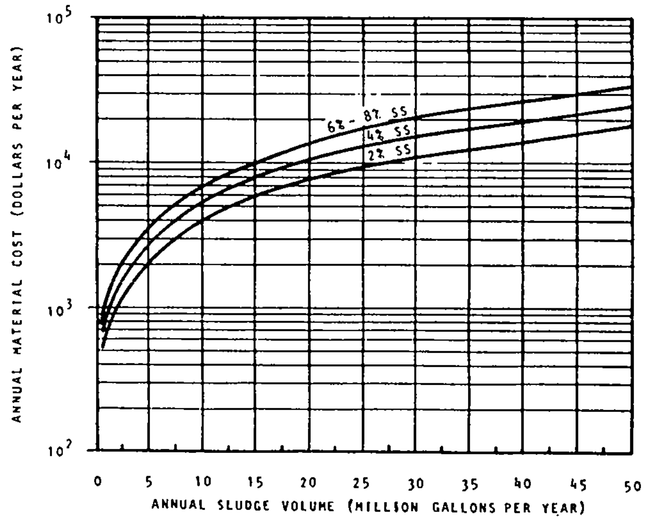


FIGURE 5-16

ANNUAL O&M REQUIREMENTS FOR SLUDGE DRYING BED DEWATERING AS A FUNCTION OF ANNUAL VOLUME AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design parameters are the same as for Figure 5-13.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL MAINTENANCE PARTS AND MATERIAL.

Step 2. Calculate the actual cost of land, CLA, from the following:

$$CLA = TLAR\ (LANDCST)$$

where

CLA = Actual cost of land, \$.
LANDCST = Actual unit cost of land, \$/acre.

Step 3. Adjust the curve capital cost to reflect actual land cost using the following:

$$ACC = CCC - CLC + CLA$$

where

ACC = Adjusted curve capital cost, \$.
CCC = Unadjusted curve capital cost, \$.

SECTION 6

SLUDGE CHEMICAL CONDITIONING CURVES

6.1 Introduction

This section presents base capital and base annual operation and maintenance curves for three sludge chemical conditioning methods: lime addition, ferric chloride addition, and polymer addition. Capital cost curves do not include the cost of land, since land area required is negligible.

As previously discussed in Section 2.5, the user should carefully note the "hours per day of operation" in the assumptions, which is 8 hours/day for all chemical conditioning processes. Many treatment plants operate chemical conditioning processes for two or three shifts daily. If the process will be operated more than 8 hours/day, the annual sludge volume from which the capital cost is derived should be adjusted downward proportionally, as was described in Section 2.5.1.

6.2 Use of Chemical Conditioning

Chemical conditioning may be used in a treatment plant prior to both sludge thickening (see Section 3) and sludge dewatering (see Section 5). The types of chemical or chemicals used and dosage applied are a function of several variables, including sludge characteristics, the requirements of the process following chemical conditioning, and chemical costs. These variables are determined through laboratory bench-scale or pilot plant testing.

Sludges (particularly biological sludges) are often difficult to dewater due to the presence of significant quantities of colloids and fines, which are difficult to destabilize. The primary objective of conditioning is to increase particle size by combining the small particles into larger aggregates, and by decreasing hydration, decrease the effects of hydrostatic repulsion. Chemical conditioning, therefore, enhances flocculation and dewatering.

6.3 Chemical Conditioning Using Lime

Lime is often used for conditioning sludge due to its slight dehydration effect on colloidal particles. Moreover, $CaCO_3$, formed by the reaction of lime and bicarbonate, provides a granular structure which increases sludge porosity and reduces sludge compressibility, thereby enhancing dewatering.

Base capital and O&M cost curves for chemical conditioning using lime are presented in Figures 6-1 through 6-6 for sludges of 2, 4, and 6 percent solids, using various lime dosages in lb/ton dry sludge solids. O&M requirements are given in Figures 6-7, 6-8, and 6-9 for sludges of 2, 4, and 6 percent solids, respectively. The curves are based on the algorithm in Appendix A-13 using the assumptions noted on the curves.

FIGURE 6-1

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.

Assumptions: Costs are based on the use of hydrated lime; operation = 8 hr/day, 7 days/week.

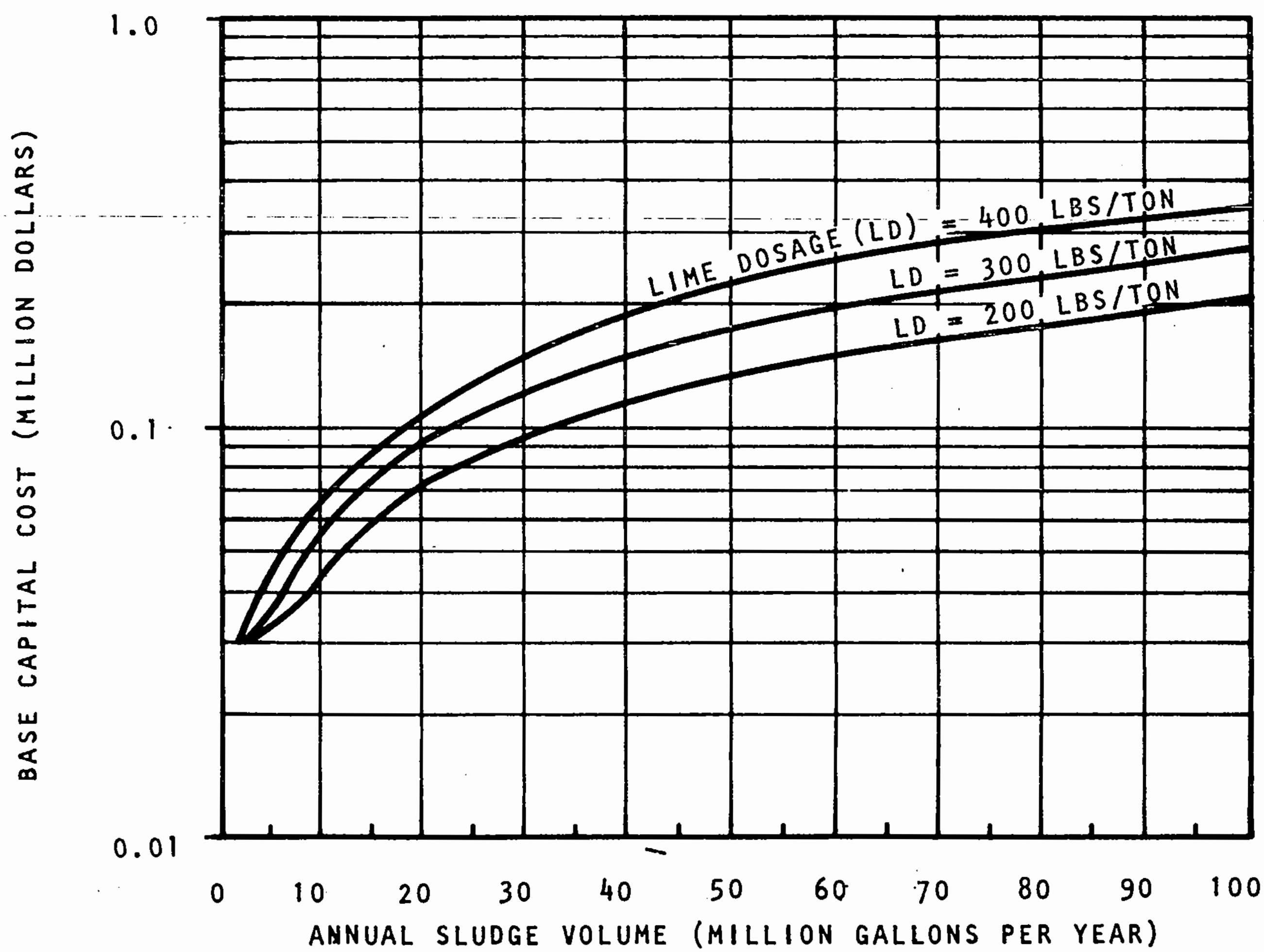


FIGURE 6-2

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.

Assumptions: Costs are based on the use of hydrated lime; operation = 8 hr/day, 7 days/week.

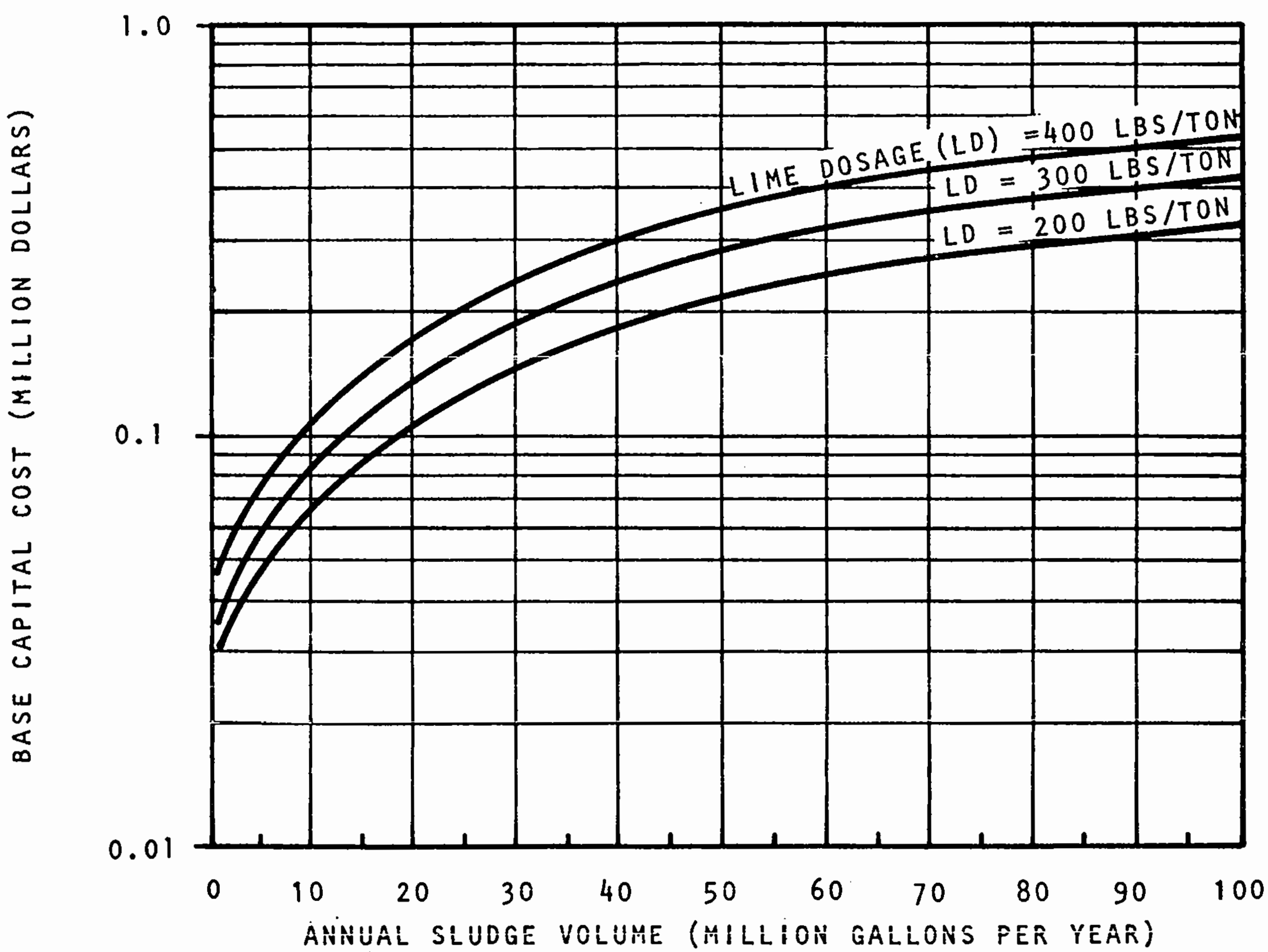


FIGURE 6-3

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.

Assumptions: Costs are based on the use of hydrated lime; operation = 8 hr/day, 7 days/week.

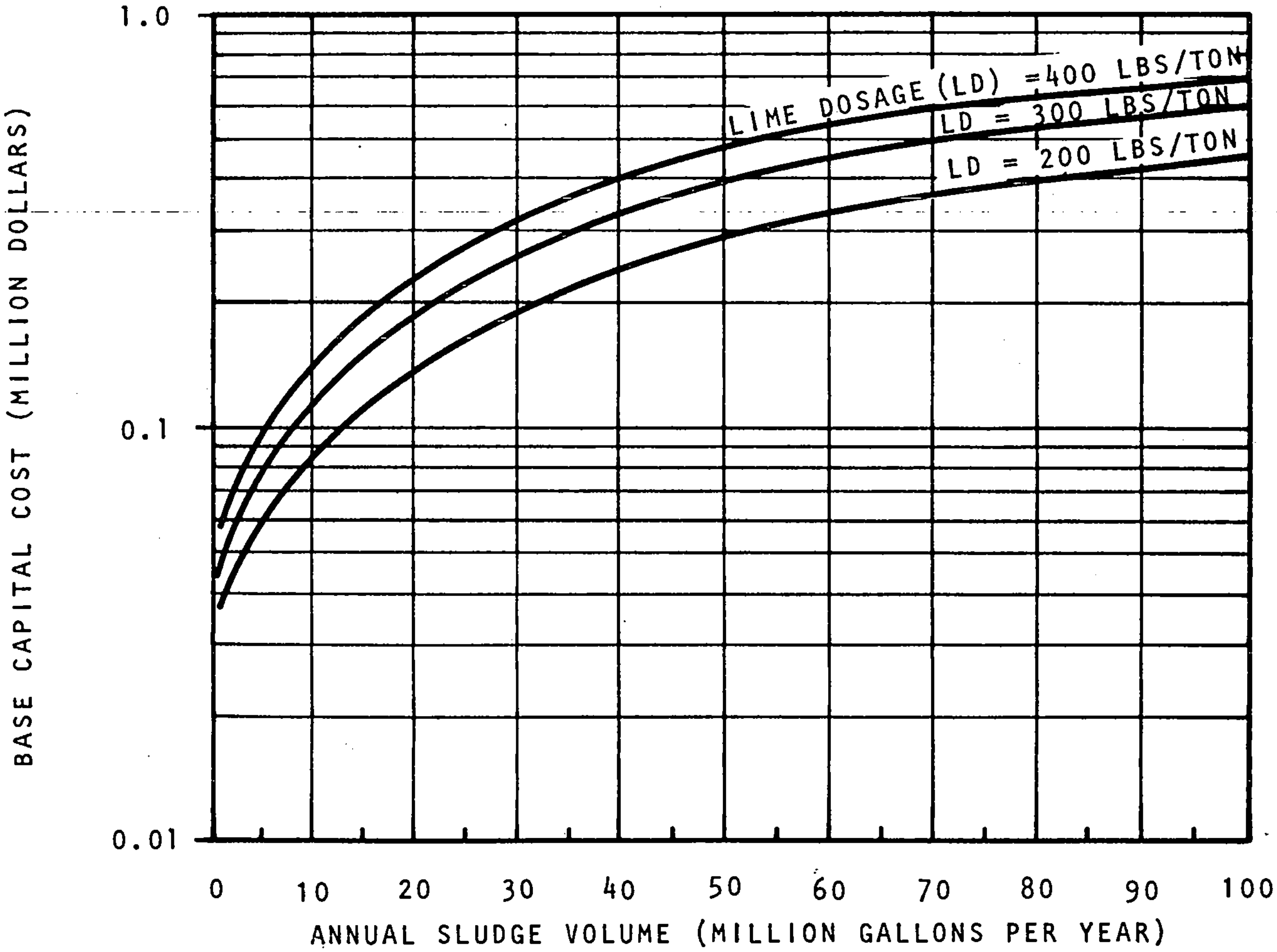


FIGURE 6-4

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-1; labor cost = $13.50/hr; cost of lime = $0.052/lb.

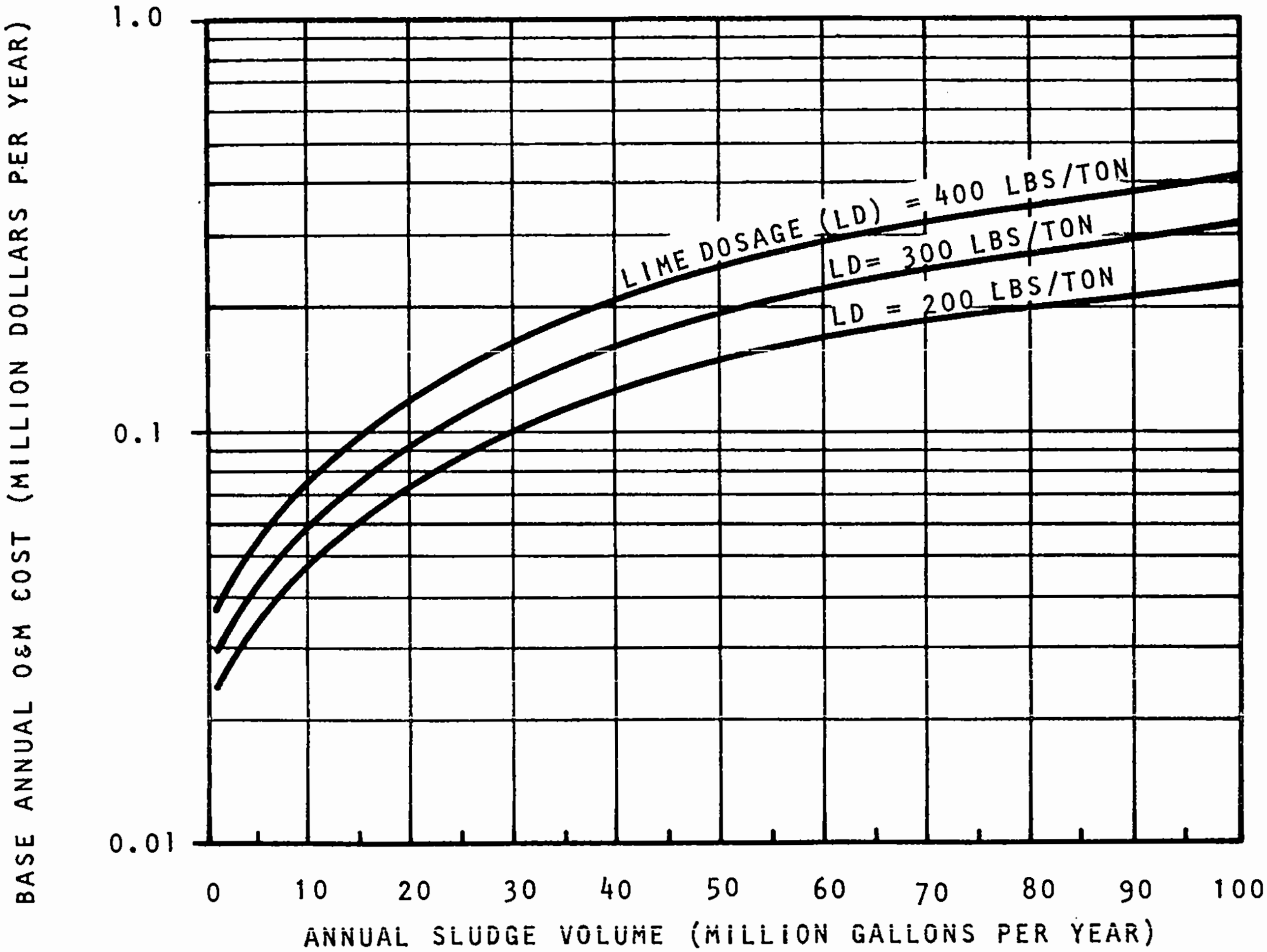


FIGURE 6-5

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-2; labor cost = $13.50/hr; cost of lime = $0.052/lb.

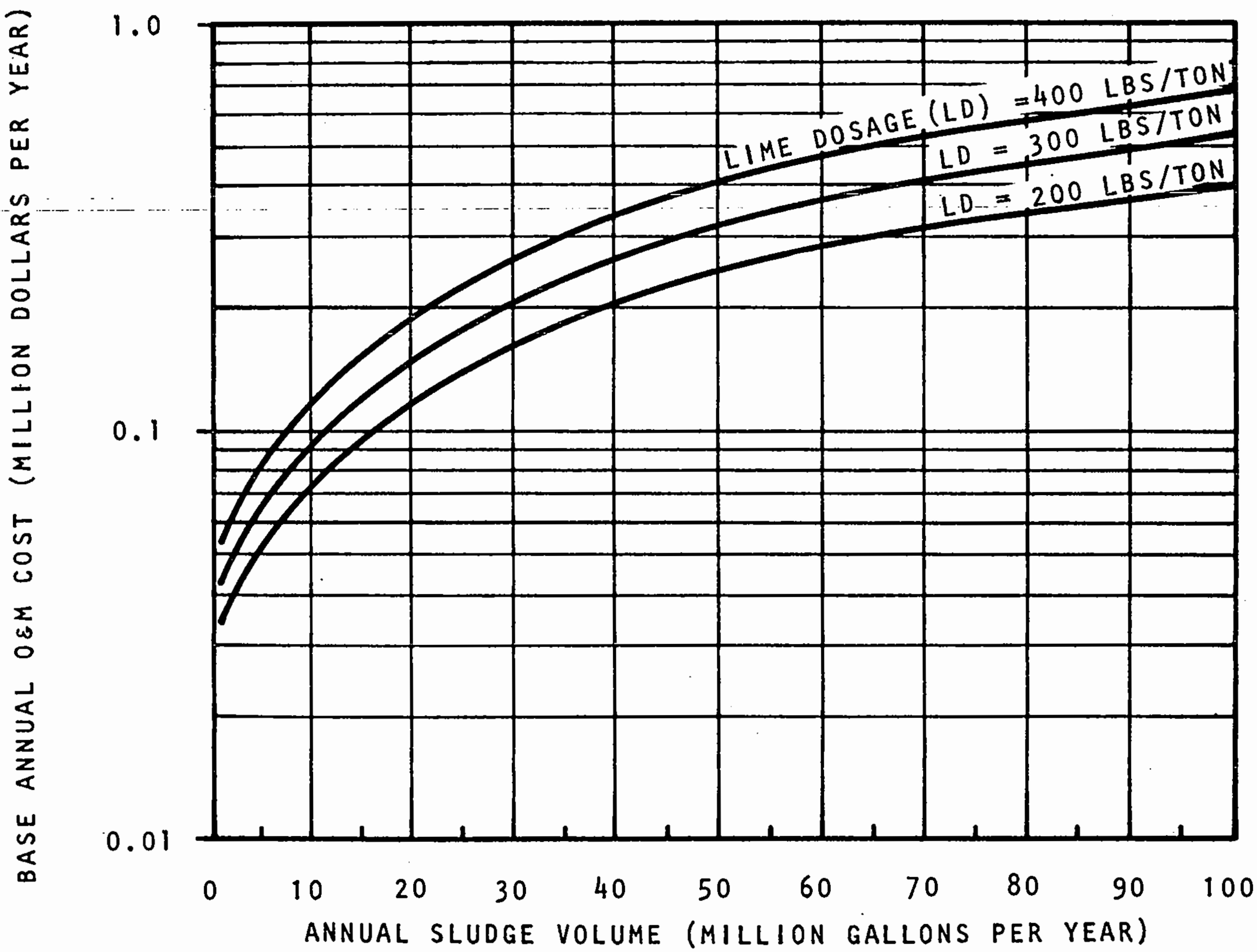


FIGURE 6-6

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-3; labor cost = $13.50/hr; cost of lime = $0.052/lb.

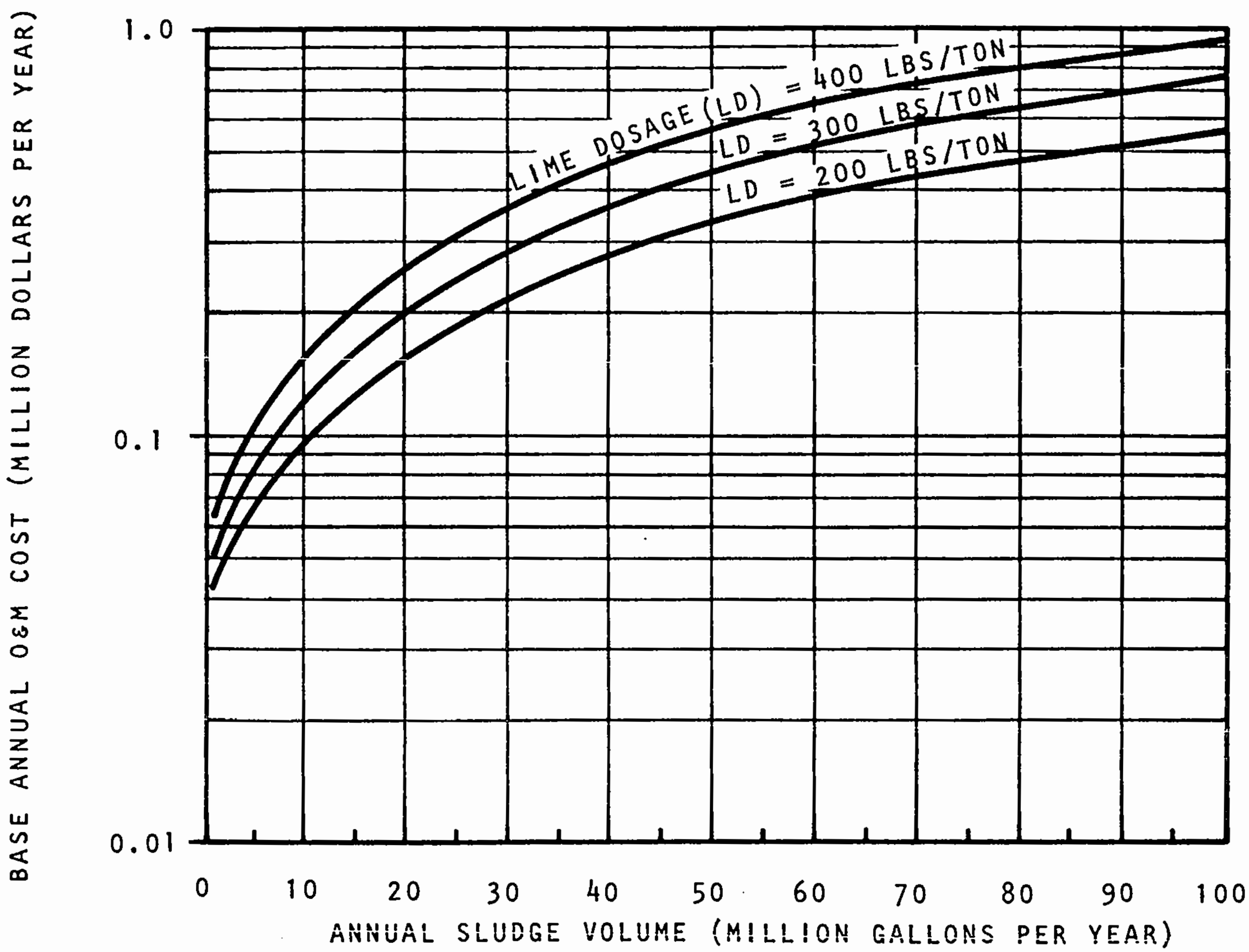
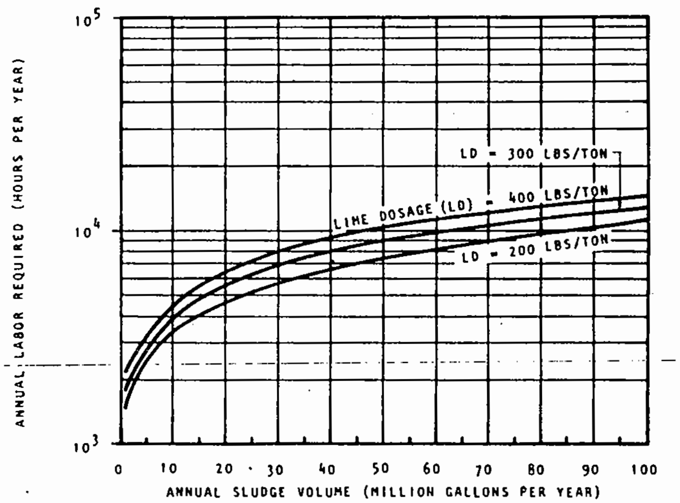
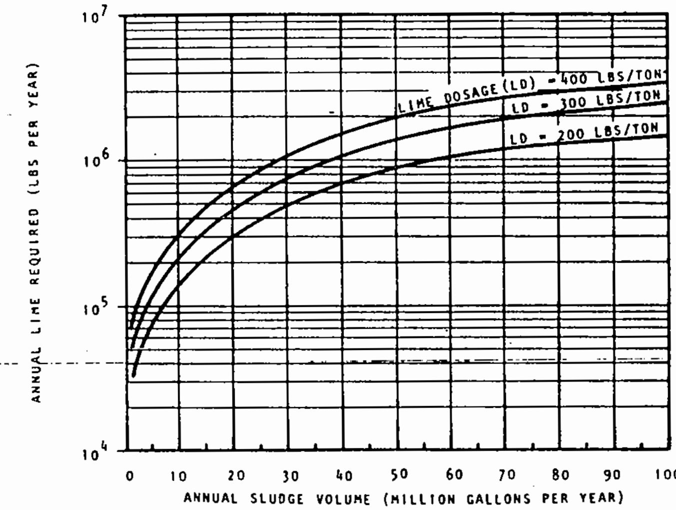
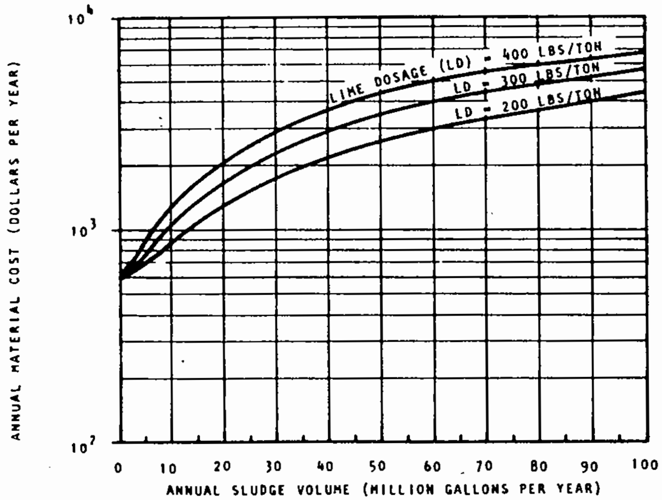


FIGURE 6-7

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.





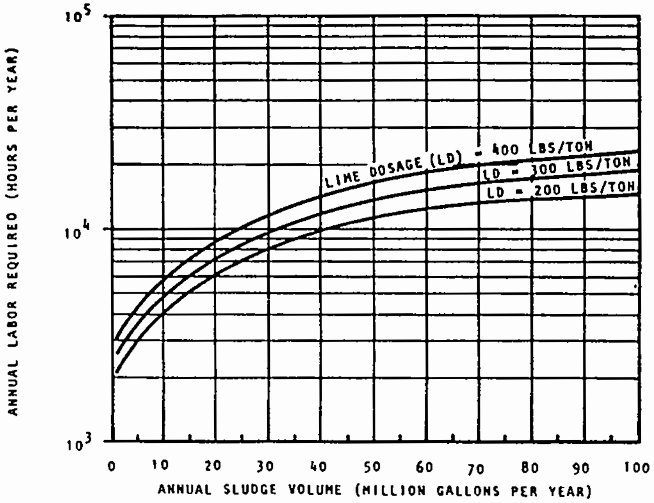


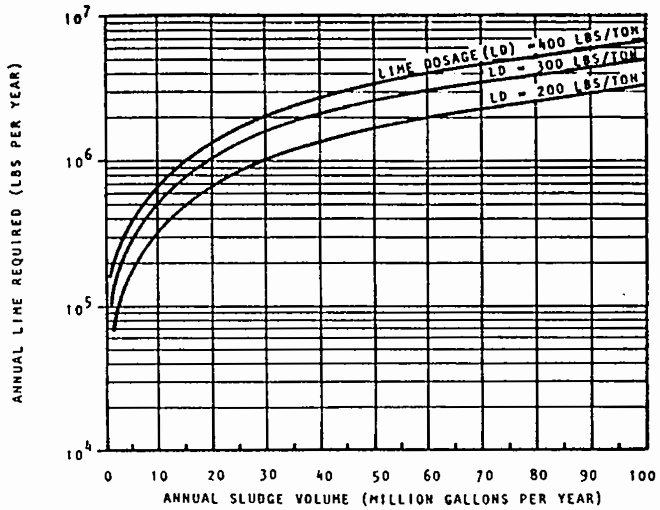
Assumptions: Design parameters are the same as for Figure 6-1.

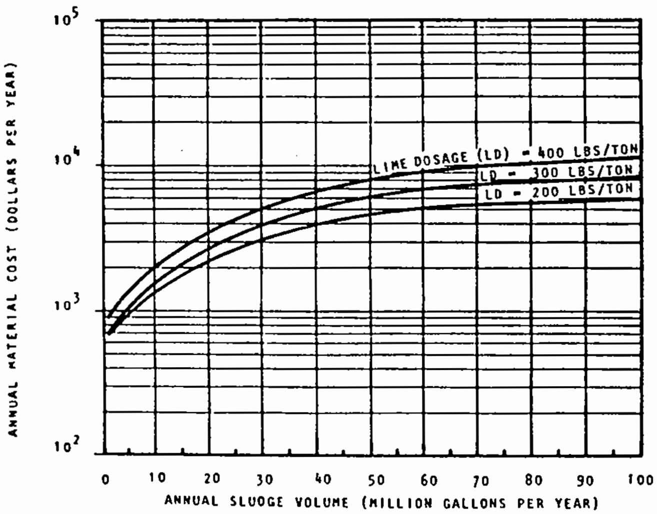
NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 6-8

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.





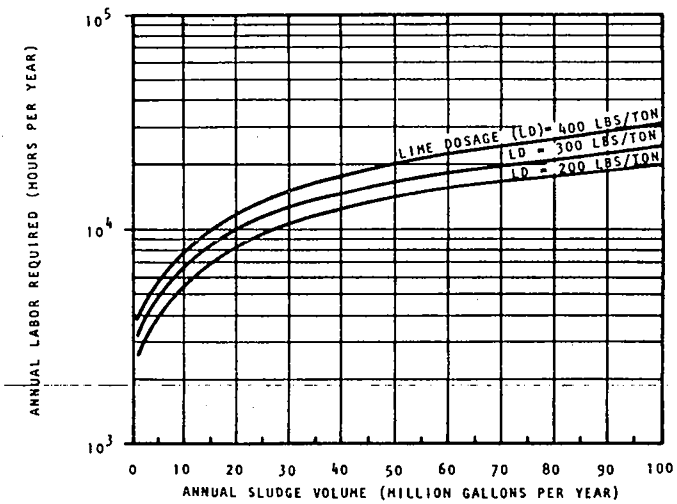


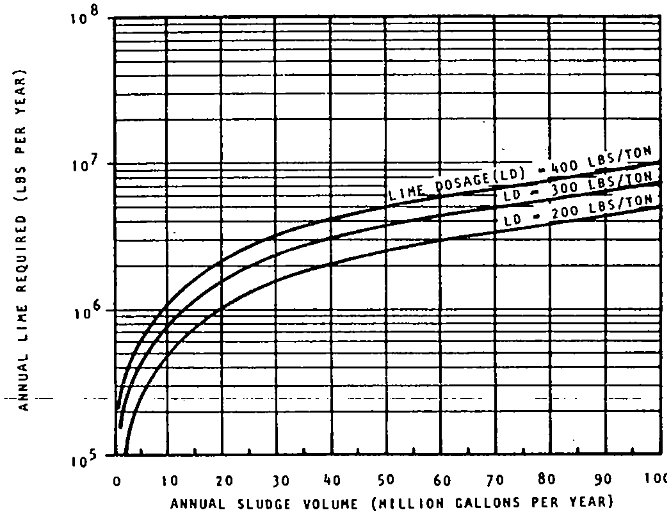
Assumptions: Design parameters are the same as for Figure 6-2.

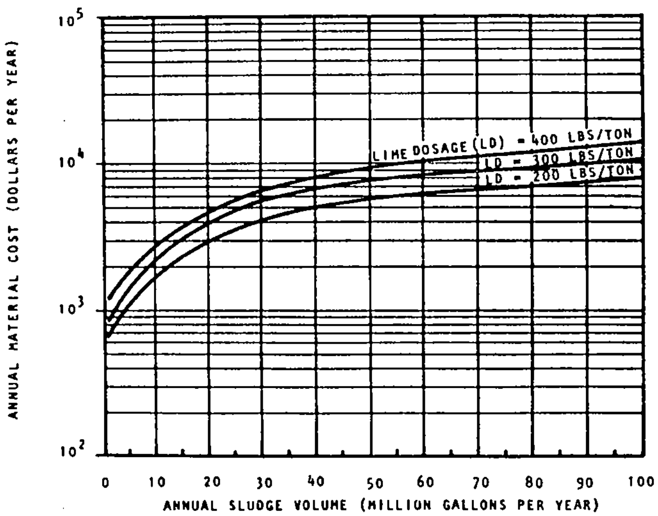
NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 6-9

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH LIME AS A FUNCTION OF ANNUAL VOLUME AND LIME DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.







Assumptions: Design parameters are the same as for Figure 6-3.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

6.4 Chemical Conditioning Using Ferric Chloride

Ferric chloride is used in sludge conditioning as a colloid destabilizer. When added to water, ferric chloride hydrolyzes, forming positively charged ion complexes which neutralize the negatively charged solids, causing aggregation. In addition, it also reacts with the bicarbonate alkalinity in the sludge to form hydroxides that act as flocculants.

Base capital and O&M costs for chemical conditioning using ferric chloride are presented in Figures 6-10 through 6-15 for sludges of 2, 4, and 6 percent solids, using various ferric chloride dosages in lb/ton dry sludge solids. O&M requirements are shown in Figures 6-16 through 6-18. The costs are based on the algorithm in Appendix A-14 using the assumptions noted on the curves.

6.5 Chemical Conditioning Using Polymer Addition

Polymers are long-chain, water-soluble chemicals which have active sites for adhering to sludge particle surfaces. Polymers act to destabilize sludge particles through dehydration, charge neutralization, and agglomerization of small particles by bridging between particles. The result is the formation of a polymer-sludge particle matrix which is easily dewatered.

Figures 6-19 through 6-24 present base capital and O&M costs for chemical conditioning using polymer addition for sludges of 2, 4, and 6 percent solids. O&M requirements are given in Figures 6-25 through 6-27. Each figure has curves for various polymer dosages in lb/ton dry sludge solids. The curves were generated with the algorithm in Appendix A-16 using the assumptions noted on the curves.

FIGURE 6-10

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.

Assumptions: Costs are based on the use of dry ferric chloride; operation = 8 hr/day, 7 days/week.

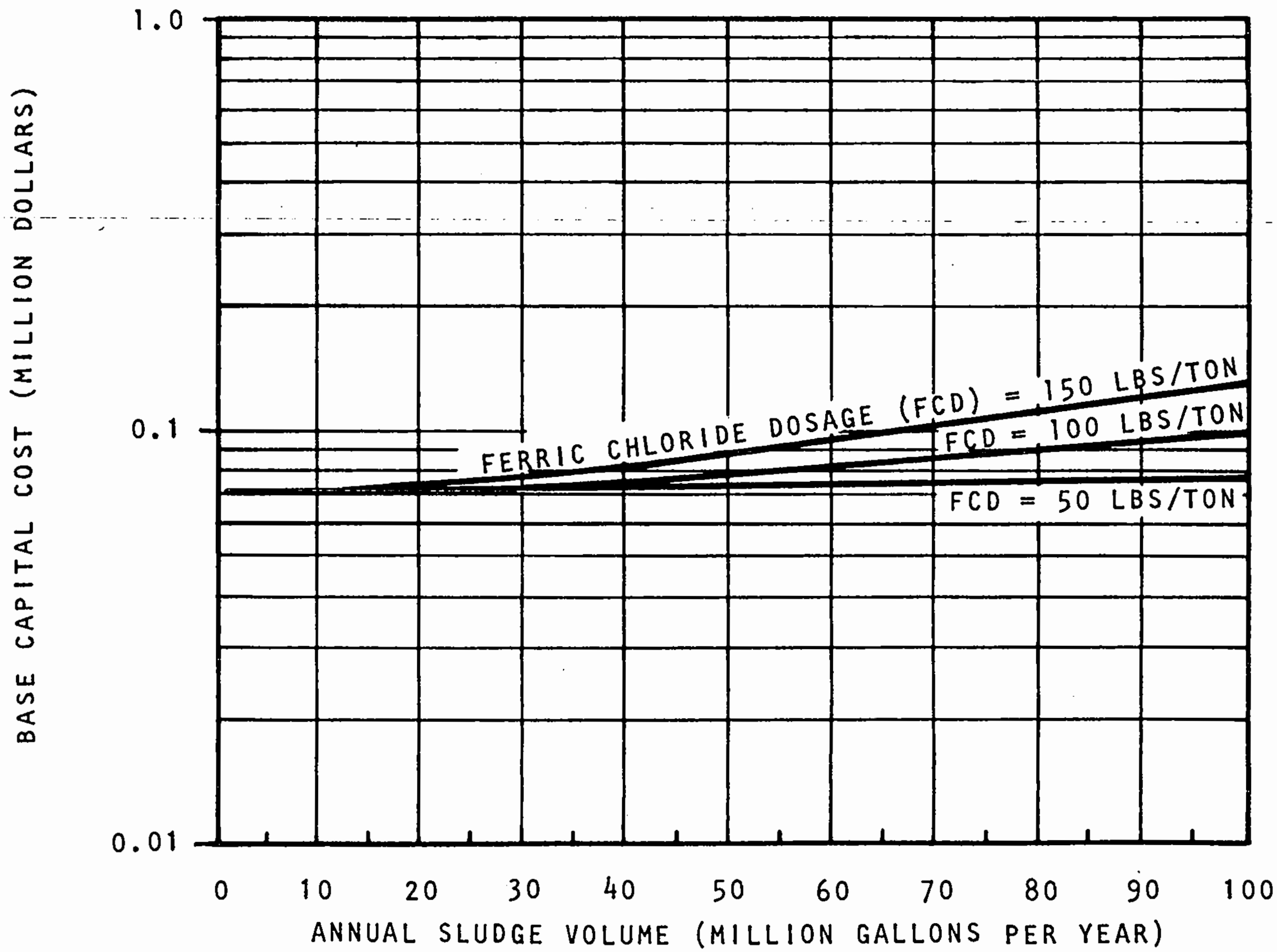


FIGURE 6-11

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.

Assumptions: Costs are based on the use of dry ferric chloride; operation = 8 hr/day, 7 days/week.

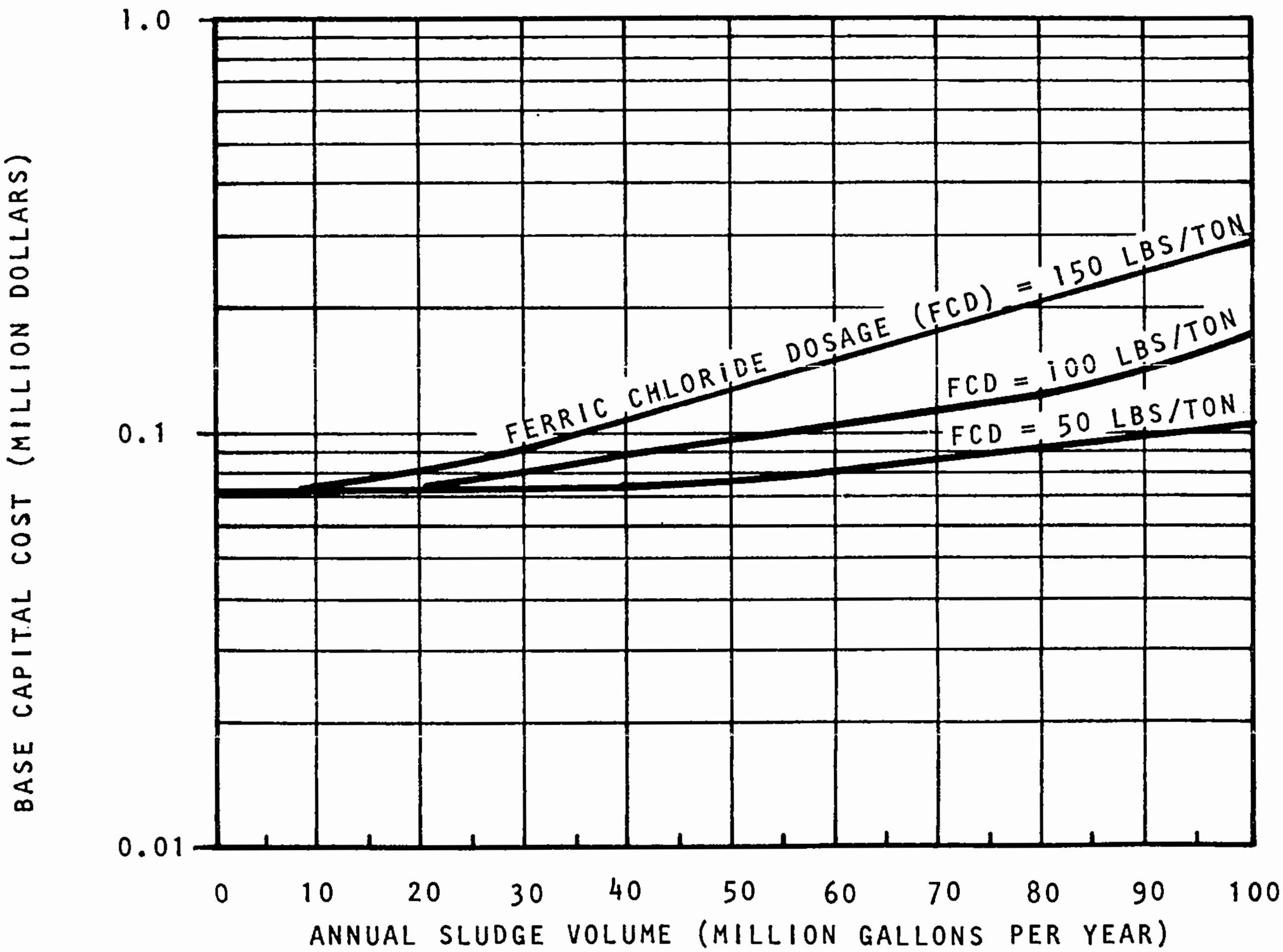


FIGURE 6-12

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.

Assumptions: Costs are based on the use of dry ferric chloride; operation = 8 hr/day, 7 days/week.

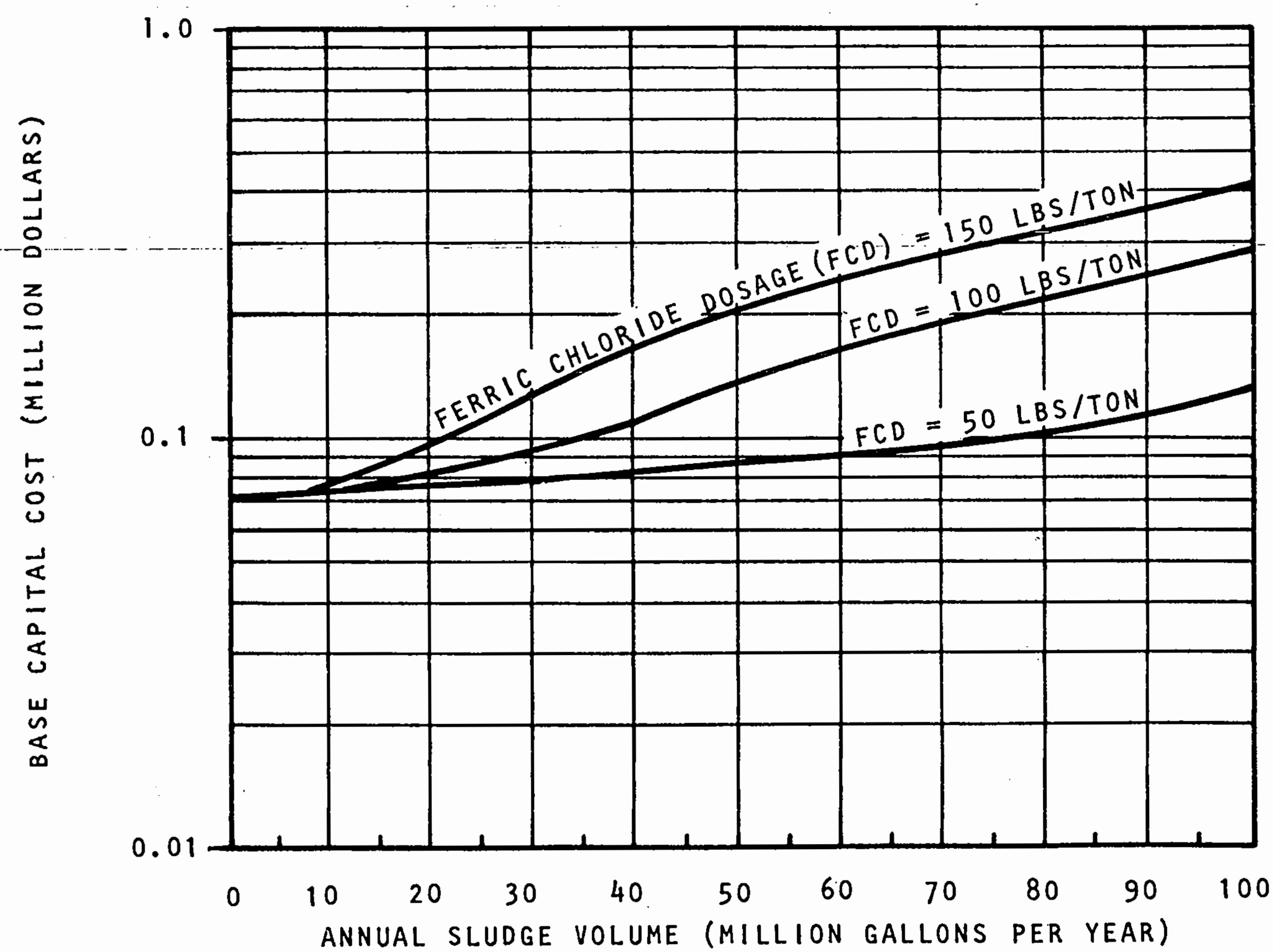


FIGURE 6-13

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-10; labor cost = $13.50/hr; cost of ferric chloride = $0.494/lb.

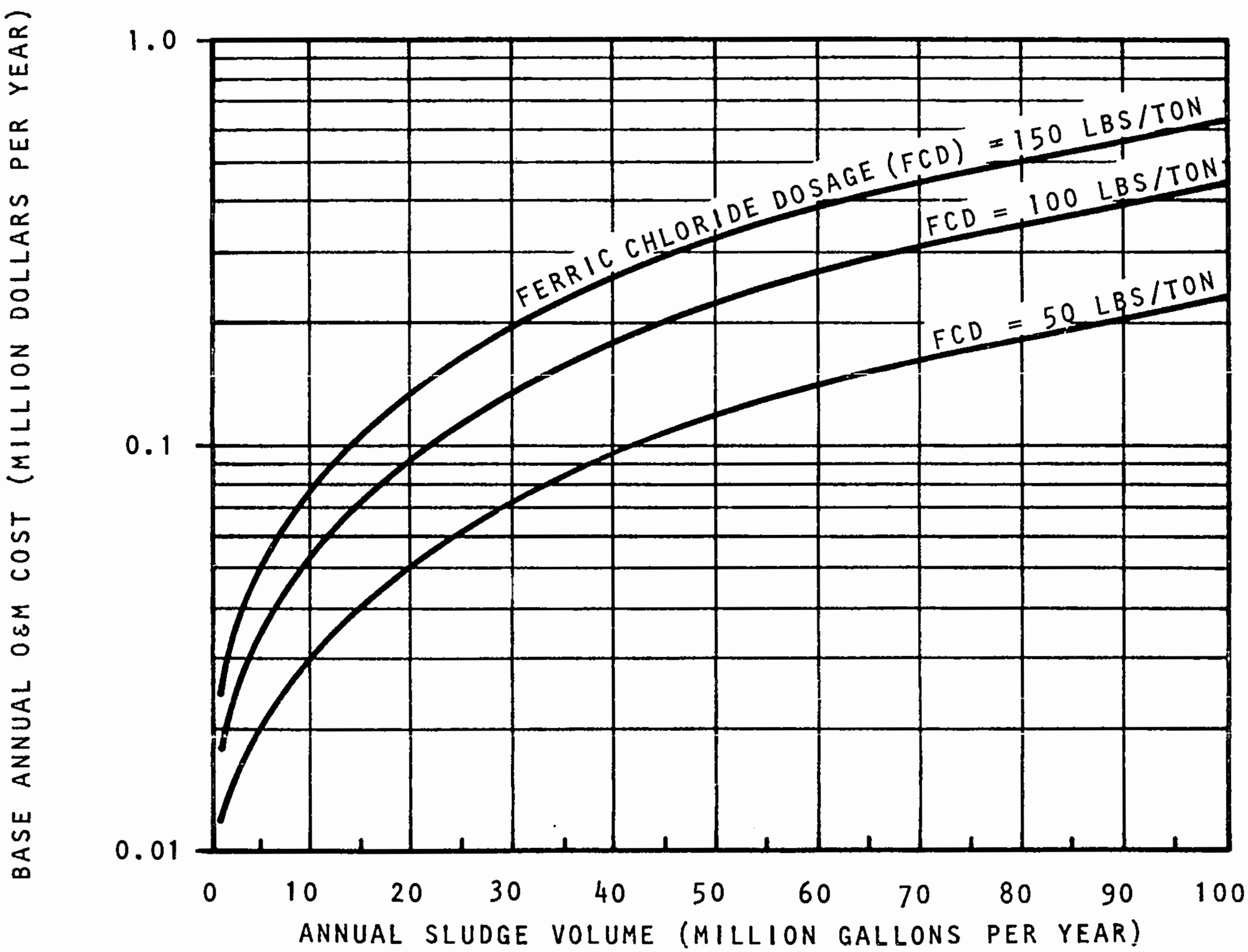


FIGURE 6-14

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-11; labor cost = $13.50/hr; cost of ferric chloride = $0.494/lb.

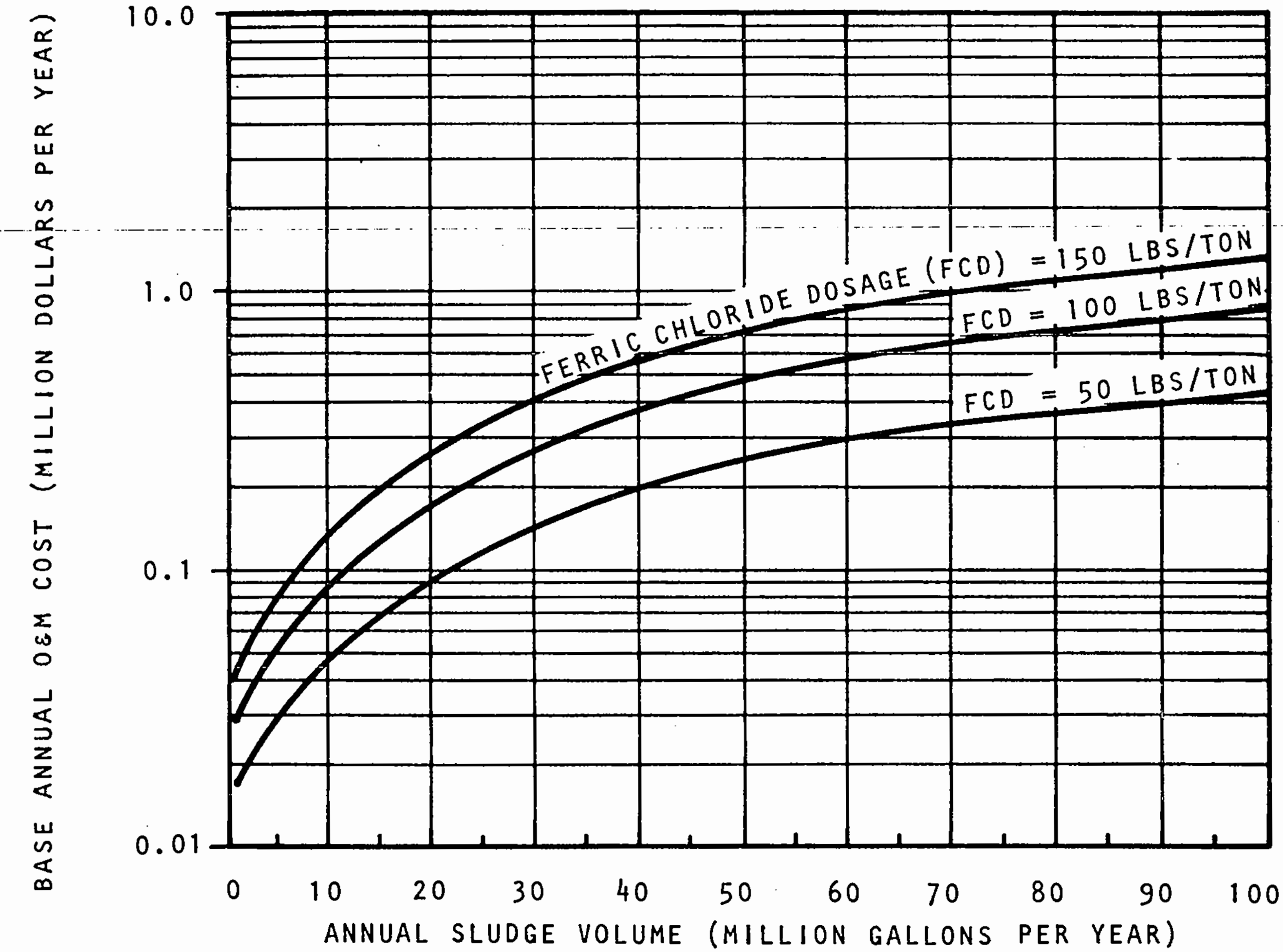


FIGURE 6-15

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-12; labor cost = $13.50/hr; cost of ferric chloride = $0.494/lb.

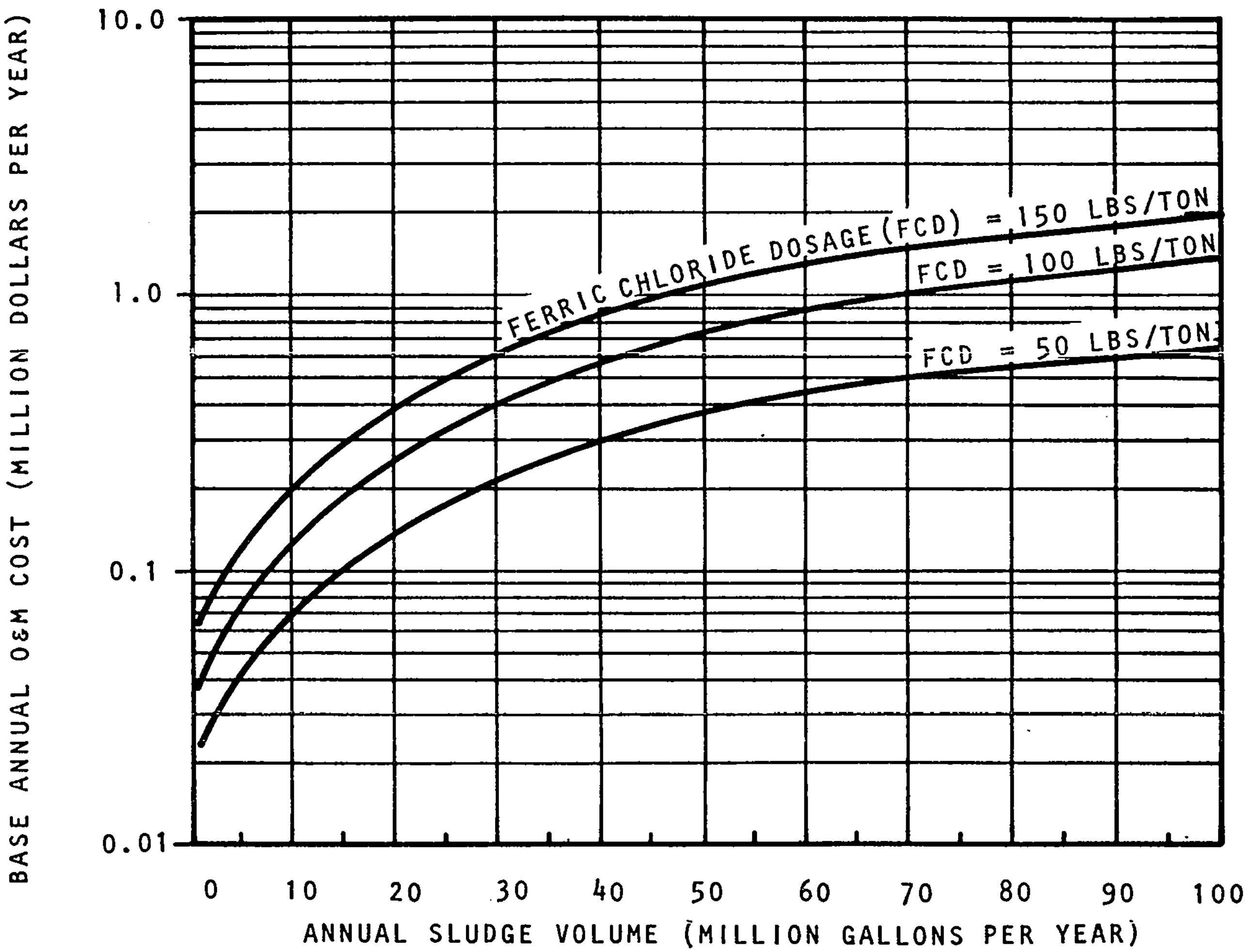
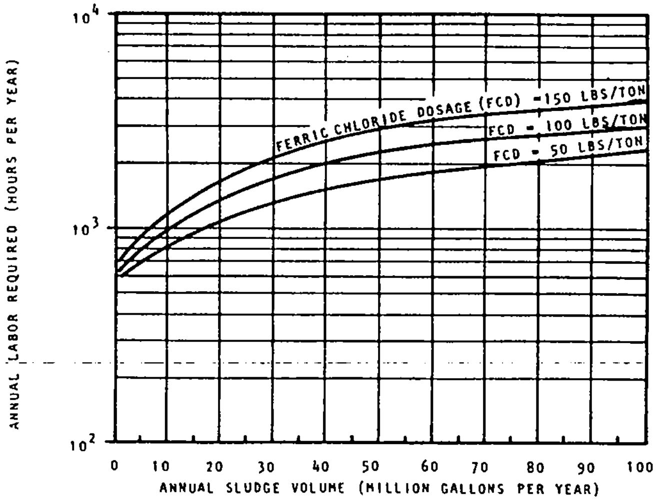
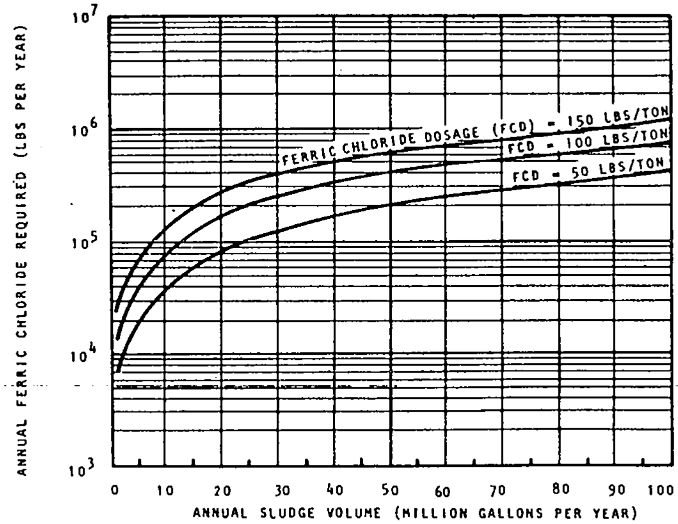
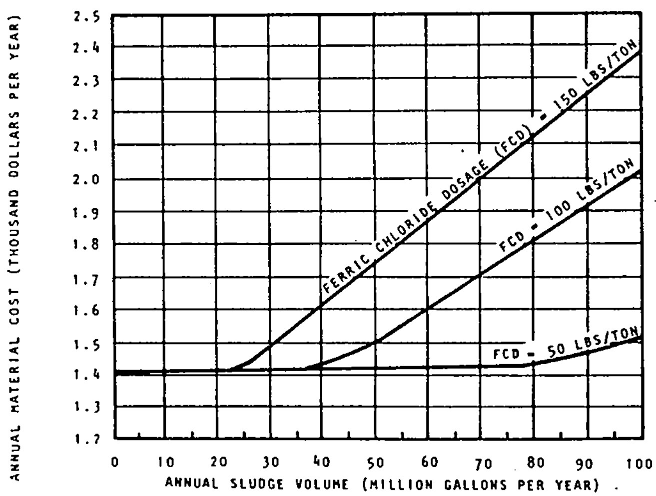


FIGURE 6-16

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.





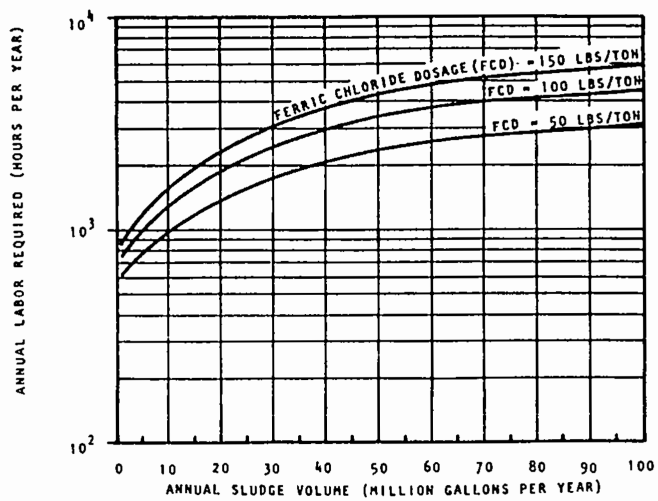


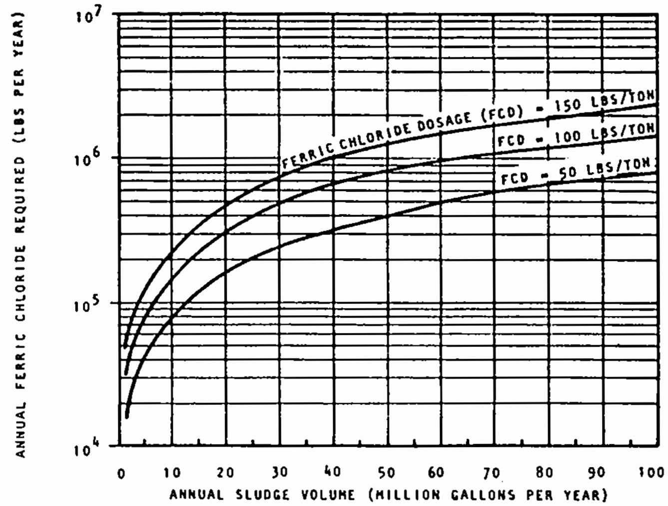
Assumptions: Design parameters are the same as for Figure 6-10.

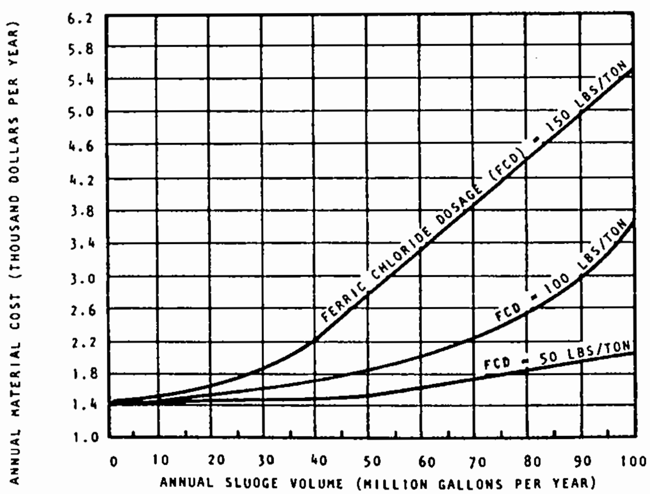
NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 6-17

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.





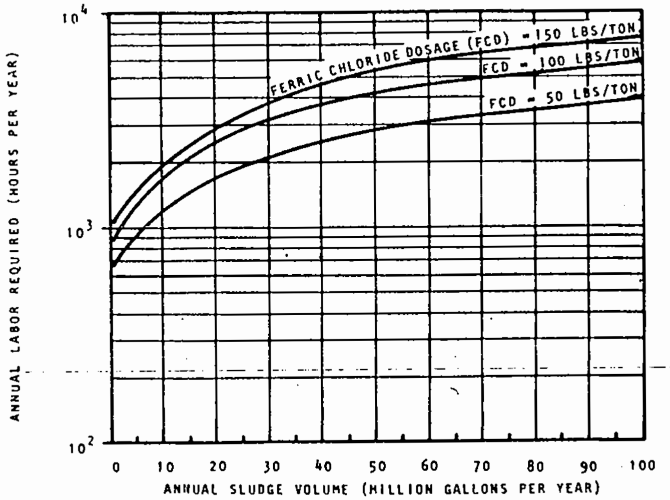


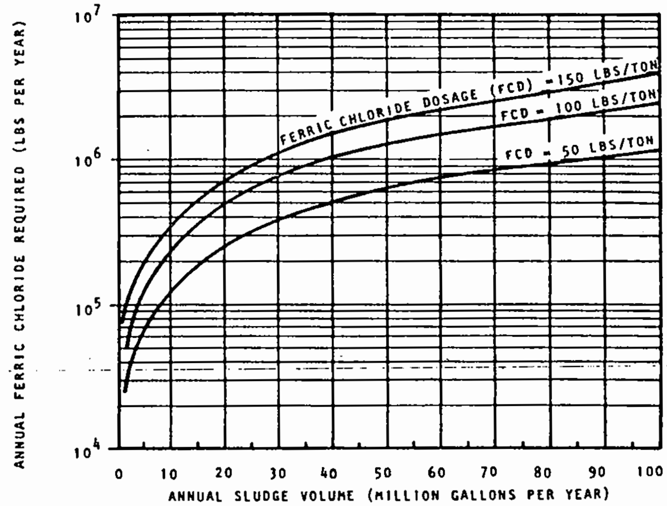
Assumptions: Design parameters are the same as for Figure 6-11.

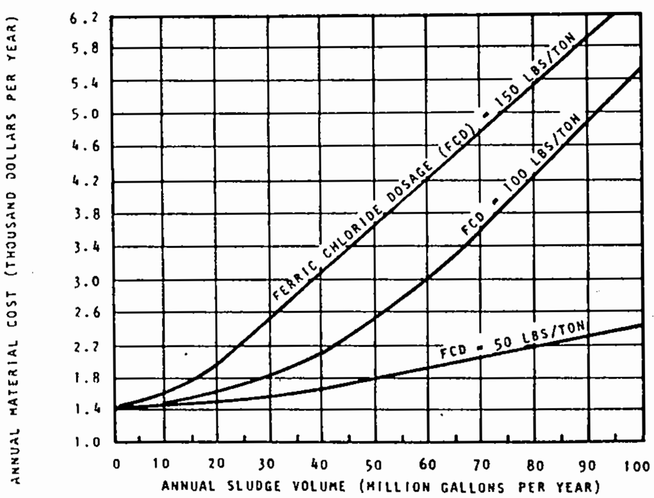
NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 6-18

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH FERRIC CHLORIDE AS A FUNCTION OF ANNUAL VOLUME AND FERRIC CHLORIDE DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.







Assumptions: Design parameters are the same as for Figure 6-12.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 6-19

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.

Assumptions: Operation = 8 hr/day, 7 days/week.

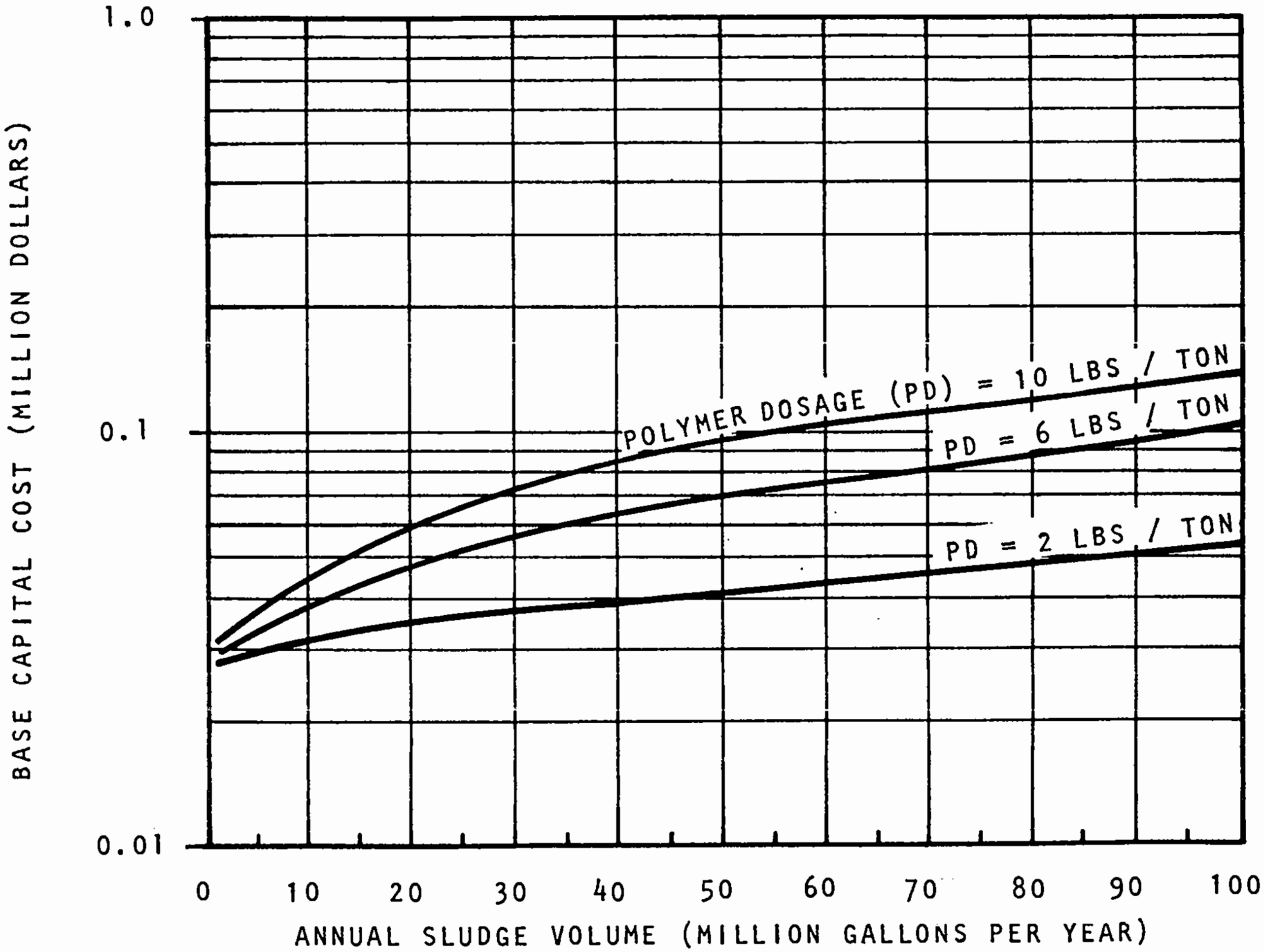


FIGURE 6-20

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.

Assumptions: Operation = 8 hr/day, 7 days/week.

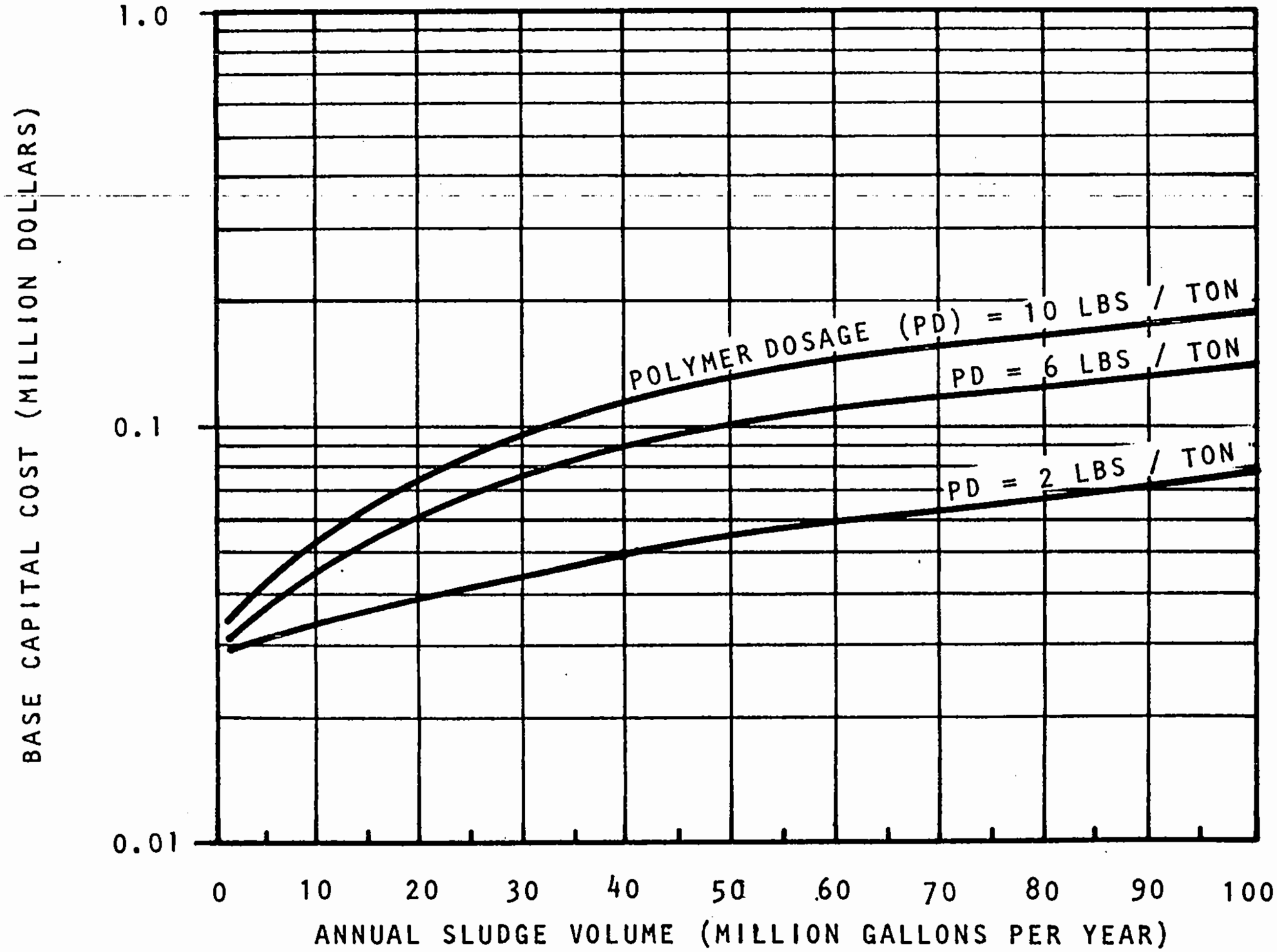


FIGURE 6-21

BASE CAPITAL COST OF CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.

Assumptions: Operation = 8 hr/day, 7 days/week.

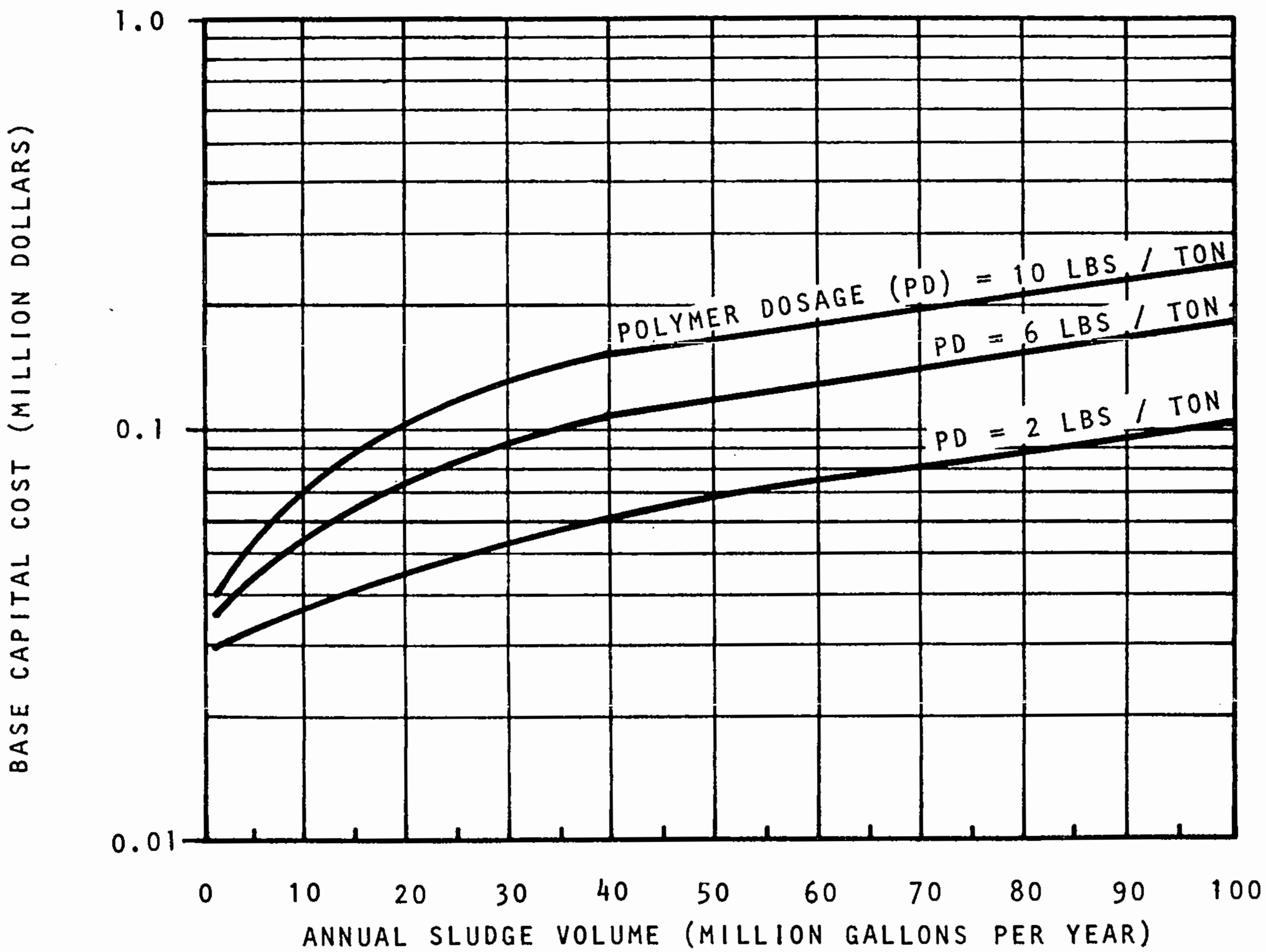


FIGURE 6-22

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-19; labor cost = $13.50/hr; cost of polymer = $2.80/lb.

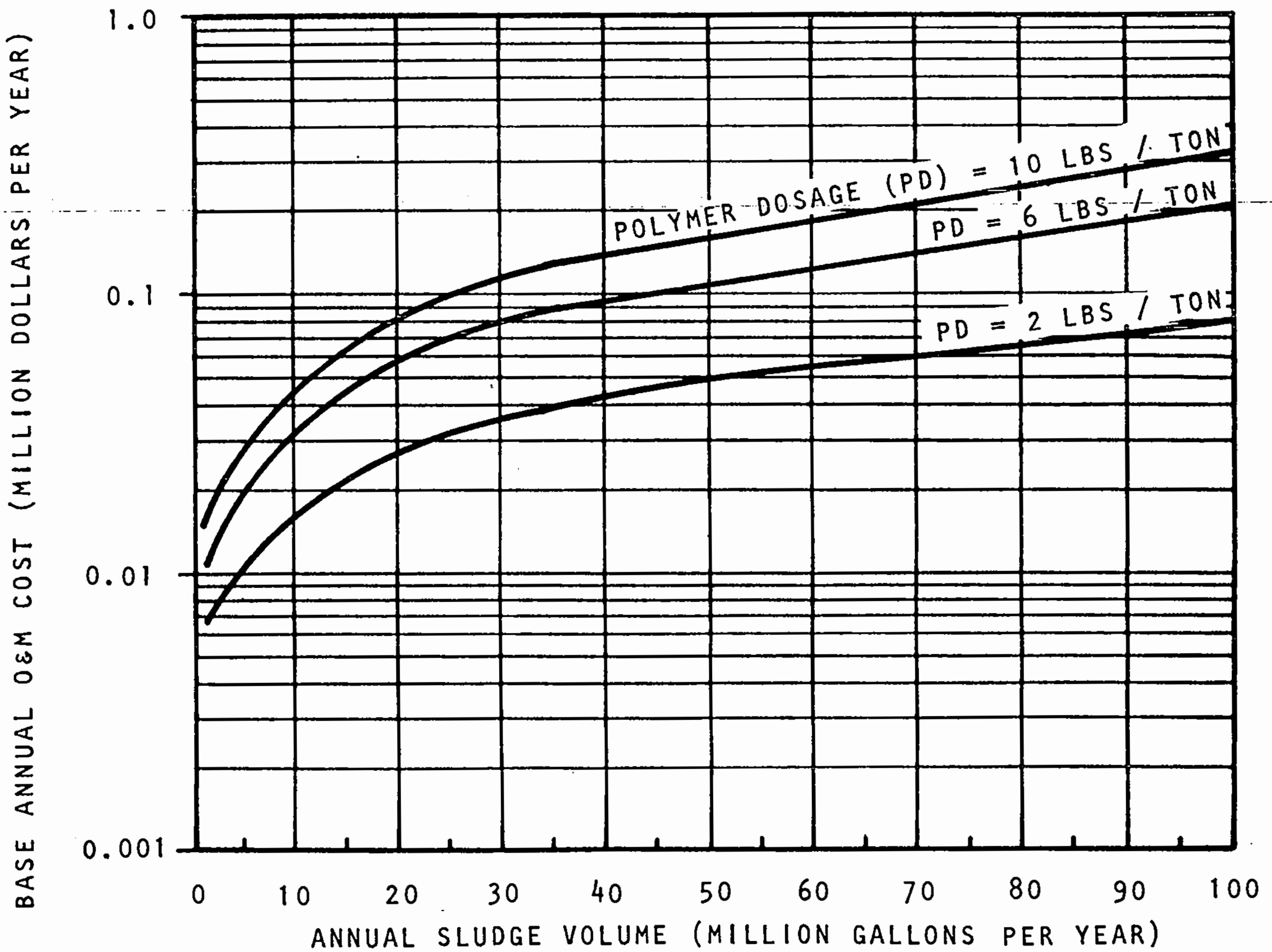


FIGURE 6-23

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-20; labor cost = $13.50/hr; cost of polymer = $2.80/lb.

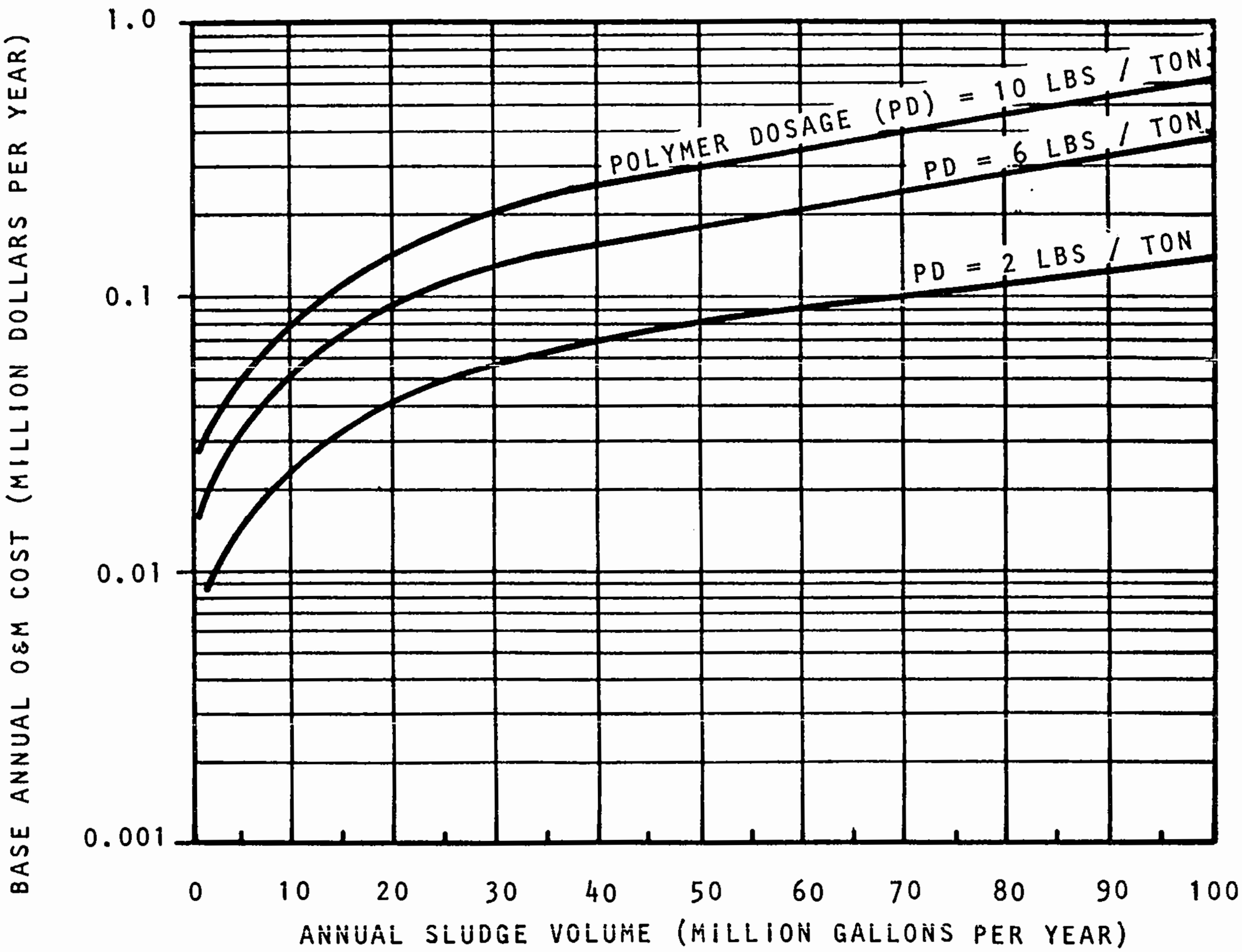


FIGURE 6-24

BASE ANNUAL O&M COST OF CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.

Assumptions: Design parameters are the same as for Figure 6-21; labor cost = $13.50/hr; cost of polymer = $2.80/lb.

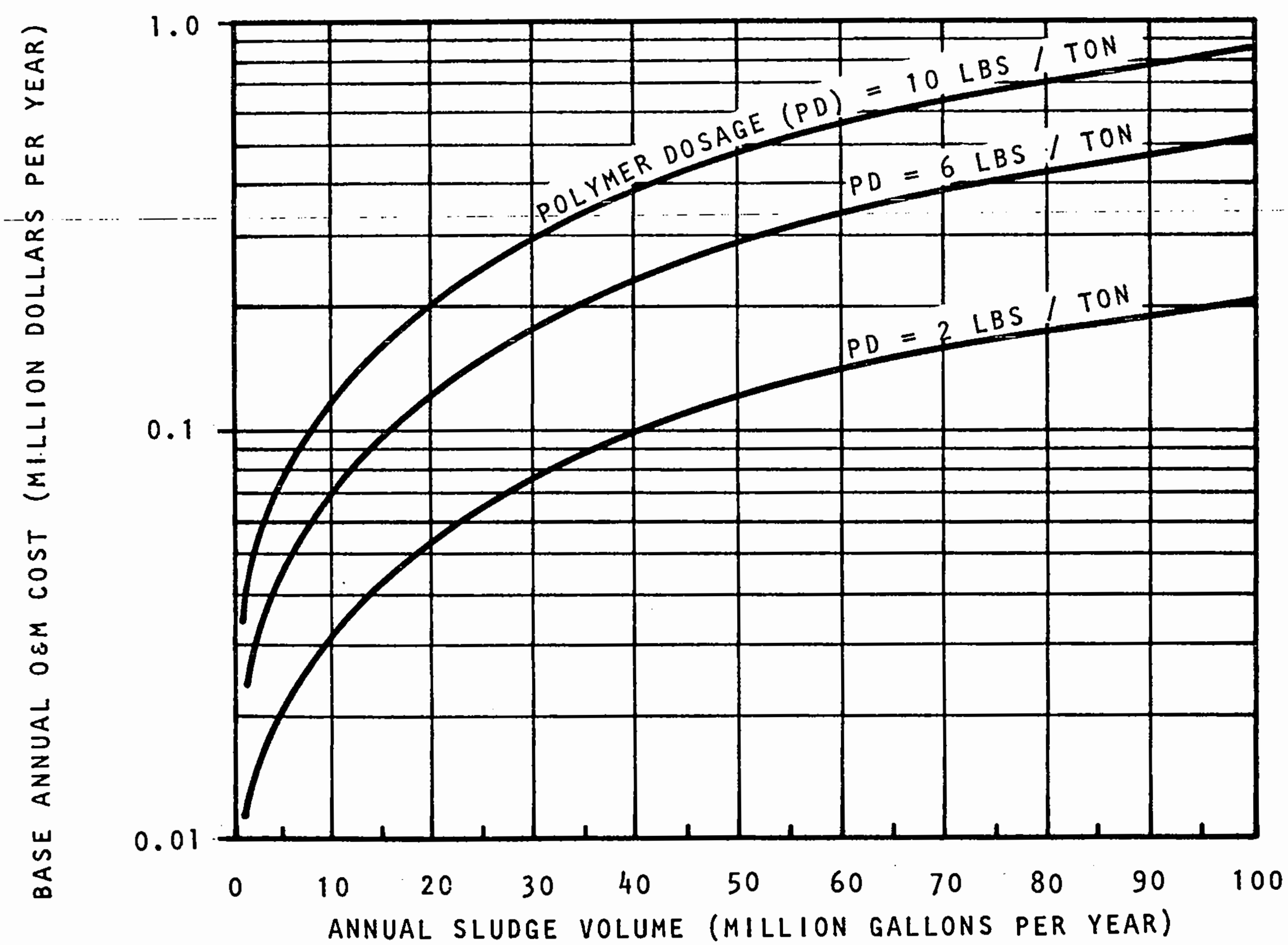
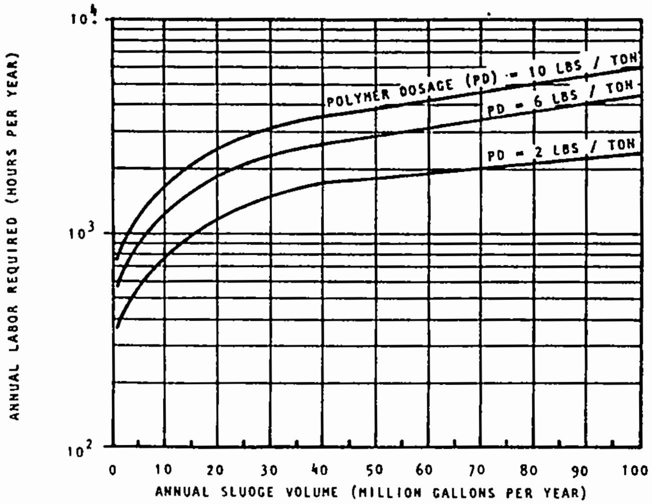
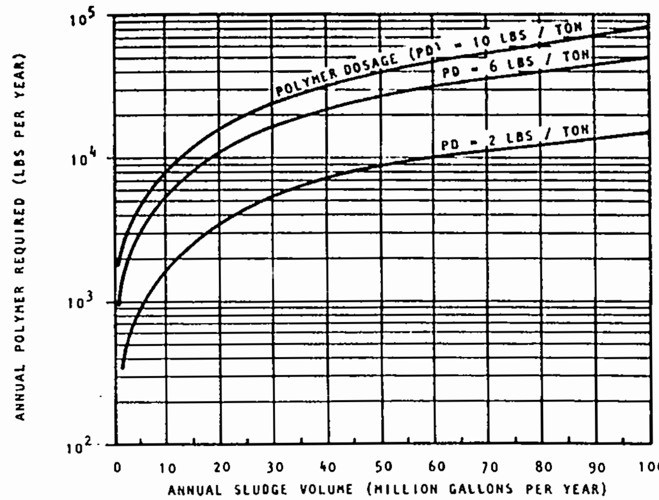
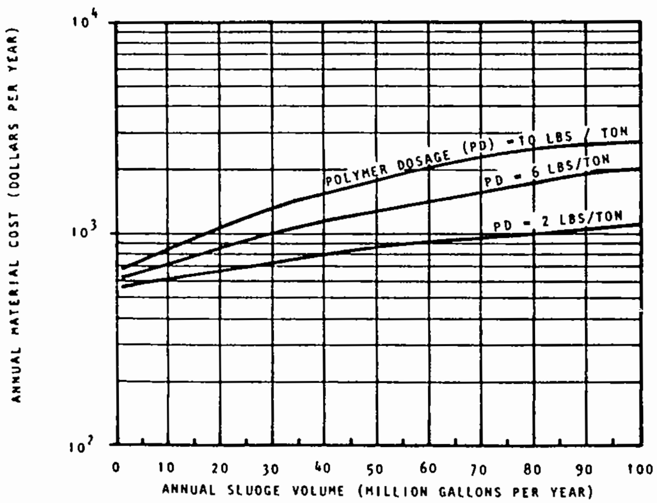


FIGURE 6-25

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 2 PERCENT.





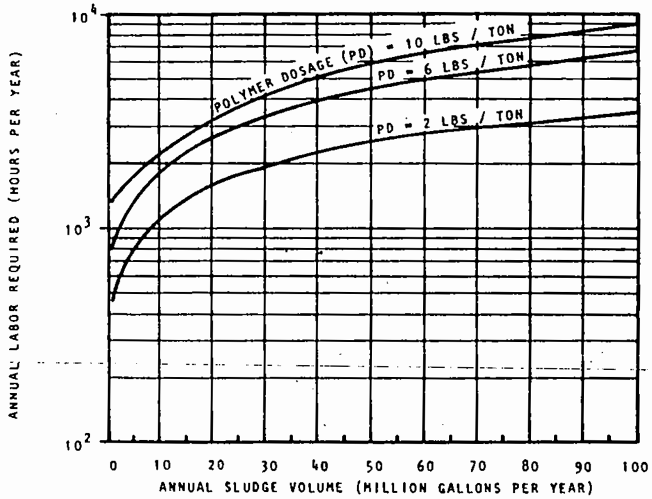


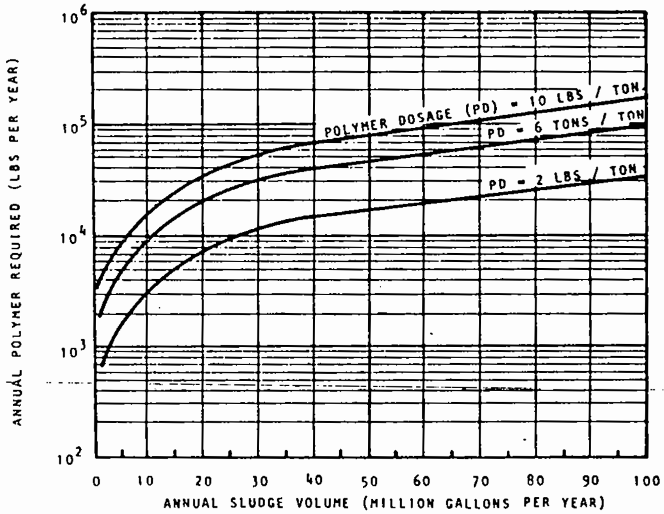
Assumptions: Design parameters are the same as for Figure 6-19.

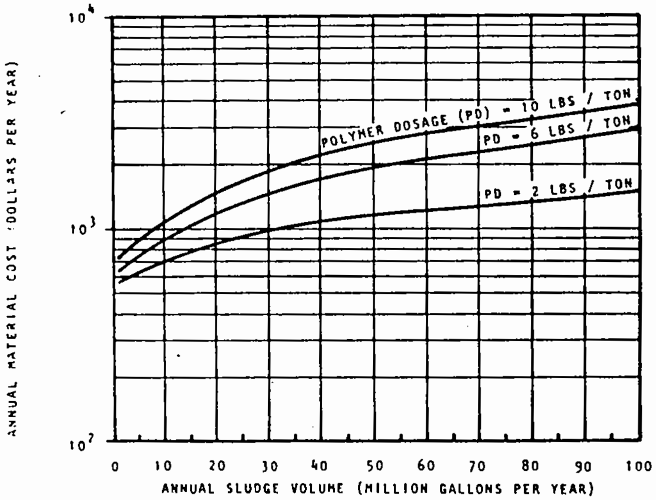
NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 6-26

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 4 PERCENT.





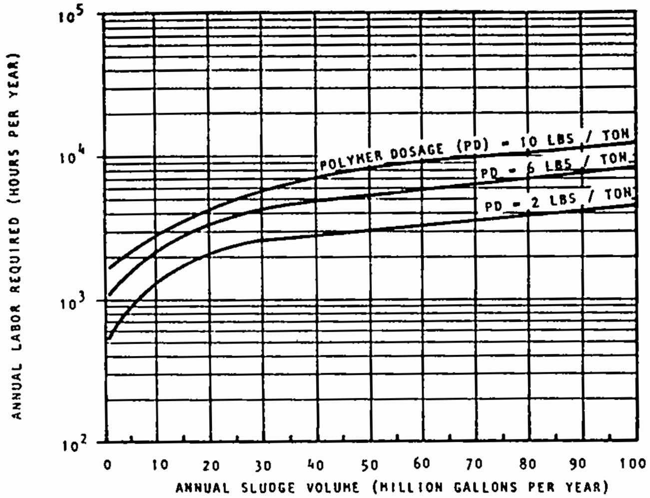


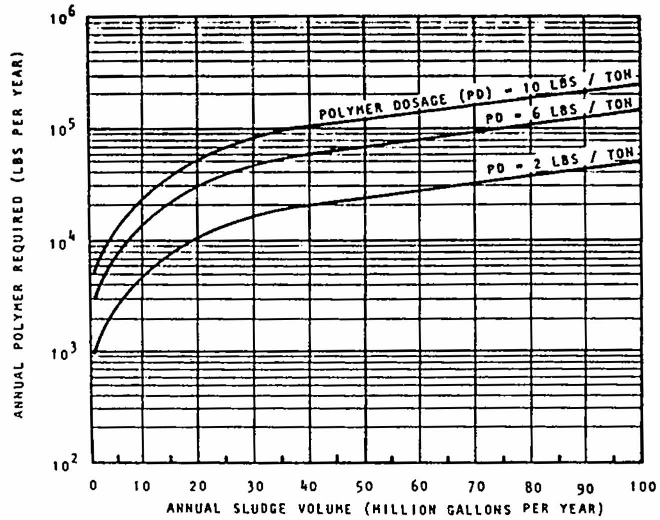
Assumptions: Design parameters are the same as for Figure 6-20.

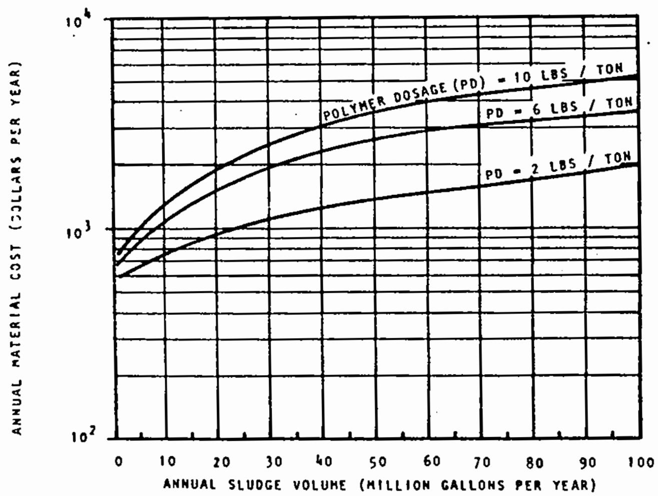
NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 6-27

ANNUAL O&M REQUIREMENTS FOR CHEMICAL CONDITIONING WITH POLYMERS AS A FUNCTION OF ANNUAL VOLUME AND POLYMER DOSAGE; SLUDGE SOLIDS CONCENTRATION = 6 PERCENT.







Assumptions: Design parameters are the same as for Figure 6-21.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

SECTION 7

SLUDGE INCINERATION CURVES

7.1 Introduction

This section presents base capital and O&M curves for the two most commonly used methods of incineration: fluidized bed and multiple hearth incineration. Incineration processes can reduce the sludge dry solids to 25 percent of the mass entering the unit through the oxidation of volatiles. These processes are particularly advantageous at locations where land or ocean disposal of sludges is limited or prohibited.

Incineration is a two-step process consisting of sludge drying and combustion. Due to the large amounts of fuel required for startup, the process is usually operated continuously.

The disadvantages of sludge incineration include the following:

- Depending on feed sludge concentration, large amounts of fuel may be required to sustain operating temperatures.
- Highly skilled personnel are required to ensure proper operation.
- Pollution control devices may be necessary to control emissions to the atmosphere.
- Relatively high capital and O&M costs are entailed.

As a result of high capital and O&M costs, incineration is not normally used in treatment plants smaller than 5 mgd, except in areas where sludge must be transported over long distances for disposal.

Operating conditions assumed when developing costs are noted on the curves. Generally, incineration is assumed to operate continuously 24 hours per day, 360 days per year, which includes shutdowns for maintenance. Fuel oil is burned to sustain operating temperatures. Capital costs do not include land costs, since they are minor compared to the cost of equipment and structures.

The cost of pollution control devices is not included in capital costs, since they depend on applicable federal, state, and local emission standards, and type of equipment used. In general, pollution control would raise base capital costs by 10 to 20 percent.

7.2 Fluidized Bed Incineration

Fluidized bed incinerators utilize a fluidized bed of sand as a heat reservoir to promote uniform combustion of sludge. Air is injected into the incinerator at a pressure of 3 to 5 psig to fluidize the bed. Temperatures are maintained between 1,400 and 1,500 °F using gas or fuel oil as an auxiliary fuel.

Dewatered sludge is introduced either above or directly into the sand bed, and is oxidized as it moves through the bed. Exhaust gases and ash are carried upward to the top of the incinerator and through air pollution control devices, usually Venturi scrubbers.

Base capital and O&M curves for fluidized bed incineration are presented on Figures 7-1 through 7-3. Curves are based on the algorithm in Appendix A-16, using the assumptions noted on the figures. Additional information on algorithm development, design parameters, and other assumptions is provided in Appendix A-16.

7.3 Multiple Hearth Incineration

Multiple hearth incinerators are multi-chambered vertically mounted furnaces with hearths located above one another. Within each hearth is a set of rabble arms used to move the sludge in a spiral pattern around each hearth. Dewatered sludge is fed onto the top hearth of the incinerator, and is swept radially towards the center where the sludge drops to the second hearth. The sludge is then swept spirally to the periphery of the second hearth, and passes to the next lower hearth. This pattern is continued through subsequent hearths. As the sludge moves toward the bottom, further oxidation occurs, yielding an ash which is removed from the bottom. Hot rising gases flow in a direction countercurrent to the sludge flow, out the top of the furnace, and through any necessary pollution control devices.

Base capital and O&M curves for multiple hearth incineration are presented in Figures 7-4 through 7-6. Curves are based on the algorithm in Appendix A-17, using the assumptions noted on the curves. Additional information on algorithm development, design parameters, and other assumptions is provided in Appendix A-17.

FIGURE 7-1

BASE CAPITAL COST OF FLUIDIZED BED INCINERATION AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS INCINERATED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Loading rate = 9 lb wet sludge/hr/sq ft; operating temperature = 1,100° F; sludge solids are 70 percent volatile; process operates 24 hours per day, 360 days per year.

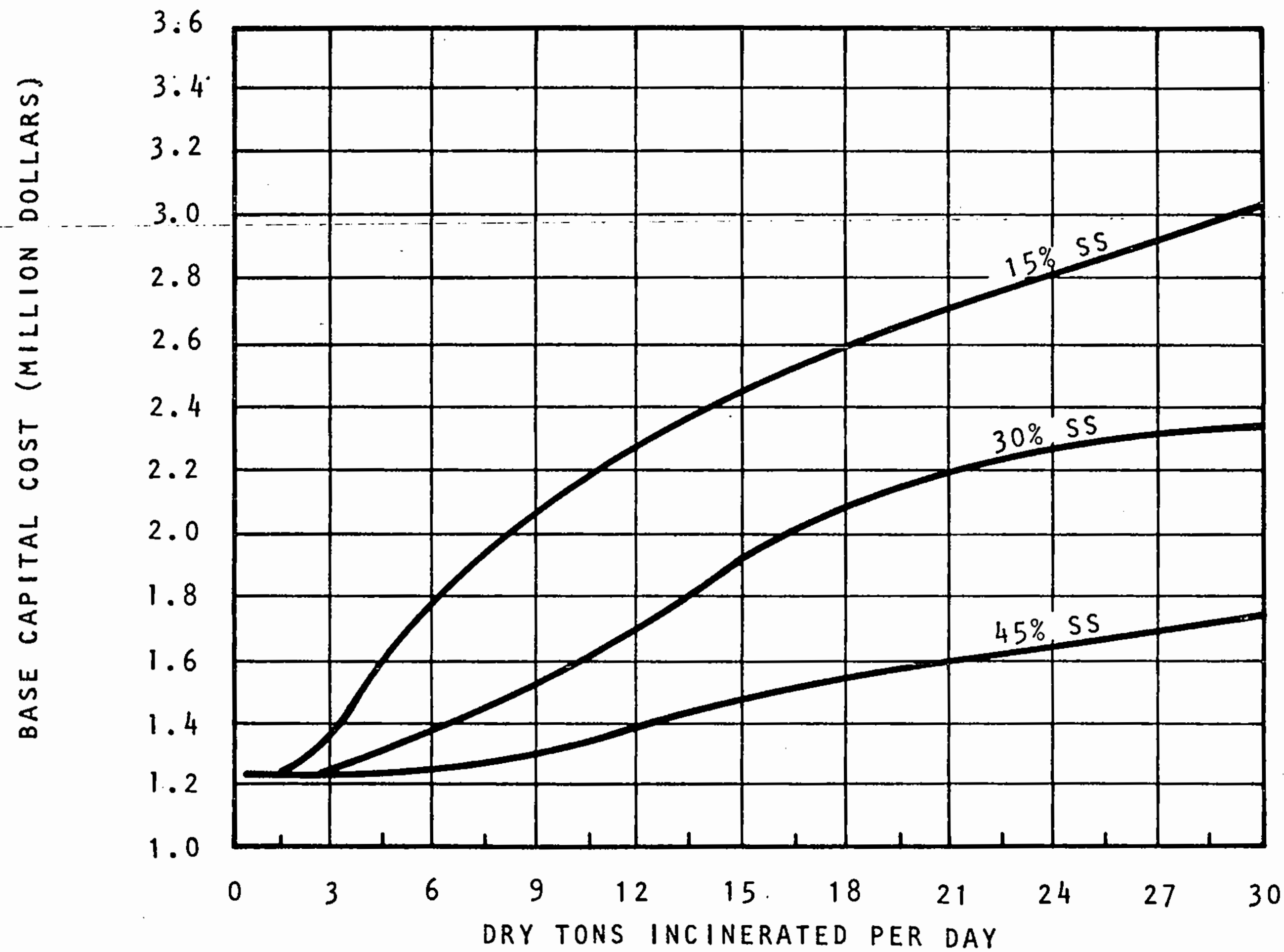


FIGURE 7-2

BASE ANNUAL O&M COST OF FLUIDIZED BED INCINERATION AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS INCINERATED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 7-1; labor cost = \$13.50/hr; cost of electricity = \$0.094/kWhr; cost of diesel fuel = \$1.35/gal.

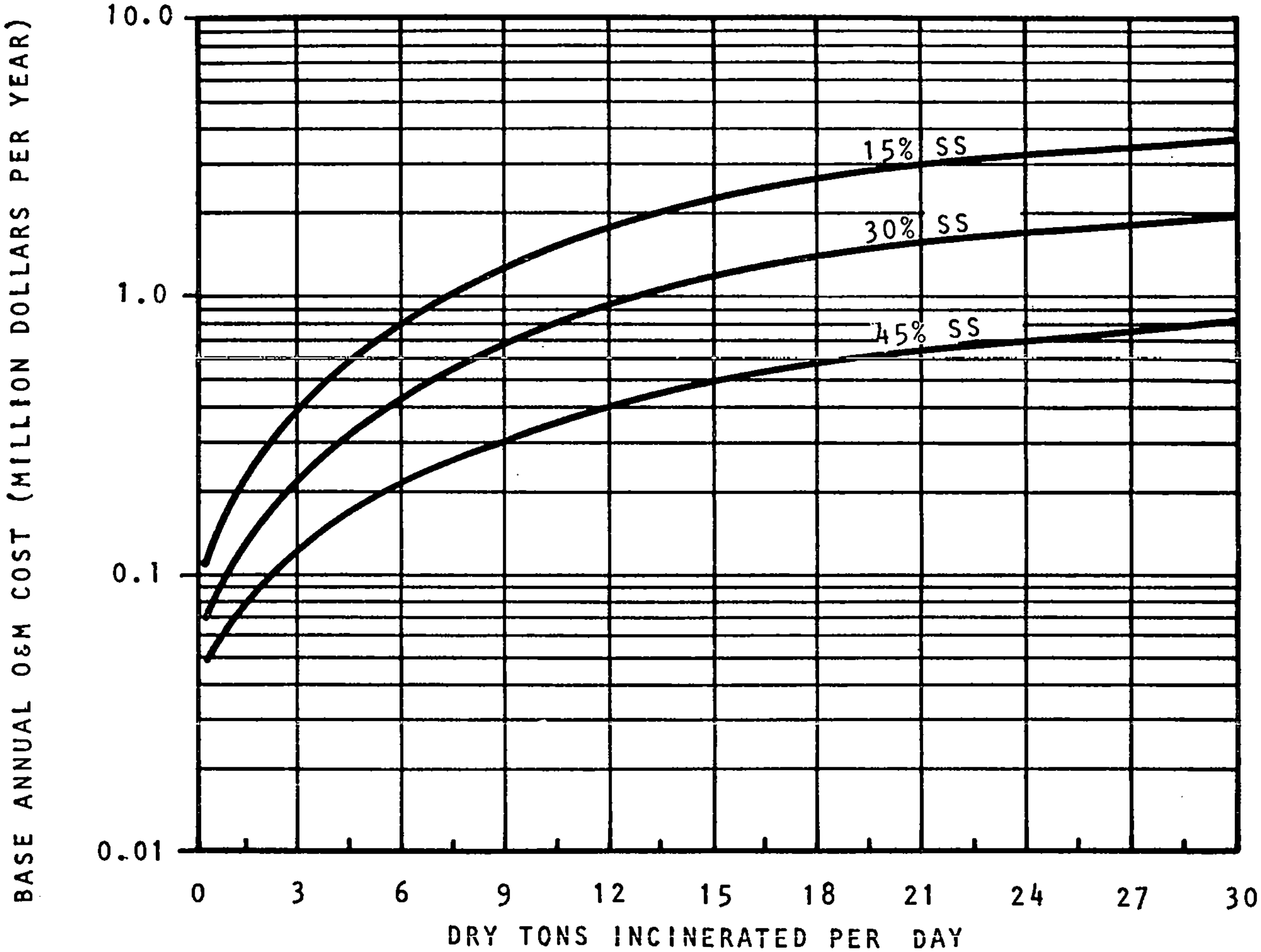


FIGURE 7-3

ANNUAL O&M REQUIREMENTS FOR FLUIDIZED BED INCINERATION AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS INCINERATED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 7-1.

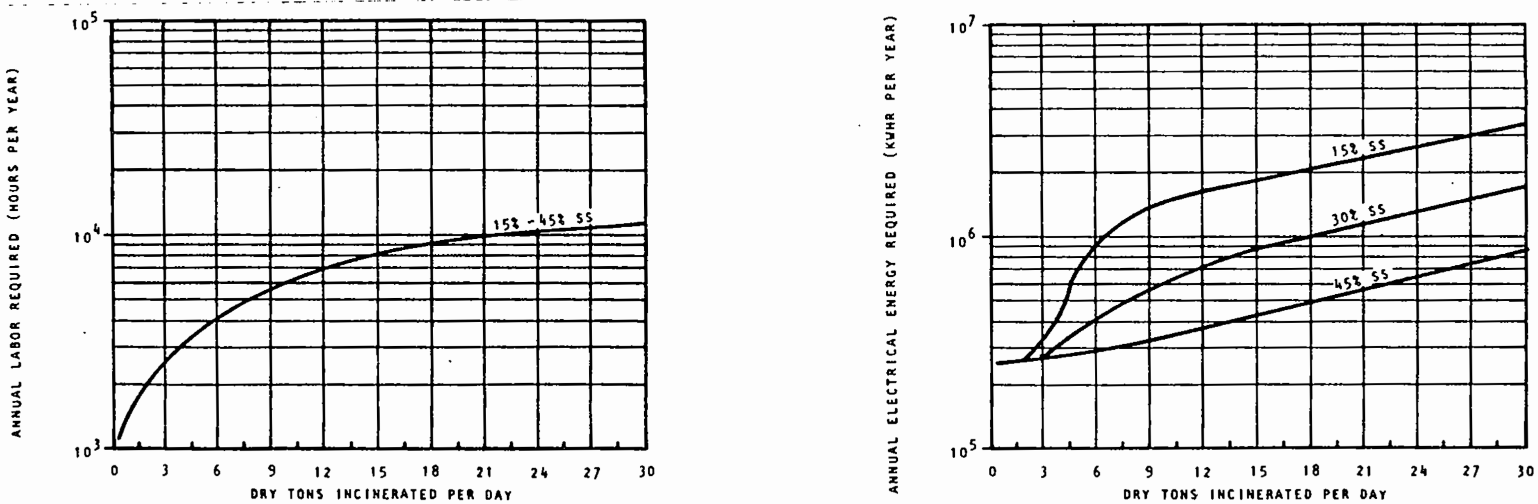
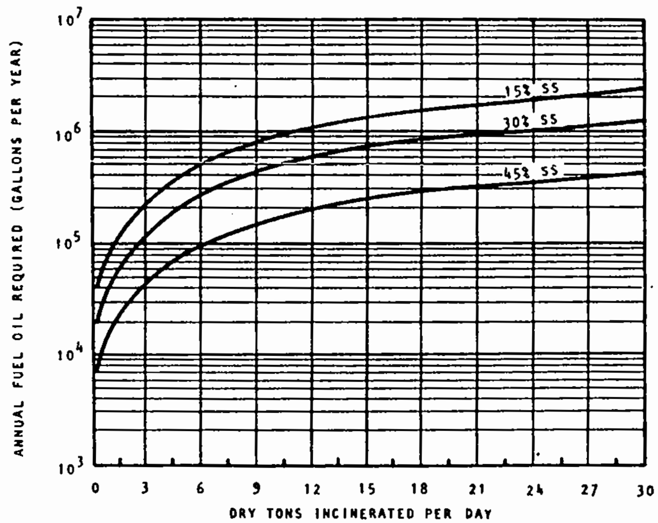


FIGURE 7-3 (CONTINUED)

Assumptions: Design parameters are the same as for Figure 7-1.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.



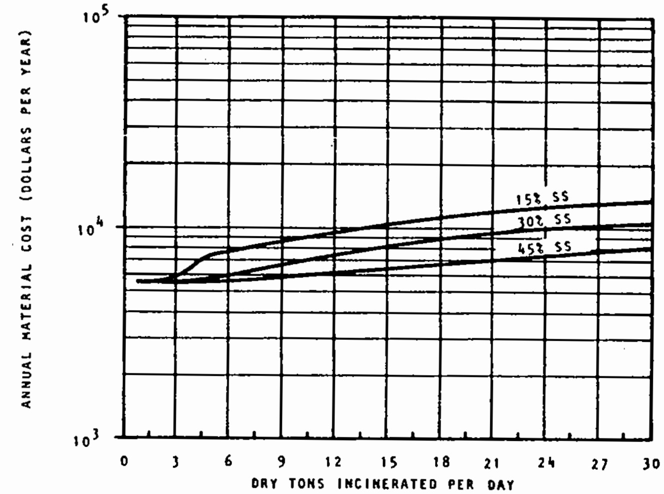


FIGURE 7-4

BASE CAPITAL COST OF MULTIPLE HEARTH INCINERATION AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS INCINERATED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Loading rate = 6 lb wet sludge/hr/sq ft; operating temperature = 1,100° F; sludge solids are 70 percent volatile; process operates 24 hours per day, 360 days per year.

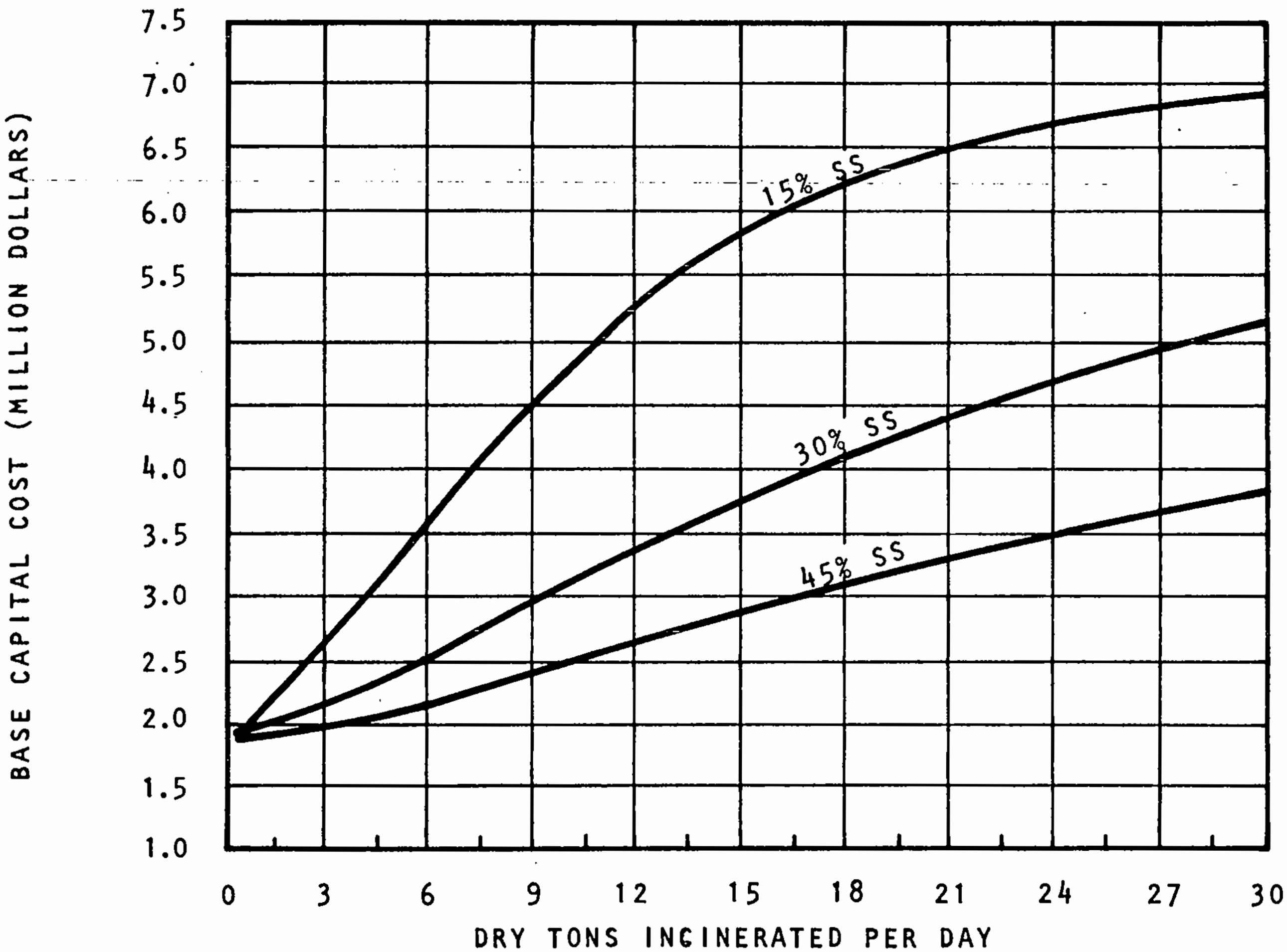


FIGURE 7-5

BASE ANNUAL O&M COST OF MULTIPLE HEARTH INCINERATION AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS INCINERATED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 7-4; labor cost = $13.50/hr; cost of electricity = $0.094/kWhr; cost of diesel fuel = $1.35/gal.

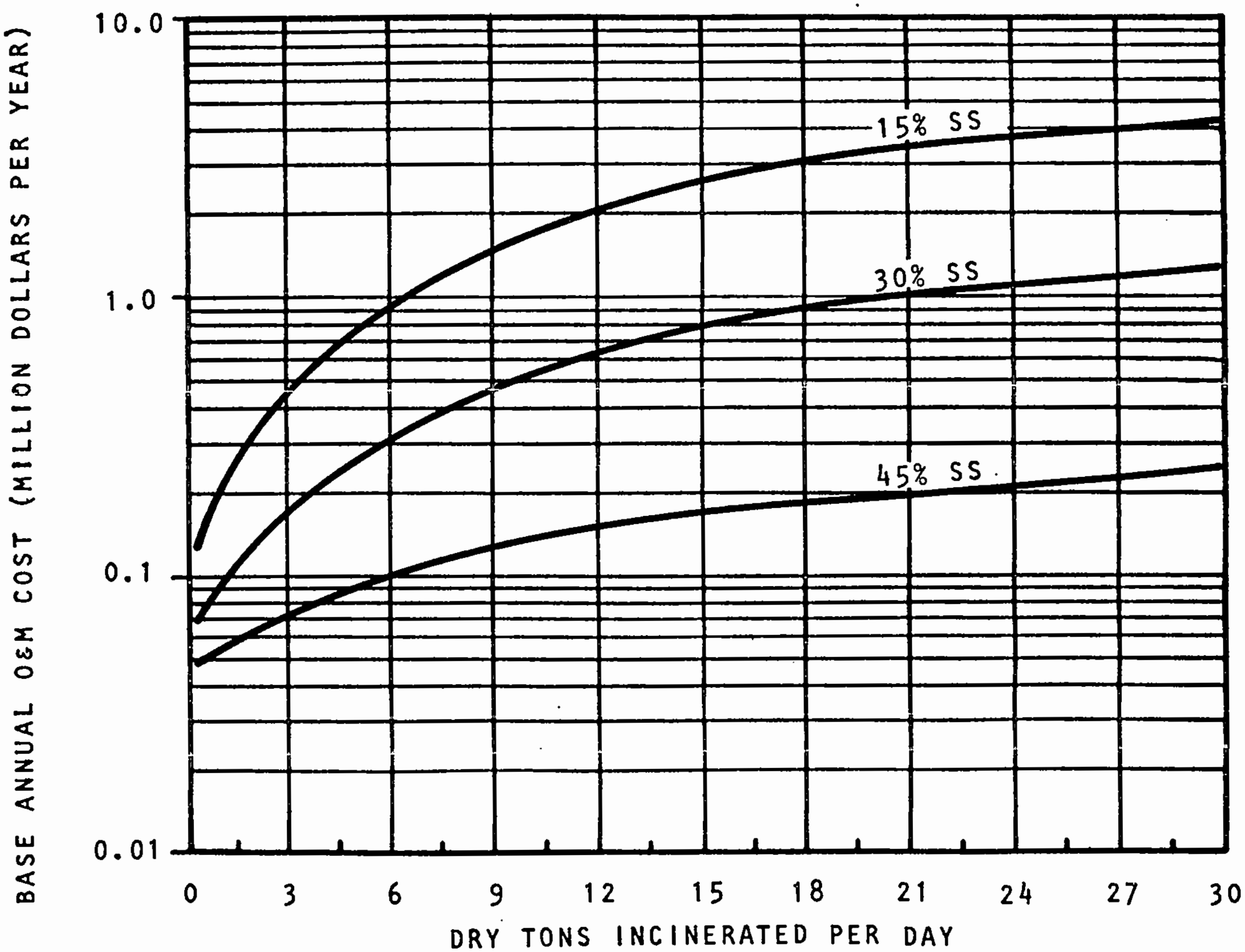
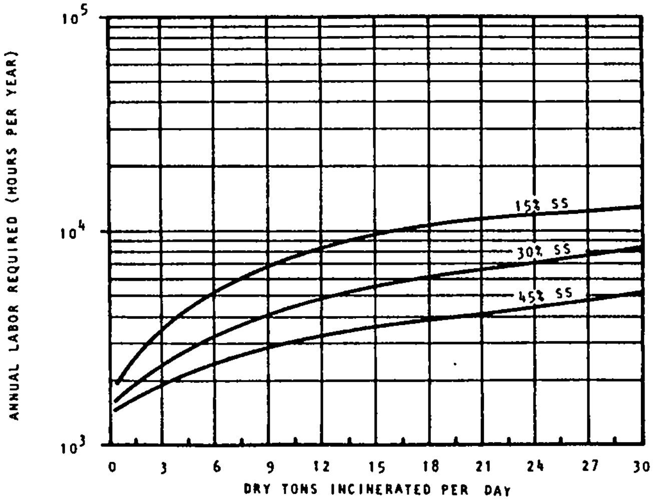


FIGURE 7-6

ANNUAL O&M REQUIREMENTS FOR MULTIPLE HEARTH INCINERATION AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS INCINERATED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design parameters are the same as for Figure 7-4.



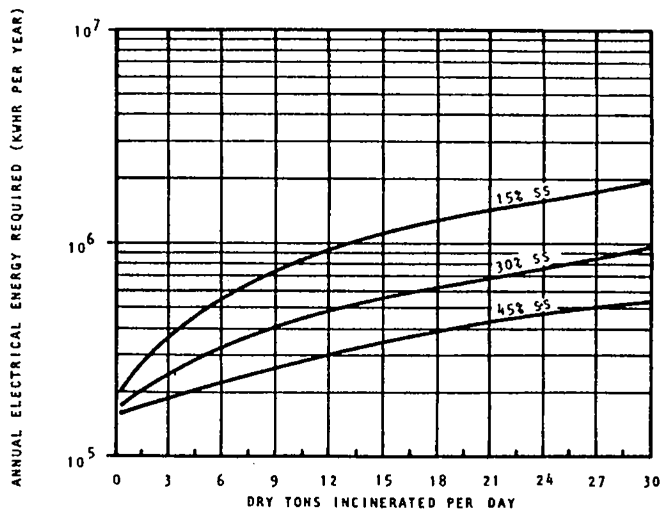
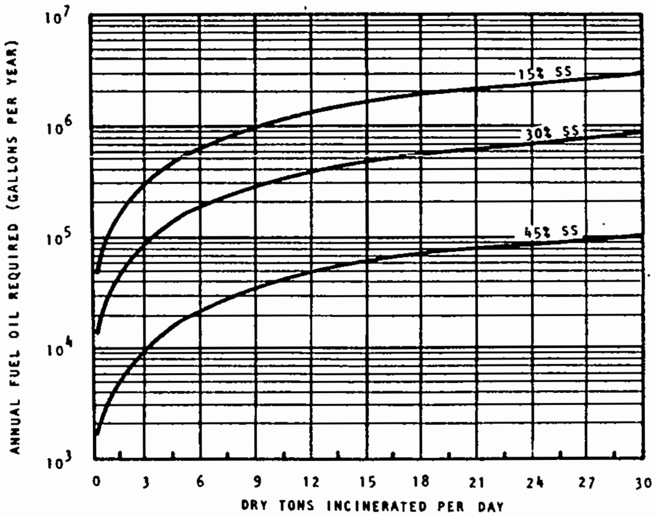
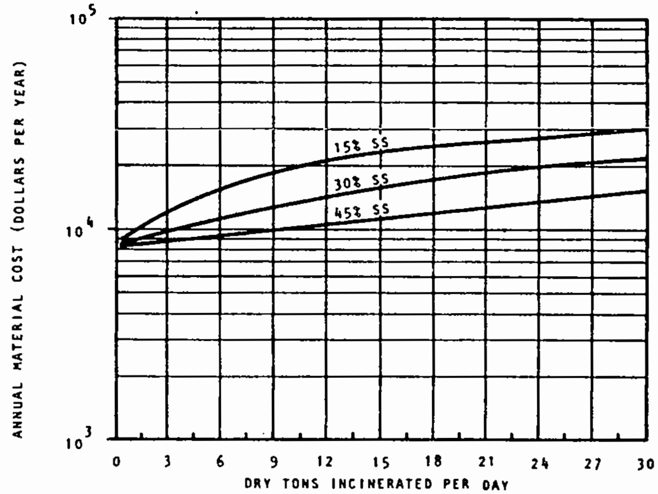


FIGURE 7-6 (CONTINUED)

Assumptions: Design parameters are the same as for Figure 7-4.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.





SECTION 8

SLUDGE COMPOSTING CURVES

8.1 Introduction

This section presents capital and annual operating and maintenance curves for two sludge composting methods: (a) windrows and (b) aerated static piles. Also included are figures for both composting methods which show land area and O&M requirements as a function of the quantity of dry sludge solids composted annually.

Composting is the thermophilic biological decomposition of organic matter in sludge to yield a relatively stable humus-like material. Dewatered sludges are prepared for composting by mixing with a bulking agent to achieve a solids content of approximately 40 percent, and a porous structure. The bulking agent usually helps remove moisture and makes the mixture more manageable. Typically, previously composted sludge, sawdust, or rice hulls are used as the bulking agent in the windrow process; and wood chips, rice hulls, or straw can serve as bulking agents in aerated static pile composting. Previously composted sludge is not a suitable bulking agent for aerated static pile composting, since a more substantial bulking agent is required to provide porosity, which allows air to be drawn through the pile. In the windrow process, frequent turning of the windrow accomplishes aeration. Therefore, porosity is not as critical, and the bulking agent choice is more flexible.

Approximately 20 to 30 percent of the volatile solids are converted to carbon dioxide and water. If properly operated, high temperatures achieved during composting can result in the destruction of virtually all pathogens and parasites. A potential for regrowth does exist, however. Although volatile solids and water are removed during processing, the total compost volume is generally greater due to added bulking agent and lower density of the compost product.

The cost of land for the composting facility is included in the capital cost for both composting processes. The procedure for adjusting the curve capital costs to account for an actual land cost which is different from that assumed is presented in Subsection 8.4.

8.2 Windrow Composting

In windrow composting, prepared sludges are spread on paved areas in windrows with an approximately triangular or trapezoidal cross sectional area of 35 ft^2. Windrows are 300 ft long, or less for small plants. Windrows are mechanically turned (daily for the first 2 weeks and three times per week thereafter) to maintain aerobic conditions over the composting period of about 30 days.

Capital costs, O&M costs, and O&M requirements presented in Figures 8-1 through 8-3 are based on the algorithm presented in Appendix A-18. The algorithm assumes that previously composted sludge is used as the bulking agent. Additional assumptions used in developing cost curves are noted in Table 8-1. Detailed information on cost algorithm development, design parameters, and other assumptions used in obtaining costs is provided in Appendix A-18. The user should use the algorithm if conditions are significantly different from the assumptions noted in Table 8-1. A land area requirement curve used for adjusting capital costs for land costs different from the assumed value ($3,120/acre) is provided in Figure 8-4. The procedure for adjusting capital costs is presented in Subsection 8.4.

8.3 Aerated Static Pile Composting

Aerated static pile composting is similar in principle to windrow composting. However, in the aerated static pile process, the mixture of dewatered sludge and bulking agent remains stationary; aerobic conditions are maintained using a blower system.

Capital costs, O&M costs, and O&M requirements presented in Figures 8-5 through 8-7 are based on the algorithm presented in Appendix A-19. The algorithm assumes that wood chips are used as the bulking agent. Additional assumptions used in developing cost curves are noted in Table 8-2. Appendix A-19 contains information on cost algorithm development, design parameters, and other assumptions used in obtaining costs. The user should use the algorithm if conditions are significantly different from the assumptions noted in Table 8-2. A land area requirement curve used for adjusting capital costs for land costs different from the assumed value is presented in Figure 8-8.

8.4 Land Cost Adjustment

Because a significant land area is usually required for composting facilities, it is assumed that new land will need to be purchased by the municipality. For this reason, the capital costs presented in the curves for these unit processes include the cost of land at an assumed unit cost of $3,120 per acre. Because land costs are highly variable, the user may desire to change this unit cost and, hence, the unit process capital cost to more accurately fit local costs. This may be accomplished using the following procedure:

Step 1. Calculate the cost of land assumed in the curve cost, CLC, from the following:

$$CLC = TLAR\ (3{,}120)$$

where

CLC = Curve land cost, $.

TLAR = Land area required, acres, obtained from Figure 8-4 or 8-8 as appropriate.

3,120 = Assumed curve land cost, $/acre.

FIGURE 8-1

BASE CAPITAL COST OF WINDROW SLUDGE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design assumptions are listed on Table 8-1.

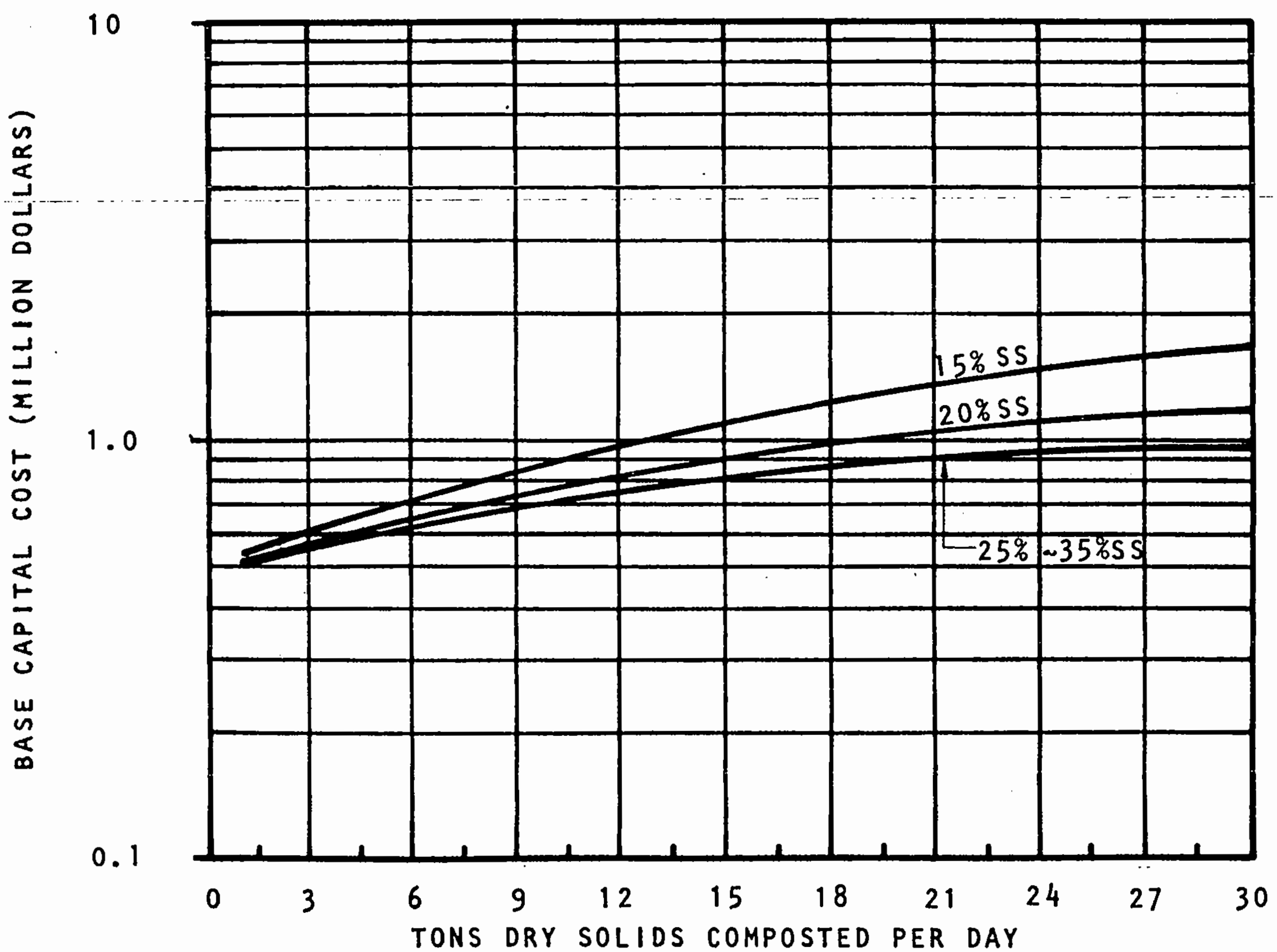


FIGURE 8-2

BASE ANNUAL O&M COST OF WINDROW SLUDGE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design assumptions are listed on Table 8-1.

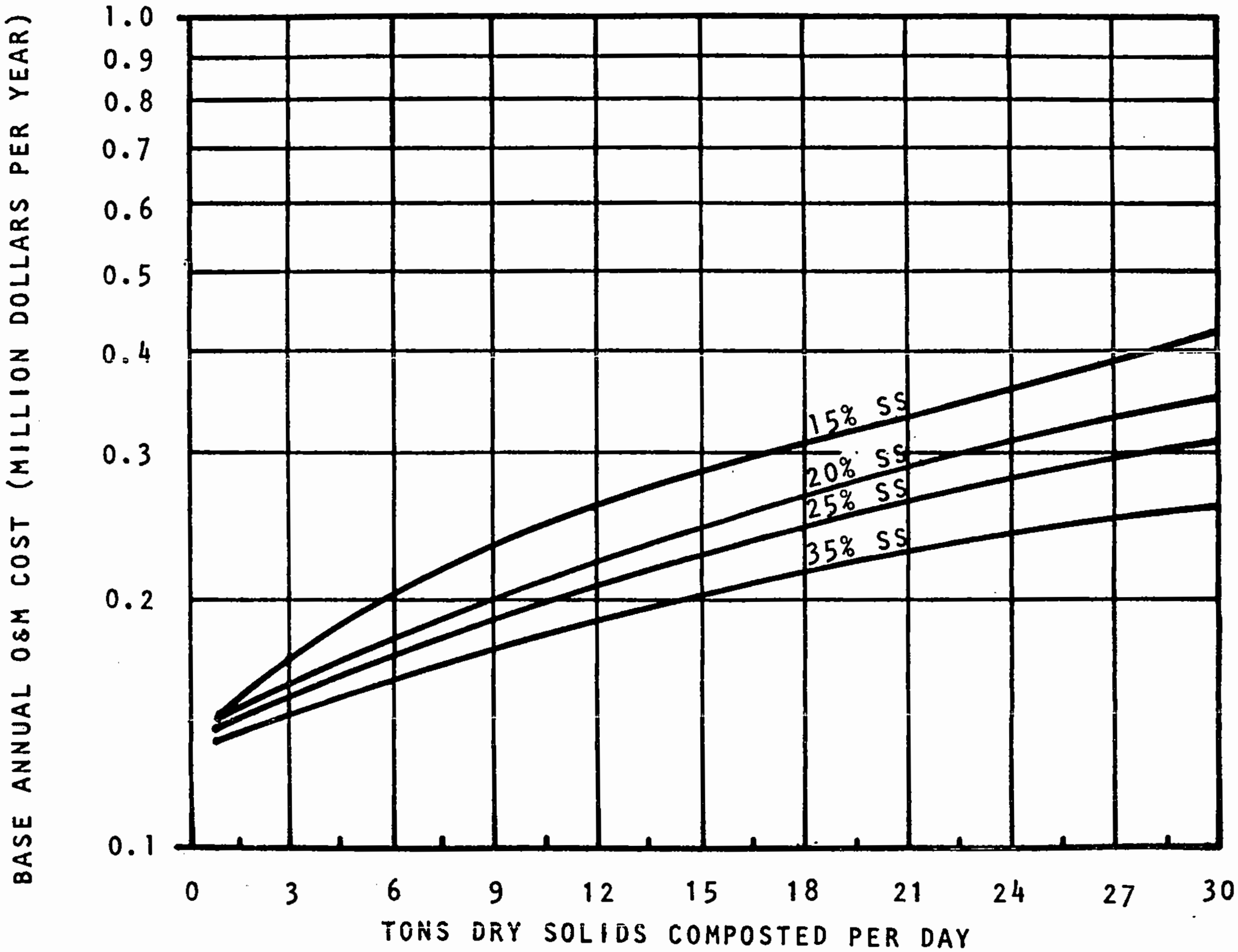
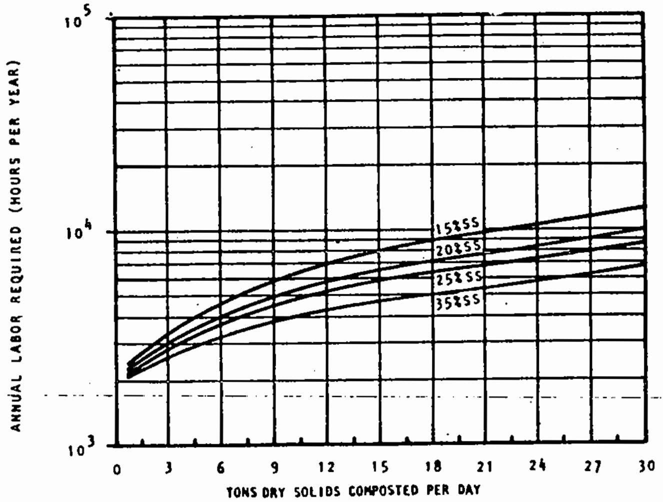
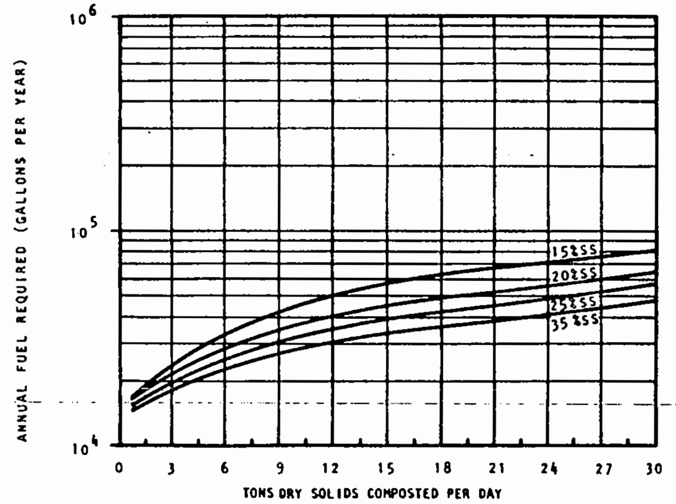
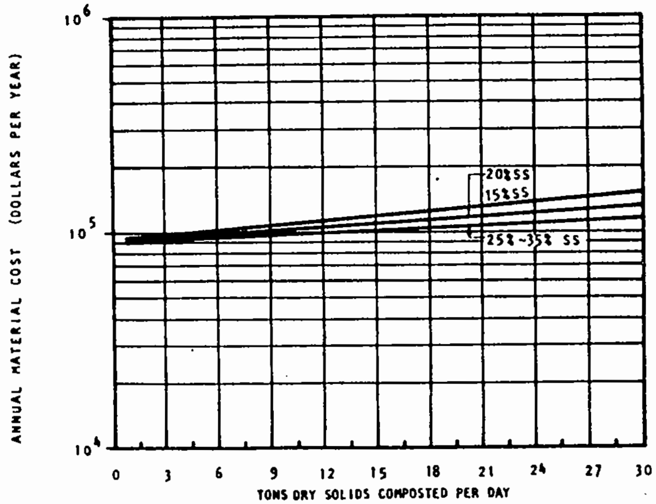


FIGURE 8-3

ANNUAL O&M REQUIREMENTS FOR WINDROW SLUDGE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY AND SLUDGE SOLIDS CONCENTRATION







Assumptions: Design assumptions are listed on Table 8-1.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF PARTS AND MATERIALS.

TABLE 8-1

ASSUMPTIONS USED IN OBTAINING COSTS AND REQUIREMENTS FOR WINDROW COMPOSTING SHOWN IN FIGURES 8-1 THROUGH 8-4

Parameter	Assumed Value
Percent sludge solids in dewatered sludge	20 percent
Percent volatile solids in dewatered sludge solids	35 percent
Percent volatile solids destroyed during composting	30 percent
Percent solids in compost product	65 percent
Dewatered sludge specific weight	1,820 lb/yd^3
Compost product specific weight	865 lb/yd^3
Mixed dewatered sludge and compost specific weight	1,685 lb/yd^3
Windrow cross section	35 ft^2
Windrow length	300 ft
Truck unloading and mixing area	300 ft^2/ton/day dry solids
Finished compost storage area	900 ft^2/ton/day dry solids
Fraction of site requiring clearing (brush and trees)	0.7
Fraction of site requiring light grading	0.3
Fraction of site requiring medium grading	0.4
Fraction of site requiring extensive grading	0.3
Cost of site clearing (brush and trees)	$1,560/acre
Cost of light grading	$1,040/acre
Cost of medium grading	$2,600/acre
Cost of extensive grading	$5,200/acre
Cost of land	$3,120/acre
Cost of diesel fuel	$1.35/gal
Cost of labor	$13.50/hr
Cost of paving	$60,320/acre

FIGURE 8-4

AREA REQUIRED FOR WINDROW SLUDGE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design assumptions are listed on Table 8-1.

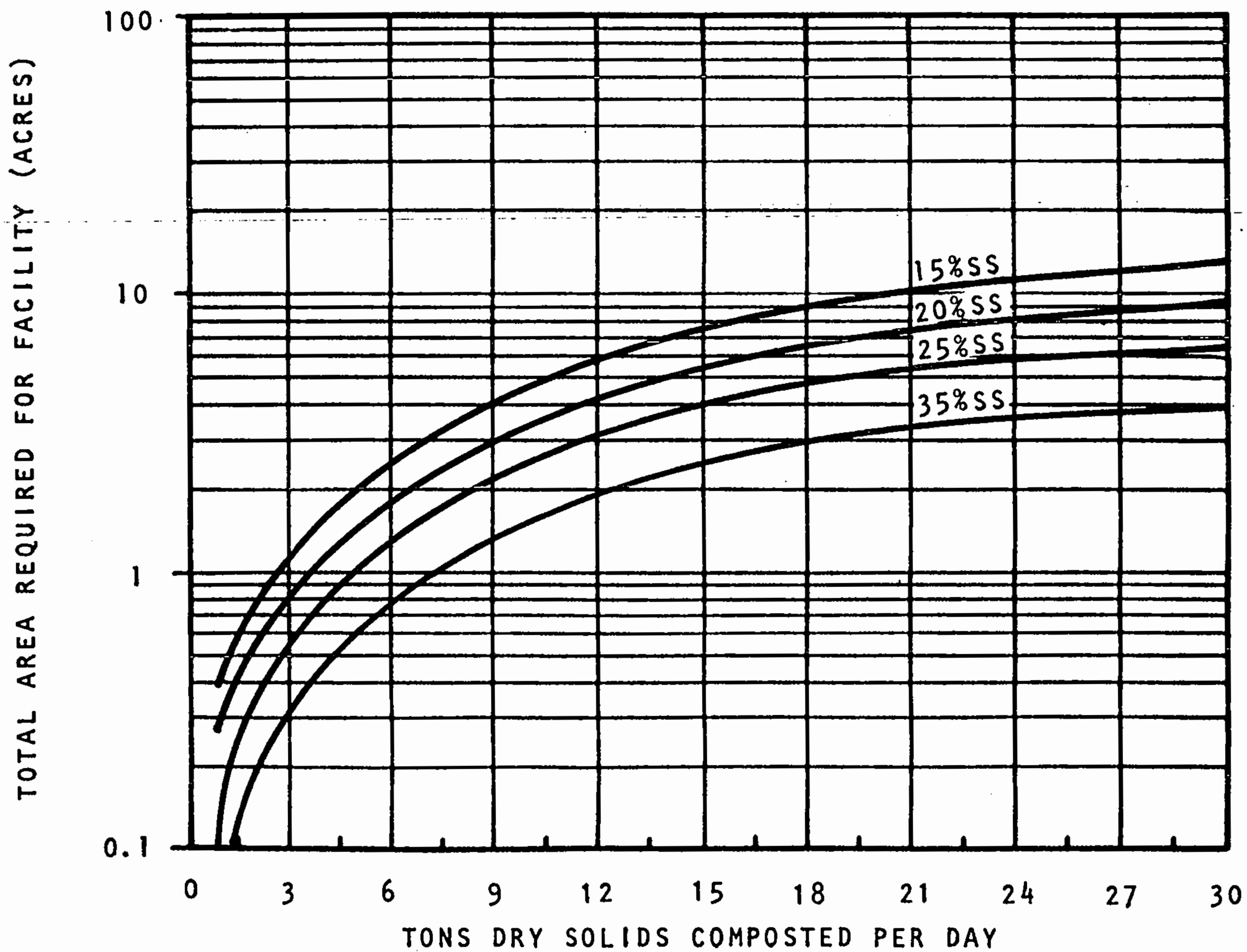


FIGURE 8-5

BASE CAPITAL COST OF AERATED STATIC PILE SLUDGE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: . Design assumptions are listed on Table 8-2.

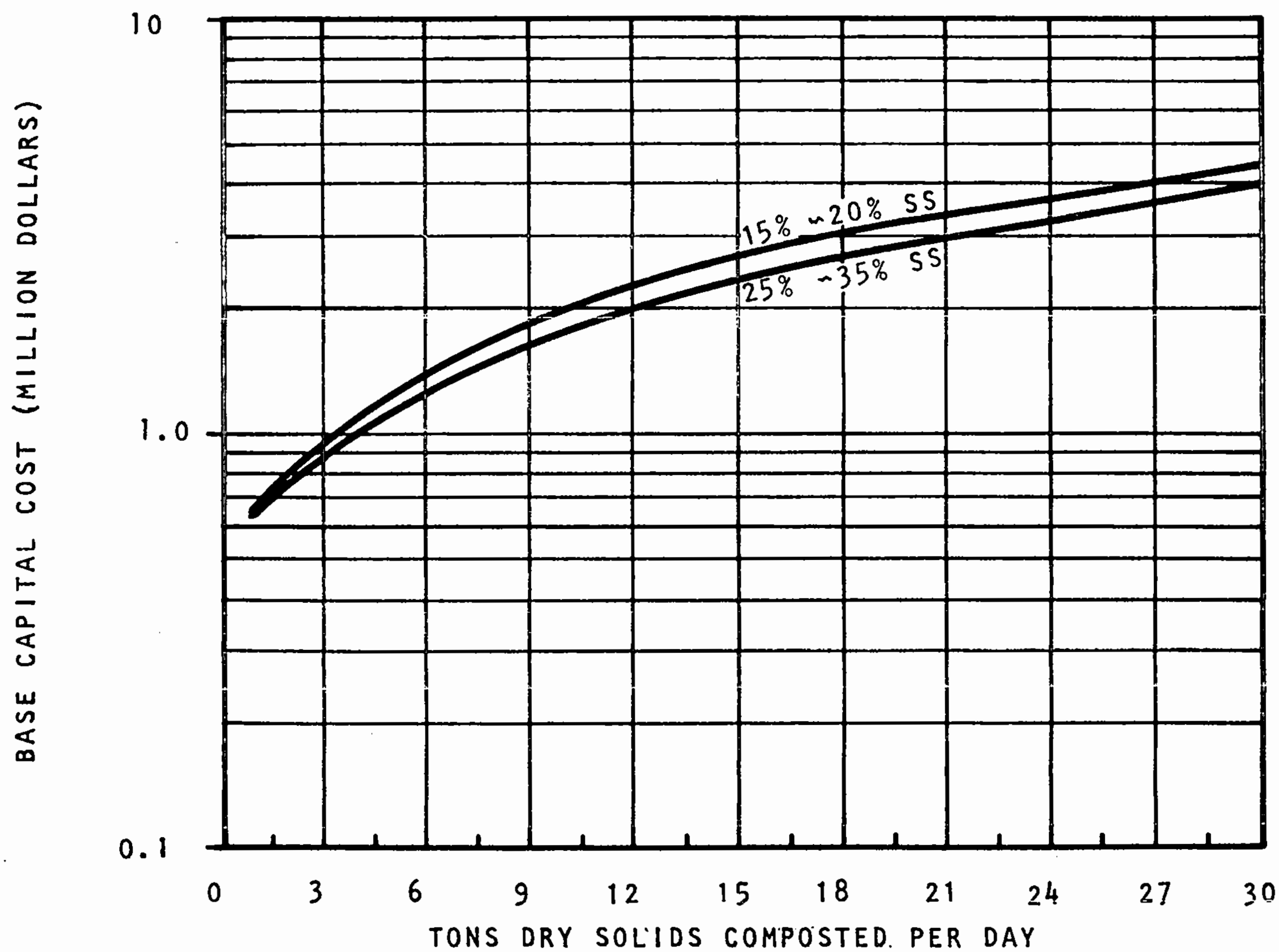


FIGURE 8-6

BASE ANNUAL O&M COST OF AERATED STATIC PILE SLUDGE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY AND SLUDGE SOLIDS CONCENTRATION

Assumptions: Design assumptions are listed on Table 8-2.

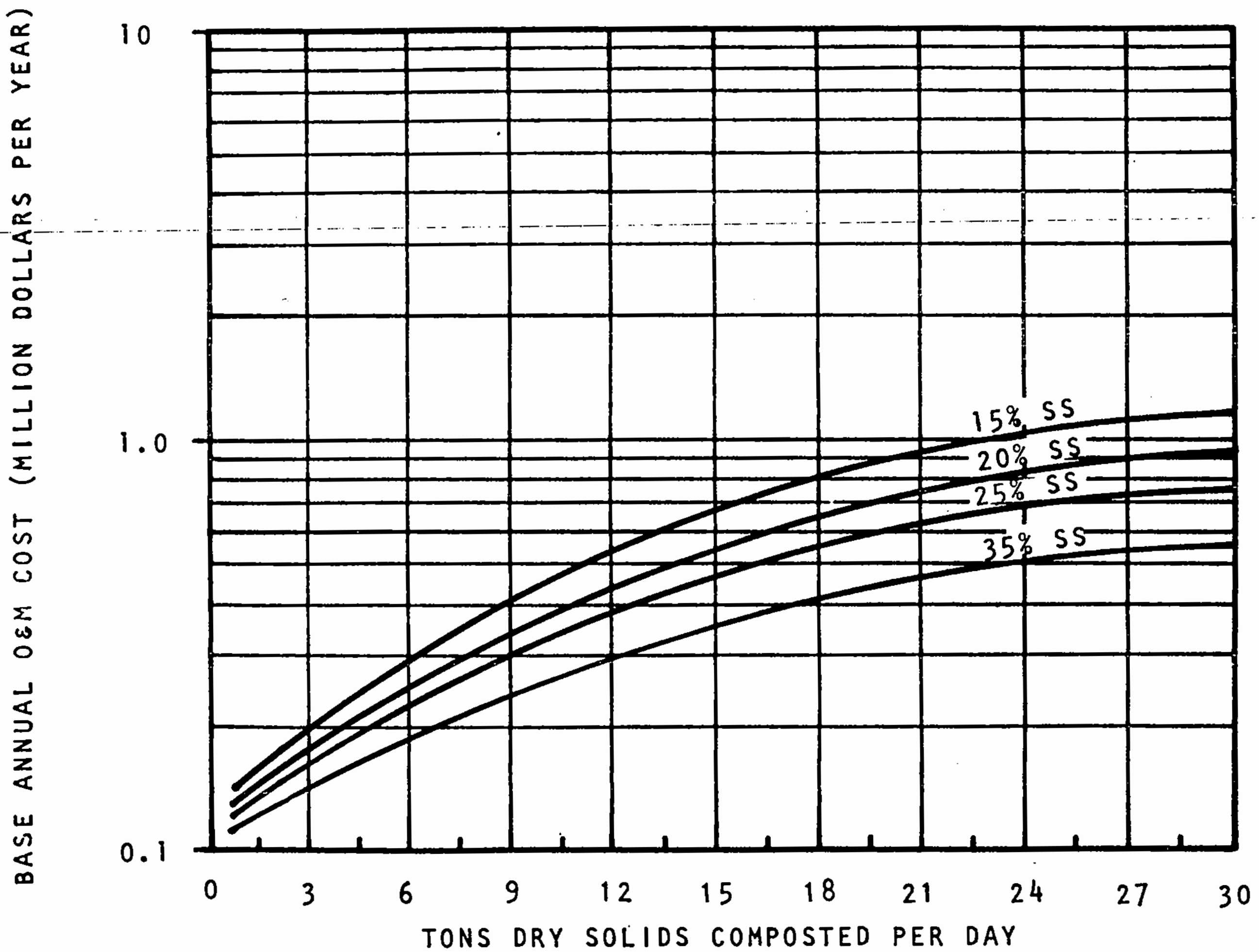
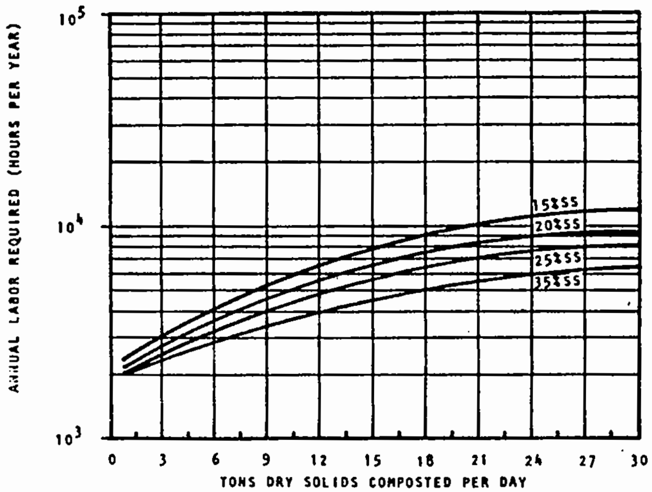
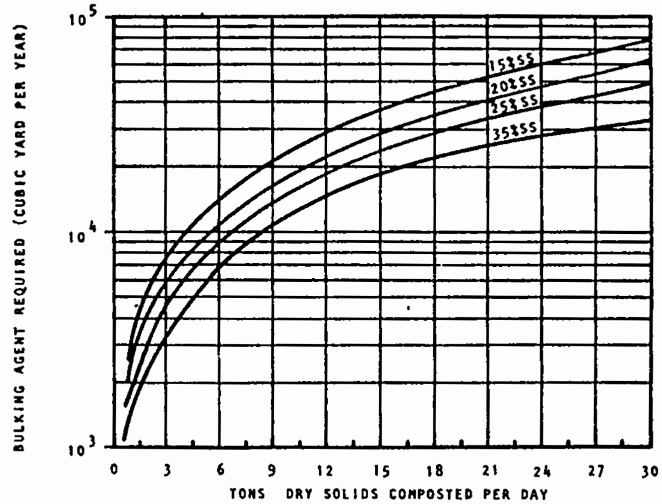
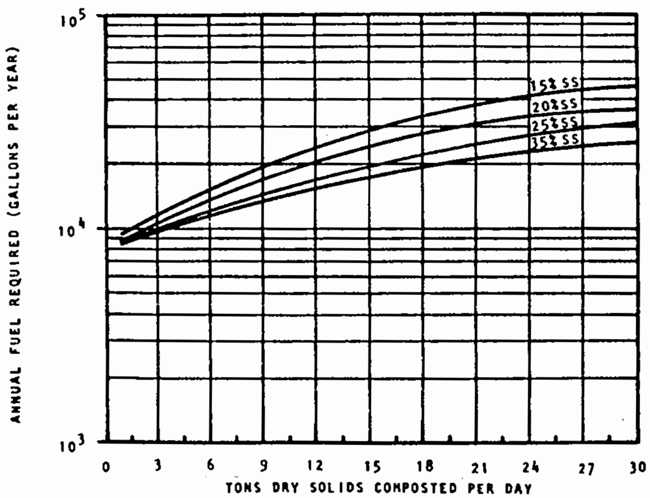


FIGURE 8-7

ANNUAL O&M REQUIREMENTS FOR AERATED STATIC PILE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY AND SLUDGE SOLIDS CONCENTRATION





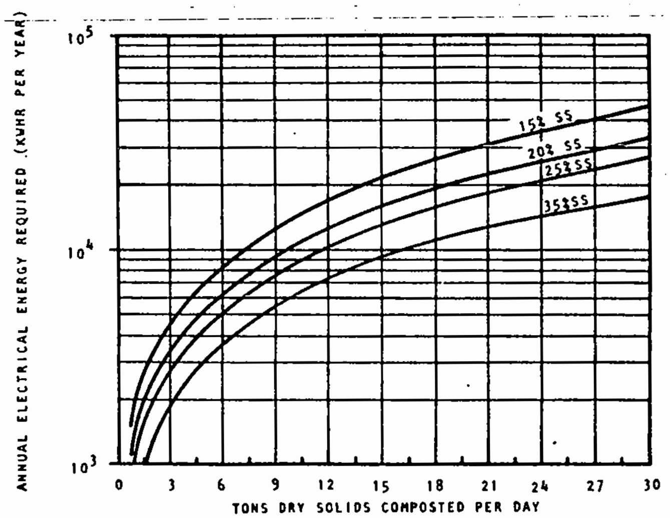


Assumptions: Design parameters are listed on Table 8-2.

FIGURE 8-7 (CONTINUED)

Assumptions: Design parameters are listed on Table 8-2.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF PARTS AND MATERIALS.



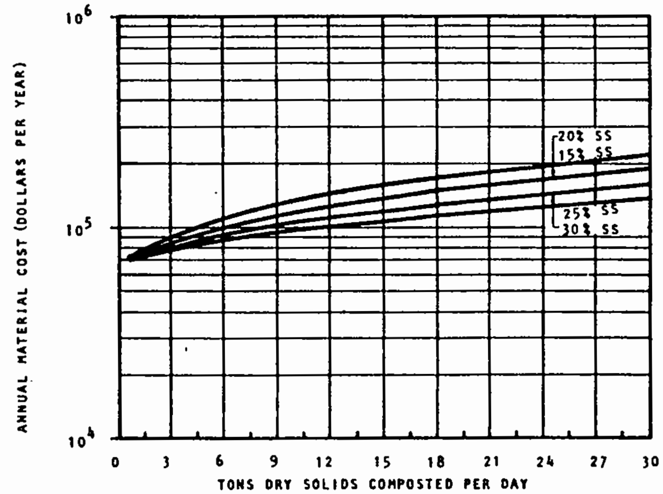


TABLE 8-2

ASSUMPTIONS USED IN OBTAINING COSTS AND REQUIREMENTS FOR AERATED STATIC PILE COMPOSTING SHOWN IN FIGURES 8-5 THROUGH 8-8

Parameter	Assumed Value
Percent sludge solids in dewatered sludge	20 percent
Percent volatile solids in dewatered sludge solids	35 percent
Percent volatile solids destroyed during composting	45 percent
Percent solids in compost product	65 percent
Compost product specific weight	1,000 lb/yd^3
Mixed dewatered sludge and bulking agent specific weight	1,100 lb/yd^3
Bulking agent mixing ratio	2.5 yd^3/ton dewatered sludge
New bulking agent mixing ratio	0.625 yd^3/ton dewatered sludge
New bulking agent specific weight	500 lb/yd^3 dewatered sludge
Recycled bulking agent mixing ratio	1.875 yd^3/ton dewatered sludge
Recycled bulking agent specific weight	600 lb/yd^3
Truck unloading and mixing area	300 ft^2/ton/day dry solids
Composting area	7,000 ft^2/ton/day dry solids
Drying area	3,000 ft^2/ton/day dry solids
Finished compost storage area	900 ft^2/ton/day dry solids
Bulking agent storage area	2,000 ft^2/ton/day dry solids
Fraction of site requiring clearing	0.7
Fraction of site requiring light grading	0.3
Fraction of site requiring medium grading	0.4
Fraction of site requiring extensive grading	0.3

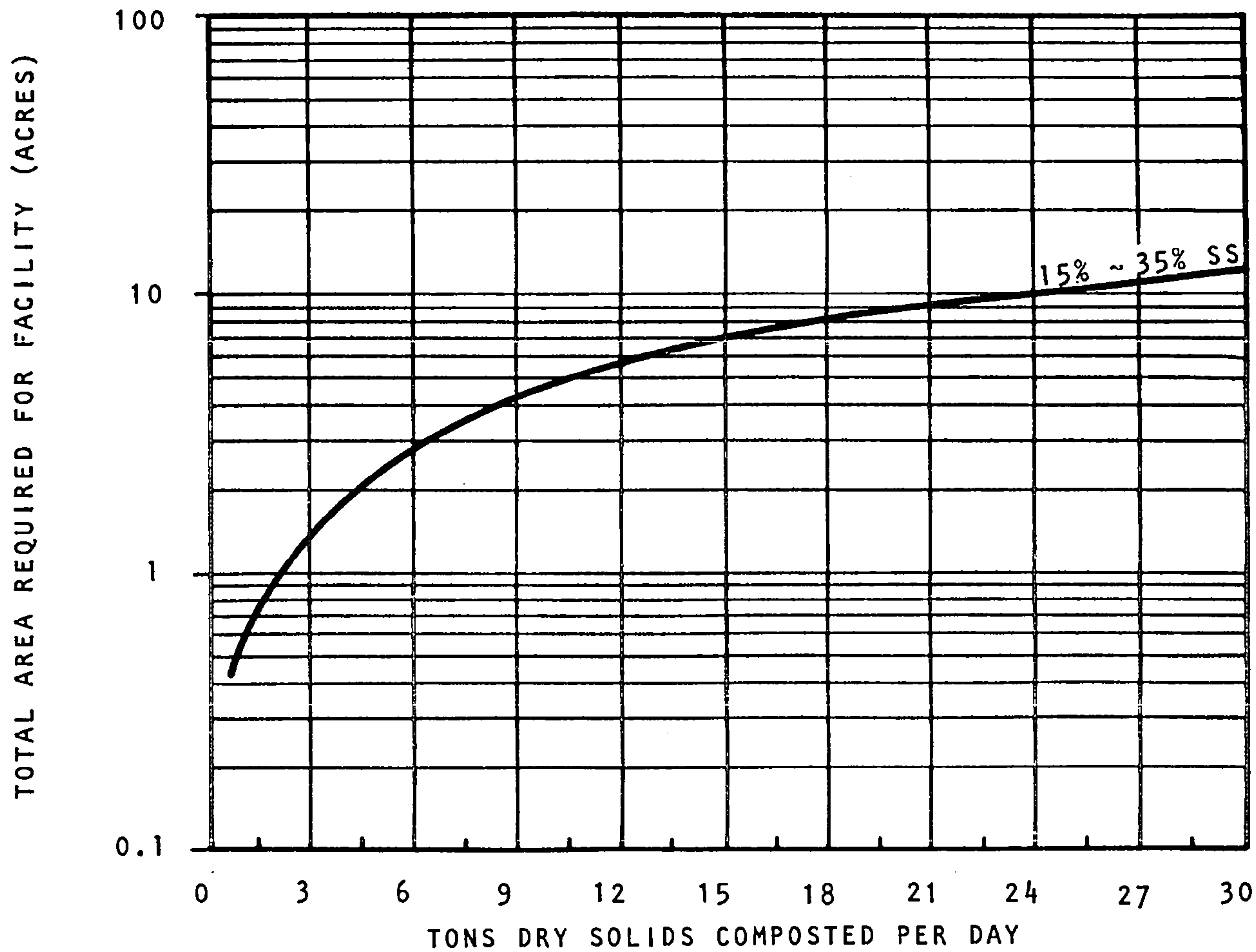
Table 8-2 (continued)

Parameter	Assumed Value
Cost of site clearing	\$1,560/acre
Cost of light grading	\$1,040/acre
Cost of medium grading	\$2,600/acre
Cost of extensive grading	\$5,200/acre
Cost of land	\$3,120/acre
Cost of diesel fuel	\$1.35/gal
Cost of electricity	\$0.094/kWhr
Cost of labor	\$13.50/hr
Cost of paving	\$3.15/ft^2

FIGURE 8-8

AREA REQUIRED FOR AERATED STATIC PILE SLUDGE COMPOSTING AS A FUNCTION OF THE WEIGHT OF DRY SLUDGE SOLIDS COMPOSTED DAILY

Assumptions: Design parameters are listed on Table 8-2.



Step 2. Calculate the actual cost of land, CLA, from the following:

$$CLA = TLAR\ (LANDCST)$$

where

CLA = Actual cost of land, $.
LANDCST = Actual unit cost of land, $/acre.

Step 3. Adjust the curve capital cost to reflect actual land cost using the following:

$$ACC = CCC - CLC + CLA$$

where

ACC = Adjusted curve capital cost, $.
CCC = Unadjusted curve capital cost, $.

SECTION 9

SLUDGE TRANSPORT CURVES

9.1 Introduction

This section presents capital and annual O&M curves for four commonly accepted means of sludge transportation: truck hauling, rail hauling, barge hauling, and pipelines. Truck hauling is further subdivided into (a) liquid sludge hauling and (b) dewatered sludge hauling. Pipeline sludge transportation is divided into (a) pipelines and (b) ocean outfalls. Obviously, ocean outfalls constitute not only a means of sludge transportation, but also of disposal.

9.2 Truck Hauling

Truck hauling of sludge is a method of transportation widely used at small- and medium-size treatment facilities. The principal advantages of truck transport include its relatively low capital cost when compared with other modes of transportation, and the flexibility it provides since terminal points and haul routes can be readily changed.

Capital costs and O&M costs and other requirements are presented in Figures 9-1 through 9-3 for liquid sludge truck transport, and in Figures 9-4 through 9-6 for dewatered sludge truck transport. Costs and requirements are based on the cost algorithms in Appendices A-20 and A-21 for liquid sludge truck transport and dewatered sludge truck transport, respectively. Assumptions used in developing cost curves are noted on the curves. Additional information on cost algorithm development, design parameters, and other assumptions can be obtained by referring to the respective appendices.

9.2.1 Capital Cost Multiplication Factor Curve

In the truck haul of sludge, it is assumed that the municipality purchases the haul trucks and has them available regardless of the number of days per year (DPY) that sludge is hauled. For example, if sludge is hauled only 100 days per year, it is assumed that the haul trucks are idle the remaining 265 days each year. Since all of the sludge generated each year must be hauled, a decrease in the number of annual days that sludge is hauled requires that more trucks are purchased; conversely, an increase in the number of annual days that sludge is hauled requires the purchase of fewer trucks.

The capital cost curves in Figures 9-1 and 9-4 are based on 200 days per year of sludge truck hauling. To adjust for differences in the number of days per year that sludge is actually hauled, the user should multiply the curve capital cost shown in Figure 9-1 or 9-4 by the appropriate factor taken from the curves in Figure 9-7.

FIGURE 9-1

BASE CAPITAL COST OF LIQUID SLUDGE TRUCK HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Truck loading time = 0.4 hr; truck unloading time = 0.4 hr; trucks average 30 mph for 20-, 50-, and 100-mile hauls, 40 mph for 200- and 400-mile hauls; work schedule is 7 hr/day, 200 days/yr (see Figure 9-7 for days per year adjustment factor).

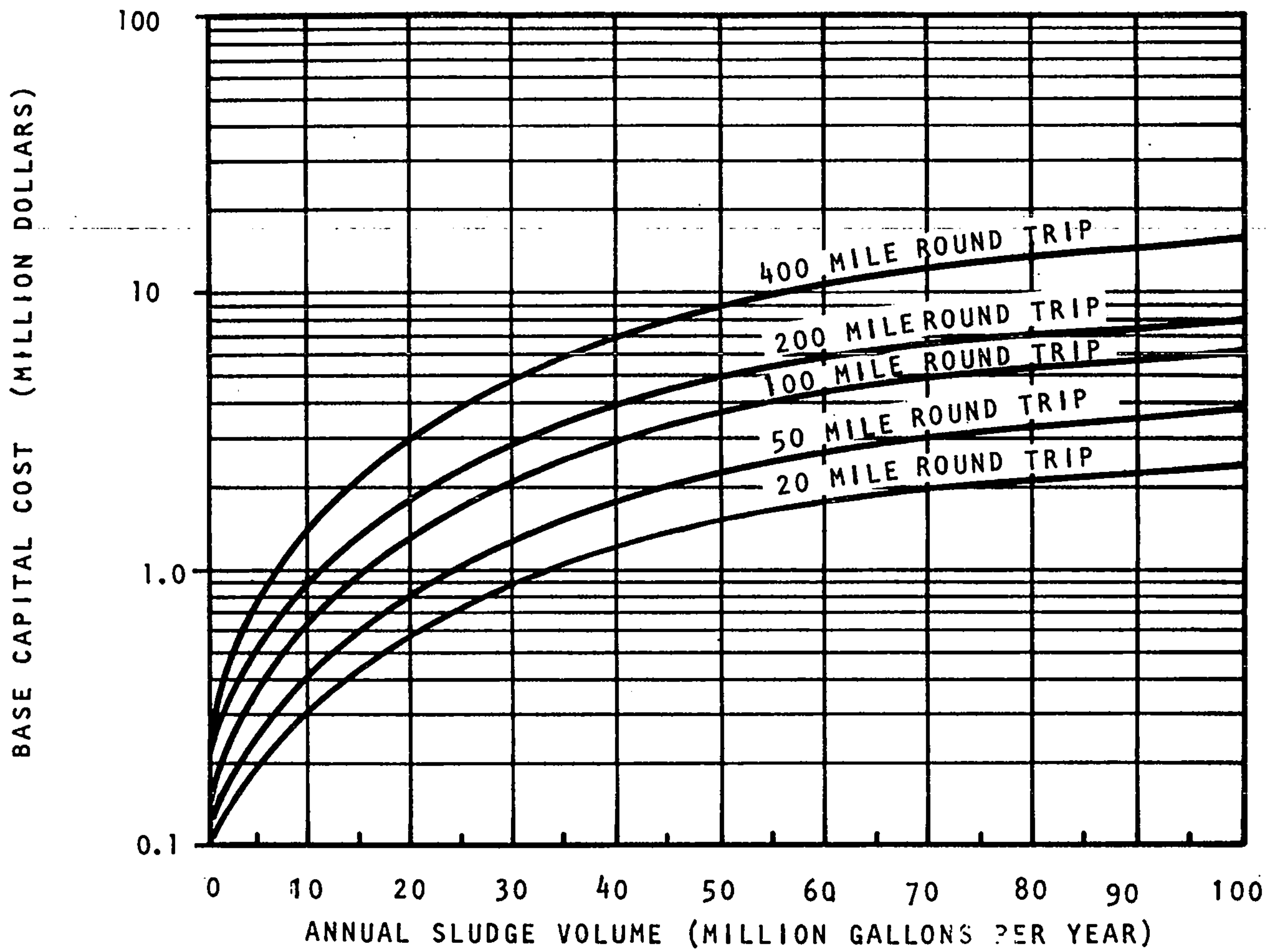


FIGURE 9-2

BASE ANNUAL O&M COST FOR LIQUID SLUDGE TRUCK HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Design parameters are the same as for Figure 9-1; cost of diesel fuel = \$1.35/gal; cost of labor = \$13.50/hr.

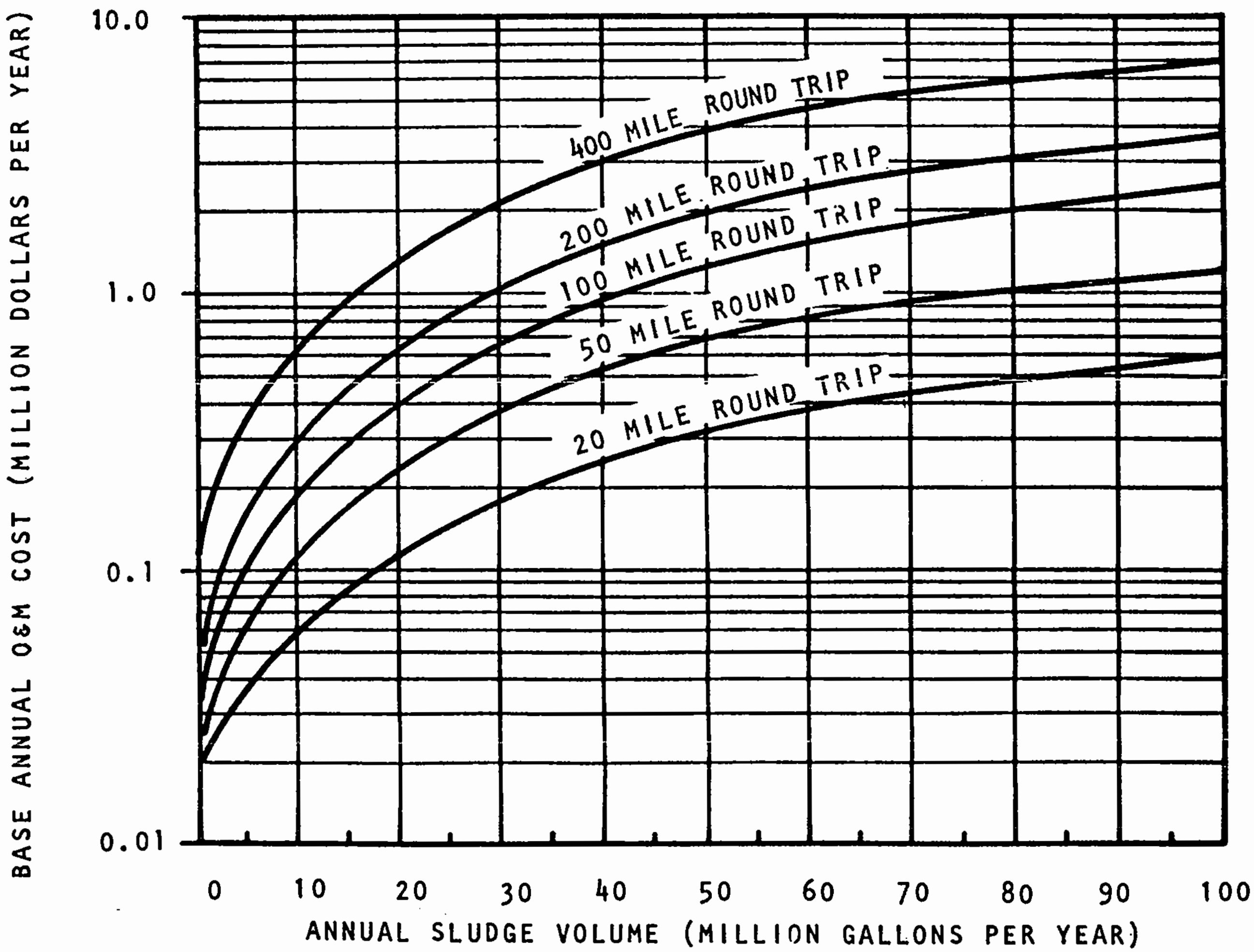
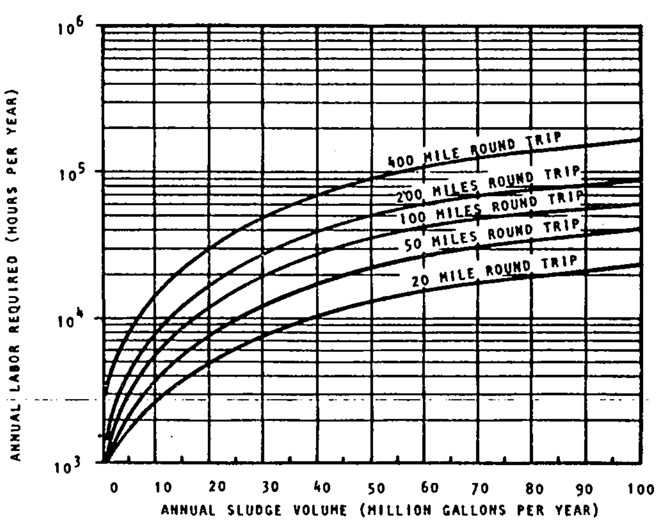
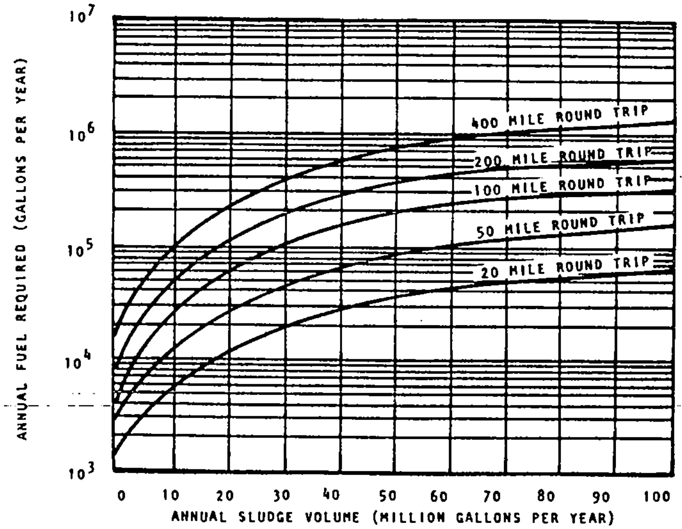
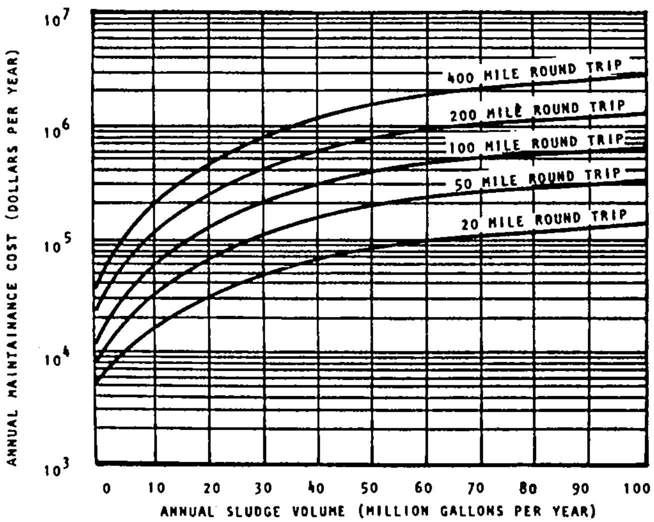


FIGURE 9-3

ANNUAL O&M REQUIREMENTS FOR LIQUID SLUDGE TRUCK HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE







Assumptions: Design parameters are the same as for Figure 9-1.

FIGURE 9-4

BASE CAPITAL COST OF DEWATERED SLUDGE TRUCK HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Truck loading time = 0.4 hr; truck unloading time = 0.4 hr; trucks average 30 mph for 20-, 50-, and 100-mile hauls, 40 mph for 200- and 400-mile hauls; work schedule is 7 hr/day, 200 days/yr (see Figure 9-7 for days per year adjustment factor); volumetric conversions factor: 1 cu yd = approximately 202 gal.

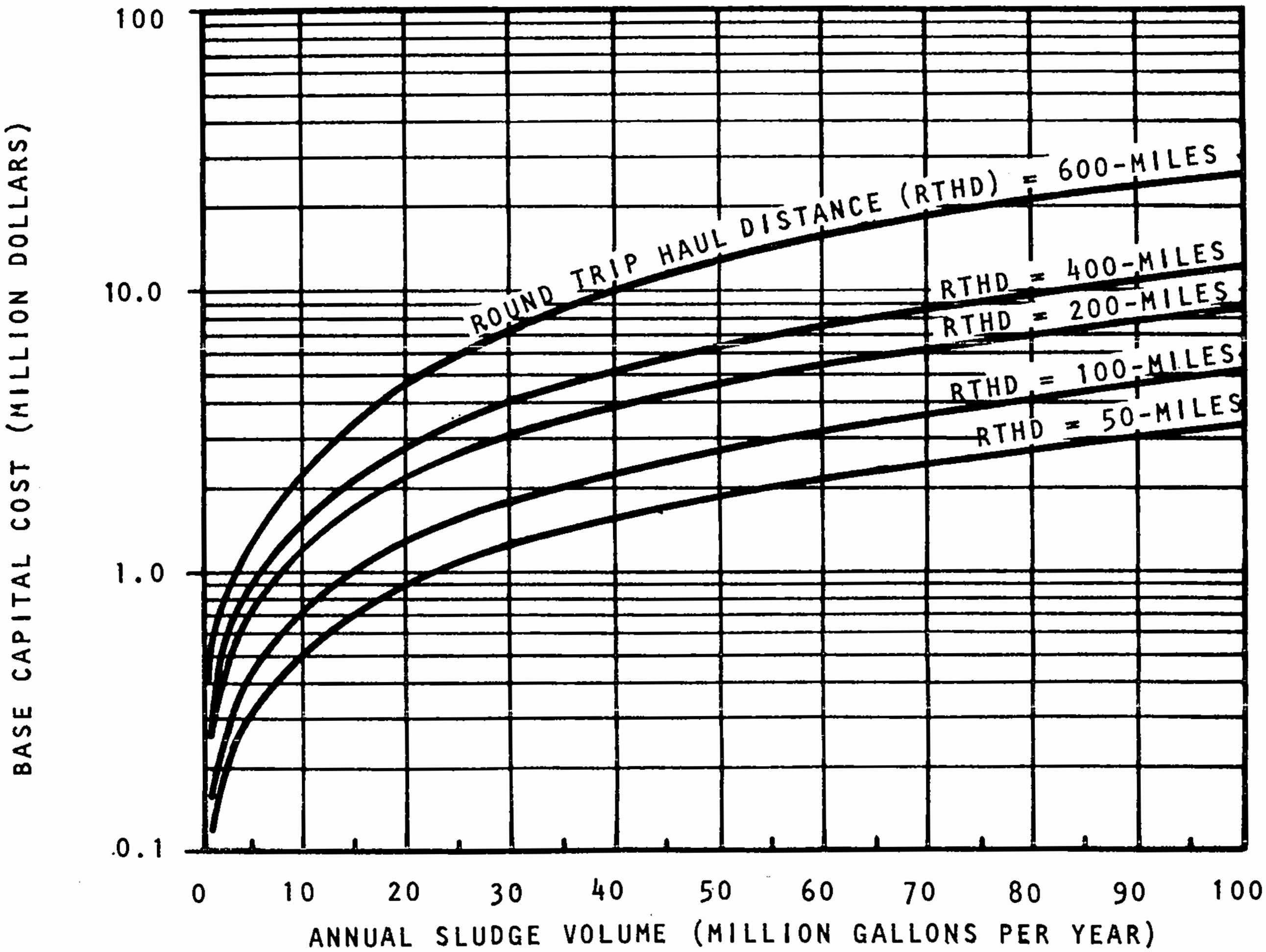


FIGURE 9-5

BASE ANNUAL O&M COST OF DEWATERED SLUDGE TRUCK HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Design parameters are the same as for Figure 9-4; cost of diesel fuel = \$1.35/gal; cost of labor = \$13.50/hr; volumetric conversion factor: 1 cu yd = approximately 202 gal.

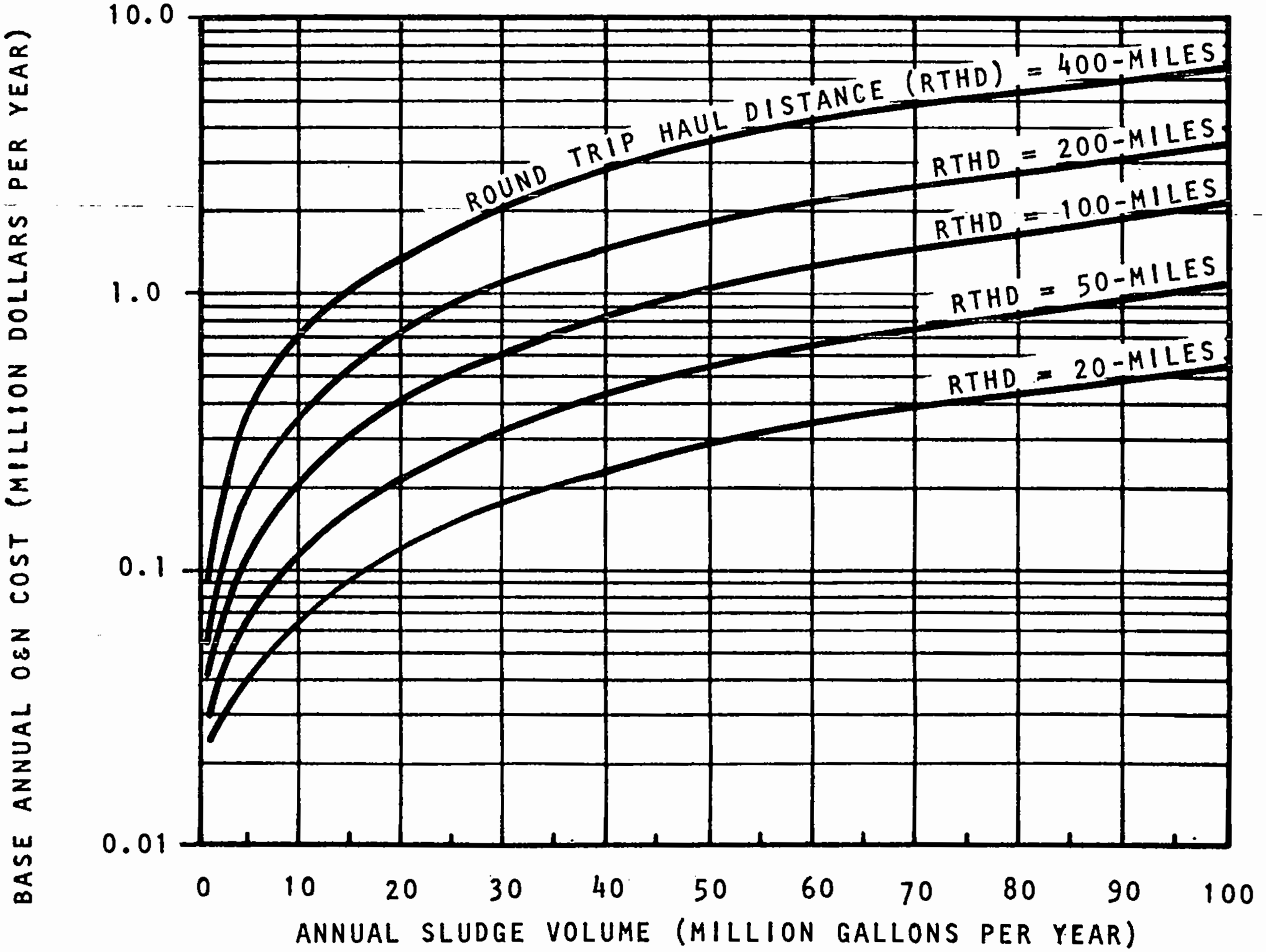
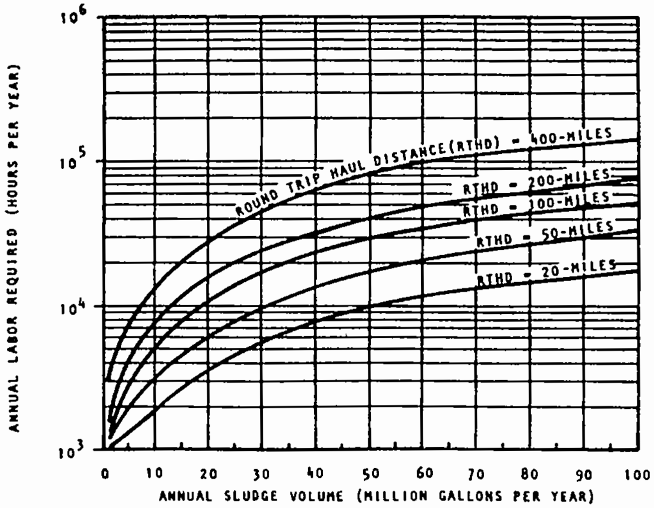
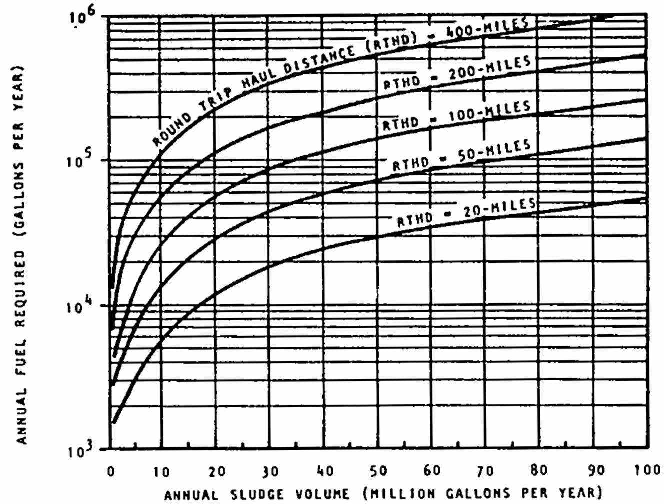
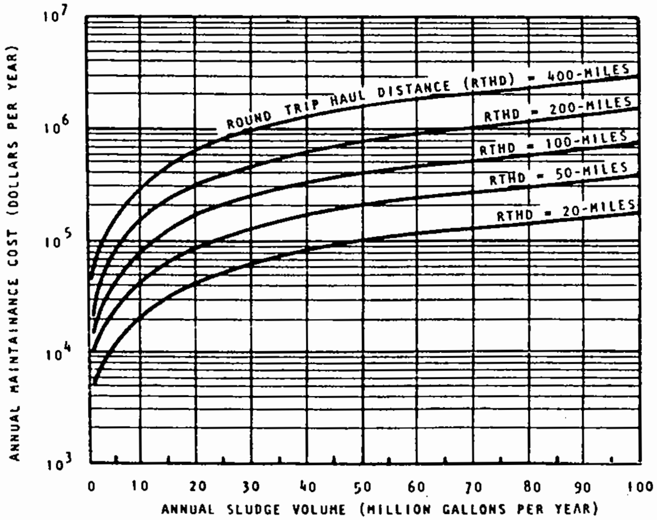


FIGURE 9-6

ANNUAL O&M REQUIREMENTS FOR DEWATERED SLUDGE TRUCK HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE



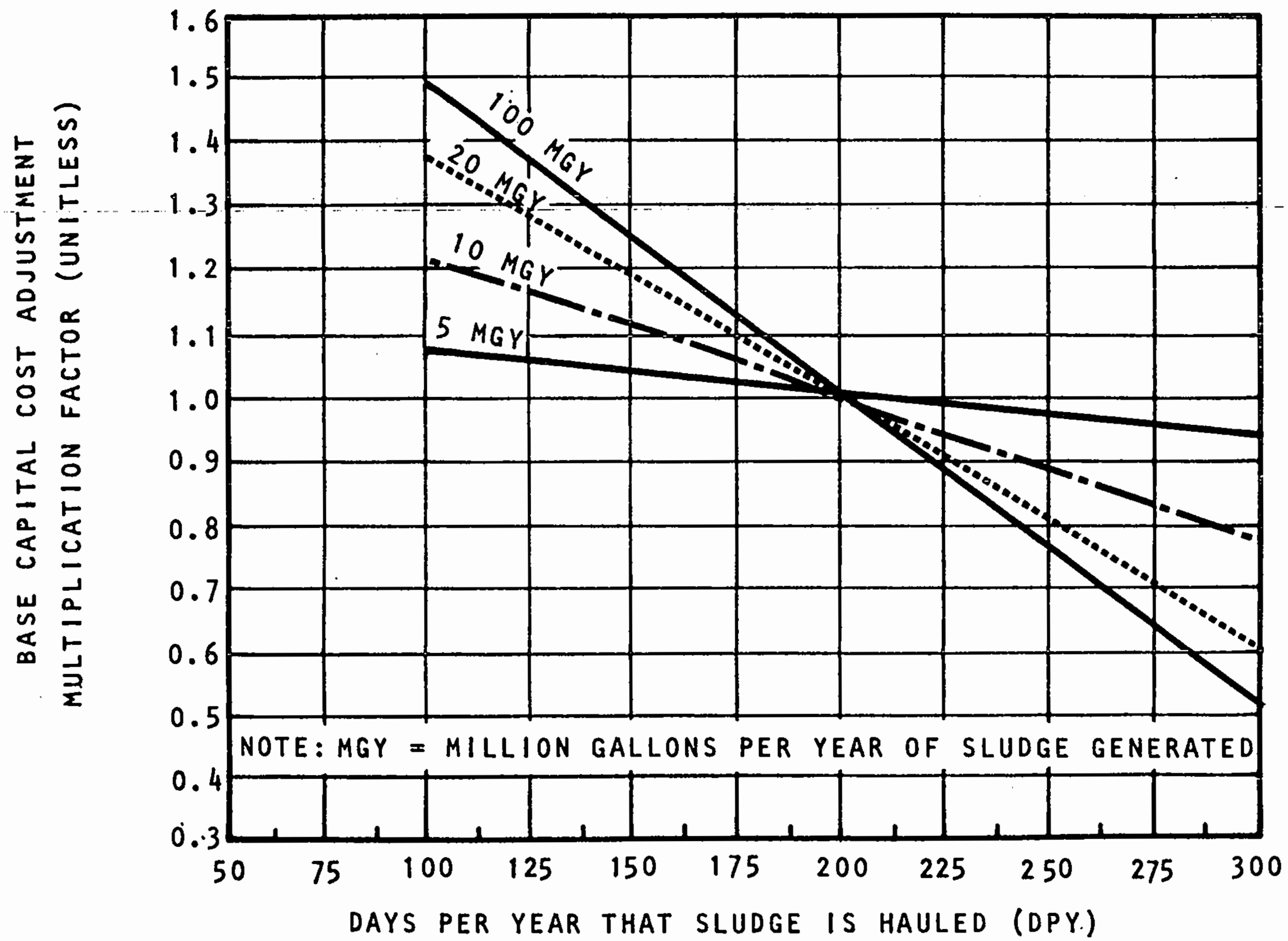




Assumptions: Design parameters are the same as for Figure 9-4.

FIGURE 9-7

CAPITAL COST ADJUSTMENT MULTIPLICATION FACTOR TO ACCOUNT FOR VARYING DAYS PER YEAR THAT SLUDGE IS HAULED



For example, assume that the capital cost for hauling 20 million gallons per year (20-mile round trip) of sludge taken from Figure 9-1 is $570,000, based on the assumption that sludge is hauled 200 days per year. If sludge is actually hauled only 100 days per year, the capital cost derived from Figure 9-1 should be increased by the factor of 1.38 shown in Figure 9-7 (i.e., 1.38 x $87,000 = $792,000). Conversely, if sludge is actually going to be hauled 300 days per year, the capital cost derived from Figure 9-1 should be decreased by the factor of 0.61 shown in Figure 9-7 (i.e., 0.61 x $570,000 = $348,000).

As shown in Figure 9-7, the cost factors to adjust capital cost for days per year that sludge is hauled are not significant for very small sludge volumes, but increase or decrease rapidly above 5,000,000 gallons per year of sludge hauled. The user should estimate cost adjustments by interpolation for annual sludge volumes other than those shown in Figure 9-7.

9.3 Rail Hauling

Rail transport of sludge can be a cost-effective and energy-efficient operation when hauling large volumes of sludge over long distances. However, this mode of transportation has several disadvantages such as: fixed terminal points; ongoing administration burden; and potential risk of spills due to the possibility of leaking valves and derailment.

Capital and O&M cost curves for rail hauling presented on Figures 9-8 through 9-14 are based on the cost algorithm presented in Appendix A-22. Additional information on cost algorithm development, design parameters, and other assumptions used in obtaining costs is provided in Appendix A-22.

9.4 Barge Hauling

Barge hauling for ocean disposal of liquid sludge has been practiced for many years. The method has been limited in the past to use by large treatment plants, since small- and medium-size treatment plants generally do not produce enough sludge to make barge haul/ocean disposal a cost-effective alternative. However, through inter-facility pumping to a central facility, several smaller treatment plants combined can produce enough sludge to make barge hauling a cost-effective alternative.

The cost curves presented in Figures 9-15 through 9-16 were obtained using the algorithm in Appendix A-23. Design assumptions used in obtaining costs are shown on each figure. Additional information on cost algorithm development, design parameters, and other assumptions is provided in Appendix A-23.

9.5 Pipeline Transport

Pipelines have been used successfully for transporting liquid sludge from very short distances up to distances of 10 miles or more. The principles applied in sludge pipeline and water pipeline design are quite similar. However, the tendency for sludges to adhere to surfaces results in higher frictional losses which must be accounted for.

FIGURE 9-8

BASE CAPITAL COST OF LIQUID SLUDGE RAIL HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED

Assumptions: Rail cars are leased and their cost is included in annual O&M cost; costs in this figure are for loading and unloading facilities only.

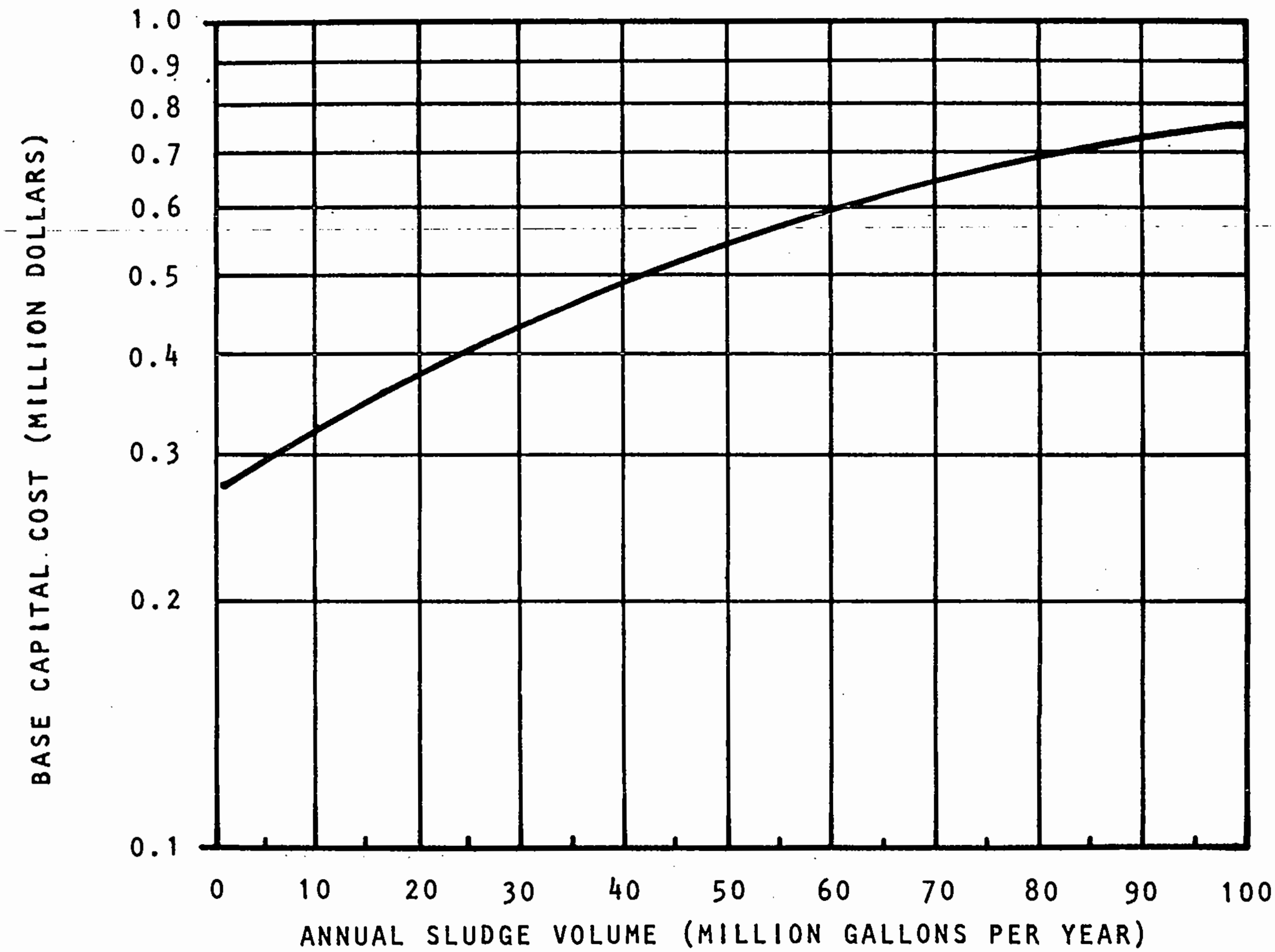


FIGURE 9-9

NORTH CENTRAL AND CENTRAL REGION: BASE ANNUAL O&M COST OF LIQUID SLUDGE RAIL HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Railroad mileage credit = $0.25/mile; annual rail tank car lease rate = $9,000/yr; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

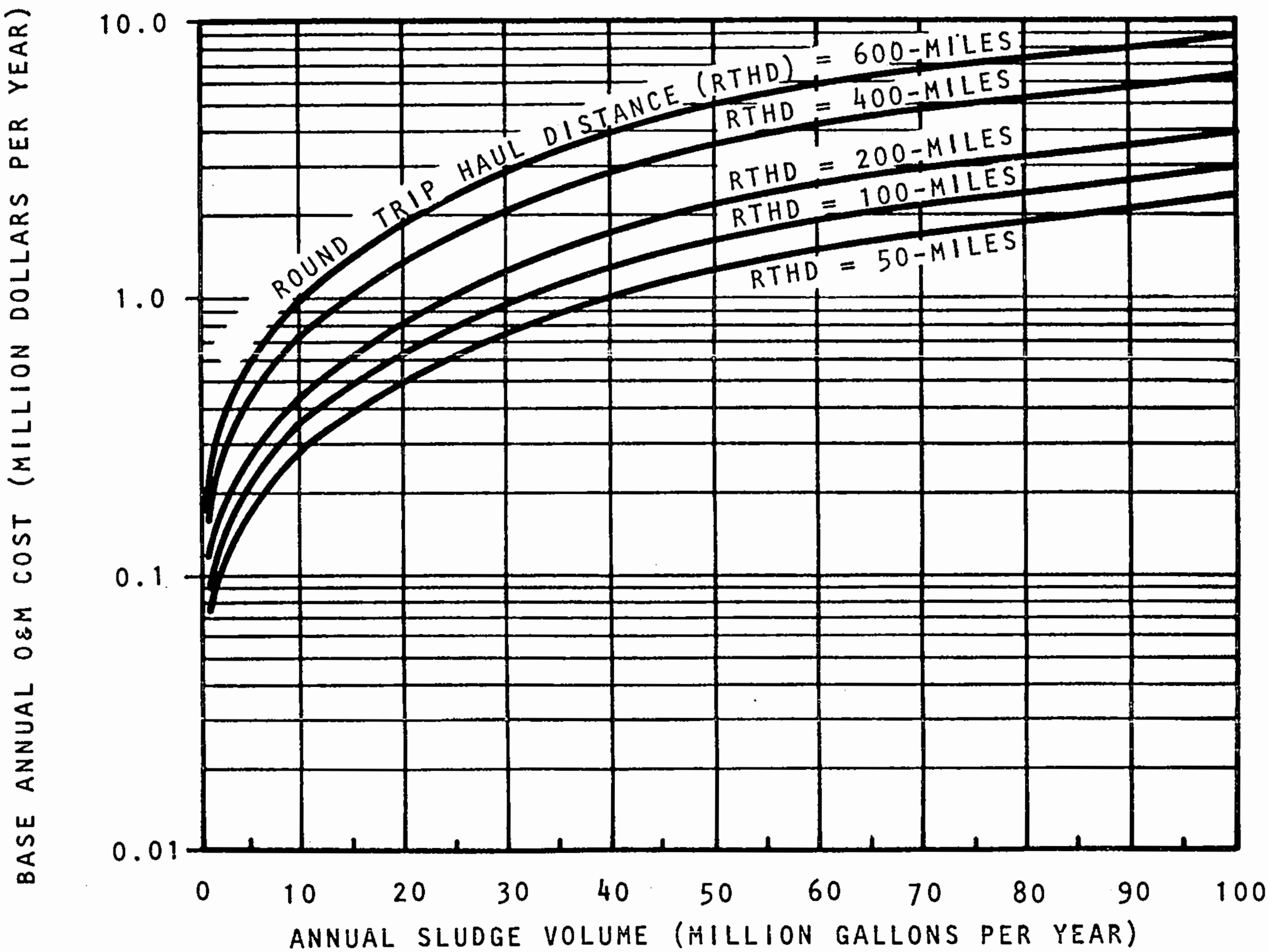


FIGURE 9-10

NORTHEAST REGION: BASE ANNUAL O&M COST OF LIQUID SLUDGE RAIL HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Railroad mileage credit = $0.25/mile; annual rail tank car lease rate = $9,000/yr; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

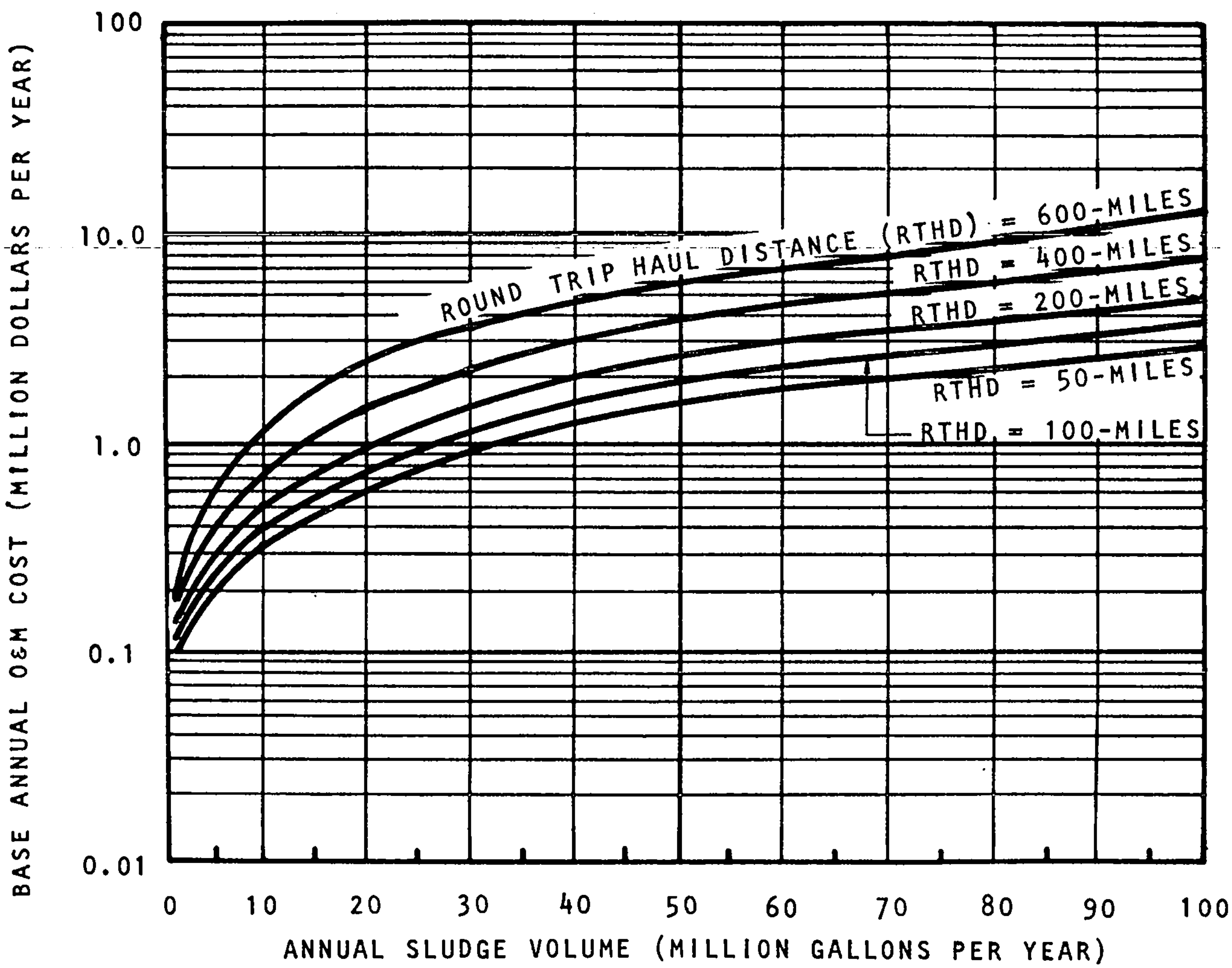


FIGURE 9-11

SOUTHEAST REGION: BASE ANNUAL O&M COST OF LIQUID SLUDGE RAIL HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Railroad mileage credit = $0.25/mile; annual rail tank car lease rate = $9,000/yr; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

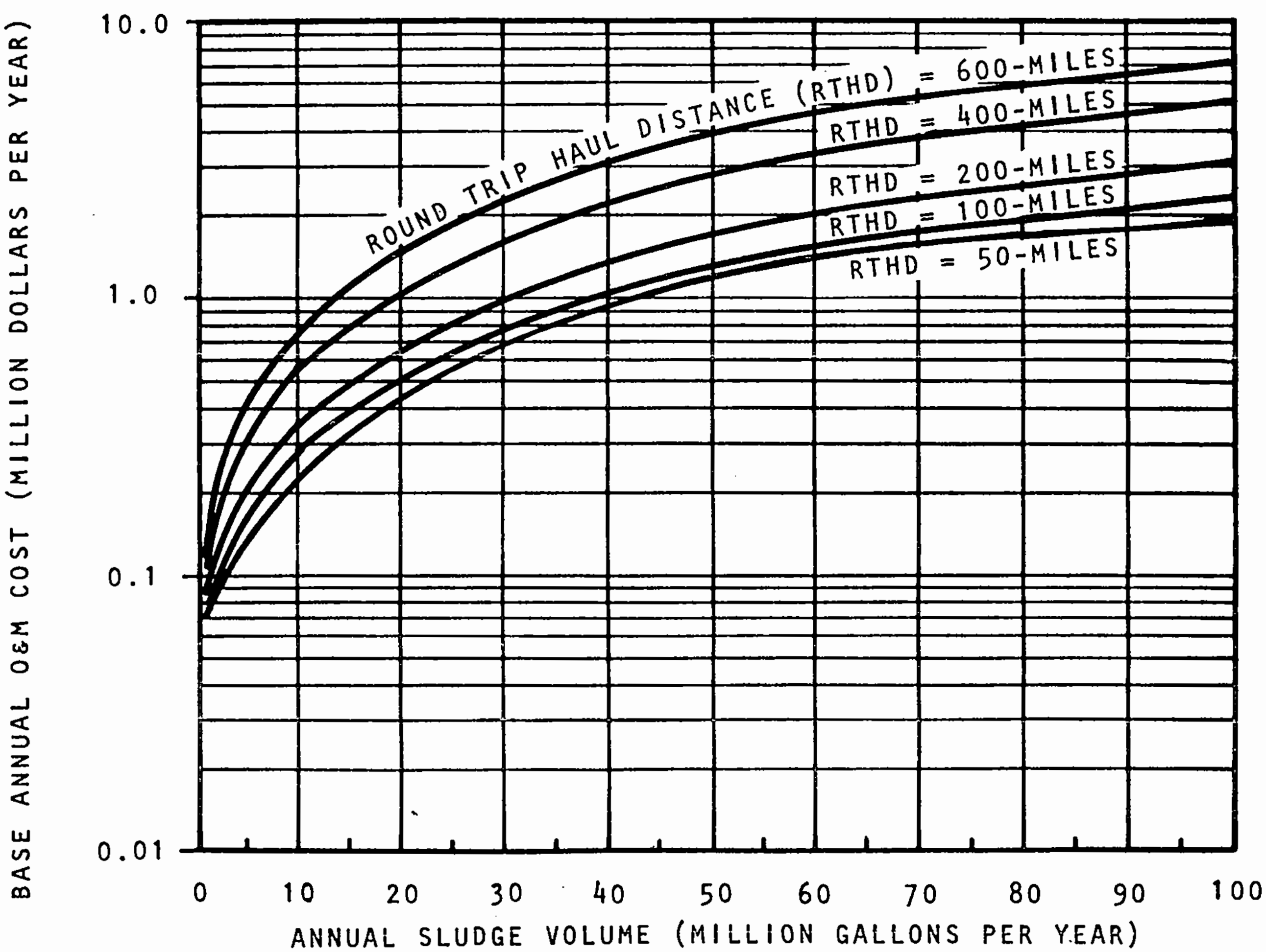


FIGURE 9-12

SOUTHWEST REGION: BASE ANNUAL O&M COST OF LIQUID SLUDGE RAIL HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Railroad mileage credit = $0.25/mile; annual rail tank car lease rate = $9,000/yr; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

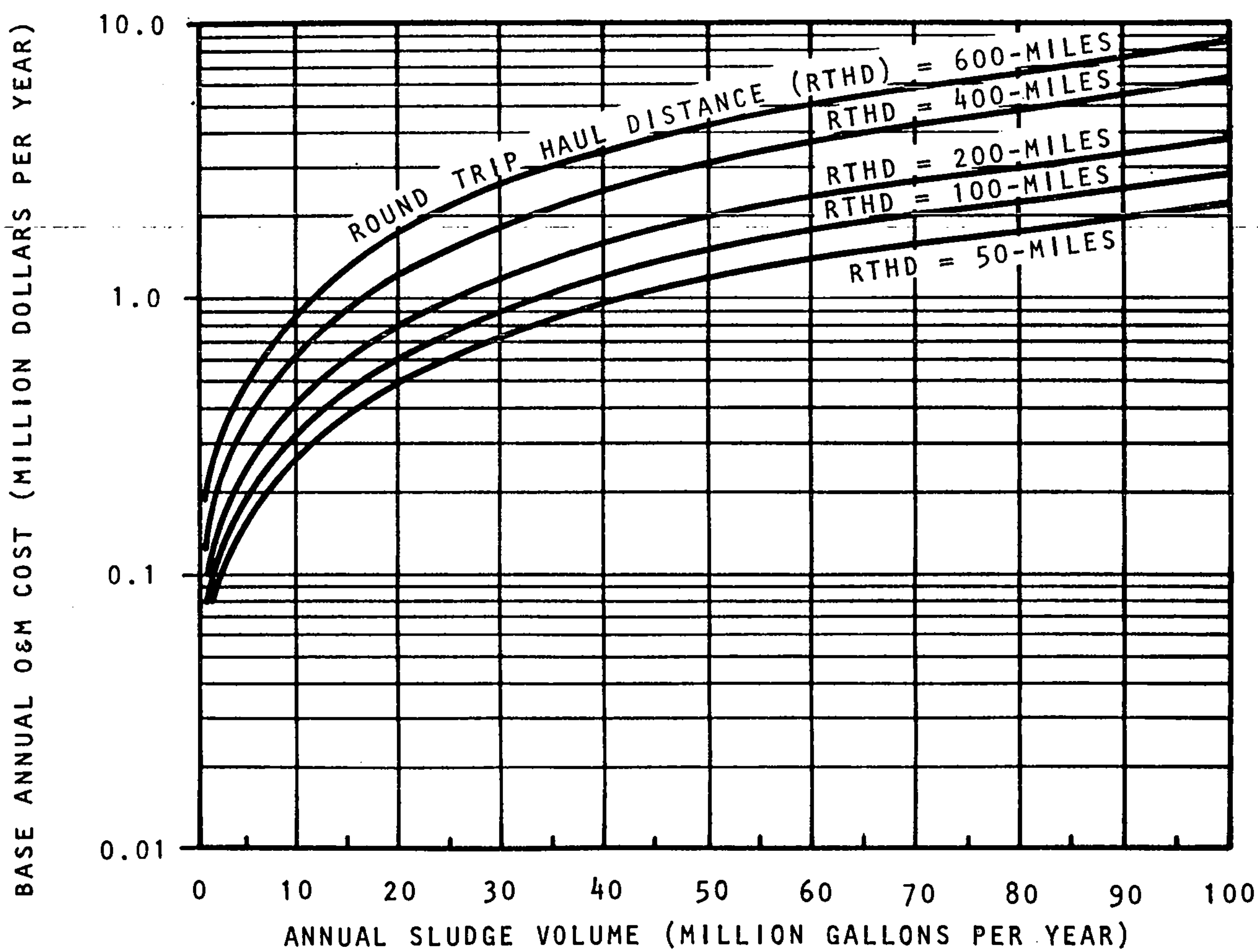


FIGURE 9-13

WEST COAST REGION: BASE ANNUAL O&M COST OF LIQUID SLUDGE RAIL HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Railroad mileage credit = $0.25/mile; annual rail tank car lease rate = $9,000/yr; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

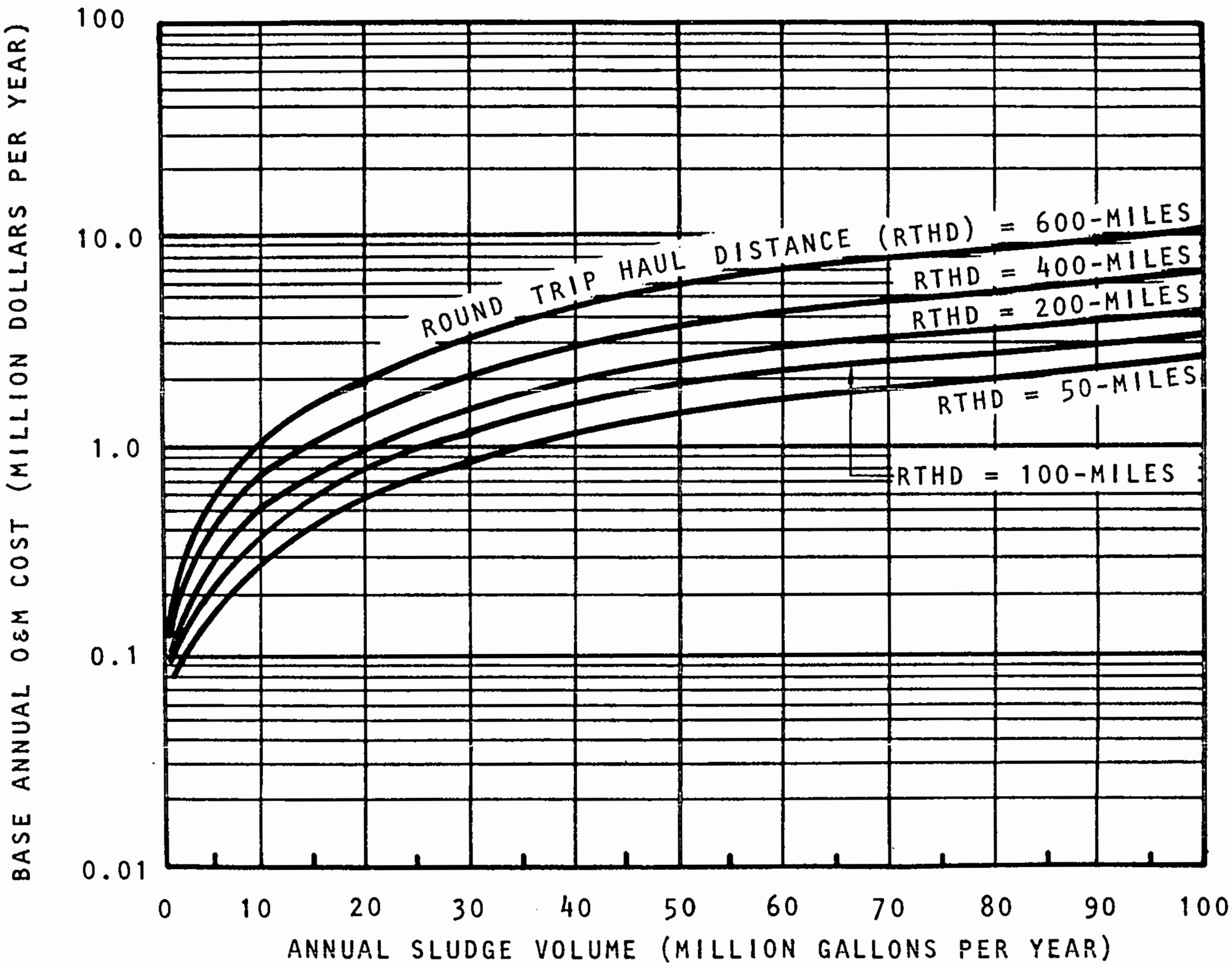
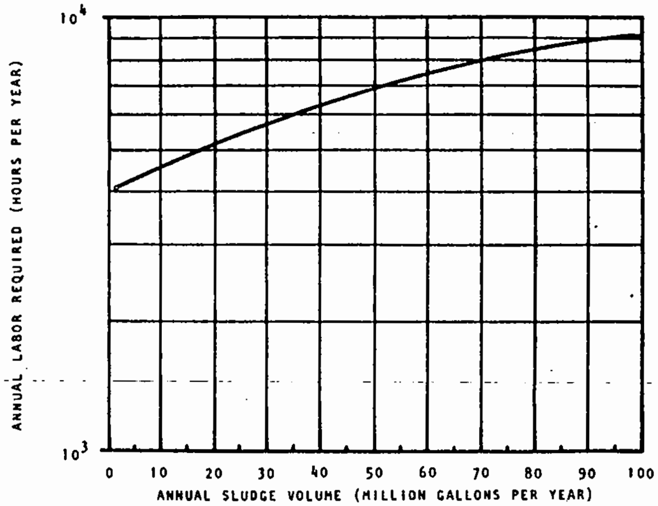
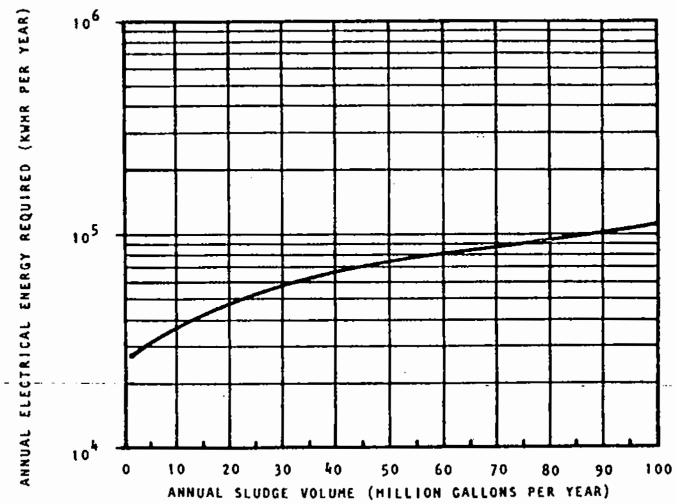
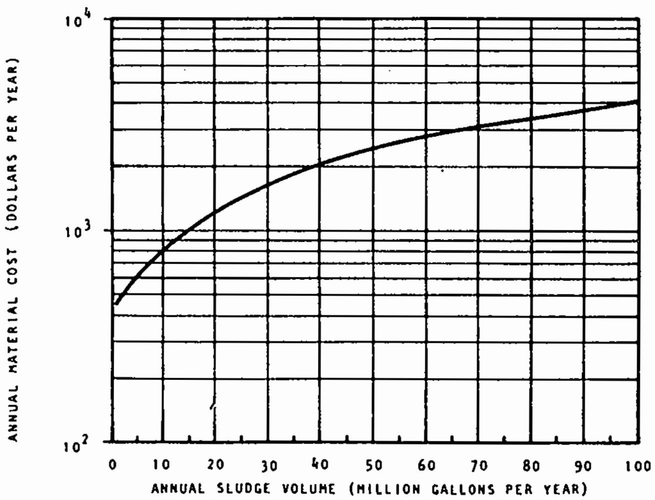


FIGURE 9-14

ANNUAL O&M REQUIREMENTS FOR LIQUID SLUDGE RAIL HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED



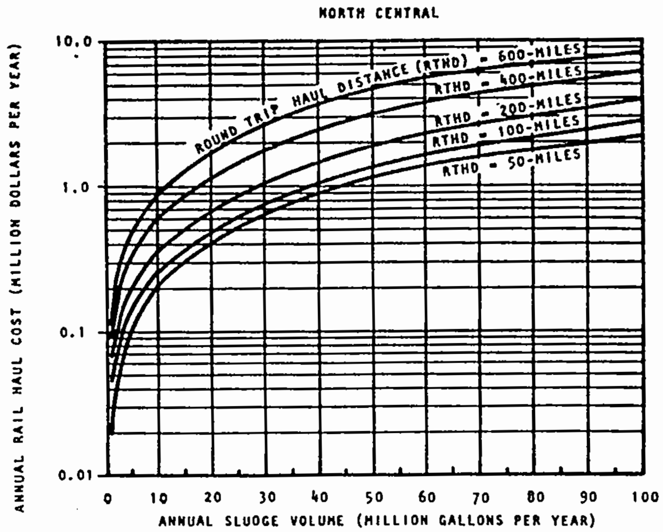


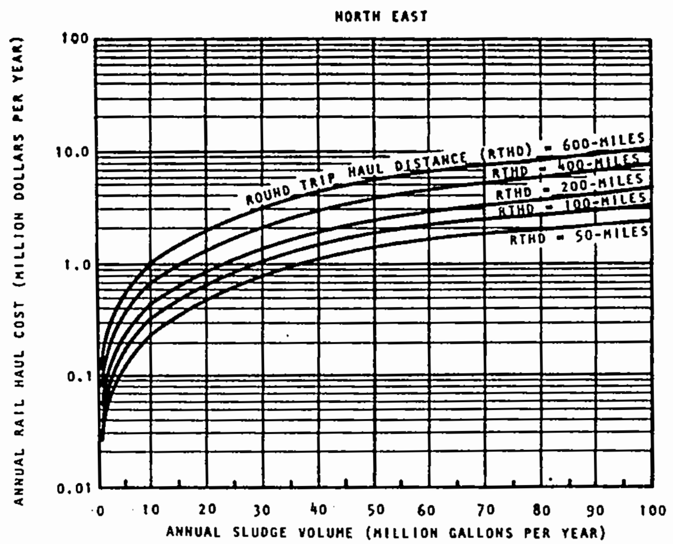


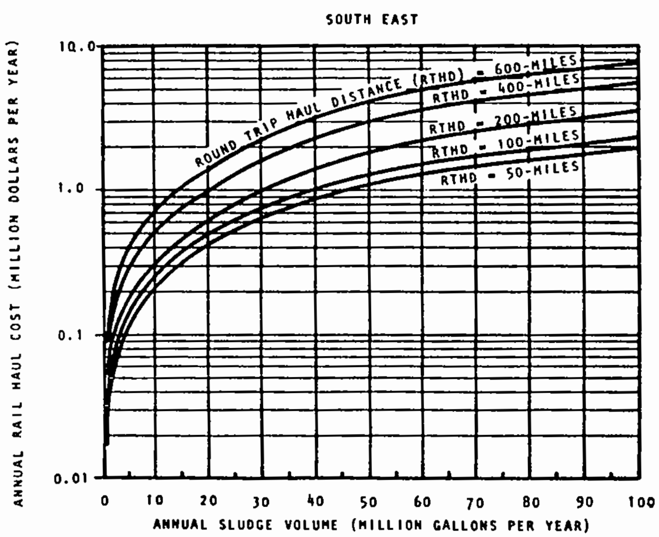
Assumptions: Design parameters are the same as for Figure 9-15.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 9-14 (CONTINUED)





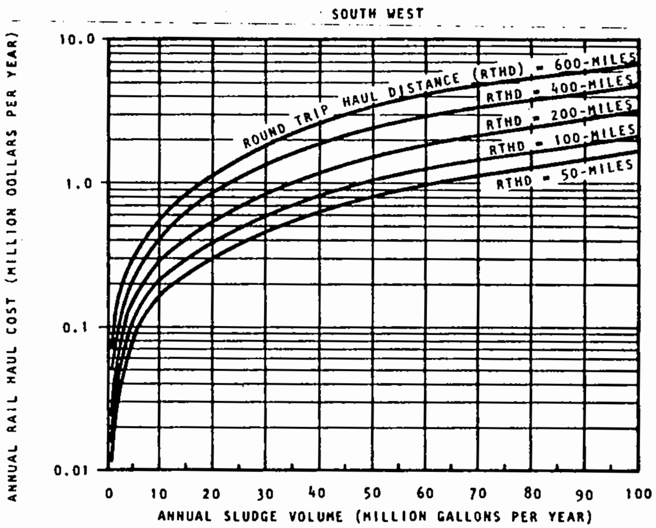


Assumptions: Design parameters are the same as for Figure 9-15.

FIGURE 9-14 (CONTINUED)

Assumptions: Design parameters are the same as for Figure 9-15.

Annual rail haul costs are a function of round trip haul distance and region of the country.



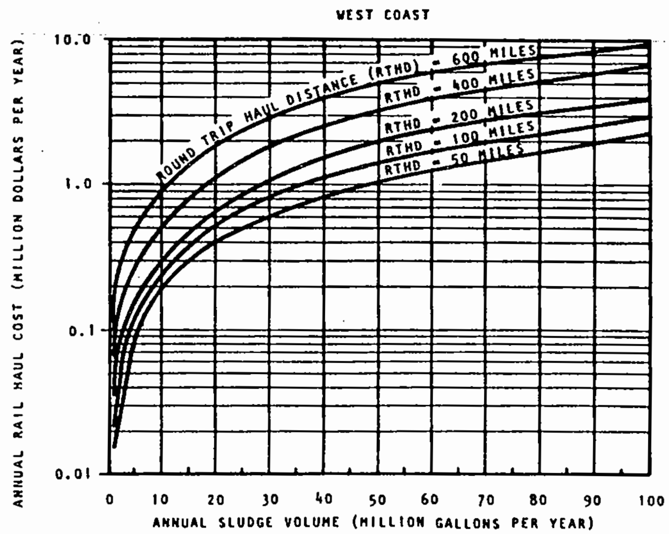


FIGURE 9-15

BASE CAPITAL COST OF LIQUID SLUDGE BARGE HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Average barge speed = 3 mph; barge downtime = 8 hr/trip; 2 days of separate sludge storage at loading facility; 4 hr required to fill barge; purchase cost of index barge (3,000 liquid ton capacity) = $2,028,000.

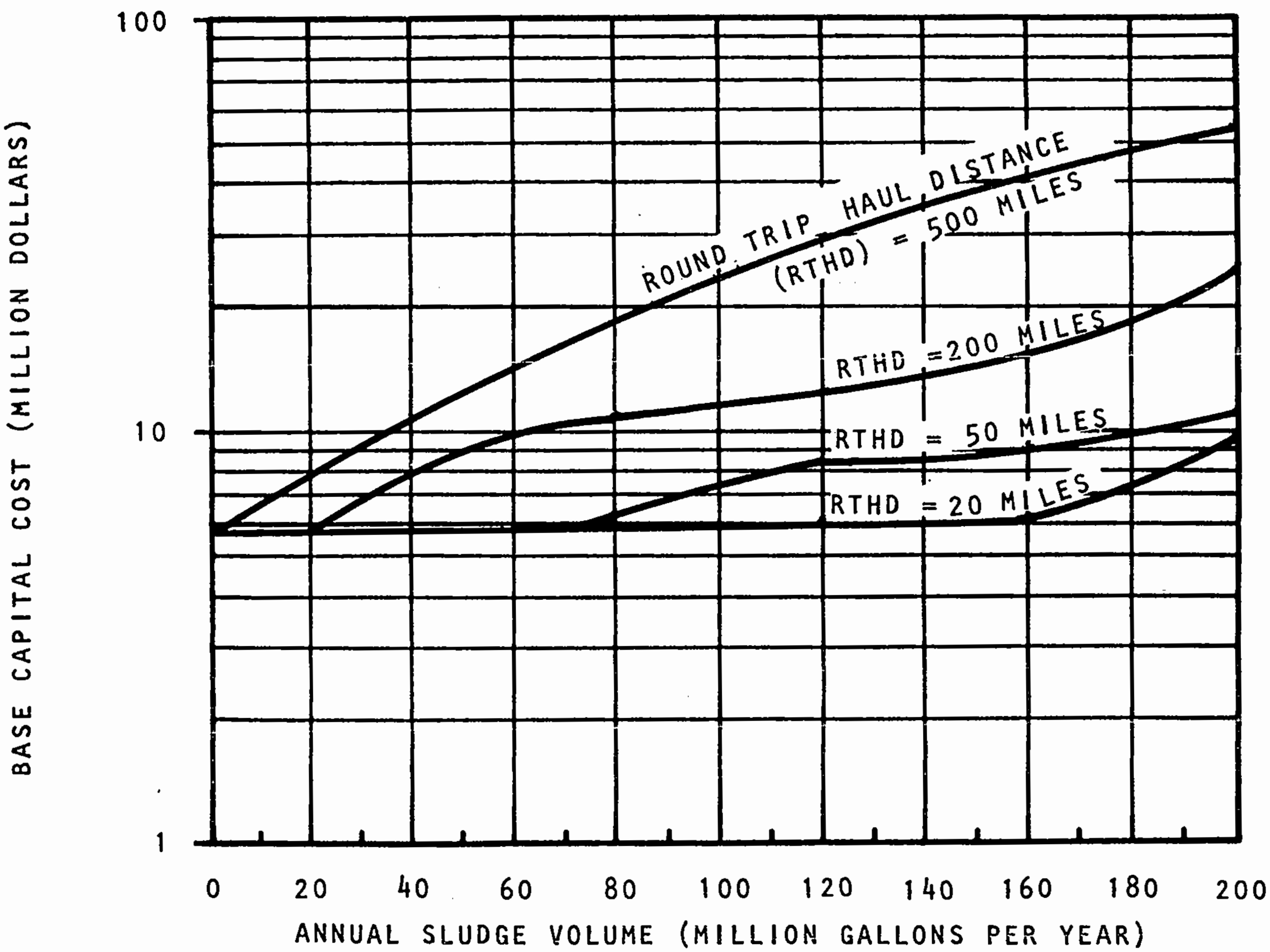
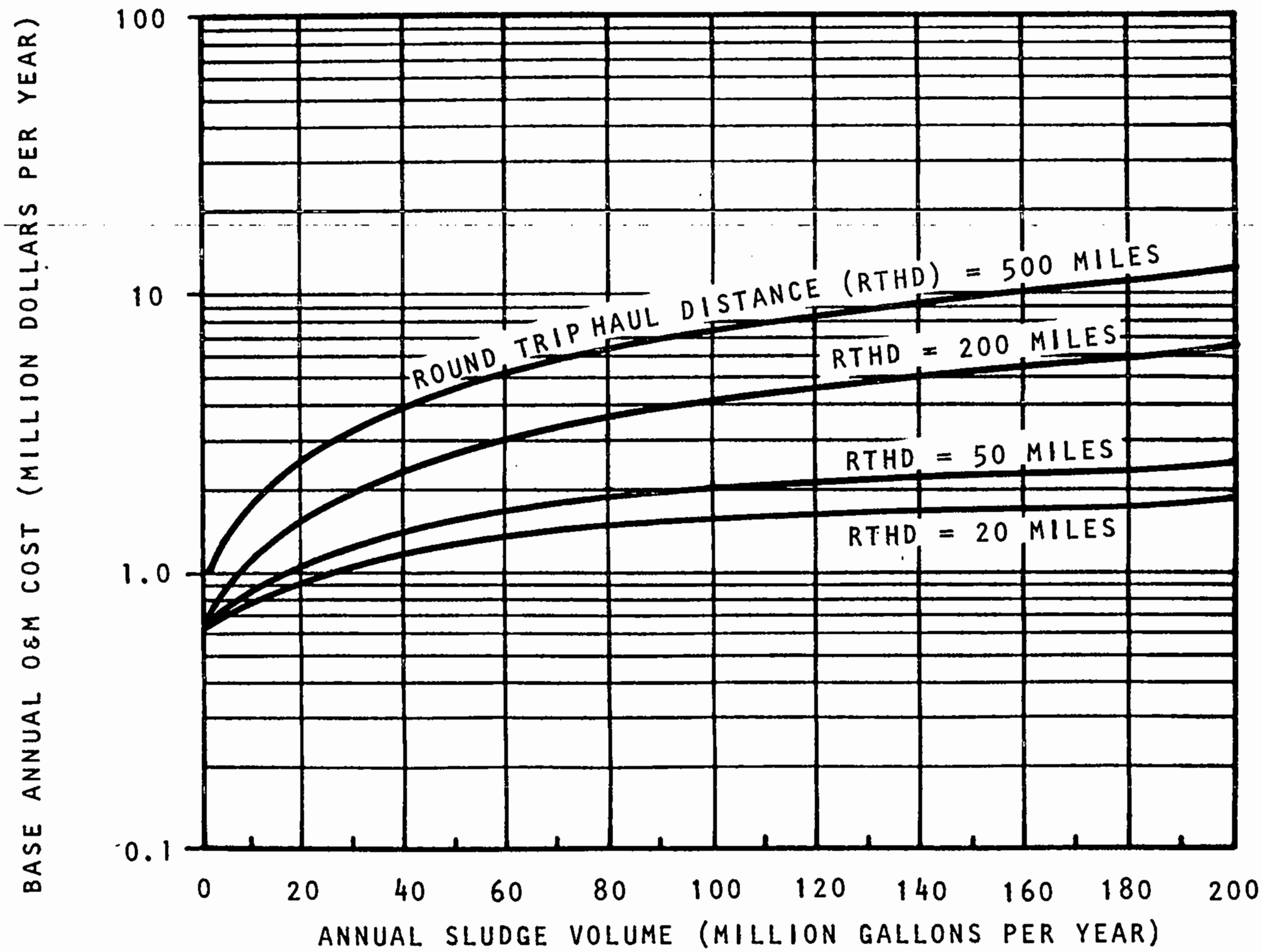


FIGURE 9-16

BASE ANNUAL O&M COST FOR LIQUID SLUDGE BARGE HAULING AS A FUNCTION OF ANNUAL VOLUME HAULED AND ROUND TRIP HAUL DISTANCE

Assumptions: Design parameters are the same as for Figure 9-15; cost of sludge storage tanks = $0.45/gal of capacity; cost of sludge pumps and piping = $166/gpm; cost of docking facilities = $520,000/barge; cost of tugboat rental = $360/hr.



Ocean outfalls are a special type of pipeline transportation which constitute both a sludge transportation and disposal method. Ocean outfalls tend to be more capital-intensive than pipelines due to the environmental conditions under which construction occurs.

Capital and O&M costs and requirements are presented in Figures 9-17 through 9-19 for a 1-mile pipeline; Figures 9-20 through 9-22 for a 5-mile pipeline; and Figures 9-23 through 9-25 for a 10-mile pipeline. Capital and O&M costs and requirements for an ocean outfall are presented in Figures 9-26 through 9-28. Cost curves were obtained using the cost algorithm in Appendix A-24 for pipeline transport and Appendix A-25 for ocean outfall, using the assumptions shown on each curve. The user should refer to the cost algorithms for additional information on cost algorithm development, design parameters, and other assumptions.

FIGURE 9-17

BASE CAPITAL COST OF A 1-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE

Assumptions: Hazen-Williams friction coefficient = 90; sludge being pumped is digested with a solids concentration of 4 percent; number of 2- or 4-lane highway crossings = 1; number of railroad tracks crossed = 1; no divided highways or rivers crossed; 20 hr/day pumping; fraction of pipeline length over 6 ft deep = 0.5; no rock excavation required; costs do not include easement purchase.

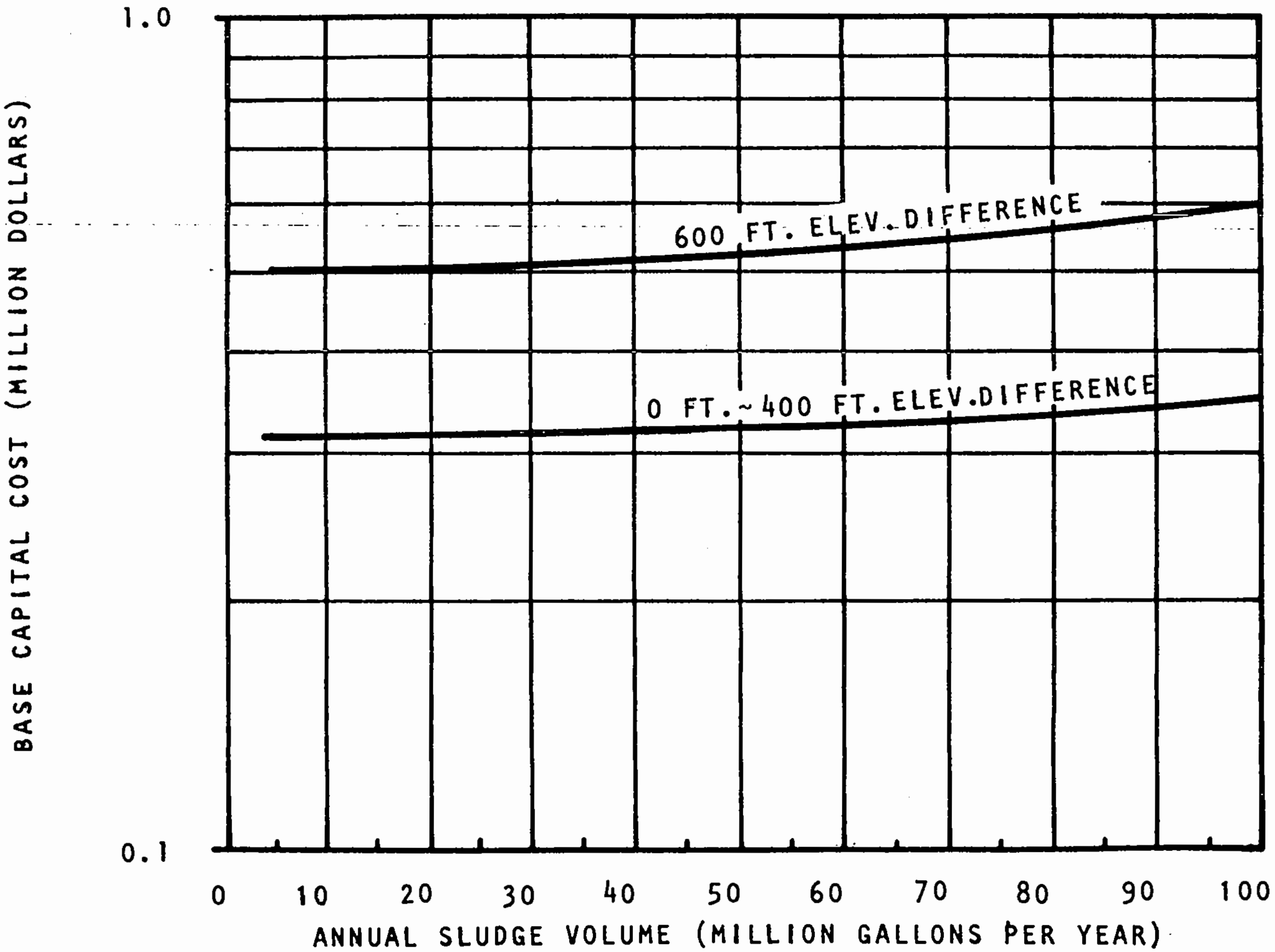


FIGURE 9-18

BASE ANNUAL O&M COST OF A 1-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE

Assumptions: Design parameters are the same as for Figure 9-17; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

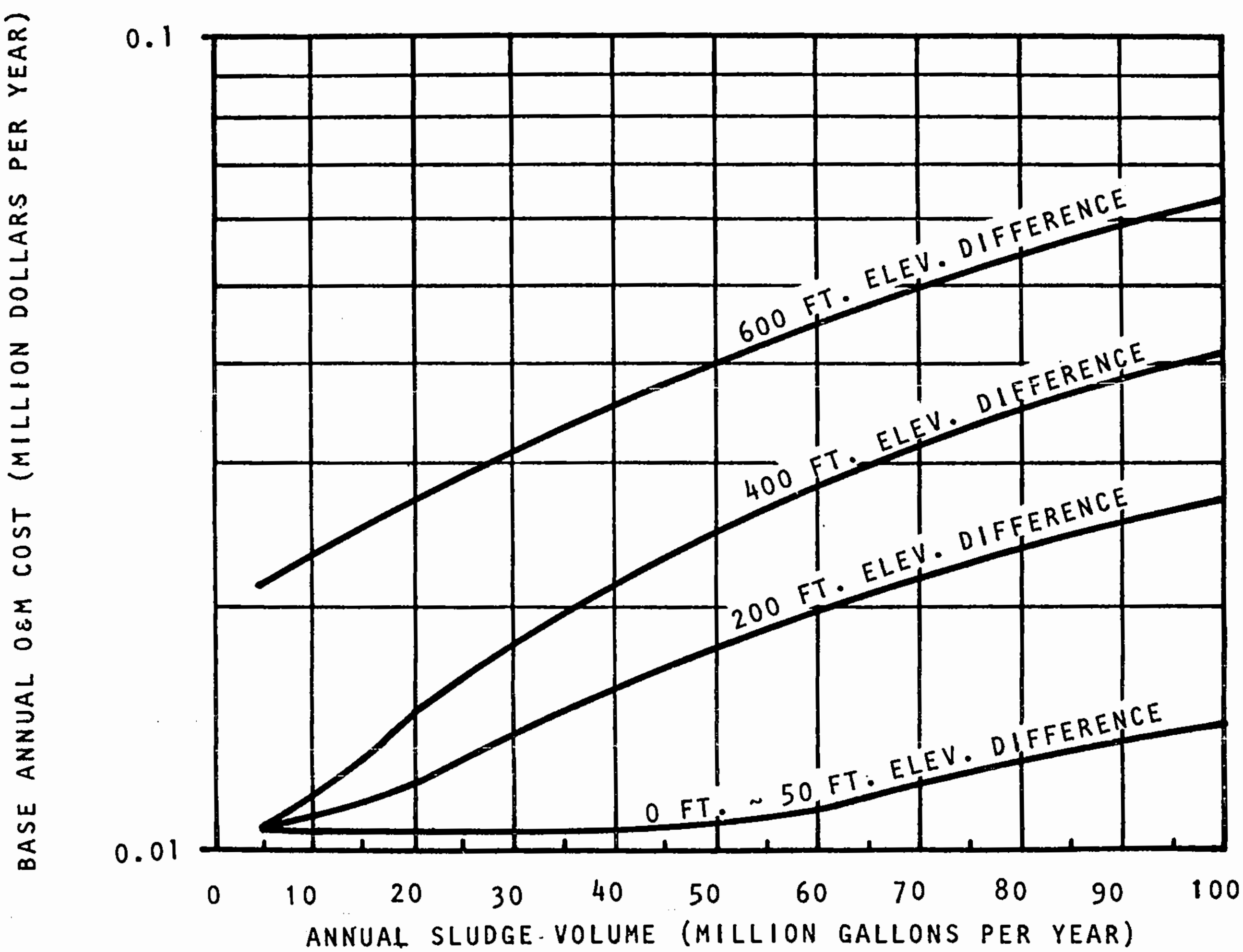
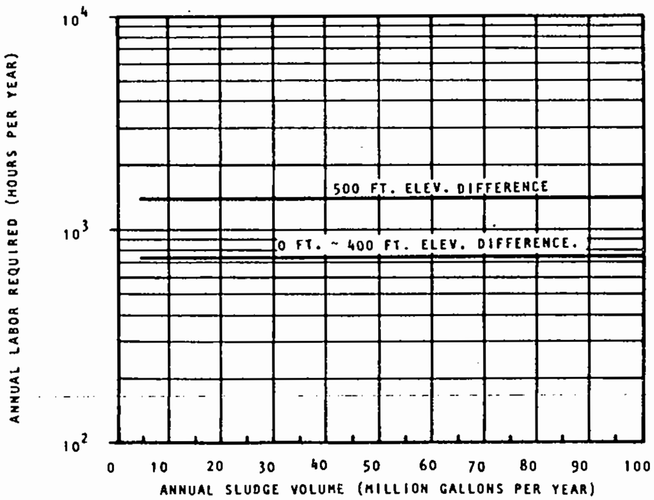
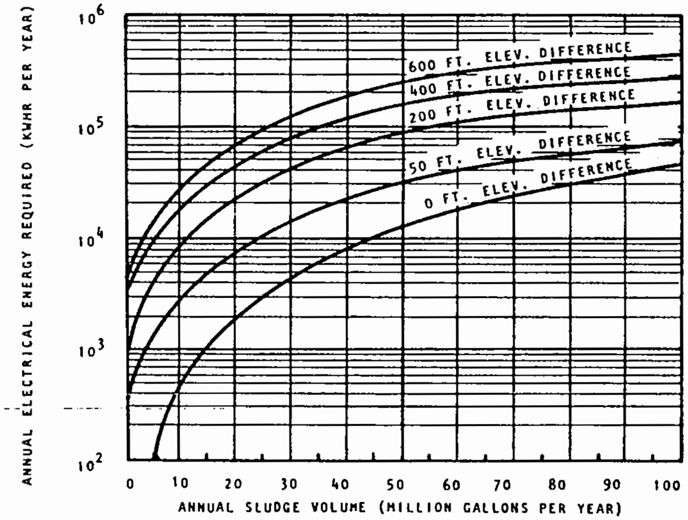
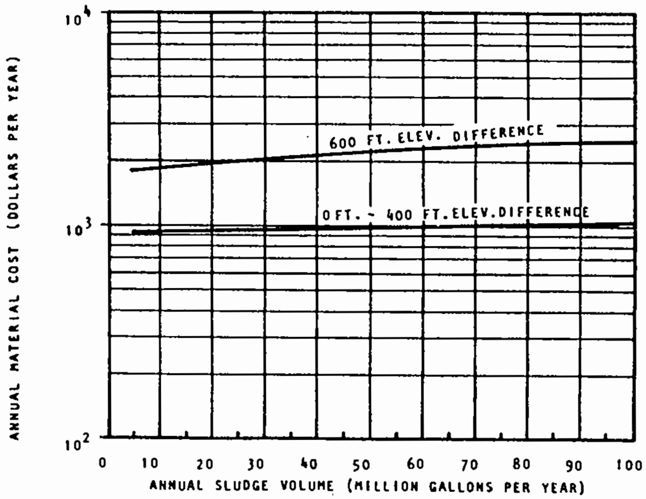


FIGURE 9-19

ANNUAL O&M REQUIREMENTS FOR A 1-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE







Assumptions: Design parameters are the same as for Figure 9-17.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF PUMPING STATION PARTS AND MATERIALS.

FIGURE 9-20

BASE CAPITAL COST OF A 5-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE

Assumptions: Hazen-Williams friction coefficient = 90; sludge being pumped is digested with a solids concentration of 4 percent; number of 2- or 4-lane highway crossings = 5; number of railroad tracks crossed = 1; no divided highways or rivers crossed; 20 hr/day pumping; fraction of pipeline length over 6 ft deep = 0.5; no rock excavation required; costs do not include easement purchase.

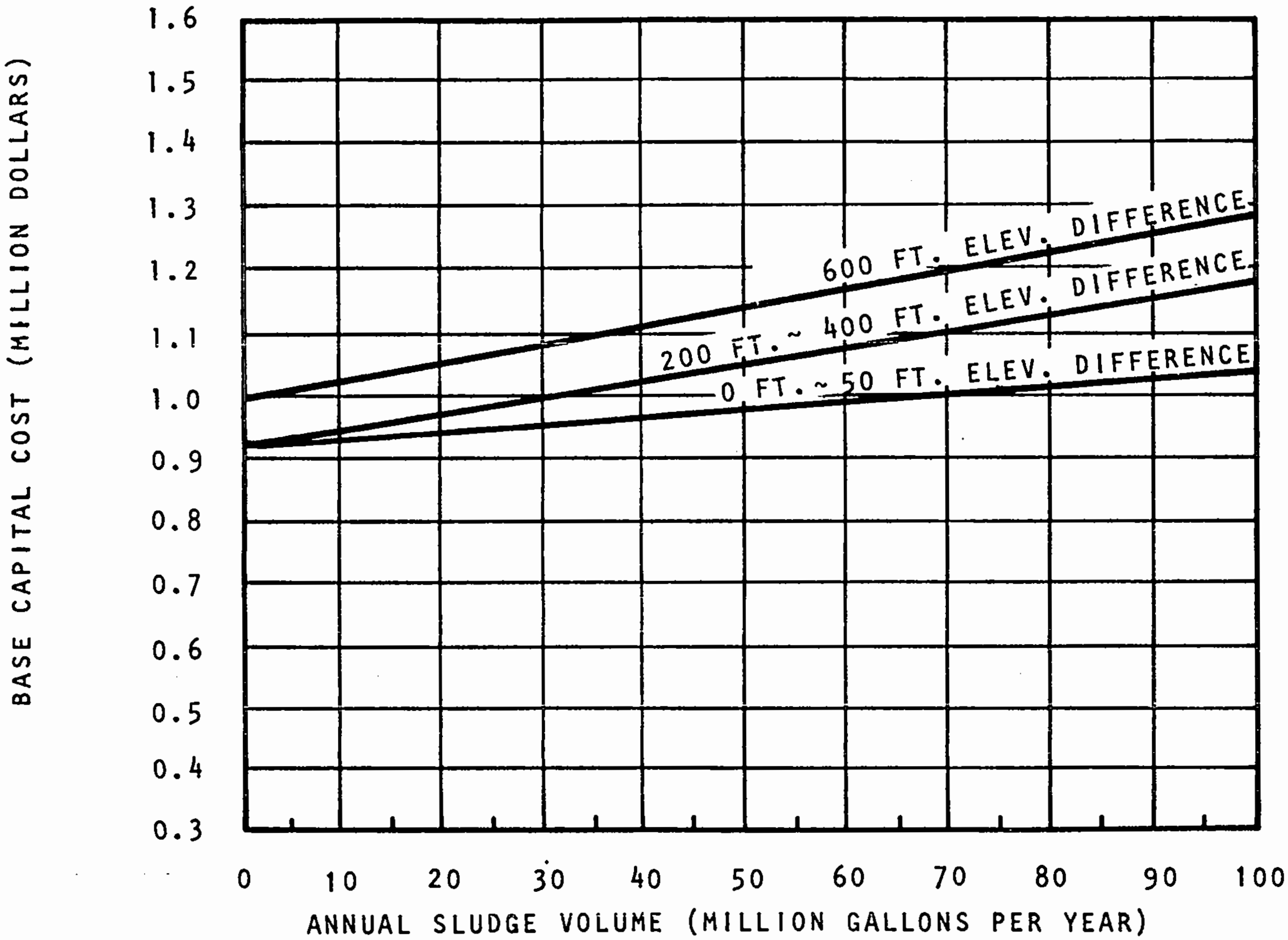


FIGURE 9-21

BASE ANNUAL O&M COST OF A 5-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE

Assumptions: Design parameters are the same as for Figure 9-20; cost of labor = \$13.50/hr; cost of electricity = \$0.094/kWhr.

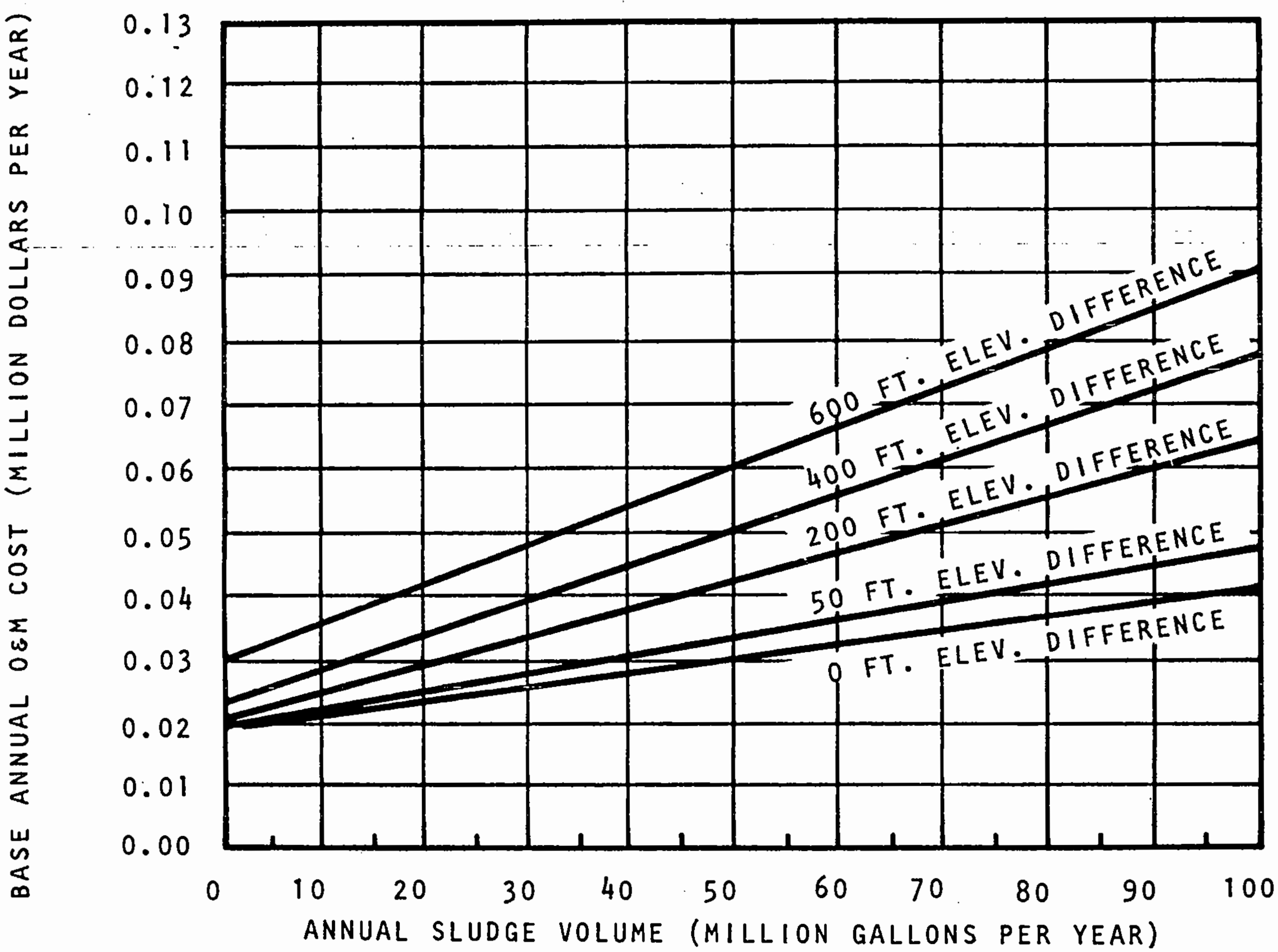
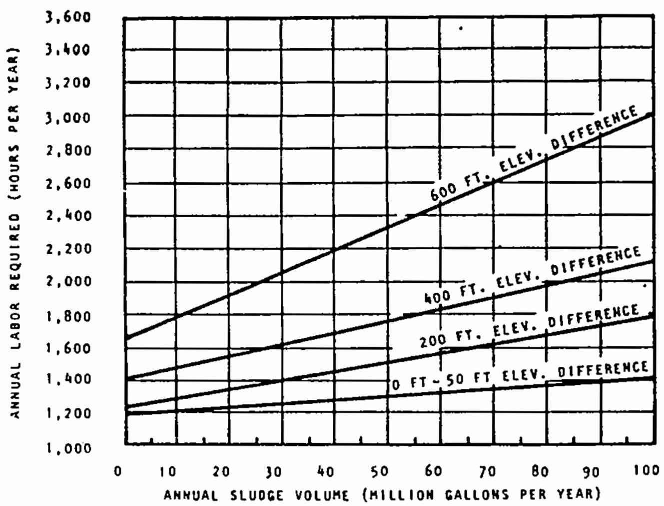
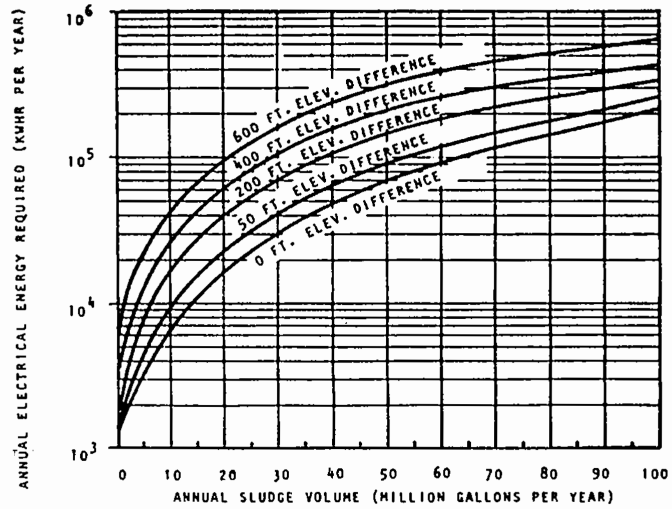
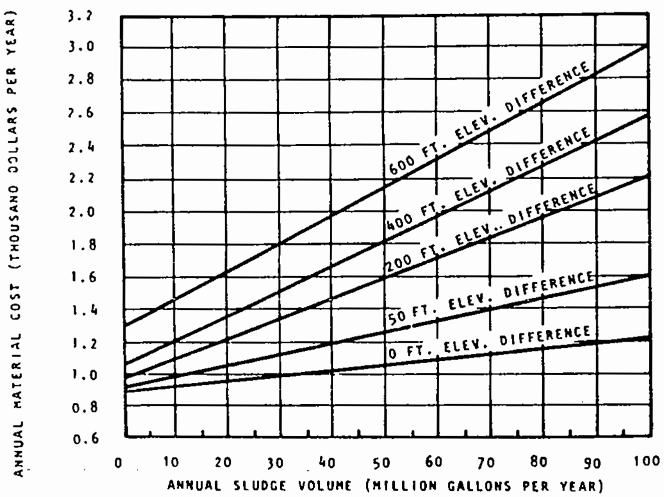


FIGURE 9-22

ANNUAL O&M REQUIREMENTS FOR A 5-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE







Assumptions: Design parameters are the same as for Figure 9-20.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF PUMPING STATION PARTS AND MATERIALS.

FIGURE 9-23

BASE CAPITAL COST OF A 10-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE

Assumptions: Hazen-Williams friction coefficient = 90; sludge being pumped is digested with a solids concentration of 4 percent; number of 2- or 4-lane highway crossings = 10; number of railroad tracks crossed = 2; no divided highways or rivers crossed; 20 hr/day pumping; fraction of pipeline length over 6 ft deep = 0.5; no rock excavation required; costs do not include easement purchase.

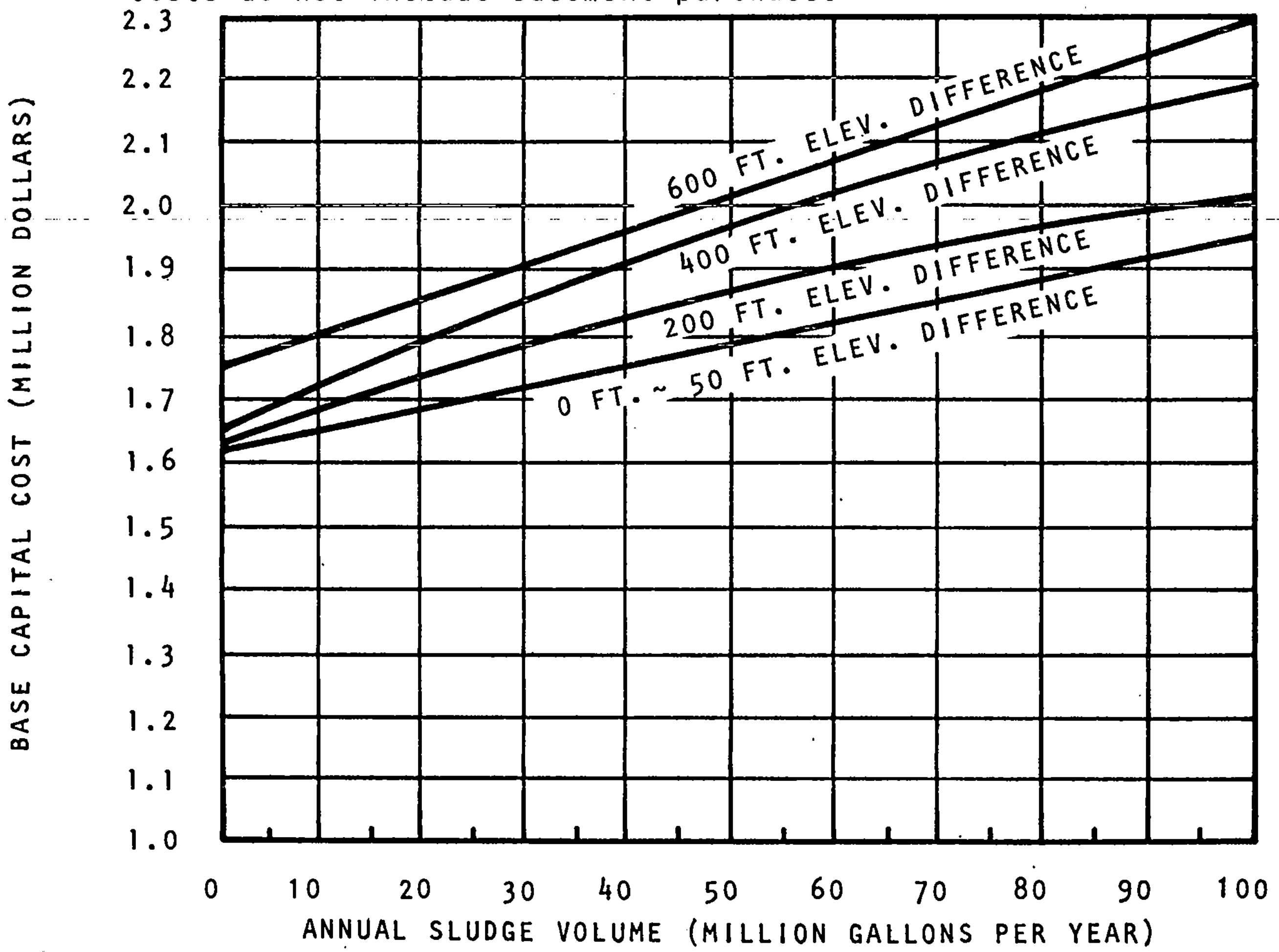


FIGURE 9-24

BASE ANNUAL O&M COST OF A 10-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE

Assumptions: Design parameters are the same as for Figure 9-23; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

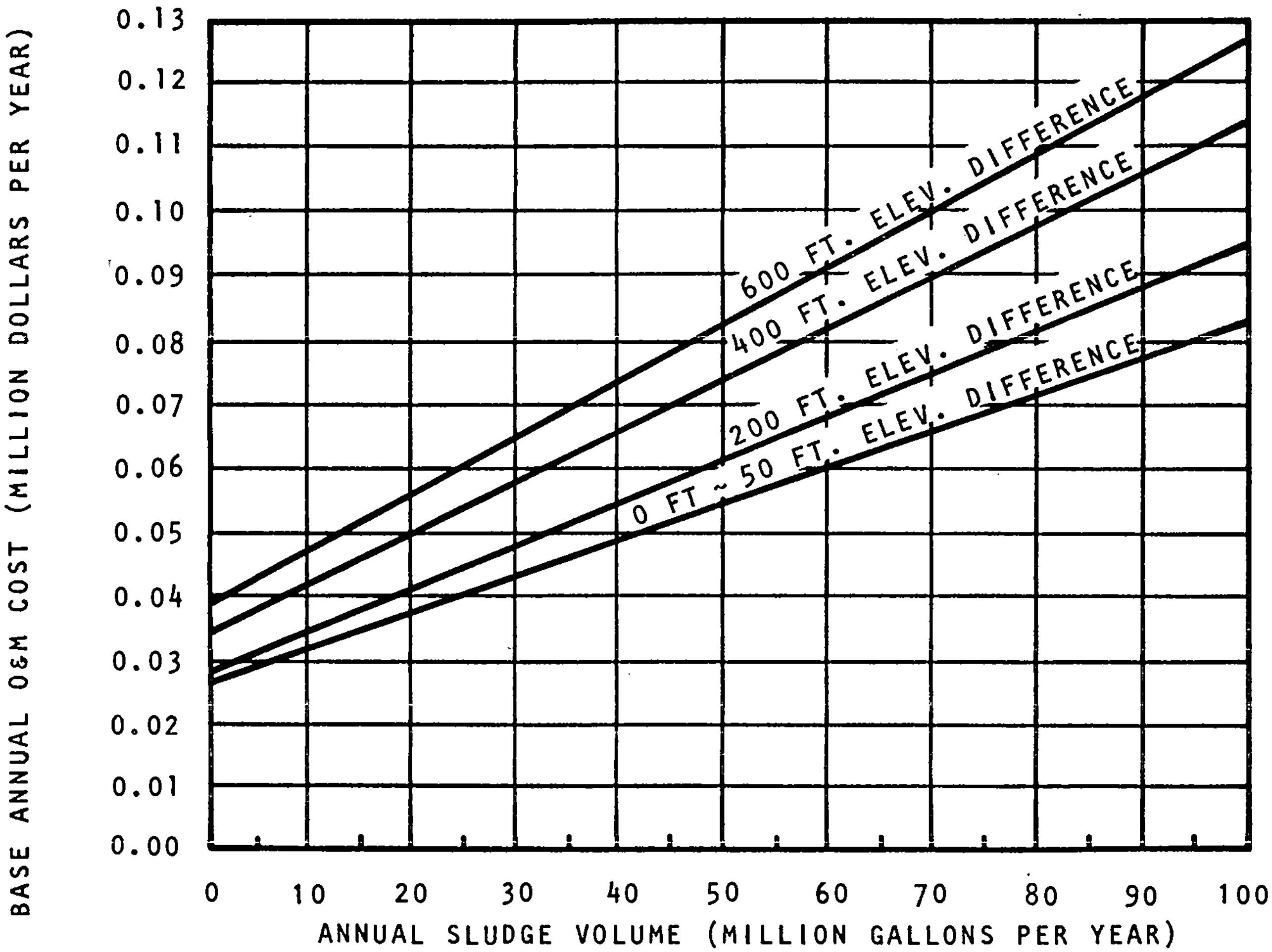
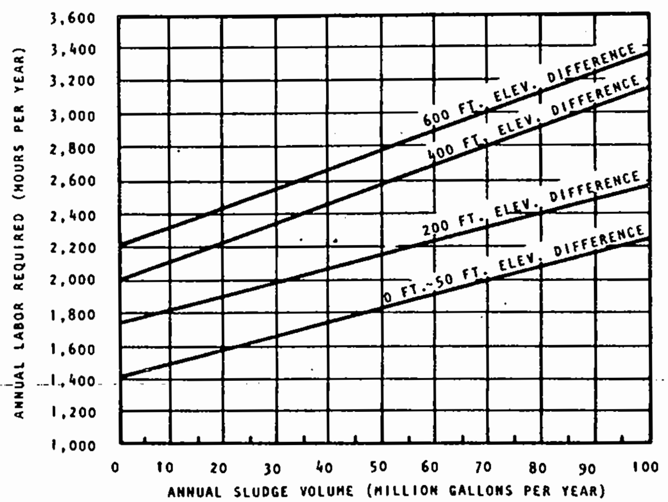
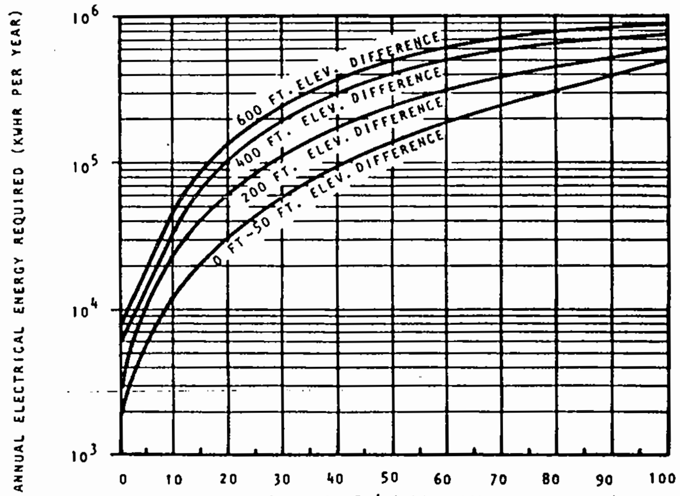
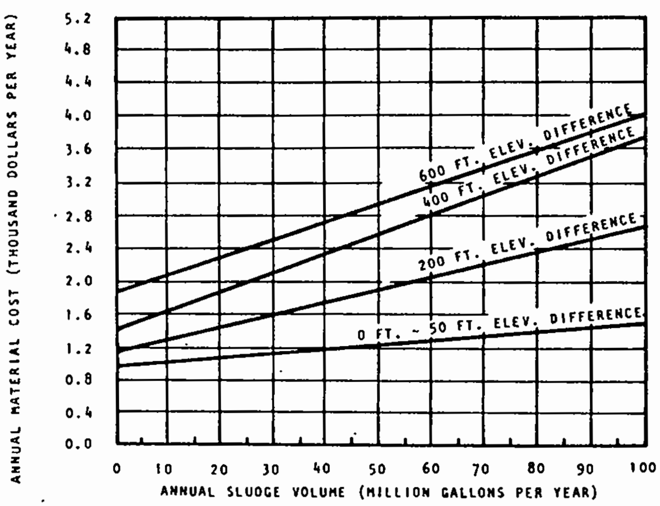


FIGURE 9-25

ANNUAL O&M REQUIREMENTS FOR A 10-MILE LIQUID SLUDGE TRANSPORT PIPELINE AND PUMP STATION(S) AS A FUNCTION OF ANNUAL VOLUME PUMPED AND ELEVATION DIFFERENCE







Assumptions: Design parameters are the same as for Figure 9-23.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL COSTS OF PUMPING STATION PARTS AND MATERIALS.

FIGURE 9-26

BASE CAPITAL COST OF A LIQUID SLUDGE OCEAN OUTFALL AS A FUNCTION OF ANNUAL VOLUME DISCHARGED AND OUTFALL LENGTH

Assumptions: Onshore pipeline length = 2,500 ft; nearshore pipeline length = 1,000 ft; diffuser pipeline length = 500 ft; offshore pipeline length is the indicated outfall length minus 4,000 ft; Hazen-Williams friction coefficient = 90; 20 hr/day pumping.

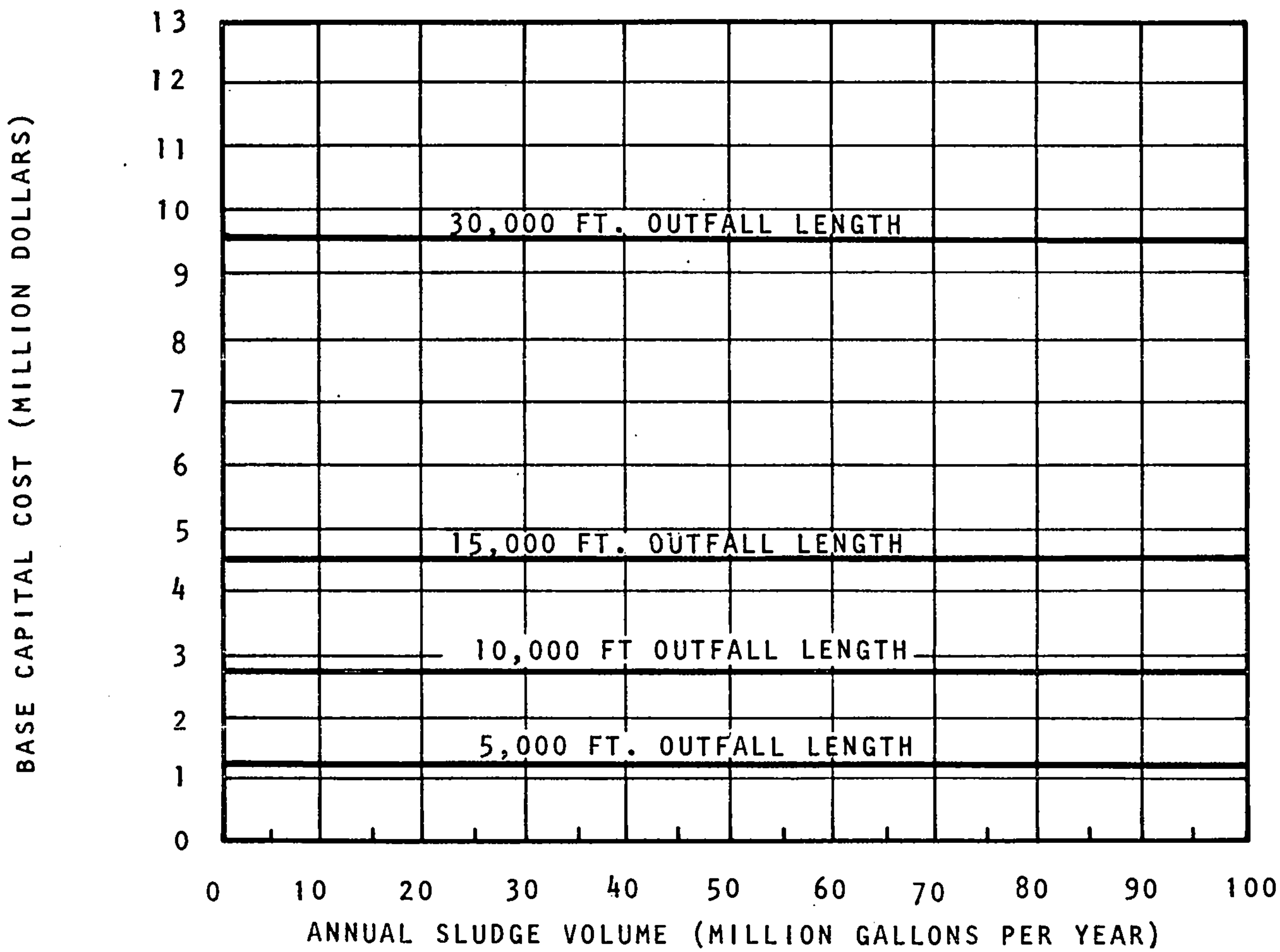


FIGURE 9-27

BASE ANNUAL O&M COST OF A LIQUID SLUDGE OCEAN OUTFALL AS A FUNCTION OF ANNUAL VOLUME DISCHARGED AND OUTFALL LENGTH

Assumptions: Design parameters are the same as for Figure 9-26; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

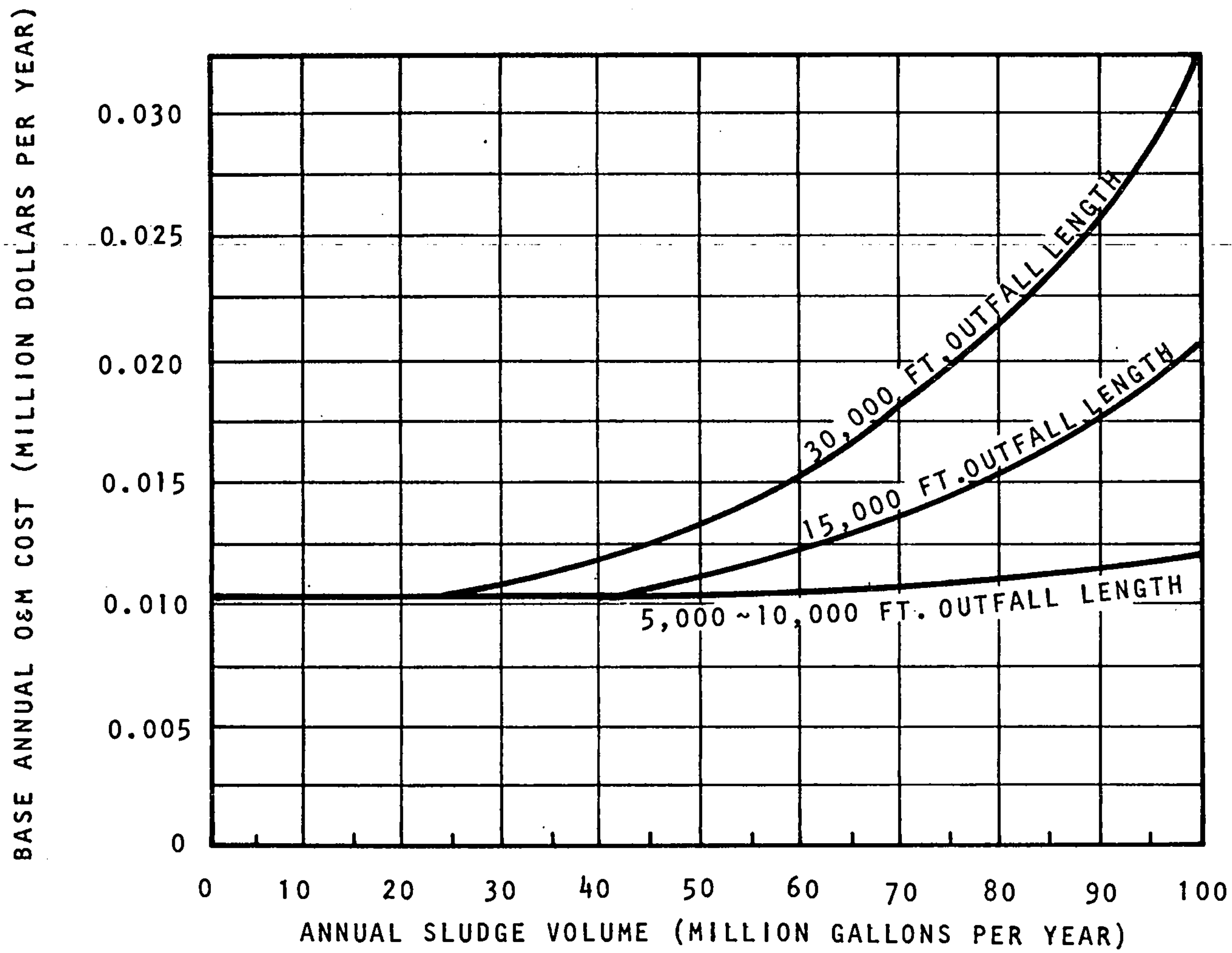
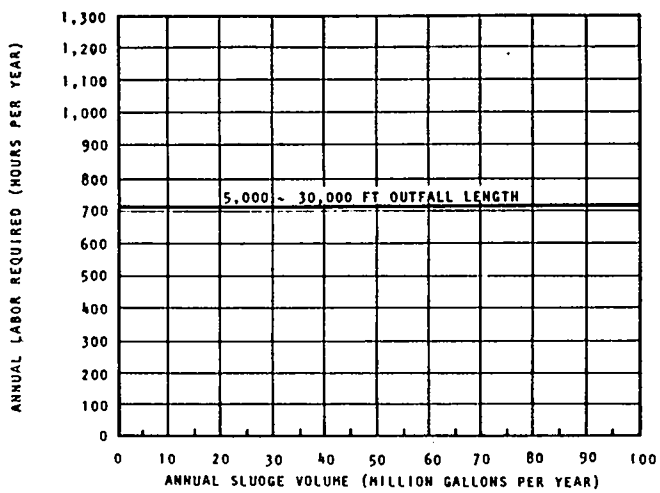
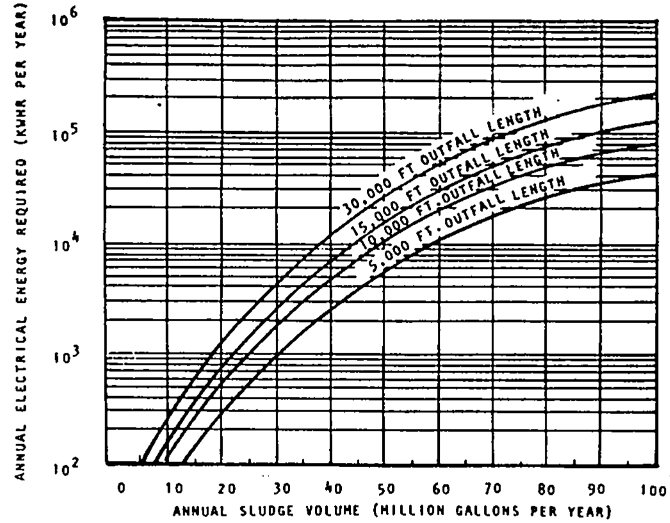
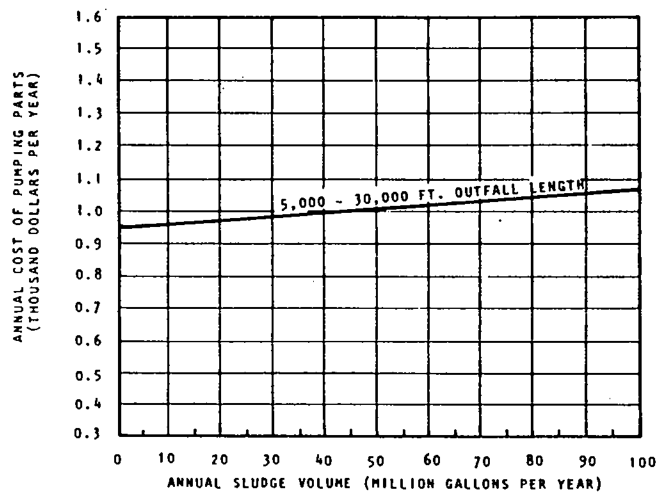


FIGURE 9-28

ANNUAL O&M REQUIREMENTS FOR A LIQUID SLUDGE OCEAN OUTFALL AS A FUNCTION OF ANNUAL VOLUME DISCHARGED AND OUTFALL LENGTH







Assumptions: Design parameters are the same as for Figure 9-26.

SECTION 10

SLUDGE APPLICATION TO LAND CURVES

10.1 Introduction

This section presents base capital and annual O&M curves for various sludge land application programs and sludge landfill operations. Also included are procedures for adjusting curve costs to account for variations in several site-specific variables. These variables are: days of application per year, land cost, and costs for clearing, grading, and lime addition. Any adjustment for days of application should be made prior to the other adjustments.

With all of the methods except land reclamation, sludge is applied at regular intervals throughout the useful life of the site. The useful life of the site may be determined by various factors, usually the accumulation of pollutants. For example, with cropland or forest land application, the site life time ranges from 5 to 20 years, based on a limitation imposed by heavy metal accumulation.

With land reclamation, the objective is to provide nutrients for establishing vegetation through a heavy, one-time sludge application. For this reason, land reclamation costs are based on a one-time application.

10.2 Land Application to Cropland

Use of wastewater treatment plant sludge as a source of fertilizer nutrient to enhance crop production is widespread in the United States. Land application of sludge to cropland affords an environmentally acceptable means of sludge disposal, while providing the farmer with a substitute or supplement for conventional fertilizers.

Sludge application rates for agricultural utilization are usually low, i.e., in the range of 3 to 10 tons/acre/year. Sludges are applied by surface spreading or subsurface injection. Surface application methods include spreading by specially equipped farm tractors, tank wagons, special applicator vehicles equipped with flotation tires, tank trucks, and portable or fixed irrigation systems. Sludge is usually applied only once a year.

Base capital costs, base annual O&M costs, and other O&M requirements for land application to cropland are presented in Figures 10-1 through 10-3. A multiplication factor curve to adjust for variations in days of application per year is given in Figure 10-4. Curves are based on the algorithm in Appendix A-26, using the assumptions noted on Table 10-1. Appendix A-26 should be

FIGURE 10-1

BASE CAPITAL COST OF APPLYING SLUDGE TO CROPLAND AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-1 (see Figure 10-4 to adjust for difference in days per year of application).

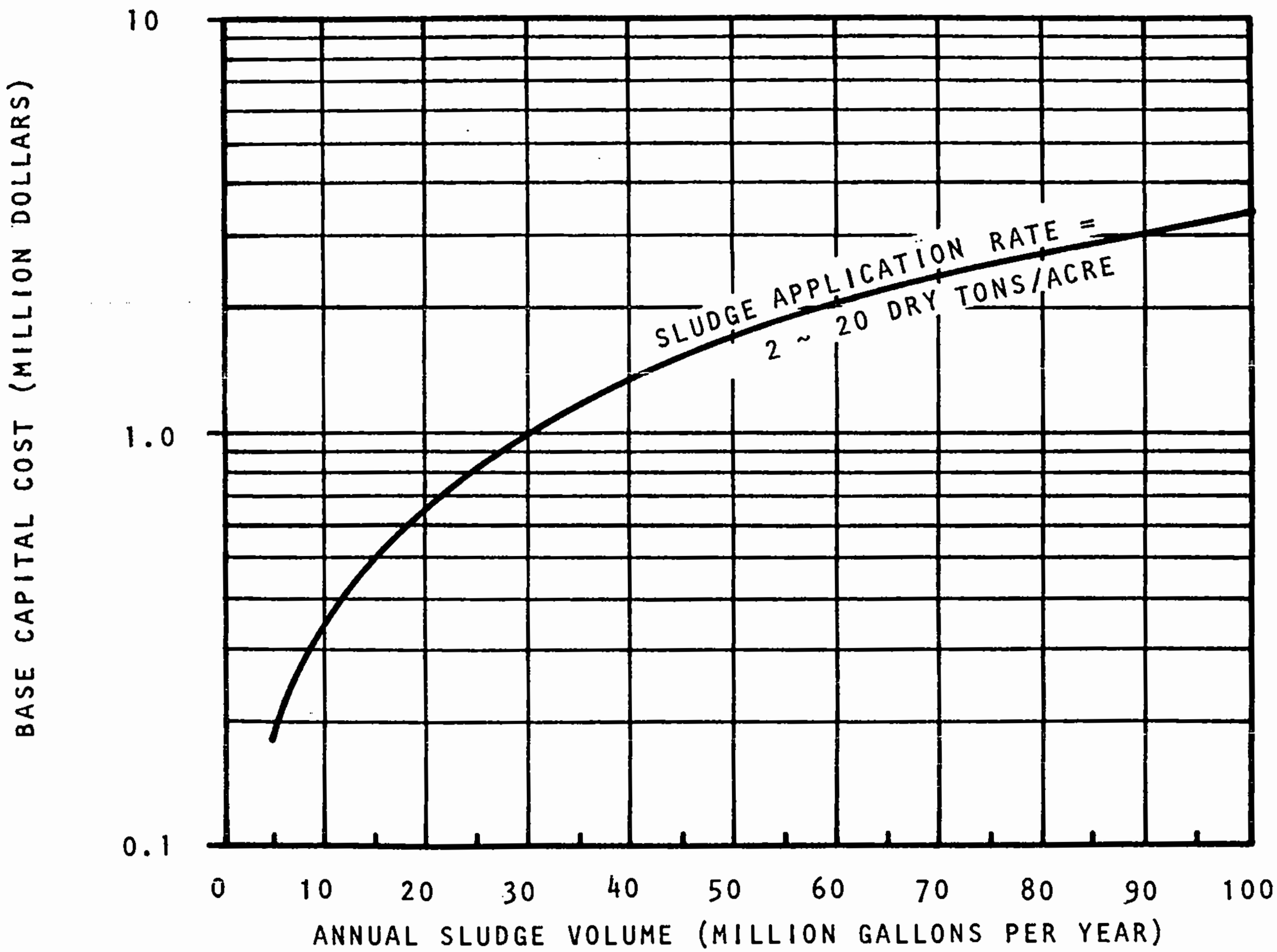


FIGURE 10-2

BASE ANNUAL O&M COST OF APPLYING SLUDGE TO CROPLAND AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-1.

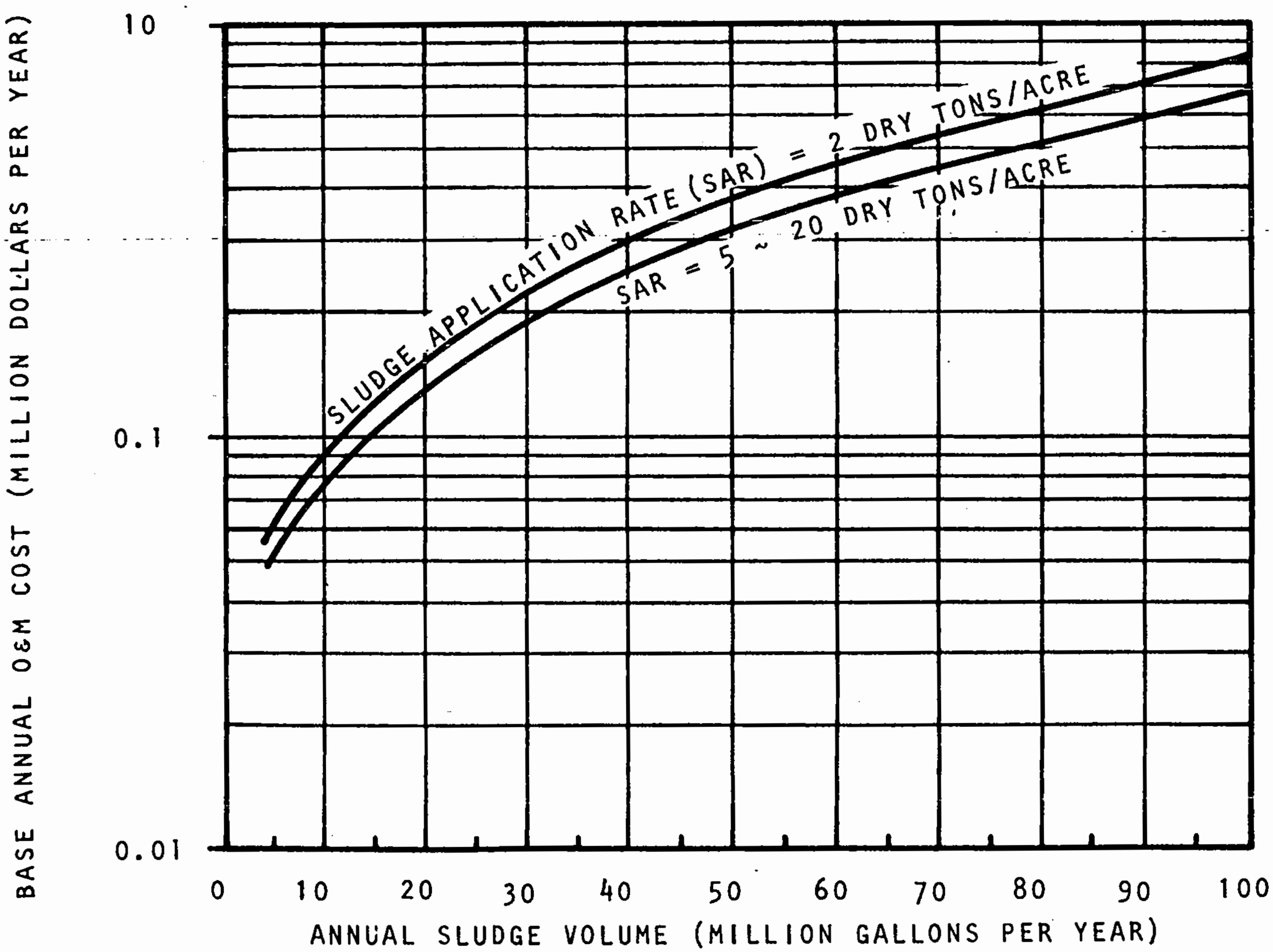
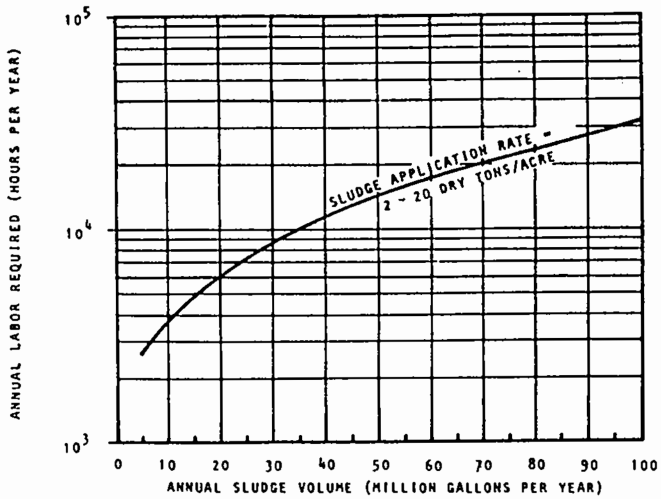
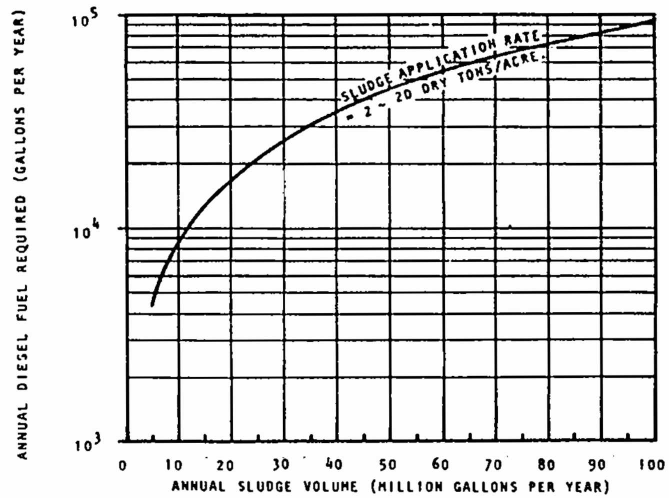
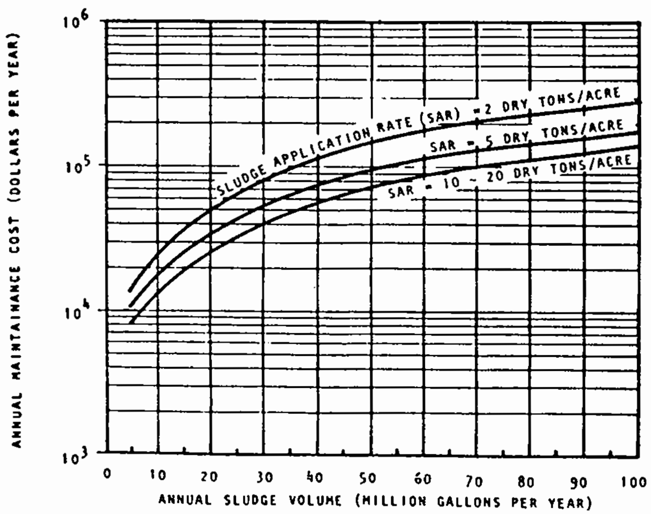


FIGURE 10-3

ANNUAL O&M REQUIREMENTS FOR APPLYING SLUDGE TO CROPLAND AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE







Assumptions: Design parameters are listed in Table 10-1.

FIGURE 10-4

MULTIPLICATION FACTOR TO ADJUST SLUDGE APPLICATION TO CROPLAND COSTS IN FIGURE 10-1 FOR VARIATIONS IN DAYS OF APPLICATION PER YEAR

Assumptions: Design parameters are listed in Table 10-1; number of days per year that sludge is applied is variable.

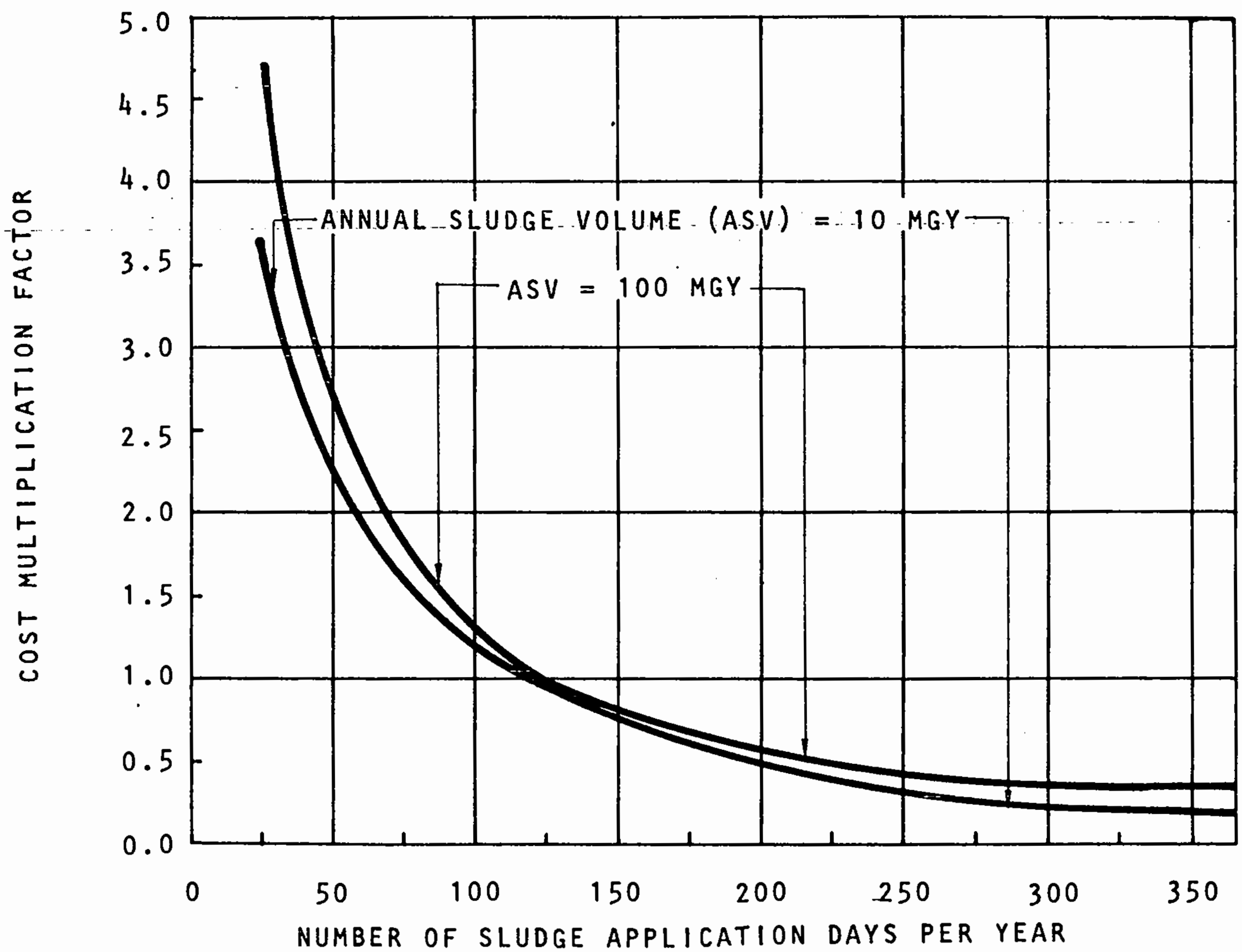


TABLE 10-1

ASSUMPTIONS USED IN DEVELOPING COST REQUIREMENT CURVES FOR LAND APPLICATION OF SLUDGE TO CROPLAND

Parameter	Assumed Value
Sludge Solids Concentration	5 percent
Daily Application Period	6 hr/day
Annual Application Period	120 days/yr
Fraction of Land Required in Addition to Application Area	0.4
Fraction of Land Area Requiring Lime Addition	0
Fraction of Land Area Requiring Light Grading	0
Cost of Land	0
Cost of Lime Addition	0
Cost of Grading Earthwork	0
Cost of Operation Labor	$13.50/hr
Cost of Diesel Fuel	$1.35/gal

consulted for additional information. In addition, the user should see the discussion in Appendix A-27 regarding similarities in application costs for food chain cropland and non-food chain cropland.

10.3 Sludge Application to Marginal Land for Land Reclamation

Sludges have been successfully applied to disturbed or marginal land to enhance reclamation in Pennsylvania and other states. Disturbed lands consist of land created as a result of a disturbance such as mining or mineral processing operations. Marginal lands are those which sustain little vegetation such as very sandy and unproductive areas.

Sludge application for land reclamation is usually a one-time application, i.e., sludge is not applied again at periodic intervals. Therefore, a continual supply of land must be provided for application in future years. Since this algorithm calculates the land required for an annual equivalent application, the costs of land and site improvements (clearing, grading, etc.) are added to the base annual O&M cost.

Sludge application rates vary widely, depending on numerous site and sludge characteristics. Rates reported in the literature vary from 10 to 180 dry tons per acre.

Base capital costs, base annual O&M costs, and other O&M requirements for sludge application to marginal land are presented in Figures 10-5 through 10-7. A multiplication factor curve to adjust for variations in days of sludge application per year is shown in Figure 10-8. Curves are based on the algorithm in Appendix A-28, using the assumptions noted on Table 10-2. Additional information on algorithm development, design parameters, and other assumptions is provided in Appendix A-28.

10.4 Land Application to Forest Land Sites

Application of sludge to forest land has been successfully demonstrated in the states of Washington, Michigan, and South Carolina. Commercial timber and fiber production lands, as well as federal and state forests, are potential application sites for properly managed programs.

Sludge application rates for forest land application are dependent upon factors such as sludge characteristics, tree maturity, tree species, and soil characteristics. Unlike other land application programs which involve annual sludge application, forest land sludge application to a specific site is often done at multi-year intervals, e.g., every 5 years.

Base capital costs, base annual O&M costs, and other O&M requirements are presented in Figures 10-9 through 10-11. A multiplication factor curve to adjust costs for variations in days of sludge application per year is given in Figure 10-12. Curves are based on the algorithm in Appendix A-29, using the assumptions noted on Table 10-3. The user should consult Appendix A-29 for additional information.

FIGURE 10-5

BASE CAPITAL COST OF APPLYING SLUDGE TO MARGINAL LAND FOR RECLAMATION AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED

Assumptions: Design parameters are listed in Table 10-2 (see Figure 10-8 to adjust for differences in days per year of application).

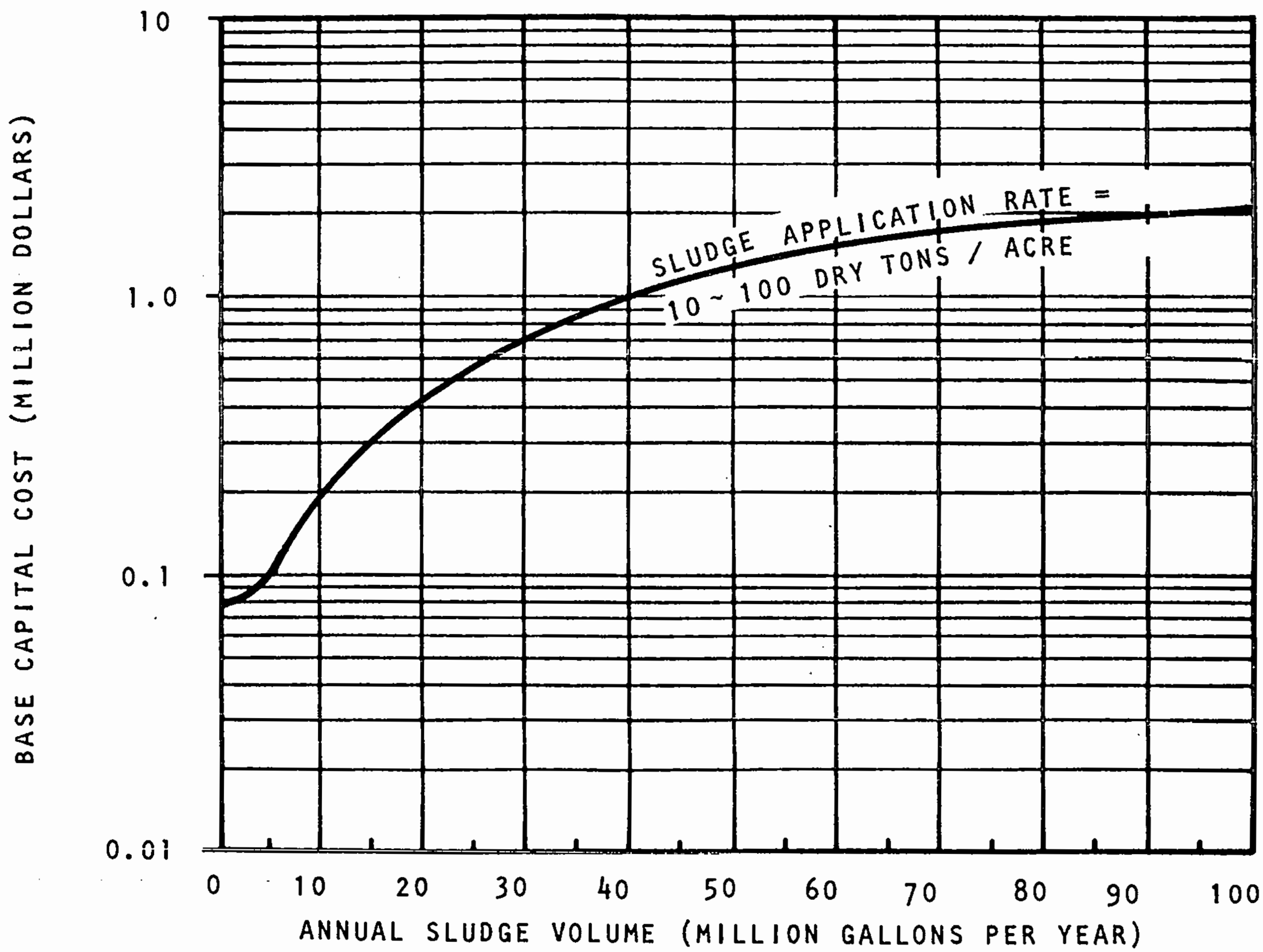


FIGURE 10-6

BASE ANNUAL O&M COST FOR APPLYING SLUDGE TO MARGINAL LAND FOR RECLAMATION AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-2.

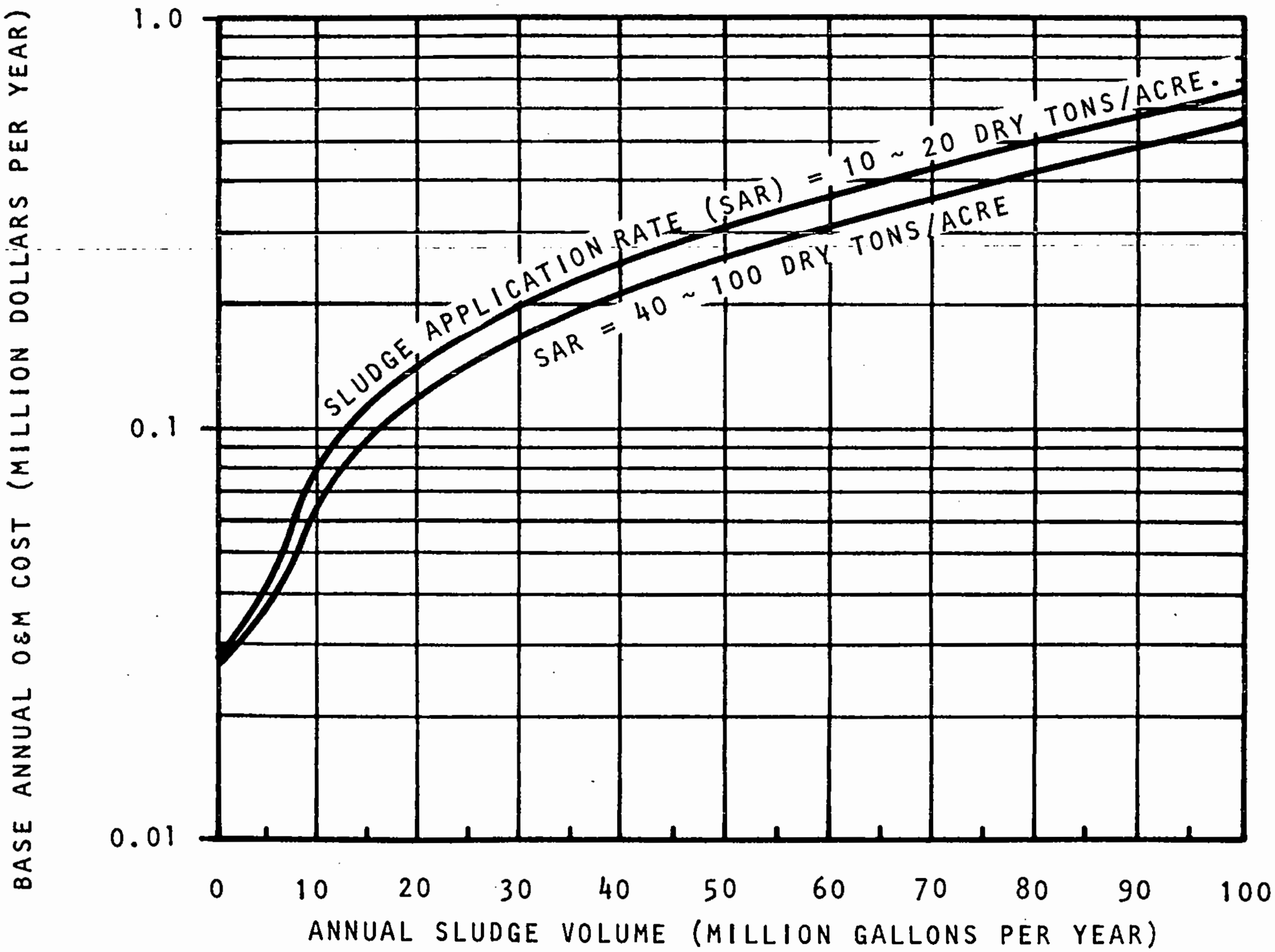
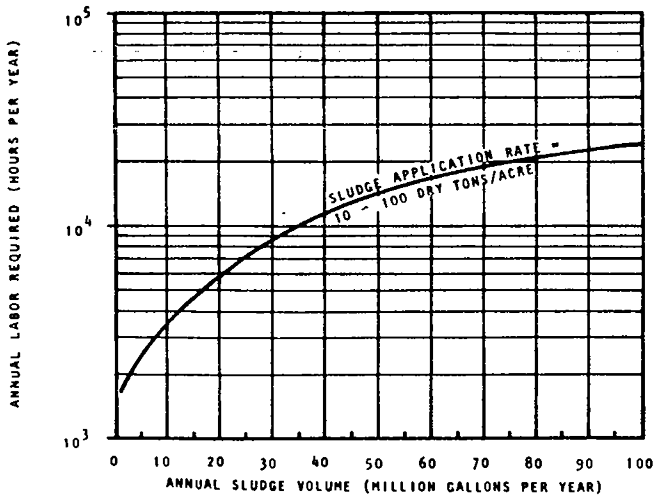


FIGURE 10-7

ANNUAL O&M REQUIREMENTS FOR APPLYING SLUDGE TO MARGINAL LAND FOR RECLAMATION AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED

Assumptions: Design parameters are listed in Table 10-2.



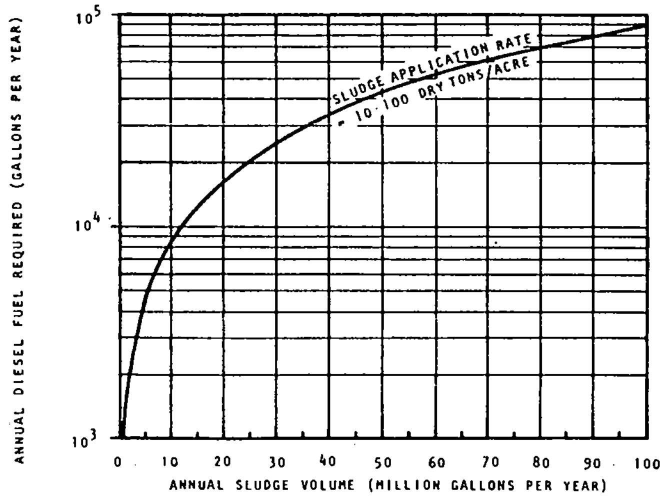
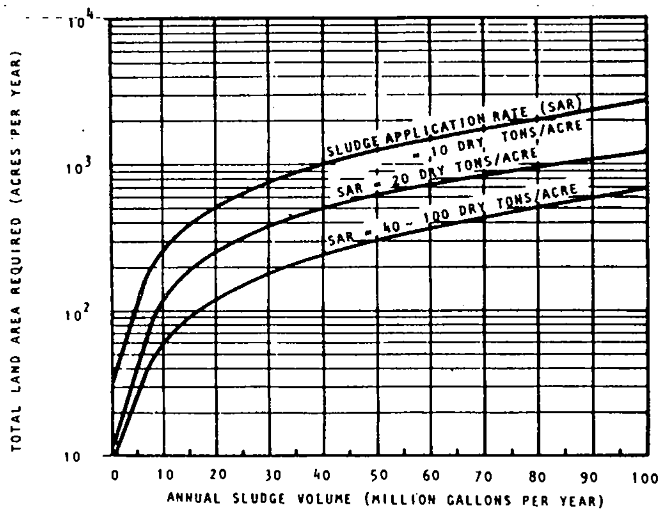


FIGURE 10-7 (CONTINUED)

Assumptions: Design parameters are listed in Table 10-2.



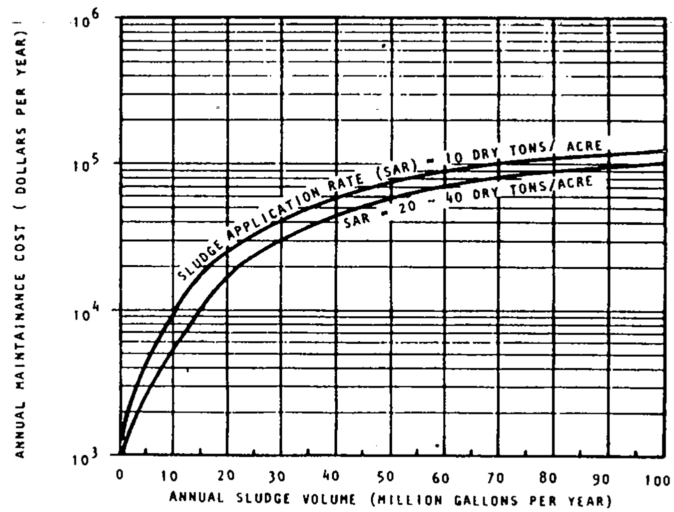


FIGURE 10-8

MULTIPLICATION FACTOR TO ADJUST SLUDGE APPLICATION TO MARGINAL LAND COSTS IN FIGURE 10-5 FOR VARIATIONS IN DAYS OF APPLICATION PER YEAR

Assumptions: Design parameters are listed in Table 10-2; number of days per year that sludge is applied is variable.

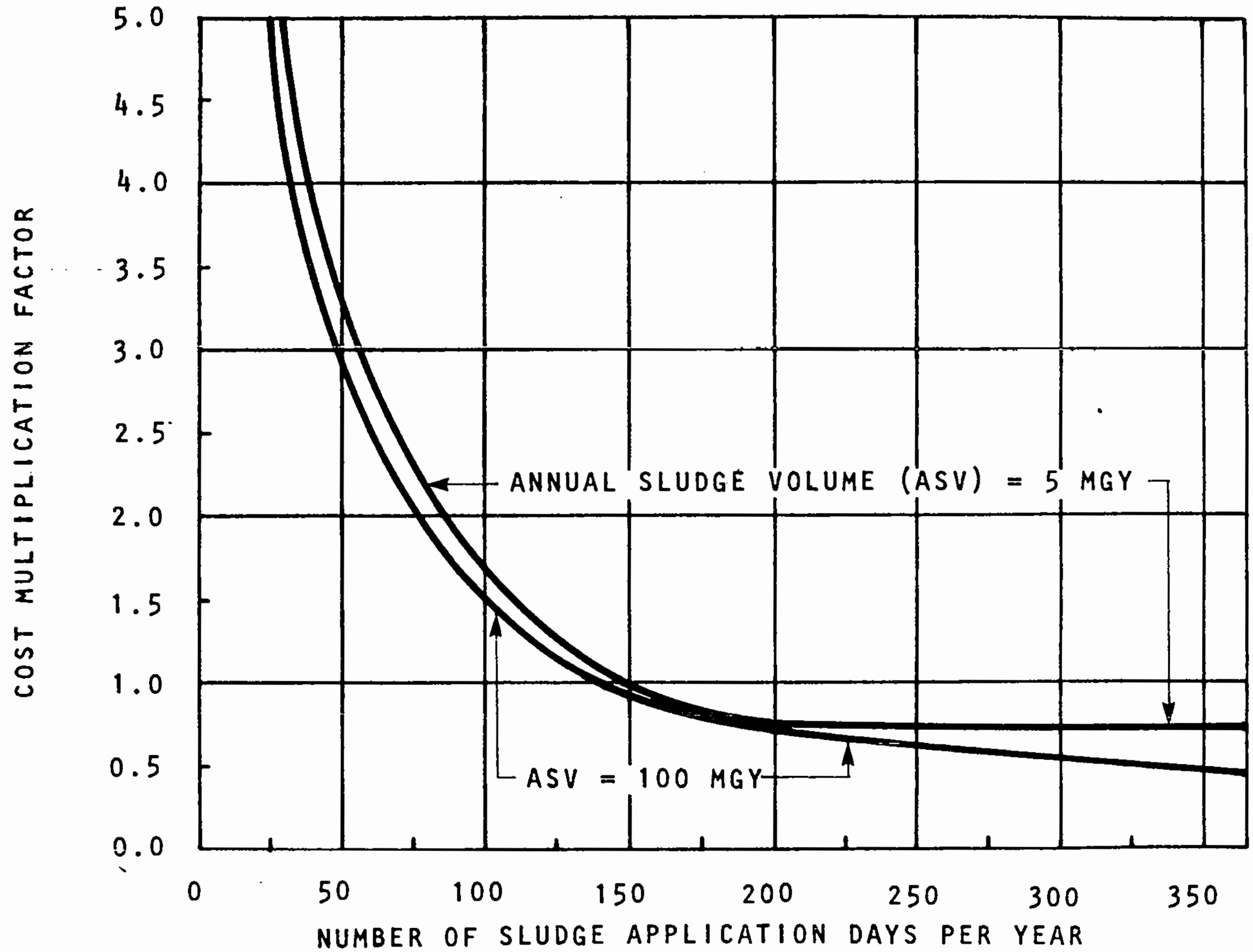


TABLE 10-2

ASSUMPTIONS USED IN DEVELOPING COST REQUIREMENT CURVES FOR LAND APPLICATION OF SLUDGE TO MARGINAL LAND

Parameter	Assumed Value
Sludge Solids Concentration	5 percent
Daily Application Period	7 hr/day
Annual Application Period	140 days/yr
Fraction of Land Required in Addition to Application Area	0.3
Fraction of Land Area Requiring Lime Addition	0
Fraction of Land Area Requiring Grading	0
Cost of Land	0
Cost of Lime Addition	0
Cost of Grading Earthwork	0
Cost of Operation Labor	$13.50/hr
Cost of Diesel Fuel	$1.35/gal
Cost of Monitoring Wells	$5,200 each

FIGURE 10-9

BASE CAPITAL COST OF APPLYING SLUDGE TO FOREST LAND AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-3 (see Figure 10-12 to adjust for differences in days per year of application).

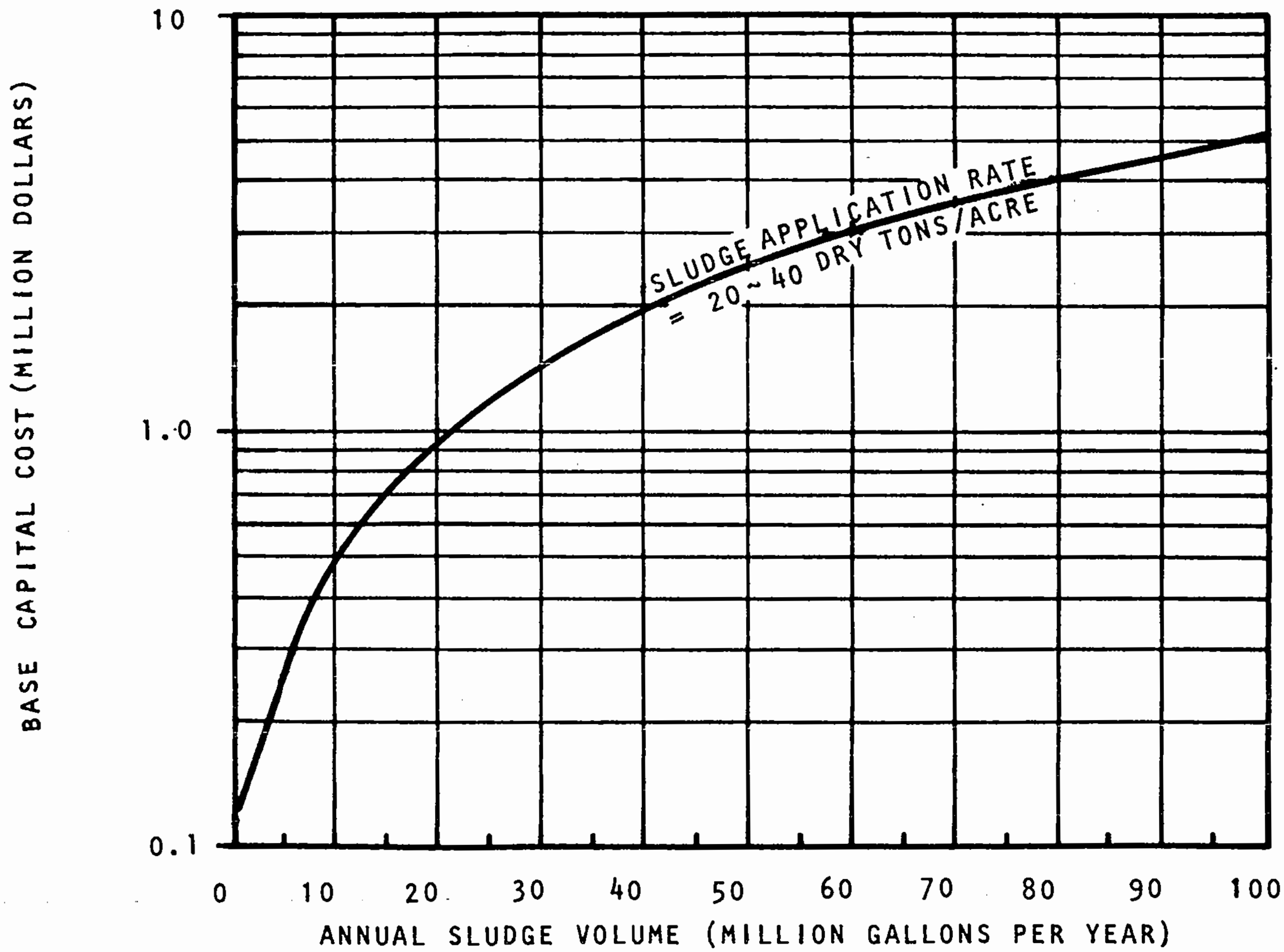


FIGURE 10-10

BASE ANNUAL O&M COST OF APPLYING SLUDGE TO FOREST LAND AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-3.

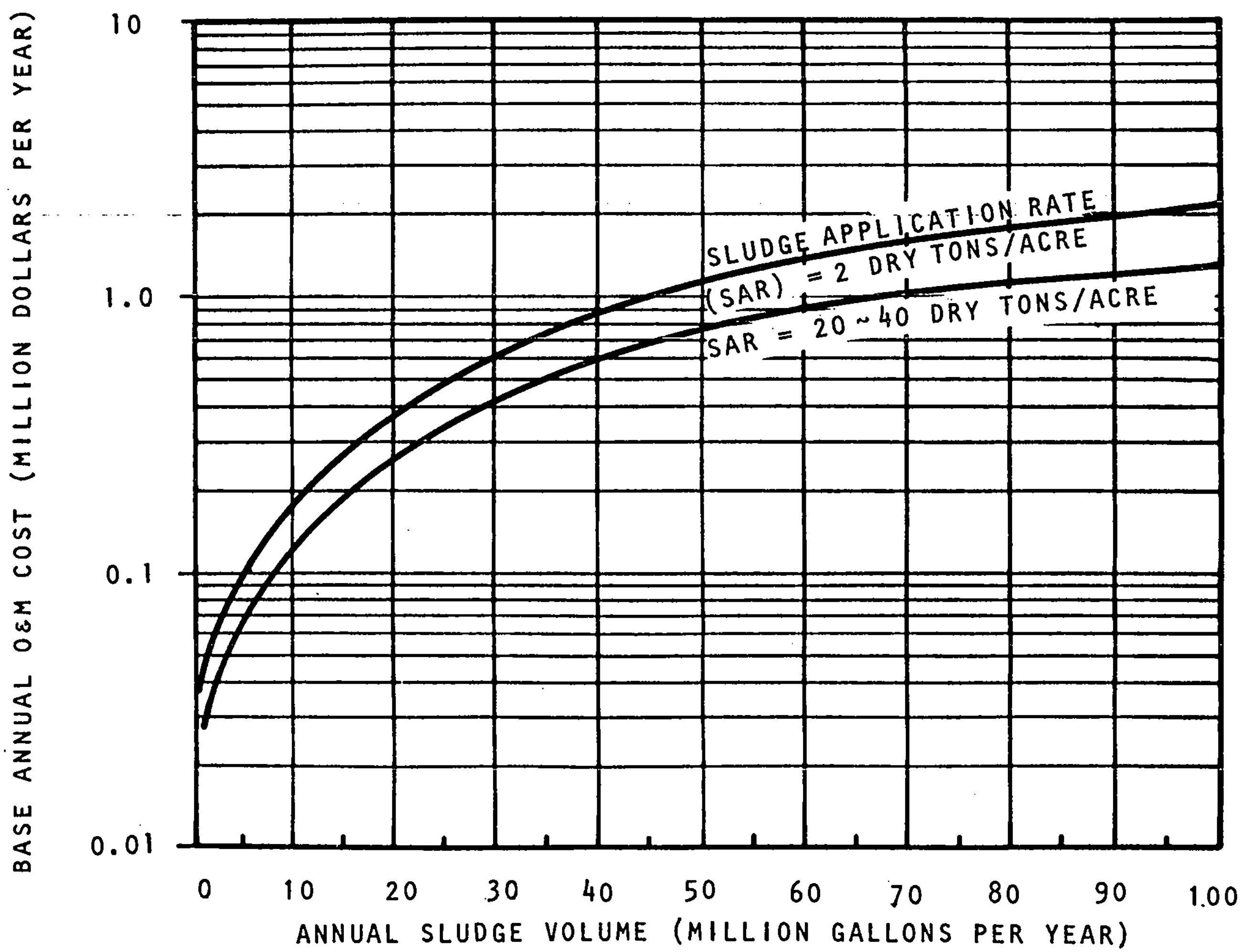
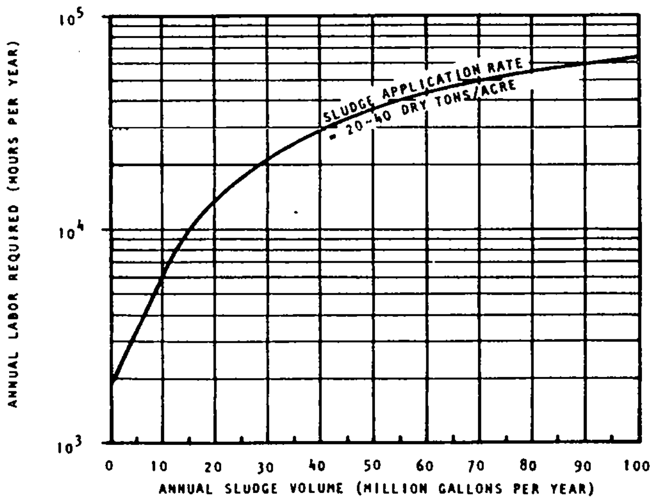


FIGURE 10-11

ANNUAL O&M REQUIREMENTS FOR APPLYING SLUDGE TO FOREST LAND AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-3.



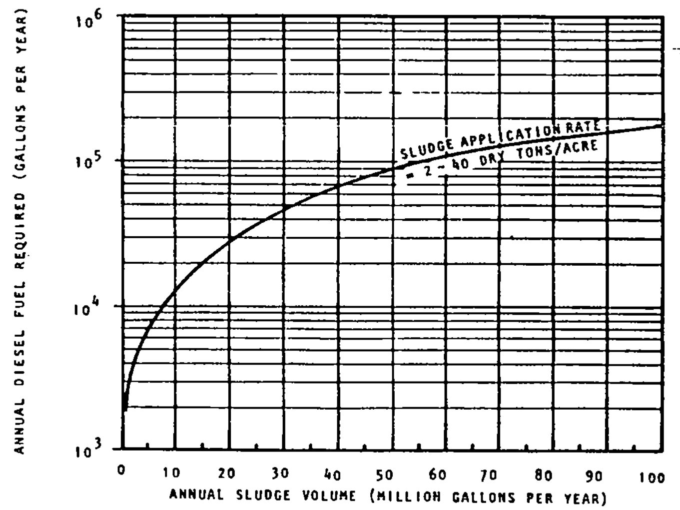
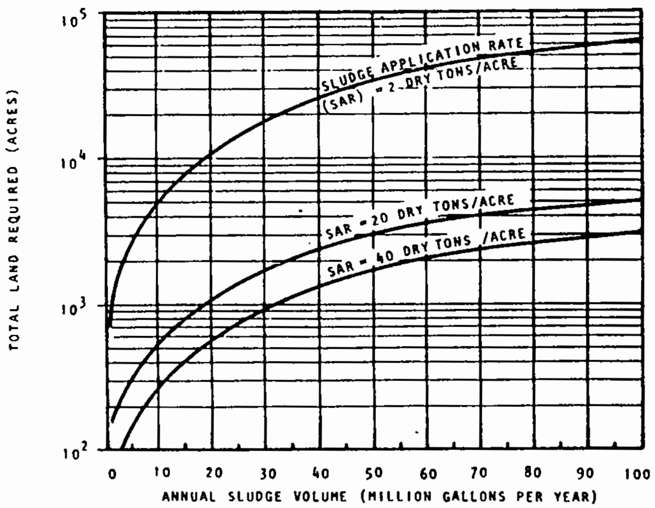


FIGURE 10-11 (CONTINUED)

Assumptions: Design parameters are listed in Table 10-3.



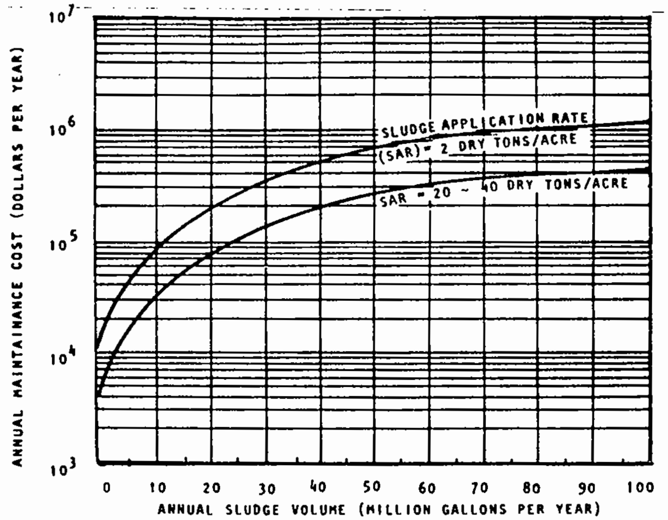


FIGURE 10-12

MULTIPLICATION FACTOR TO ADJUST SLUDGE APPLICATION TO FOREST LAND COSTS IN FIGURE 10-9 FOR VARIATIONS IN DAYS OF APPLICATION PER YEAR

Assumptions: Design parameters are listed in Table 10-3; number of days per year that sludge is applied is variable.

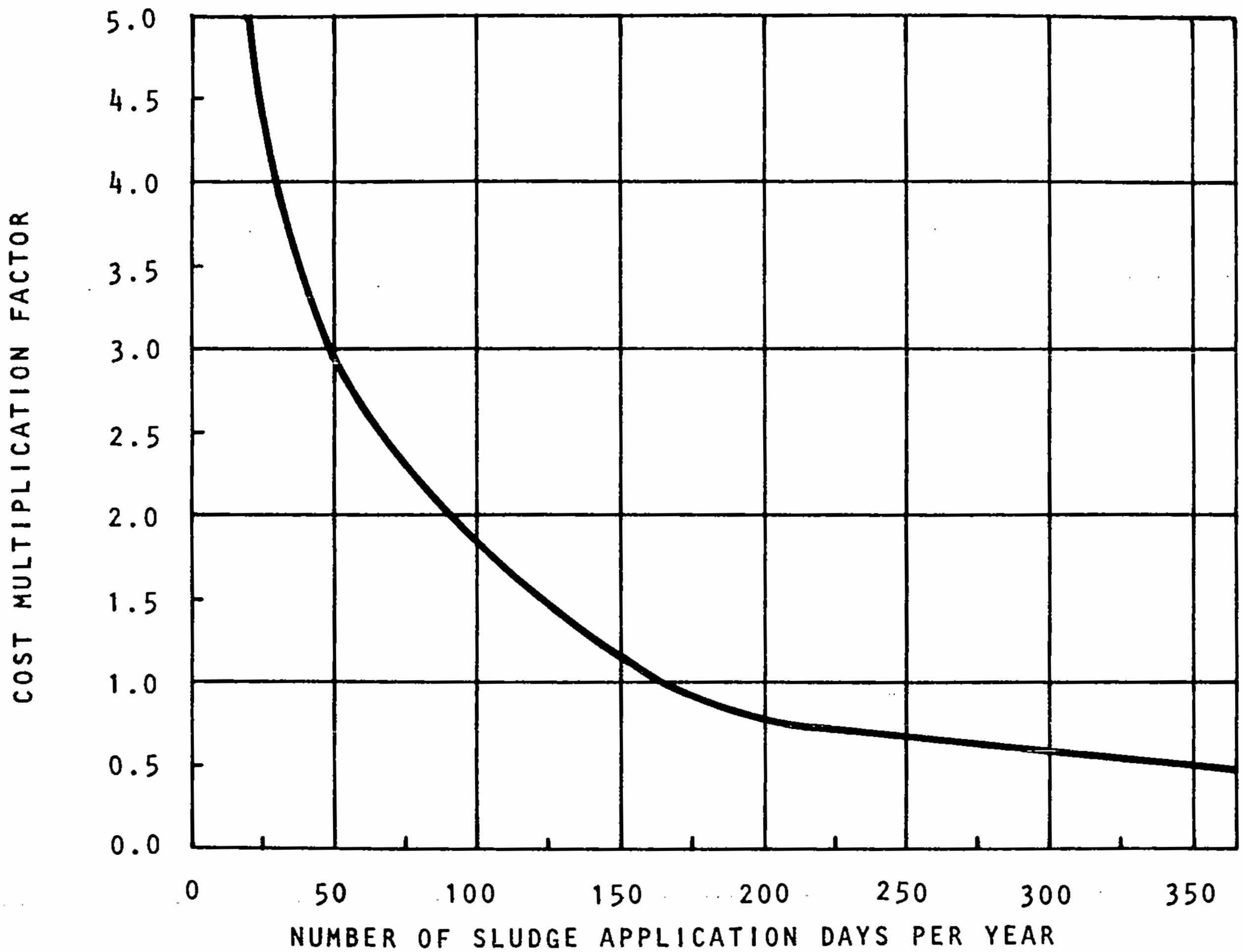


TABLE 10-3

ASSUMPTIONS USED IN DEVELOPING COST REQUIREMENT CURVES FOR LAND APPLICATION OF SLUDGE TO FOREST LAND SITE

Parameter	Assumed Value
Sludge Solids Concentration	5 percent
Daily Application Period	7 hr/day
Annual Application Period	150 days/yr
Frequency of Application	5 yr
Fractior of Land Required in Addition to Application Area	0.2
Fraction of Land Area Requiring Clearing	0.05
Fraction of Land Area Requiring Grading	0
Cost of Land	0
Cost of Grading Earthwork	0
Cost of Operation Labor	$13.50/hr
Cost of Diesel Fuel	$1.35/gal
Cost of Monitoring Wells	$5,200 each
Cost of Clearing	$1,040/acre

10.5 Land Application to Dedicated Disposal Site

Land application to a dedicated disposal site differs from other land application programs in that the site is used primarily or exclusively for the land spreading of sludge. Sludge application rates are much higher for dedicated disposal sites than for the other land application programs, ranging from 20 to 200 tons of dry solids/acre/year. Sludge is often applied to a dedicated disposal site throughout the year, except during inclement weather.

Figures 10-13 through 10-15 present base capital costs, base annual O&M costs, and other annual O&M requirements for sludge application to a dedicated disposal site. A multiplication factor curve to adjust capital costs for variations in days of sludge application per year is given in Figure 10-16. Curves are based on the algorithm in Appendix A-30, using the assumptions noted on Table 10-4. Additional information is provided for this process in Appendix A-30.

10.6 Land Disposal to Sludge Landfill

Sludge landfilling is a disposal process in which sludge is buried by a layer of cover soil. Cover soil is usually applied daily. This process should not be confused with co-disposal with municipal refuse or disposal in which a disposal (tipping) fee is paid. In this process, the sludge-generating entity owns and operates the landfill for the purpose of sludge disposal.

Base capital costs, base annual O&M costs, and other annual O&M requirements for land disposal to a sludge landfill are given in Figures 10-17 through 10-19. Figure 10-20 is used in adjusting capital costs to account for land costs different from those assumed in Figure 10-17. Curves are based on the algorithm in Appendix A-31, using the assumptions in Table 10-5. The user should consult Appendix A-31 for additional information.

10.7 Adjustment of Curve Costs for Land Costs Different from Those Assumed

Base capital cost curves for the application of sludge to croplands, forest lands, and marginal lands do <u>not</u> include the cost of land, since these costs are typically not paid by the sludge generator. However, municipalities customarily purchase land for dedicated disposal sites and sludge-only landfills. Base capital costs presented in curves for dedicated disposal and sludge landfill processes include the cost of land at an assumed unit cost of $3,120/acre. The user may want to include land costs for cropland, forest land, and marginal land application, or use a land cost other than the assumed unit cost to more accurately fit his particular situation. This may be accomplished using the following procedure after first adjusting for days of application, if necessary:

Step 1. For all processes except sludge landfill disposal, refer to Figure 10-21 and use the annual volume of sludge to be applied and the average sludge solids concentration to determine the weight of dry solids to be applied annually, TDSS. (Note: For sludge landfill disposal, total land area required (TLAR), in acres, should be obtained directly from Figure 10-20. Skip to Step 5.)

FIGURE 10-13

BASE CAPITAL COST OF APPLYING SLUDGE TO A DEDICATED DISPOSAL SITE AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-4 (see Figure 10-16 to adjust for differences in days per year of application).

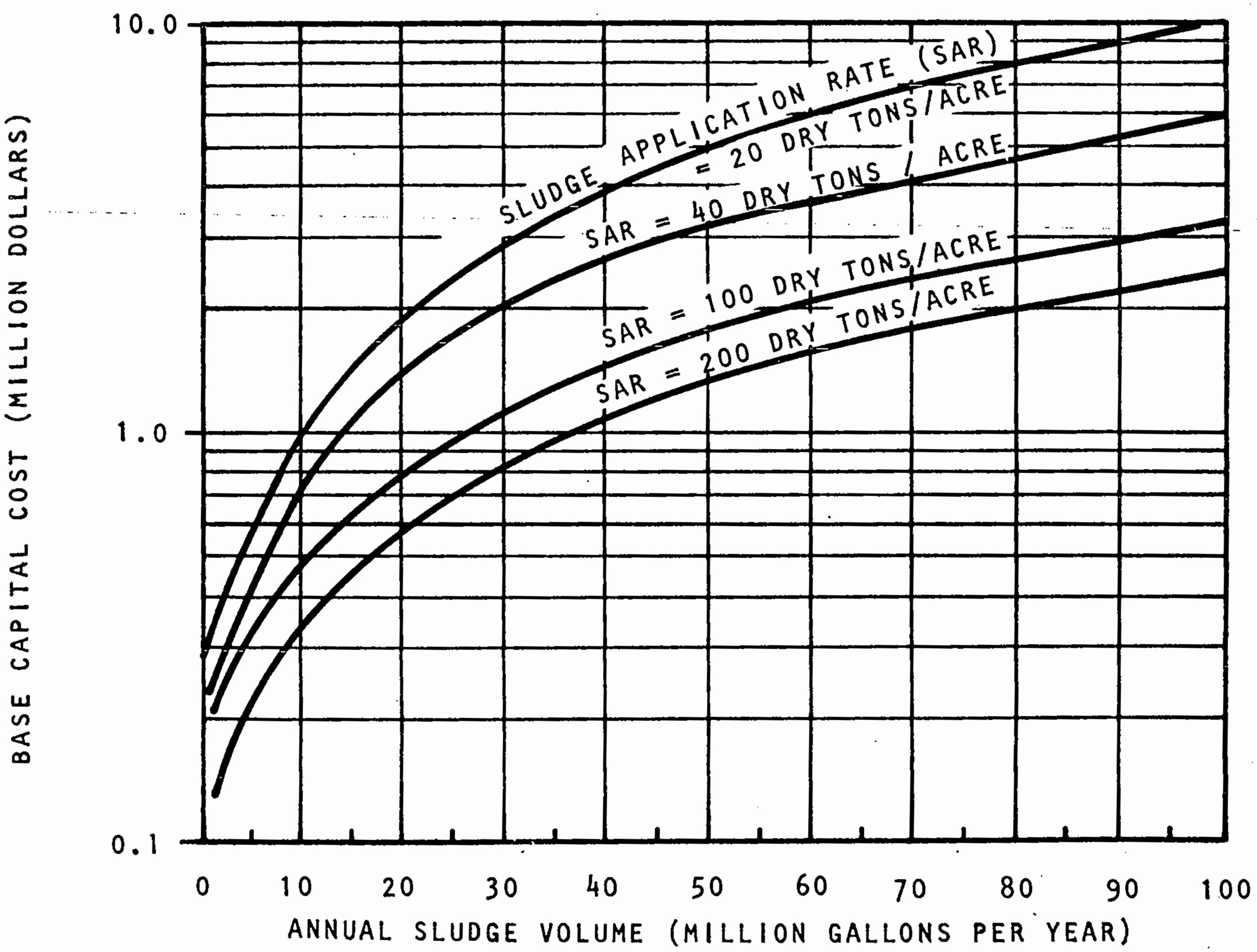


FIGURE 10-14

BASE ANNUAL O&M COST OF APPLYING SLUDGE TO A DEDICATED DISPOSAL SITE AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE

Assumptions: Design parameters are listed in Table 10-4.

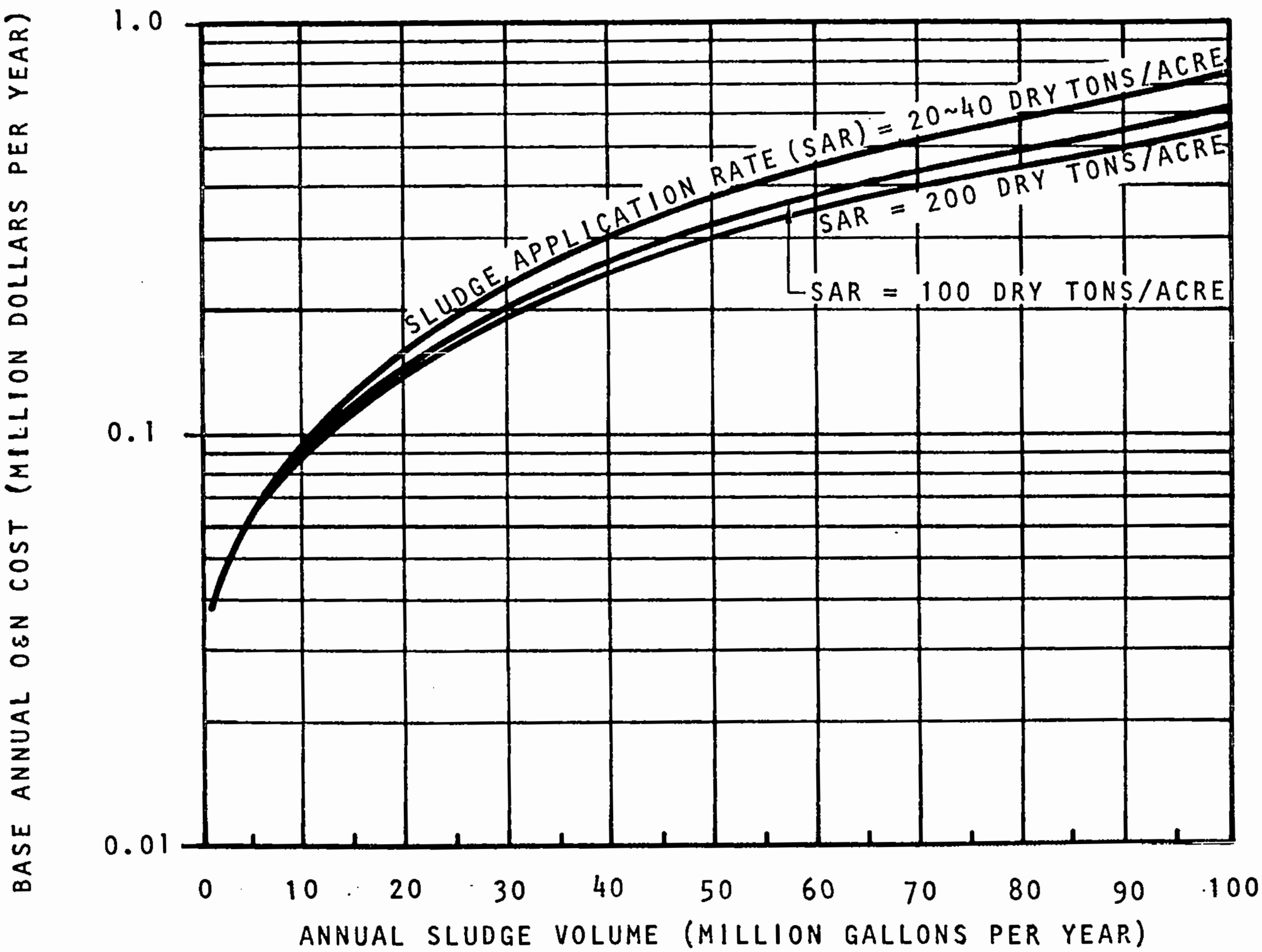
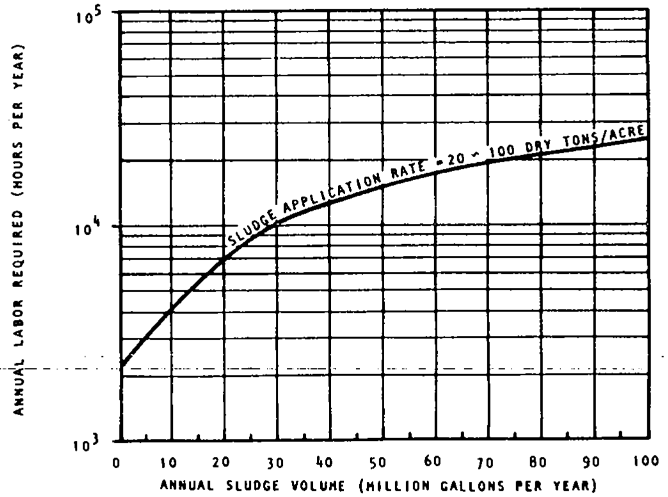
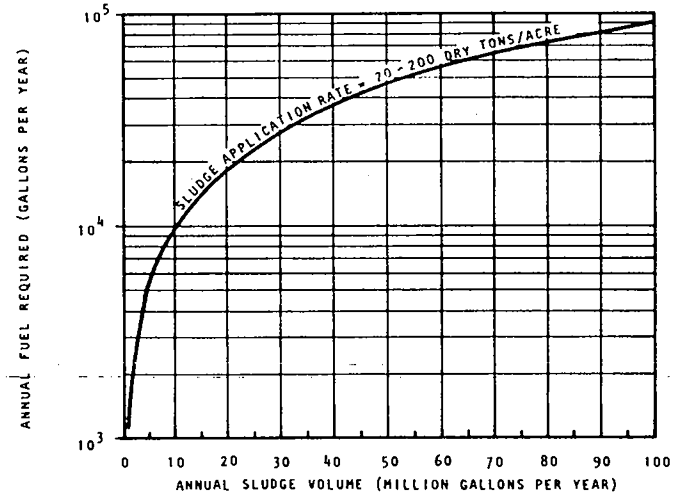
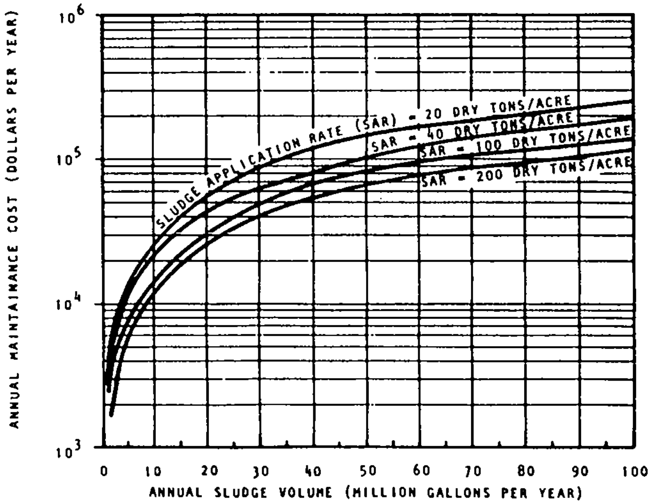


FIGURE 10-15

ANNUAL O&M REQUIREMENTS FOR APPLYING SLUDGE TO A DEDICATED DISPOSAL SITE AS A FUNCTION OF ANNUAL SLUDGE VOLUME APPLIED AND DRY SOLIDS APPLICATION RATE







Assumptions: Design parameters are listed in Table 10-4.

FIGURE 10-16

MULTIPLICATION FACTOR TO ADJUST SLUDGE APPLICATION TO DEDICATED DISPOSAL SITE COSTS IN FIGURE 10-13 FOR VARIATIONS IN DAYS OF APPLICATION PER YEAR

Assumptions: Design parameters are listed in Table 10-4; number of days per year that sludge is applied is variable.

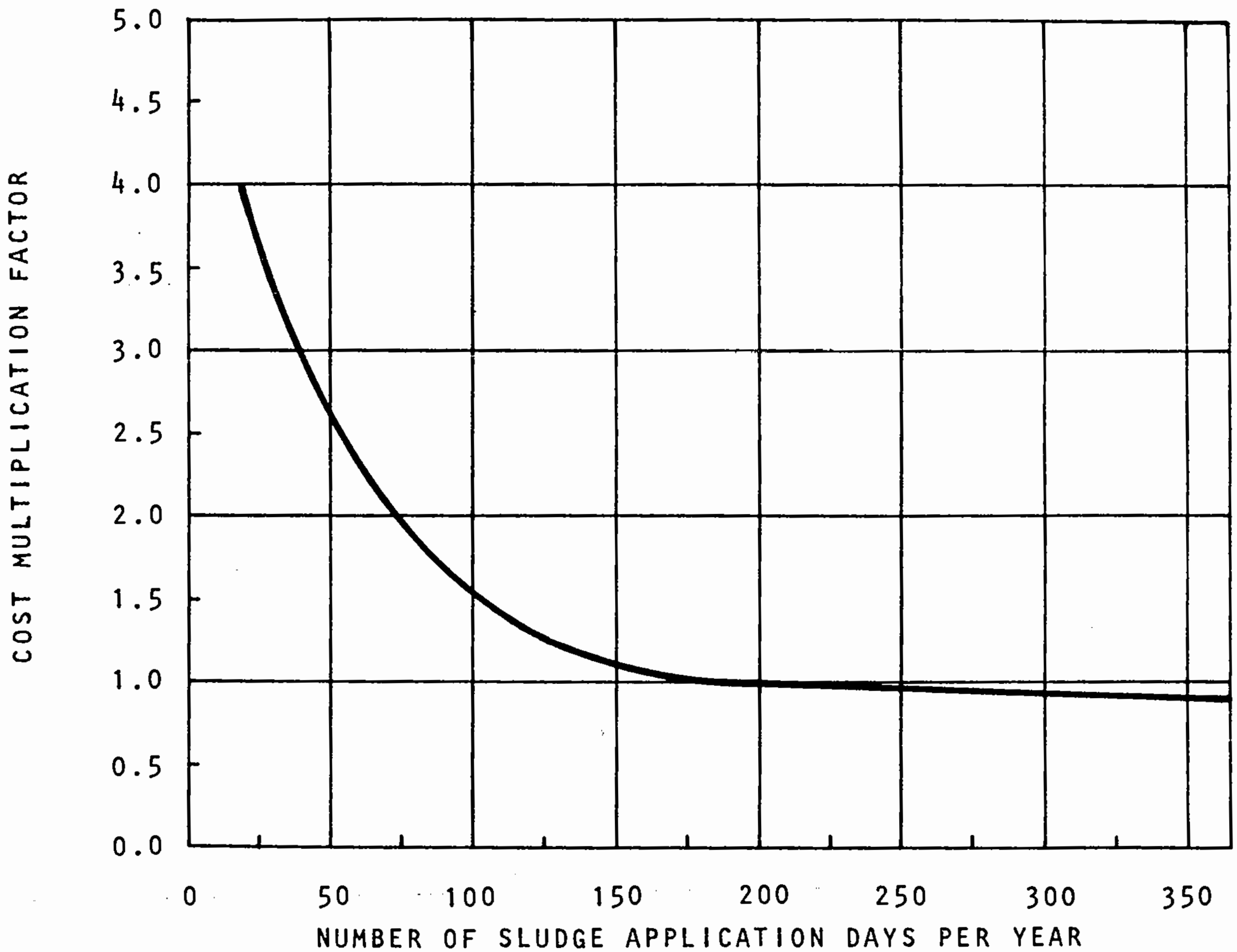


TABLE 10-4

ASSUMPTIONS USED IN DEVELOPING COST REQUIREMENT CURVES FOR LAND APPLICATION OF SLUDGE TO DEDICATED DISPOSAL SITE

Parameter	Assumed Value
Sludge Solids Concentration	5 percent
Daily Application Period	7 hr/day
Annual Application Period	200 days/yr
Fraction of Land Required in Addition to Application Area	0.4
Fraction of Land Area Requiring Clearing	0
Fraction of Land Area Requiring Grading	0
Cost of Land	$3,120/acre
Cost of Grading Earthwork	0
Cost of Operation Labor	$13.50/hr
Cost of Diesel Fuel	$1.35/gal
Cost of Monitoring Wells	$5,200 each
Cost of Clearing	0

FIGURE 10-17

BASE CAPITAL COST OF A MUNICIPALLY OWNED SLUDGE LANDFILL AS A FUNCTION OF ANNUAL SLUDGE VOLUME RECEIVED

Assumptions: Design parameters are listed in Table 10-5.

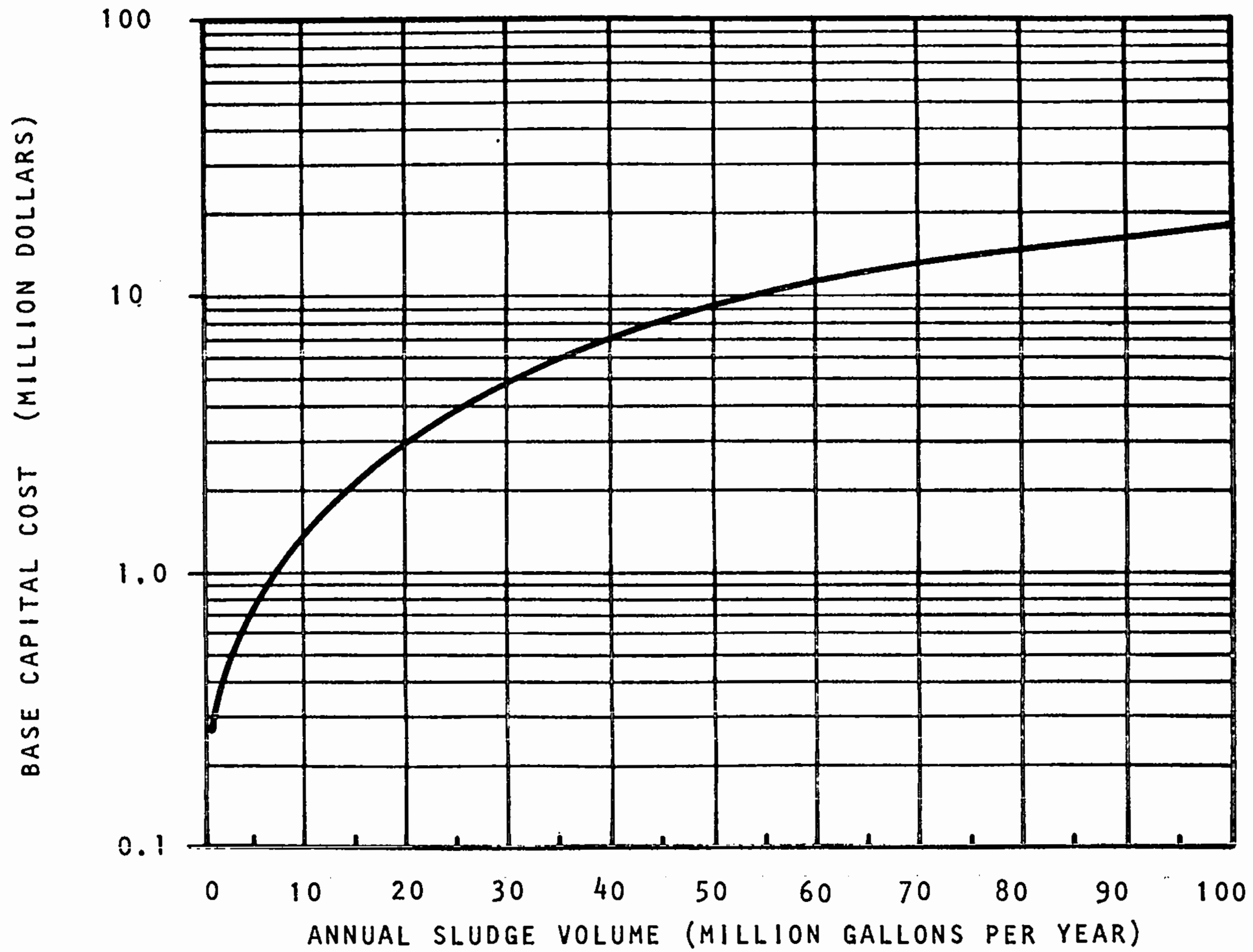


FIGURE 10-18

BASE ANNUAL O&M COST FOR A MUNICIPALLY OWNED SLUDGE LANDFILL AS A FUNCTION OF ANNUAL SLUDGE VOLUME RECEIVED

Assumptions: Design parameters are listed in Table 10-5.

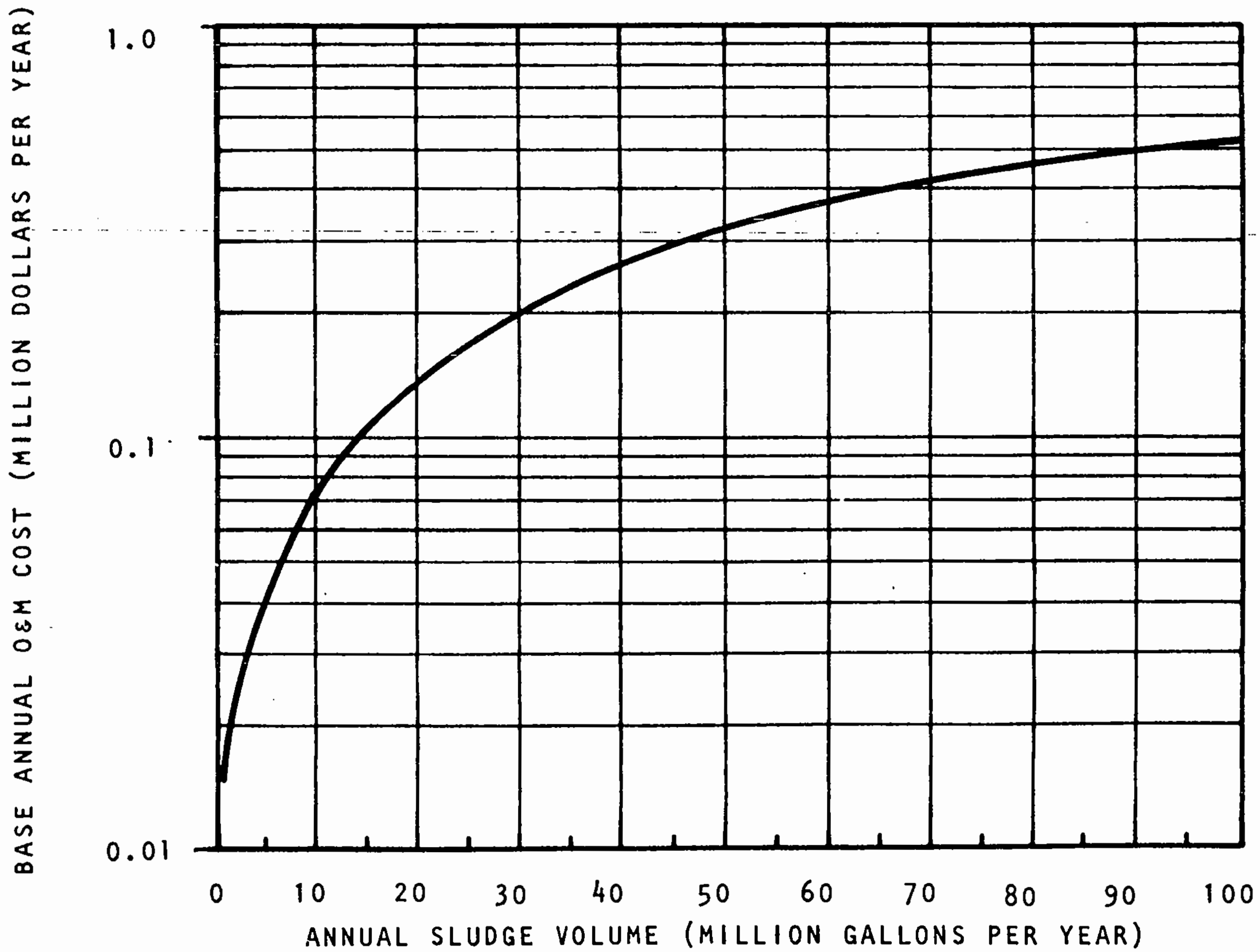
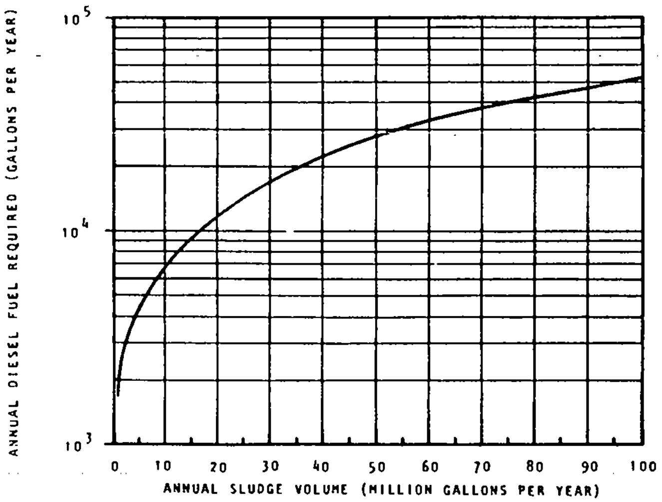


FIGURE 10-19

ANNUAL O&M REQUIREMENTS FOR A MUNICIPALLY OWNED SLUDGE LANDFILL AS A FUNCTION OF ANNUAL SLUDGE VOLUME RECEIVED

Assumptions: Design parameters are listed in Table 10-5.



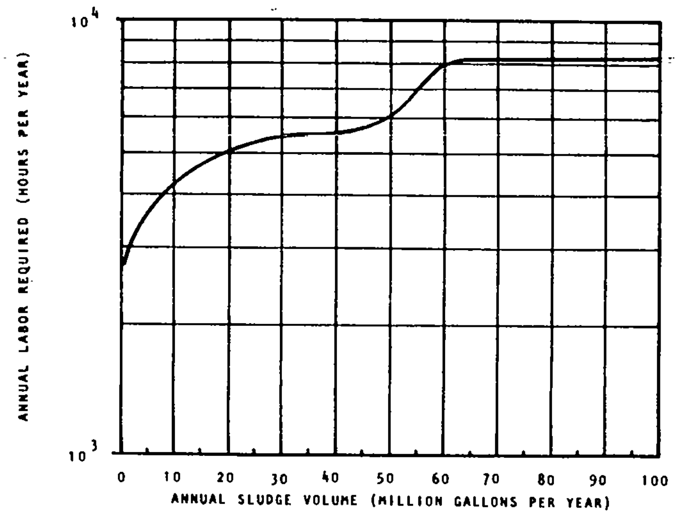


FIGURE 10-19 (CONTINUED)

Assumptions: Design parameters are listed in Table 10-5.

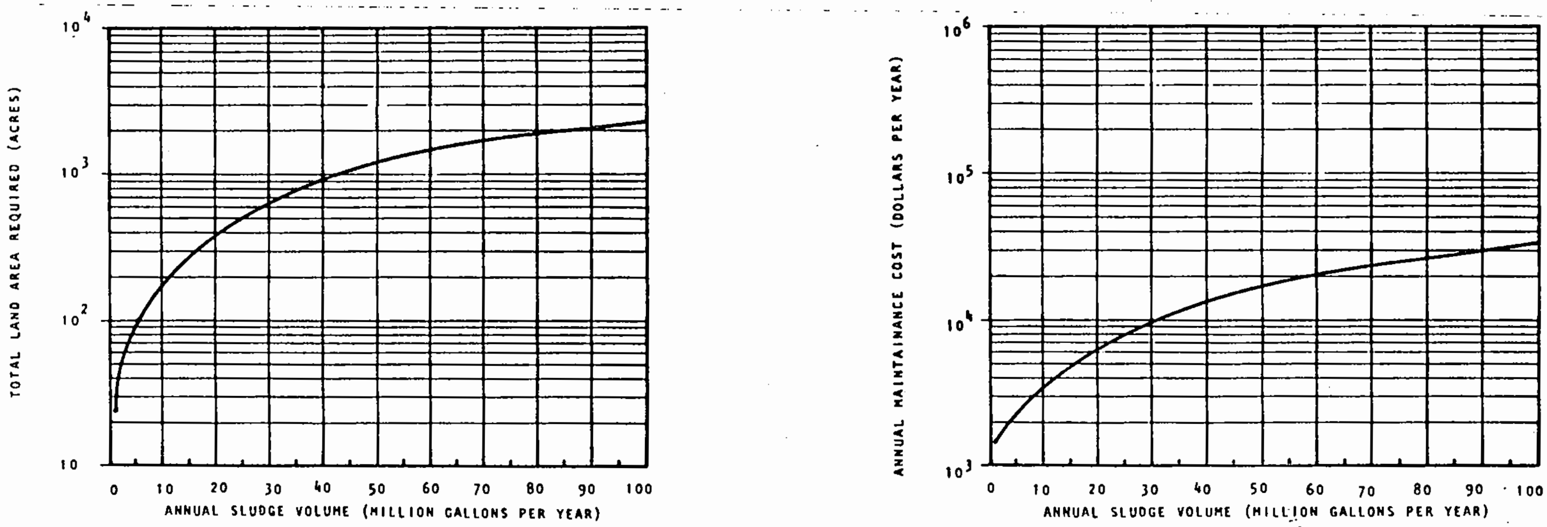


FIGURE 10-20

LAND AREA REQUIRED FOR A SLUDGE LANDFILL AS A FUNCTION OF ANNUAL SLUDGE VOLUME RECEIVED

Assumptions: Design parameters are listed in Table 10-5.

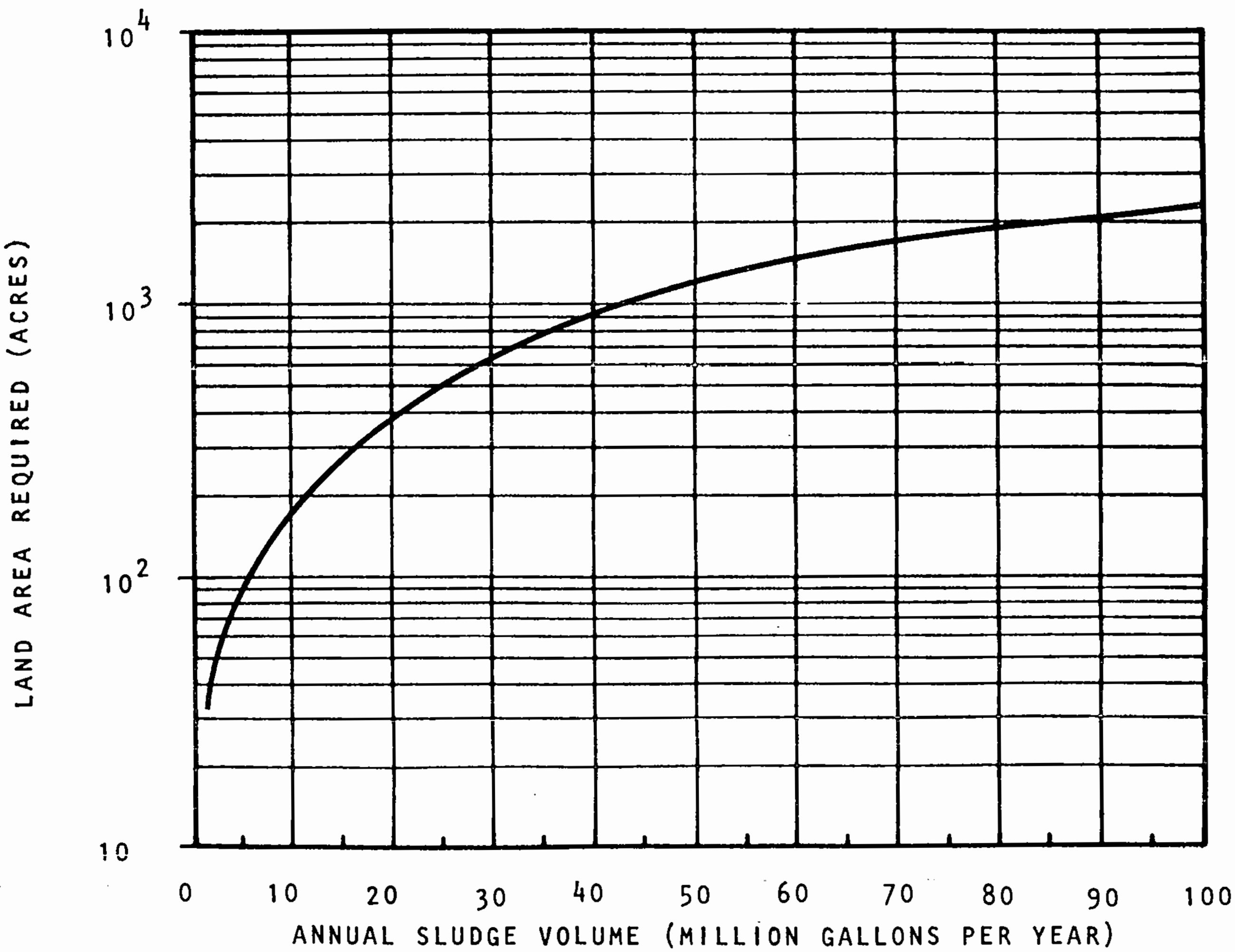


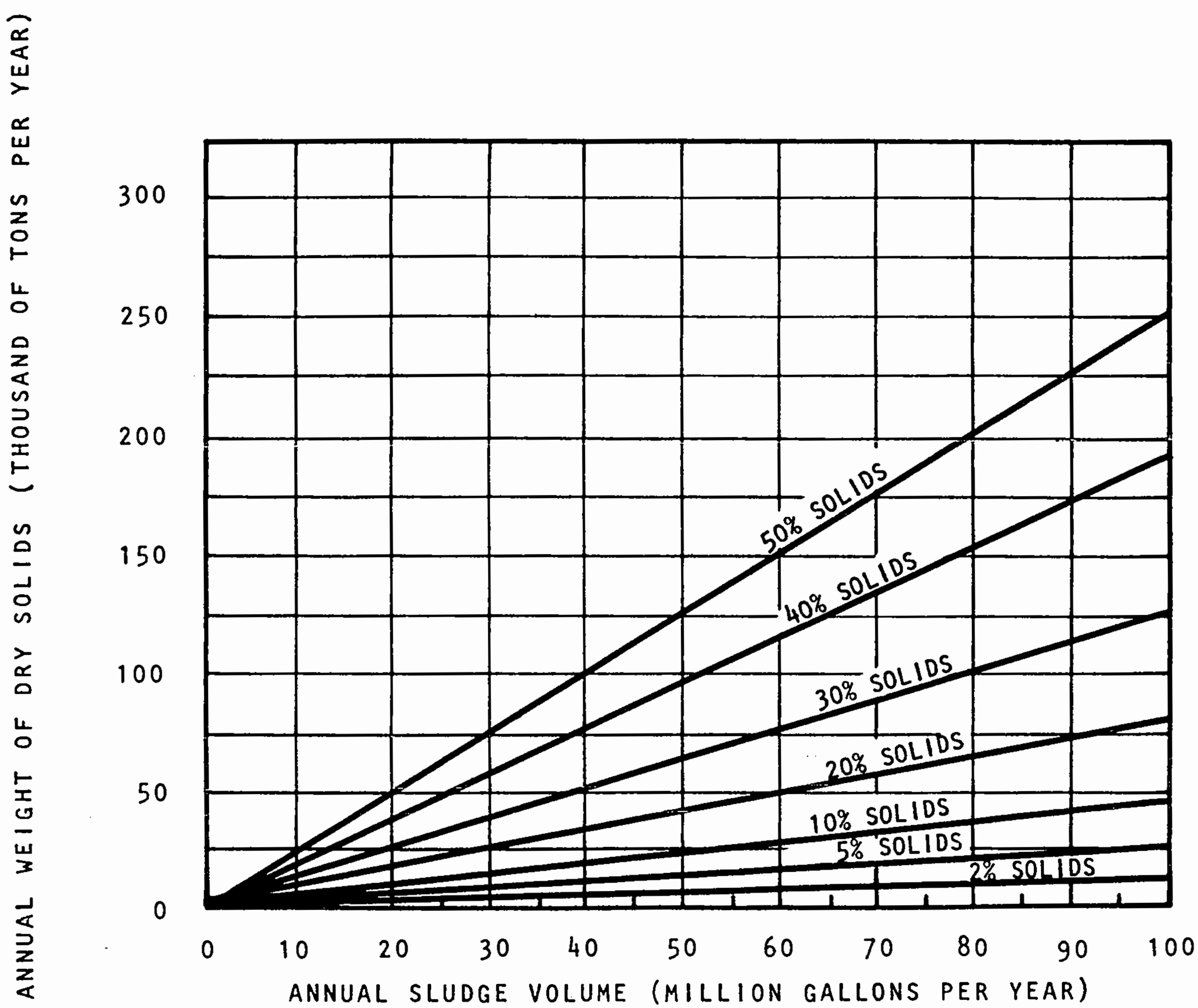
TABLE 10-5

ASSUMPTIONS USED IN DEVELOPING COST REQUIREMENT CURVES FOR LAND APPLICATION OF SLUDGE TO SLUDGE LANDFILL

Parameter	Assumed Value
Site Life	20 yr
Trench Width	10 ft
Trench Depth	10 ft
Trench Spacing	15 ft
Daily Application Period	7 hr/day
Annual Application Period	240 days/yr
Fraction of Site Used for Purposes Other Than Trenching	0.3
Fraction of Site Requiring Clearing	0.7
Fraction of Site Requiring Initial Grading	0.7
Cost of Land	$3,120/acre
Cost of Grading Earthwork	$2,600/acre
Cost of Operation Labor	$13.50/hr
Cost of Diesel Fuel	$1.35/gal
Cost of Monitoring Wells	$5,200 each
Cost of Clearing	$1,040/acre

FIGURE 10-21

WEIGHT OF SLUDGE DRY SOLIDS CONTENT AS A FUNCTION OF WET SLUDGE VOLUME AND SOLIDS CONCENTRATION



Step 2. Obtain the land area required for sludge application by dividing the weight of dry solids to be applied annually by the appropriate dry solids application rate, DSAR. Typical ranges for DSAR are given in Table 10-6.

$$SDAR = \frac{TDSS}{DSAR}$$

where

SDAR = Sludge disposal area required, acres (acres/yr for land reclamation).

TDSS = Annual dry solids applied to land, tons/yr.

DSAR = Dry sludge application rate, dry tons/acre/yr (dry tons/acre for land reclamation).

(Note: For forest land application programs, multiply the quotient in the above equation by the application frequency, e.g., if sludge is to be applied every 5 years, multiply by 5.)

Step 3. Estimate the decimal fraction of land required in addition to sludge application area (SDAR), e.g., buffer areas, unsuitable terrain, access roads, etc., FWWAB. Typical values are:

- Cropland application = 0.4.
- Forest land application = 0.2.
- Reclamation application = 0.3.
- Dedicated disposal site = 0.4.

Step 4. Calculate the total land area required, TLAR, from the following:

$$TLAR = SDAR\ (1 + FWWAB)$$

Step 5. For dedicated disposal sites and sludge landfills, calculate the cost of land assumed in the curve cost, CLC, from the following:

$$CLC = TLAR\ (3,120)$$

where

CLC = Curve land cost, \$.
3,120 = Assumed land cost, \$/acre.

Obviously, the CLC for the application of sludge to cropland, forest land, and marginal land equals zero.

TABLE 10-6

TYPICAL RANGES OF SLUDGE APPLICATION RATES (DSAR)
FOR VARIOUS LAND APPLICATION UNIT PROCESSES

Land Application Unit Process	Typical Range of Sludge Application Rates, DSAR
Cropland Application*	3-10 tons dry solids/acre/yr
Reclamation of Marginal Land†	10-100 tons dry solids/acre
Forest Land Application#	20-40 tons dry solids/acre/application
Dedicated Disposal Site*	30-100 tons dry solids/acre/yr

* Annual application.

† Usually one-time application (i.e., the sludge is applied only once to a particular land area).

Often multi-year application (e.g., every 5 years).

Step 6. Calculate the actual cost of land, CLA, from the following:

$$CLA = TLAR\ (LANDCST)$$

where

CLA = Actual cost of land, \$.
LANDCST = Actual unit cost of land, \$/acre.

Step 7. For cropland, forest land, dedicated disposal, and sludge landfill, adjust the curve capital cost to reflect actual land cost using the following:

$$ACC = CCC - CLC + CLA$$

where

ACC = Adjusted curve capital cost, \$.
CCC = Unadjusted curve capital cost, \$.

It is assumed that cropland application, forest land application, dedicated disposal site, and sludge landfill disposal programs use the same land repeatedly. Therefore, the land purchase cost for these application programs should be added to the capital cost. However, reclaimed disturbed or marginal land usually receives sludge only once. Therefore, land costs for a marginal land reclamation sludge application program should be added to the annual O&M cost.

10.8 Adjustment of Curve Costs to Include Clearing, Grading, and Lime Addition

In the base capital cost curves for the application of sludge to croplands, forest lands, marginal lands, and dedicated disposal sites, the estimated costs do <u>not</u> include the cost of clearing brush and trees, grading, and lime addition for soil pH adjustment. The user can add these costs directly to the costs obtained from each curve by using the following method after adjusting for days per year of application, if required:

Step 1. Calculate the total land area required (TLAR) by following Steps 1 through 4 in Subsection 10.7.

Step 2. Estimate the decimal fraction of total land area requiring: clearing of brush and trees, FWB; light grading, FRLG; medium grading, FRMG; extensive grading, FREG; and lime addition for soil pH adjustment, FRPH.

Step 3. Calculate the incremental costs for site clearing, grading, and pH adjustment using the following equations:

Cost of Clearing = (Unit Cost of Clearing, \$/acre) (FWB) (TLAR)

Cost of Grading = [(Unit Cost of Light Grading, \$/acre) (FRLG) + (Unit Cost of Medium Grading, \$/acre) (FRMG) + (Unit Cost of Extensive Grading, \$/acre) (FREG)] (TLAR)

Cost of Liming = (Unit Cost of Lime Addition, \$/acre) (FRPH) (TLAR)

Typical last quarter 1984 values for the above unit costs are given in Table 10-7. Usually the landowner pays for these incremental land preparation costs, except in the case of the dedicated disposal site process.

Step 4. Add the sum of the applicable incremental costs calculated in Step 3 to the total O&M <u>or</u> capital cost for the process being evaluated, obtained using the cost curves for that particular unit process.

As stated previously, it is assumed that cropland application, forest land application, and dedicated disposal site programs use the same land repeatedly. Therefore, the incremental land improvement costs for these application programs should be added to the capital cost. However, reclaimed disturbed or marginal land usually receives sludge only once. Therefore, land improvement costs for a disturbed or marginal land reclamation program should be added to the annual O&M cost.

TABLE 10-7

TYPICAL 1984 LAND PREPARATION COSTS FOR SLUDGE APPLICATION

Description	Unit Cost ($/acre)
Clearing of Brush and Trees	1,040
Light Grading	520-1,040
Medium Grading	1,250
Extensive Grading	2,080
Lime Addition to Cropland (2 tons lime/acre)	60
Lime Addition to Marginal Land (4 tons lime/acre)	125

SECTION 11

SLUDGE STORAGE CURVES

11.1 Introduction

Provision for the storage of sludge is an important consideration for any solids handling system. Storage is used for the following purposes:

- Ensures that solids handling systems are operating at full or optimum capacity.
- Compensates for adjacent processes which are operated at different rates or schedules.
- Provides buffer capacity necessary for shutdown due to routine maintenance or repair.

This section presents capital and annual operation and maintenance curves for three sludge storage methods: facultative lagoons, enclosed tanks, and unconfined piles. Base capital cost curves for facultative lagoons and unconfined pile storage include the cost of land. The base capital cost curve for enclosed tank storage does not include land cost, because it is assumed that the land area required for tank construction is small; tanks would thus likely be constructed in conjunction with facilities on land which is already owned by the utility. The procedure for adjusting the curve capital costs for facultative lagoons and unconfined pile storage to account for an actual land cost which is different from that assumed is presented in Subsection 11.5.

11.2 Facultative Lagoon Storage

Facultative lagoons have been used extensively in the past for liquid sludge storage. The process, however, is usually limited to storage of stabilized sludge to minimize odor problems.

Facultative sludge lagoons consist of an aerobic surface layer, usually from 1 to 3 ft deep, a deeper anaerobic zone below, and a sludge storage zone on the bottom. Both the aerobic and anaerobic zones are biologically active with anaerobic stabilization providing substantial reduction of organic material. Dissolved oxygen is supplied to the aerobic zone by (1) surface aerators, (2) algae photosynthesis, and (3) surface transfer from the atmosphere. Sludge accumulates in the lagoons and must be periodically removed.

Capital costs, O&M costs, and O&M requirements for facultative lagoon storage are presented in Figures 11-1 through 11-3. The curves are based on the algorithm in Appendix A-34 using the assumptions on the figures. The user should consult Appendix A-34 to obtain more information on algorithm development, design assumptions, and cost references.

FIGURE 11-1

BASE CAPITAL COST OF FACULTATIVE LAGOON SLUDGE STORAGE AS A FUNCTION OF LAGOON STORAGE CAPACITY

Assumptions: Sludge solids percent = 5 percent; volatile solids percent = 35 percent of sludge solids; volatile solids destroyed by storage = 14 percent; lagoon loading = 20 lb volatile solids/1,000 sq ft/day; thickened sludge solids content in lagoon = 6 percent; lagoon liquid depth = 12 ft; cost of land = $3,120/acre.

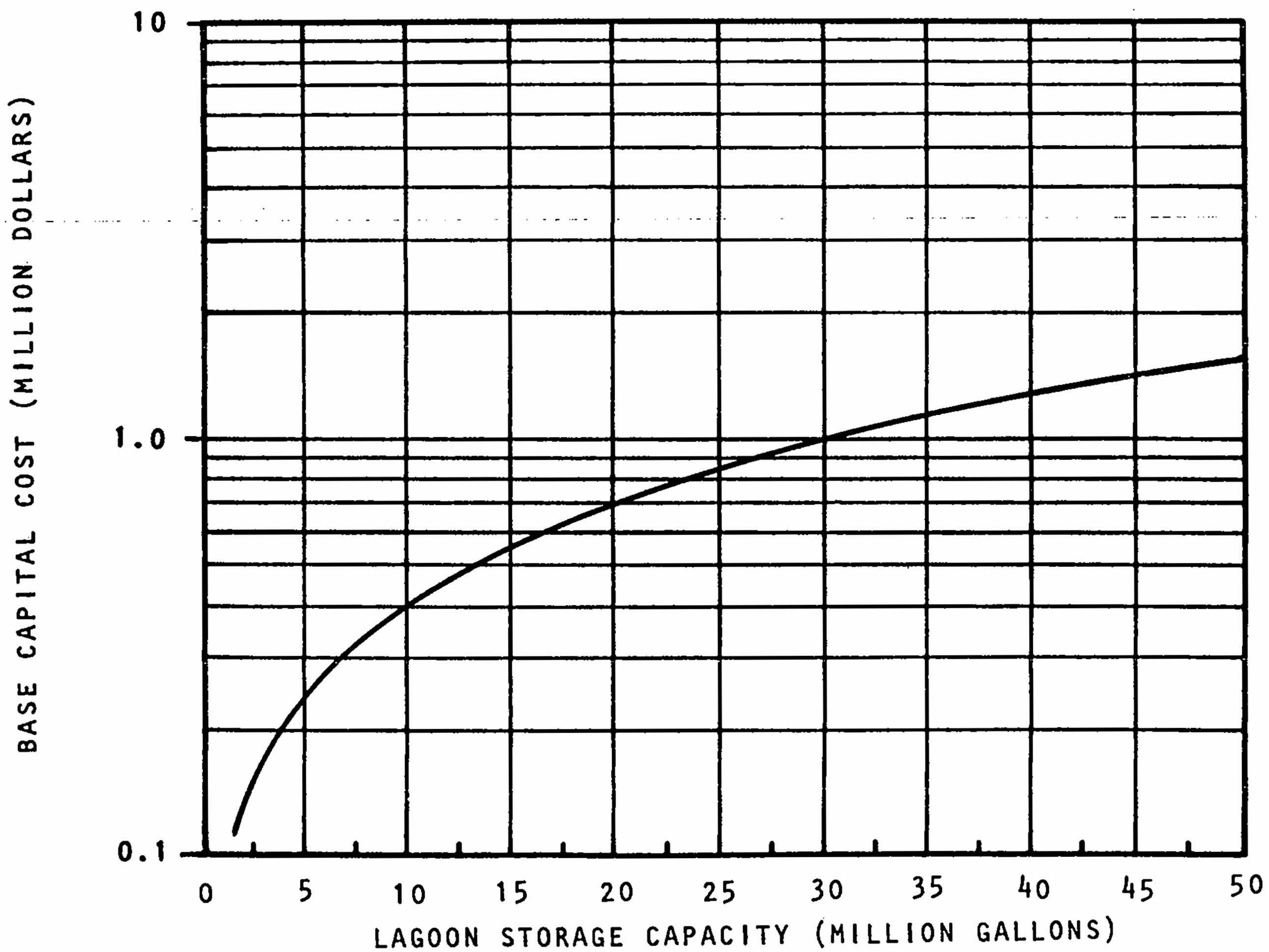


FIGURE 11-2

BASE ANNUAL O&M COST FOR FACULTATIVE LAGOON SLUDGE STORAGE AS A FUNCTION OF LAGOON STORAGE CAPACITY

Assumptions: Design parameters are the same as for Figure 11-1; cost of labor = \$13.50/hr; cost of electricity = \$0.094/kWhr.

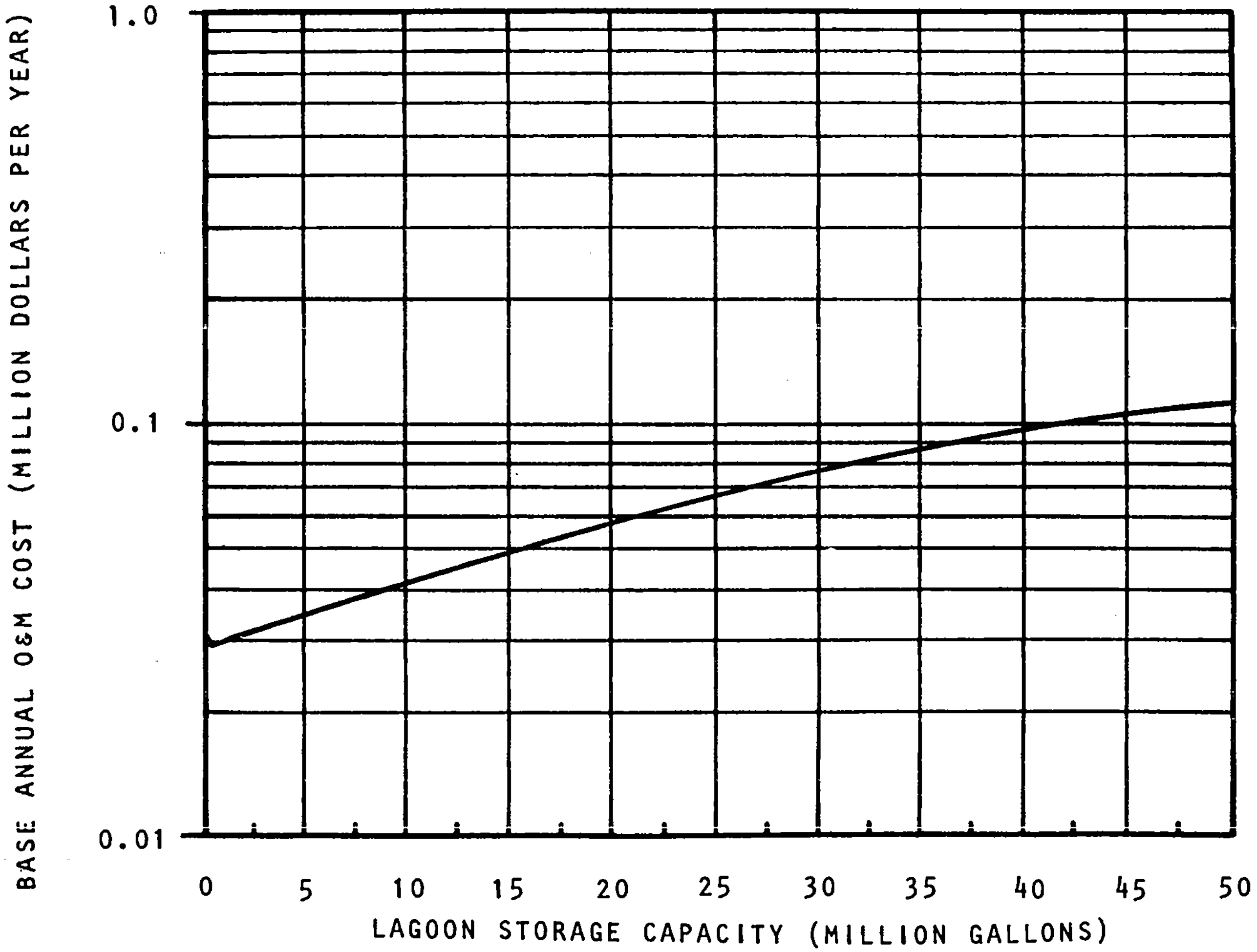
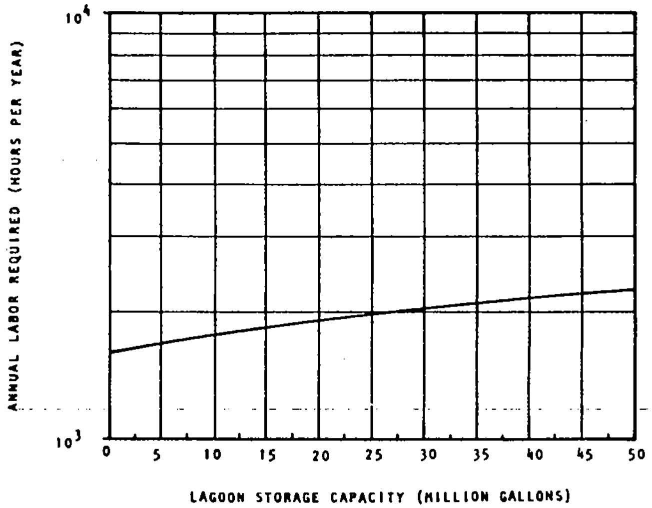
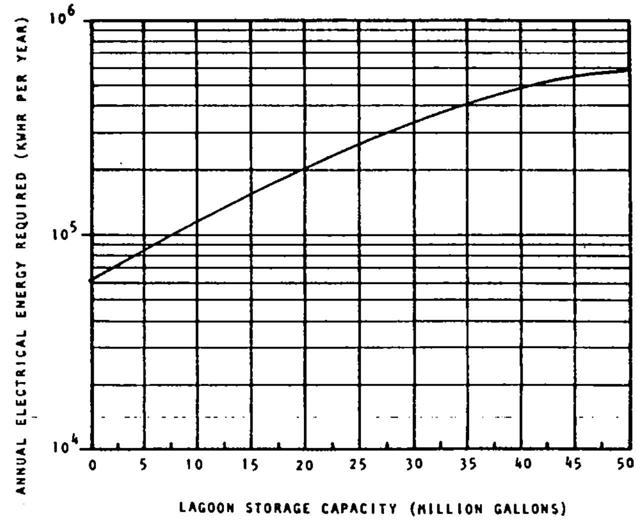
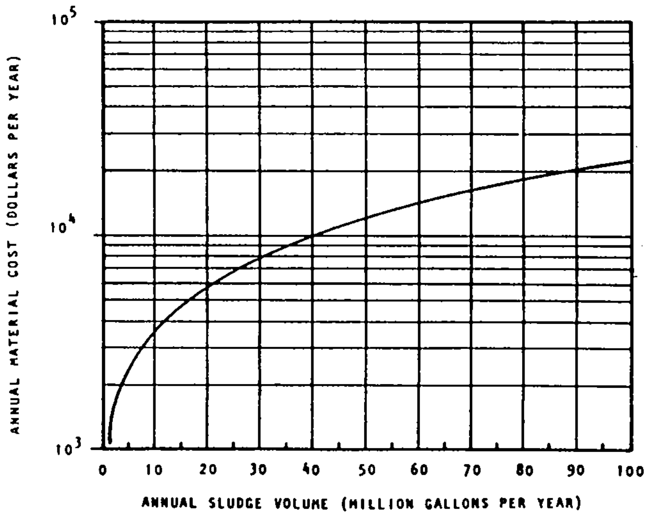


FIGURE 11-3

ANNUAL O&M REQUIREMENTS FOR FACULTATIVE LAGOON STORAGE AS A FUNCTION OF LAGOON STORAGE CAPACITY







Assumptions: Design parameters are the same as for Figure 11-1.

NOTE : THE MATERIAL COST CURVE IS FOR THE ANNUAL MAINTENANCE MATERIALS AND SUPPLIES.

11.3 Enclosed Tank Storage

Sludge may be stored in either aboveground or below-ground storage tanks. Enclosed tanks require special equipment to handle the odorous and potentially toxic and explosive gases that may be generated by storage. In addition, tanks are usually mixed to maintain a homogeneous mixture of sludge in the tank.

Base capital costs, O&M costs, and O&M requirements for both aboveground and below-ground storage tanks are presented in Figures 11-4 through 11-6. Curves are based on the algorithm in Appendix A-33, using the assumptions noted on the curves. Base capital costs include purchase and installation of tanks and appurtenant equipment. Aboveground tanks are constructed of reinforced concrete, whereas buried tanks are constructed of steel. Costs do not include provisions for sludge transfer to and from storage tanks, or the cost of land. Base annual O&M costs include labor, electrical energy, and replacement parts and materials.

11.4 Unconfined Pile Storage

Dry sludge (over 40 percent solids) may be stored at treatment plants or land application sites over relatively long periods in built-up "unconfined" piles. Storage is in a well defined area consisting of a concrete slab and drainage control structures. In areas of high rainfall, piles are covered to prevent erosion. Usually, one or more skip loaders are required to build the piles and to load sludge haul vehicles. Dewatered sludge which is relatively high in moisture (15 to 40 percent solids) and volatile organics content is not conducive to unconfined pile storage over long periods due to the development of odors.

Figures 11-7 through 11-9 present base capital costs, base annual O&M costs, and annual O&M requirements for unconfined pile storage. The curves were obtained with the algorithm in Appendix A-34, using the design assumptions noted on the curves. Additional information may be obtained by referring to Appendix A-34.

11.5 Land Cost Adjustment

Due to the significant size of the land area which is utilized by facultative lagoons and unconfined pile sludge storage, it is assumed that new land will need to be acquired by the municipality for construction of these facilities. Base capital costs presented in the curves for these unit processes include the cost of land at an assumed unit cost of $3,120/acre. Because land costs are highly variable, the user may desire to change this unit cost and, hence, the process capital cost to more accurately fit local costs. This may be accomplished using the procedures outlined below in Subsections 11.5.1 and 11.5.2 for facultative lagoons and unconfined pile storage, respectively.

11.5.1 Calculation of Total Land Area Required and Capital Cost Adjustment for Facultative Lagoon Storage

FIGURE 11-4

BASE CAPITAL COST OF ENCLOSED TANK SLUDGE STORAGE AS A FUNCTION OF TANK STORAGE CAPACITY

Assumptions: Mixing energy = 0.3 hp/1,000 cu ft of tank volume; total dynamic head = 25 ft; mixing pump efficiency = 0.7.

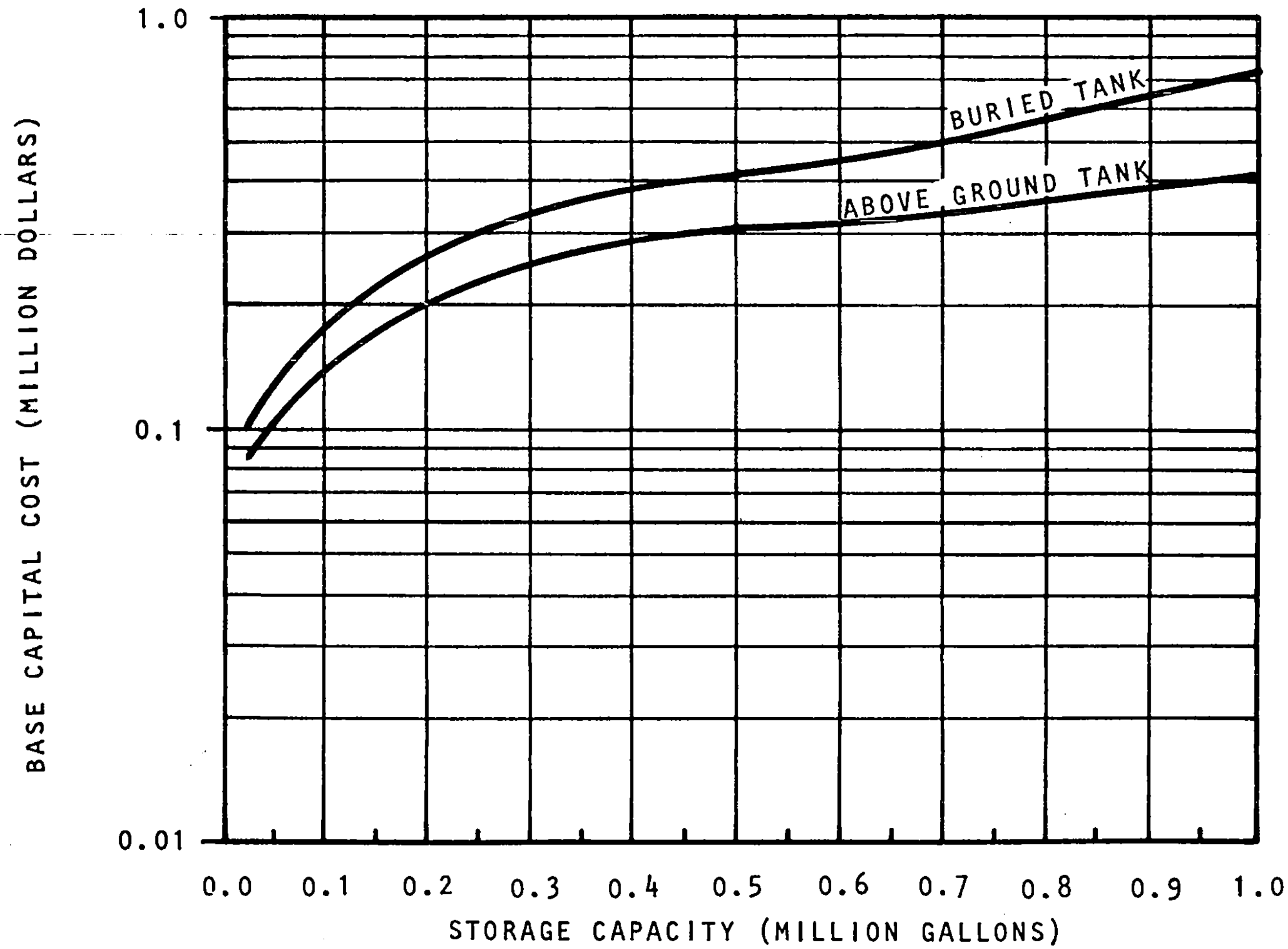


FIGURE 11-5

BASE ANNUAL O&M COST OF ENCLOSED TANK SLUDGE STORAGE AS A FUNCTION OF TANK STORAGE CAPACITY

Assumptions: Design parameters are the same as for Figure 11-4; cost of labor = $13.50/hr; cost of electricity = $0.094/kWhr.

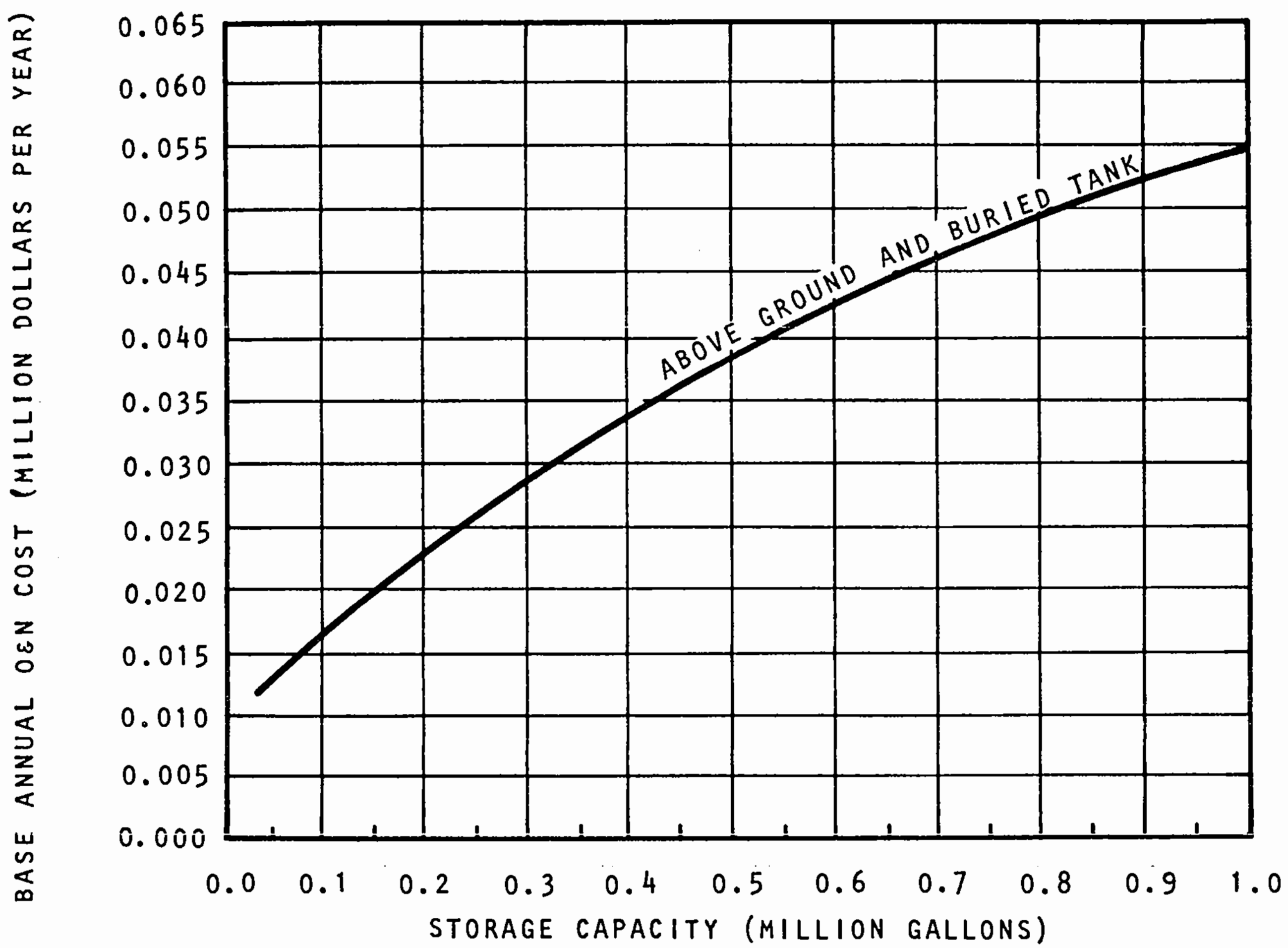
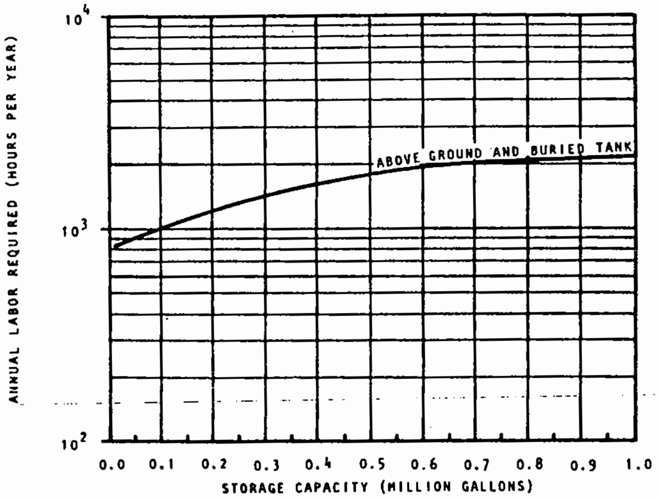
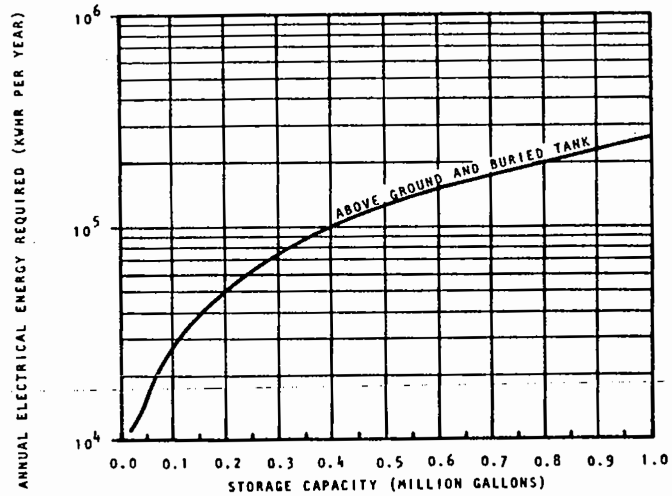
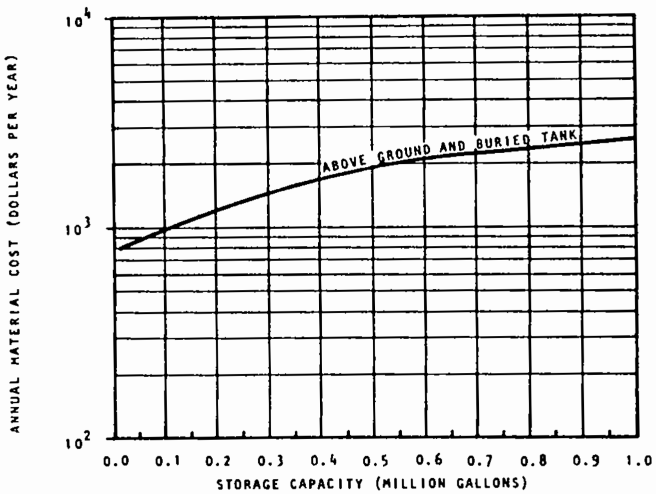


FIGURE 11-6

ANNUAL O&M REQUIREMENTS FOR ENCLOSED TANK SLUDGE STORAGE AS A FUNCTION OF TANK STORAGE CAPACITY







Assumptions: Design parameters are the same as for Figure 11-4.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL MAINTENANCE MATERIALS AND SUPPLIES.

FIGURE 11-7

BASE CAPITAL COST OF UNCONFINED PILE DEWATERED SLUDGE STORAGE AS A FUNCTION OF FACILITY STORAGE CAPACITY

Assumptions: Storage pile cross section area = 32 sq ft; storage period = 180 days; cost of skip loader(s) = $46,800 each; cost of concrete pad = $83,200/acre; cost of drainage control = $20,800/acre; cost of land = $3,120/acre.

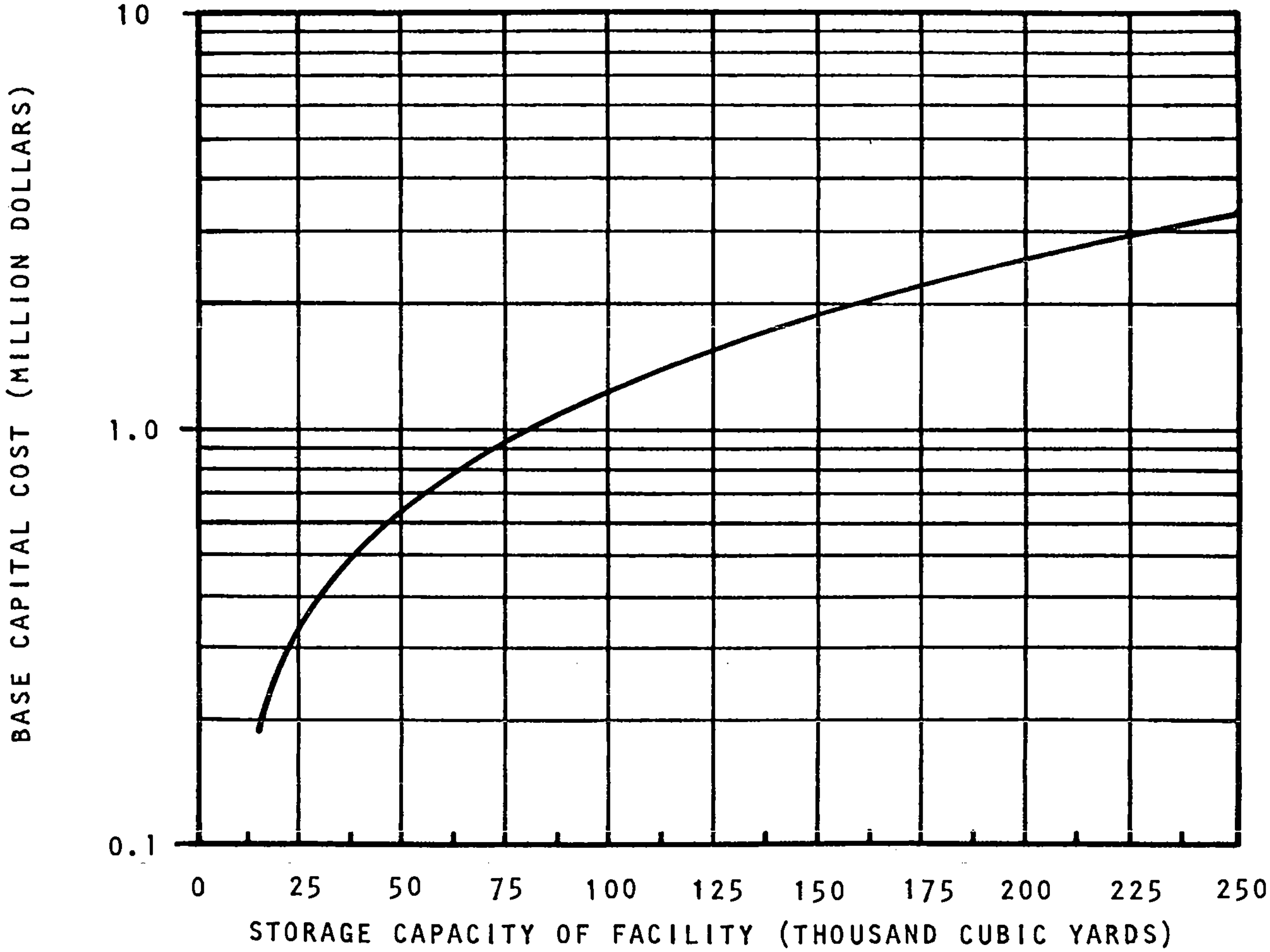


FIGURE 11-8

BASE ANNUAL O&M COST FOR UNCONFINED PILE DEWATERED SLUDGE STORAGE AS A FUNCTION OF FACILITY STORAGE CAPACITY

Assumptions: Design parameters are the same as for Figure 11-7; cost of labor = $13.50/hr; cost of diesel fuel = $1.35/gal.

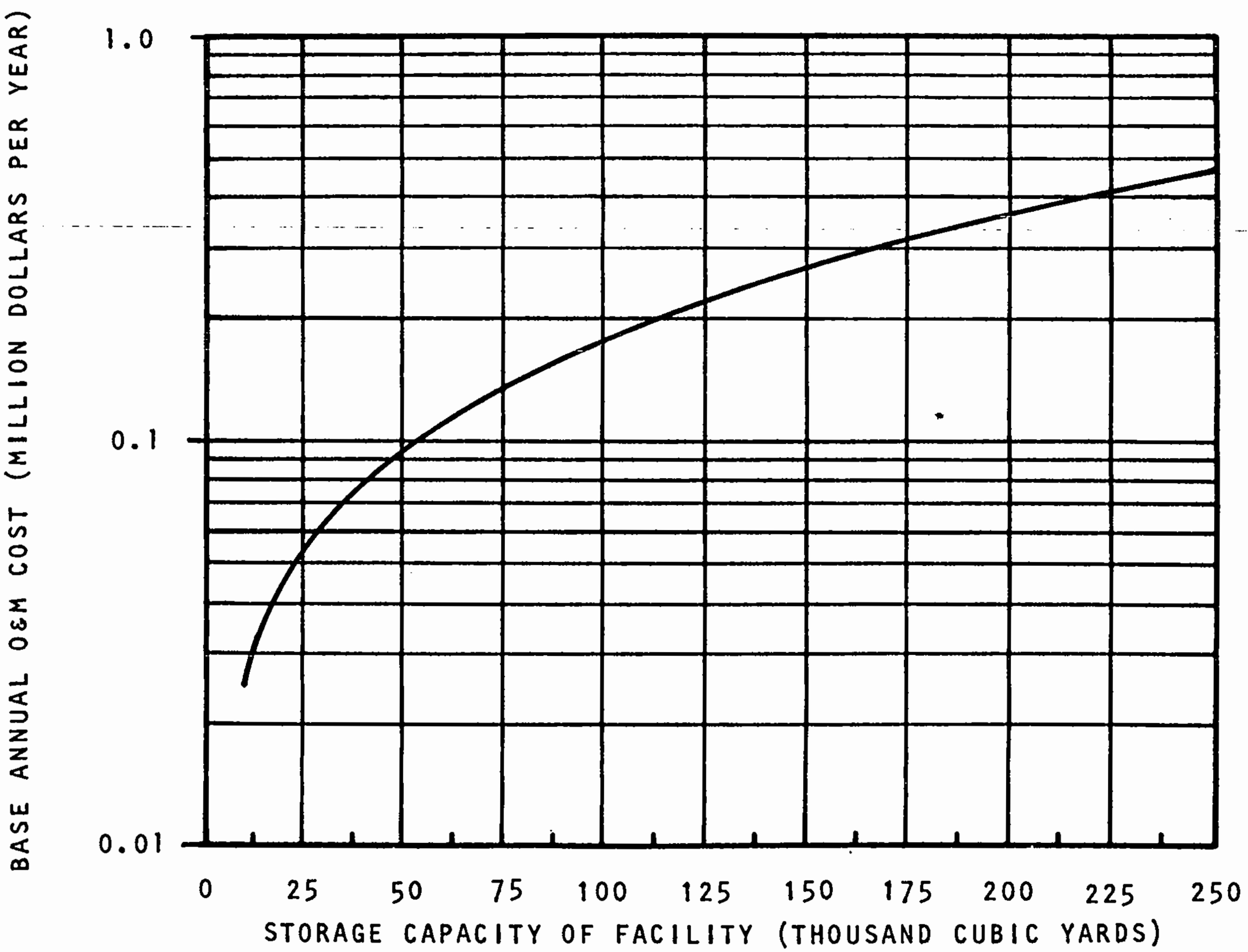
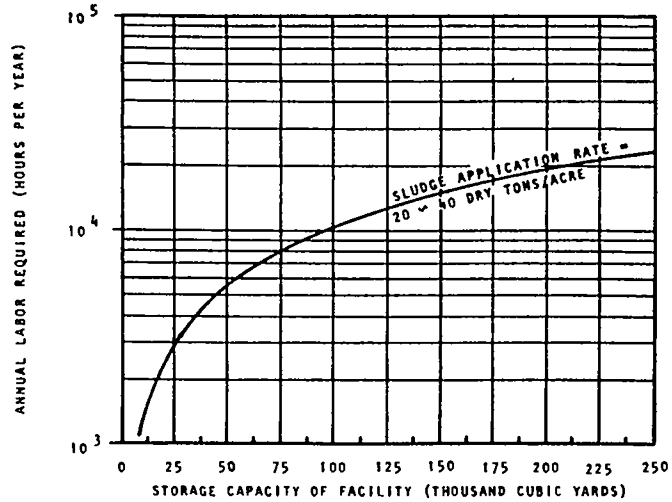
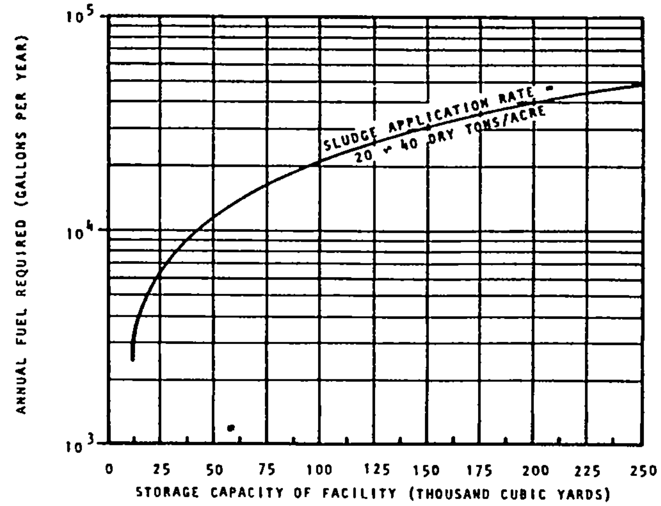
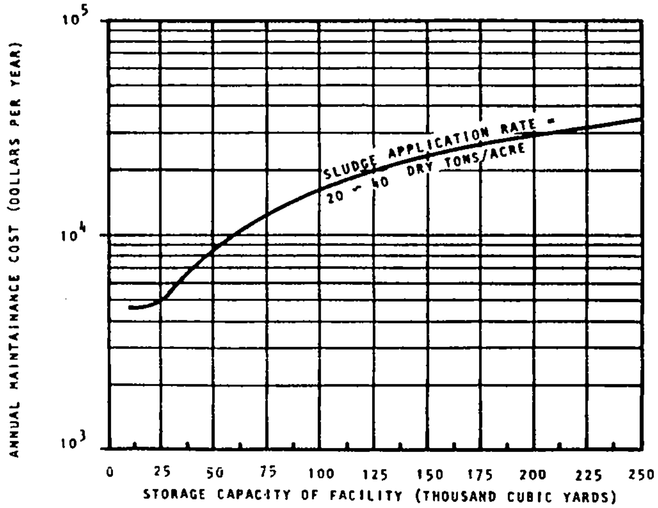


FIGURE 11-9

ANNUAL O&M REQUIREMENTS FOR UNCONFINED PILE DEWATERED SLUDGE STORAGE AS A FUNCTION OF FACILITY STORAGE CAPACITY







Assumptions: Design parameters are the same as for Figure 11-7.

NOTE : THE MATERIAL COST CURVE IS FOR ANNUAL MAINTENANCE MATERIALS AND SUPPLIES.

Step 1. Calculate daily dry sludge solids input to the lagoon(s) from the following equation:

$$DSS = \frac{SS}{100} (SV) (SSW)$$

where

DSS = Dry sludge solids input to lagoon, lb/day.

SS = Sludge solids concentration, percent.

SV = Daily sludge volume input to lagoon, gal/day.

SSW = Sludge specific weight, lb/gal, obtained from the following table (interpolate where necessary):

Sludge Solids Concentration, SS, Percent	Sludge Specific Weight,* SSW, lb/gal
2	8.38
5	8.45
10	8.57
20	8.81
30	9.06
40	9.33
50	9.62

* Based on a sludge dry solids density of 85 lb/ft^3.

Step 2. Calculate daily volatile solids input to lagoon(s) from the following equation:

$$VSS = \frac{(VSP)}{100} (DSS)$$

where

VSS = Daily volatile solids input to lagoon(s), lb/day.
VSP = Volatile solids concentration, percent of dry solids weight.

Step 3. Calculate lagoon surface area required from the following:

$$TLSA = \frac{(VSS)\ (1,000)}{LL}$$

where

TLSA = Total lagoon surface area required, ft^2.

LL = Lagoon loading, lb volatile solids/1,000 ft^2 of lagoon surface area/day.

Step 4. Calculate total land area required from the following:

$$TLAR = \frac{(TLSA)\ (2.0)}{43,560}$$

where

TLAR = Total land area required, acres.

2.0 = Factor to adjust for additional land area required for buffer space, area between lagoons, storage area, etc.

43,560 = Conversion factor, ft^2/acre.

Step 5. Calculate the cost of land assumed in the curve cost, CLC, from the following:

$$CLC = TLAR\ (3,120)$$

where

CLC = Curve land cost, \$.
3,120 = Assumed unit cost of land in curve, \$/acre.

Step 6. Calculate the actual cost of land, CLA, from the following:

$$CLA = TLAR\ (LANDCST)$$

where

CLA = Actual cost of land, \$.
LANDCST = Actual unit cost of land, \$/acre.

Step 7. Adjust the curve capital cost to reflect actual land cost using the following:

$$ACC = CCC - CLC + CLA$$

where

ACC = Adjusted curve capital cost, \$.
CCC = Unadjusted curve capital cost, \$.

11.5.2 Calculation of Total Land Area Required and Capital Cost Adjustment for Unconfined Pile Storage.

Step 1. Calculate volume of dewatered sludge to be stored from the following:

$$SVCY = \frac{(SV)\ (SP)}{202}$$

where

SVCY = Sludge volume to be stored, yd^3.
SV = Daily sludge volume, gal/day.
SP = Storage period, days.
202 = Conversion factor, gal/yd^3.

Step 2. Assuming an equilateral triangle cross section, calculate total land area required from the following:

$$TLAR = \frac{(SVCY)\ (27)\ (2)\ (1.2)}{(3)^{0.25}\ (X)^{0.5}\ (43{,}560)}$$

where

TLAR = Total land area required, acres.

27 = Conversion factor, ft^3/yd^3.

1.2 = Factor to account for spacing between piles, area for drainage control structures, etc.

X = Storage pile cross section area, ft^2.

43,560 = Conversion factor, ft^2/acre.

Step 3. Calculate the cost of land assumed in the curve cost, CLC, from the following:

$$CLC = TLAR\ (3{,}120)$$

where

CLC = Curve land cost, \$.
3,120 = Assumed unit cost of land in curve, \$/acre.

Step 4. Calculate the actual cost of land, CLA, from the following:

$$CLA = TLAR\ (LANDCST)$$

where

CLA = Actual cost of land, $.
LANDCST = Actual unit cost of land, $/acre.

Step 5. Adjust the curve capital cost to reflect actual land cost using the following:

$$ACC = CCC - CLC + CLA$$

where

ACC = Adjusted curve capital cost, $.
CCC = Unadjusted curve capital cost, $.

APPENDIX A

COST ALGORITHMS

APPENDIX A (continued)

APPENDIX A-1

GRAVITY THICKENING

A-1.1 Background

Gravity thickening utilizes the difference in specific gravity between the solids and water to achieve separation. Additional solids concentration is achieved through compaction by the overlying solids.

Gravity thickening is commonly used to thicken primary sludge and combined primary and waste biological sludge. Waste biological sludge alone generally does not thicken well in a gravity thickener. Chemical conditioning of sludge prior to thickening is often done to improve thickener performance. Chemical conditioning costs are covered in other sections of this handbook and appendix.

Circular concrete tanks are the most common configuration for gravity thickeners, although circular steel tanks and rectangular concrete tanks have also been used. The following algorithm is based on the construction and operation of circular reinforced concrete tanks. The tank is equipped with a slowly revolving sludge collector at the base of the tank. A truss-type bridge is fastened between the tank walls and the center feed well. Overflow passes over an effluent weir located around the circumference of the thickener. Capital costs include construction of the unit, including earthwork required, thickener mechanism and ancillary equipment, reinforced concrete, and installation labor. Since gravity thickeners are not normally enclosed, building space is not provided. Moreover, costs do not include equipment for the control of odors.

A-1.1.1 Process Design

In general, gravity thickener design is based primarily on surface area loading, hydraulic loading, and total tank depth. These parameters are normally obtained through laboratory batch settling tests. Procedures for conducting the tests and evaluating the design parameters are documented in the literature. In the absence of these data, the table below (adapted from Reference 4) may be used as a guide in selecting a solids loading rate for various sludges and unthickened sludge solids concentrations.

Type of Sludge	Concentration (% Solids by Weight) Unthickened	Thickened	Surface Area Dry Solids Loading Rate ($lb/ft^2/day$)
Primary Alone	2.5 to 5.5	5 to 10	20 to 30
Activated Sludge Alone	0.5 to 1.2	1 to 3	6 to 10
Combined Primary and Activated Sludge	1.5 to 4.0	3 to 7	8 to 16

Hydraulic loading rates generally vary from 400 to 800 gpd/ft^2 of surface area. Detention time generally varies from 2 to 6 hours.

A-1.1.2 Algorithm Development

The following algorithm is based on the CAPDET program. Equations used in the CAPDET algorithm for gravity thickening can be found on pages 2.61-18 through 2.61-31 of Reference 1. Cost outputs were based on these input parameters:

- Mass loading = 12 $lb/ft^2/day$.
- Underflow concentration = Influent concentration (percent) plus 2 percent.
- Depth of tank = 9 ft.
- Cost of standard 90-ft-diameter thickener mechanism = $150,000.

Additional input parameters (projected 1983 values), as shown on Table 1-1, were obtained from construction cost guides (2, 3). Cost of the standard thickener mechanism was obtained through equipment suppliers.

Capital costs obtained through the CAPDET program were fit to equations using multiple regression curve fits. Costs were expressed as functions of the thickener surface area. The O&M cost equations in this algorithm are those presented in the CAPDET program. O&M requirements (labor and electricity) are related to the solids processed per day.

A-1.2 Input Data

A-1.2.1 Daily sludge volume, SV, gal/day.

A-1.2.2 Sludge suspended solids concentration, SS, percent.

A-1.2.3 Sludge specific gravity, SSG, unitless.

A-1.2.4 Hours per day process is operated, HDP, hr/day.

A-1.2.5 Dry solids loading rate, SLR, $lb/ft^2/day$.

A-1.3 Design Parameters

A-1.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-1.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-1.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated with the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity, unitless.

A-1.3.4 Hours per day process is operated, HPD, hr/day. Default value = 24 hr/day.

A-1.3.5 Dry solids loading rate, SLR, lb/ft^2/day. Default value = 1.8 SS + 6.

A-1.4 Process Design Calculations

A-1.4.1 Calculate dry solids handled per day.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{(100)\ (2,000)}$$

where

TDSS = Daily dry solids handled, tons/day.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.

A-1.4.2 Calculate thickener total surface area.

$$TSA = \frac{(SV)\ (SS)\ (SSG)\ (62.43)\ (24)}{(100)\ (SLR)\ (7.48)\ (HPD)}$$

where

TSA = Total surface area, ft^2.
62.43 = Density of water, lb/ft^3.
7.48 = Conversion factor, gal/ft^3.

A-1.5 Process Design Output Data

A-1.5.1 Daily dry solids handled, TDSS, tons/day.

A-1.5.2 Thickener total surface area, TSA, ft^2.

A-1.6 Quantities Calculations

A-1.6.1 Maintenance labor requirements.

A-1.6.1.1 If TDSS $\leq$ 2.7 tons/day, maintenance labor is calculated by:

$$ML = 141.4\ (TDSS)^{0.566}$$

A-1.6.1.2 If 2.7 < TDSS $\leq$ 13 tons/day, maintenance labor is calculated by:

$$ML = 164.8\ (TDSS)^{0.4093}$$

A-1.6.1.3 If TDSS > 13 tons/day, maintenance labor is calculated by:

$$ML = 91.04\ (TDSS)^{0.6415}$$

where

ML = Annual maintenance labor requirement, hr/yr.

A-1.6.2 Operation labor requirement.

A-1.6.2.1 If TDSS $\leq$ 2.7 tons/day, operation labor is calculated by:

$$OL = 152\ (TDSS)^{0.7066}$$

A-1.6.2.2 If 2.7 < TDSS $\leq$ 13 tons/day, operation labor is calculated by:

$$OL = 184.2\ (TDSS)^{0.5046}$$

A-1.6.2.3 If TDSS > 13 tons/day, operation labor is calculated by:

$$OL = 93.12\ (TDSS)^{0.7704}$$

where

OL = Annual operation labor requirement, hr/yr.

A-1.6.3 Electrical energy requirement.

A-1.6.3.1 If TDSS $\leq$ 50 tons/day, electrical energy is calculated by:

$$E = 4{,}500\ (TDSS)^{0.301}$$

A-1.6.3.2 If TDSS > 50 tons/day, electrical energy is calculated by:

$$E = 1{,}464\ (TDSS)^{0.5881}$$

where

E = Annual electrical energy requirement, kWhr/yr.

A-1.7 Quantities Calculations Output Data

A-1.7.1 Annual maintenance labor requirement, ML, hr/yr.

A-1.7.2 Annual operation labor requirement, OL, hr/yr.

A-1.7.3 Annual electrical energy requirement, E, kWhr/yr.

A-1.8 Unit Price Input Required

A-1.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-1.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-1.8.3 Cost of operational and maintenance labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-1.8.4 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$13.00/hr (ENRCCI/4,006).

A-1.9 Cost Calculations

A-1.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (ML + OL)\ (COSTL)$$

where

COSTLB = Total annual cost of operation and maintenance labor, \$/yr.

A-1.9.3 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-1.9.3 Total base capital cost.

$$TBCC = [5.9 \times 10^{-7}\ (TSA)^3 - 0.013\ (TSA)^2 + 111.59\ (TSA) + 41{,}164]\ \frac{MSECI}{751}$$

where

TBCC = Total base capital cost, \$.

A-1.9.4 Annual cost of maintenance parts and materials. This cost is expressed as 1 percent of the total base capital cost.

$$COSTPM = \frac{1}{100}\ (TBCC)$$

where

COSTPM = Annual cost of operation and maintenance parts and materials, \$/yr.

A-1.9.5 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-1.10 Cost Calculation Output Data

A-1.10.1 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-1.10.2 Annual cost of electrical energy, COSTEL, \$/yr.

A-1.10.3 Annual cost of maintenance parts and materials, COSTPM, \$/yr.

A-1.10.4 Total base capital cost of gravity thickening process, TBCC, \$.

A-1.10.5 Total annual operation and maintenance cost for gravity thickening process, COSTOM, \$/yr.

APPENDIX A-2

FLOTATION THICKENING

A-2.1 Background

In dissolved air flotation (DAF) thickening, air is introduced into a solution that is being held at an elevated pressure, usually a separate supernatant recycle stream. When this stream is combined with the incoming sludge stream and released to atmospheric pressure, minute air bubbles are formed which adhere to the suspended particles and become enmeshed in the solids matrix. Since the density of the solids-air aggregate is less than that of water, the agglomerate floats to the surface. The float is continuously removed by a skimmer mechanism.

DAF thickening is used for biological sludges which have relatively low solids concentrations, sludges with higher grease concentrations, and for other sludges where DAF thickening usually provides better solids-liquid separation than a gravity thickener. Chemical conditioning of the sludge, often involving polymer addition, is usually done prior to DAF thickening to enhance performance. Chemical conditioning costs can be obtained using other sections of this manual.

DAF thickeners can be rectangular or circular, constructed of concrete or steel. This algorithm is based on the construction and operation of circular reinforced concrete tanks. The capital cost includes flotation tank construction, and purchase and installation of the pressurizing pump, air injection facilities, retention tank, back pressure regulating device, and skimmer mechanisms. Both surface and bottom sludge collectors are provided. Costs include a building of sufficient area to enclose the thickener and ancillary equipment while providing adequate space for operation and maintenance. Costs do not include mechanisms for the control of odors, often associated with thickeners.

A-2.1.1 Process Design

DAF thickener design is based primarily on surface area loading and hydraulic loading. In addition, parameters such as recycle ratio, air-to-solids ratio, polymer type and dosage, and detention time are also important. Bench-scale testing is often performed to evaluate the effects of design parameters on effluent sludge characteristics.

The table below provides typical surface area loading rates for selected chemically conditioned sludges.

Type of Sludge	Surface Area Dry Solids Loading Rate, $lb/ft^2/day$
Primary Alone	20 to 30
Activated Sludge Alone	12 to 24
Combined Primary and Activated Sludge	12 to 24

If the sludge is not chemically conditioned, the surface loading rates shown in the table above should be reduced by approximately 50 to 60 percent. Hydraulic loading rates generally vary from 1,200 to 4,000 gpd/ft^2 of surface area.

A-2.1.2 Algorithm Development

The following algorithm is based on use of the CAPDET program. CAPDET algorithms are found in Reference 1, pages 2.61-5 through 2.61-17. Costs and requirements were developed utilizing the program by varying sludge volume and solids concentration entering the thickening unit, using the following input parameters:

- Air pressure = 60 psig.
- Detention time in float tank = 0.5 hr.
- Hydraulic loading = 3 gpm/ft^2
- Recycle time in pressure tank = 2 min.
- Percent removal of solids = 80 percent.
- Air-to-solids ratio = 0.02.
- Float concentration (minimum) = 4 percent.
- Purchase cost of standard 350-ft^2 air flotation unit = $94,000 (cost includes basic mechanism to be mounted in the concrete tank, air pressurization tank, pressurization pump, pressure release valve, air injection system, and electrical panel).

Additional input parameters (projected 1983 values) shown on Table 1-1 were obtained from construction cost guides (2, 3). Cost of the standard thickener mechanism was obtained from equipment suppliers.

O&M requirement equations are those presented in the CAPDET program. Capital costs obtained using the CAPDET program were fit to an equation using a multiple regression program. Costs and requirements were expressed as functions of the parameter most closely related to costs or requirements. O&M requirements (labor and electricity) are related to the solids processed per day, and capital cost is expressed as a function of the flotation tank surface area.

A-2.2 Input Data

A-2.2.1 Daily sludge volume, SV, gal/day.

A-2.2.2 Sludge suspended solids concentration, SS, percent.

A-2.2.3 Sludge specific gravity, SSG, unitless.

A-2.2.4 Hours per day process is operated, HPD, hr/day.

A-2.2.5 Solids loading, SLR, $lb/ft^2/day$.

A-2.3 Design Parameters

A-2.3.1 Daily sludge volume, SV, gal/day. This value must be input by the user. No default value.

A-2.3.2 Sludge suspended solids concentration, SS, percent. This value must be input by the user. No default value.

A-2.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated with the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-2.3.4 Hours per day process is operated, HPD, hr/day. Default value = 24 hr/day.

A-2.3.5 Solids loading, SLR, $lb/ft^2/day$. Default value = 20 $lb/ft^2/day$.

A-2.4 Process Design Calculations

A-2.4.1 Calculate surface area.

$$TSA = \frac{(SV)\ (SS)\ (SSG)\ (8.34)\ (24)}{(SLR)\ (100)\ (HPD)}$$

where

TSA = Surface area, ft^2.

A-2.4.2 Calculate dry solids produced.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{(100)\ (2,000)}$$

where

TDSS = Daily dry solids produced, tons/day.

A-2.5 Process Design Output Data

A-2.5.1 Surface area, TSA, ft^2.

A-2.5.2 Daily dry solids produced, TDSS, tons/day.

A-2.6 Quantities Calculations

A-2.6.1 Annual operation labor requirement.

A-2.6.1.1 If TDSS $\leq$ 2.3 tons/day, operation labor is calculated by:

$$OL = 560\ (TDSS)^{0.4973}$$

A-2.6.1.2 If TDSS > 2.3 tons/day, operation labor is calculated by:

$$OL = 496\ (TDSS)^{0.5092}$$

where

OL = Annual operation labor requirement, hr/yr.

A-2.6.2 Annual maintenance labor requirement.

A-2.6.2.1 If TDSS $\leq$ 3 tons/day, maintenance labor is calculated by:

$$ML = 156\ (TDSS)^{0.4176}$$

A-2.6.2.2 If TDSS > 3 tons/day, maintenance labor is calculated by:

$$ML = 124\ (TDSS)^{0.6429}$$

where

ML = Annual maintenance labor requirement, hr/yr.

A-2.6.3 Annual electrical energy requirement.

$$E = 63{,}000\ (TDSS)^{0.9422}$$

where

E = Annual electrical energy requirement, kWhr/yr.

A-2.7 Quantities Calculations Output Data

A-2.7.1 Operation labor requirement, OL, hr/yr.

A-2.7.2 Maintenance labor requirement, ML, hr/yr.

A-2.7.3 Electrical energy requirement, E, kWhr/yr.

A-2.8 Unit Price Input Required

A-2.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-2.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-2.8.3 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-2.8.4 Cost of electricity, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-2.9 Cost Calculations

A-2.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (OL + ML)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-2.9.2 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-2.9.3 Total base capital cost.

A-2.9.3.1 If $TSA \leq 40\ ft^2$, base capital cost is calculated by:

$$TBCC = (108{,}600)\ \frac{MSECI}{751}$$

The smallest standard size unit available commercially is $40\ ft^2$.

A-2.9.3.2 If $TSA > 40\ ft^2$, base capital cost is calculated by:

$$TBCC = [-0.107 \times 10^{-5}\ (TSA)^3 + 0.0193\ (TSA)^2 + 454.5\ (TSA) + 90{,}362]\ \frac{MSECI}{751}$$

where

TBCC = Total base capital cost, $.

A-2.9.4 Annual cost of replacement parts and materials. This cost is calculated as 1 percent of the base capital cost.

$$COSTPM = \frac{1}{100}\ (TBCC)$$

where

COSTPM = Annual cost of replacement parts and materials, $/yr.

A-2.9.5 Annual cost of operation and maintenance.

$$COSTOM = COSTLB + COSTEL + COSTPM$$

where

COSTOM = Annual operation and maintenance cost, $/yr.

A-2.10 Cost Calculation Output Data

A-2.10.1 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-2.10.2 Annual cost of electrical energy, COSTEL, $/yr.

A-2.10.3 Annual cost of replacement parts and materials, COSTPM, $/yr.

A-2.10.4 Total base capital cost of flotation thickening process, TBCC, $.

A-2.10.5 Total annual operation and maintenance cost for flotation thickening process, COSTOM, $/yr.

APPENDIX A-3

ANAEROBIC DIGESTION

A-3.1 Background

During anaerobic digestion, sludges are stabilized through the biological degradation of complex organic substances in the absence of free oxygen. Typically, 25 to 45 percent of the raw sludge solids are destroyed during anaerobic digestion through conversion to methane, carbon dioxide, water, and soluble organic material. In addition, anaerobically digested sludges are generally more easily dewatered than undigested sludges.

Most sludges produced from municipal treatment plants can be stabilized through anaerobic digestion, provided that the sludge has a low concentration of heavy metals and a volatile solids content above 50 percent. However, since microorganisms are sensitive to fluctuating operating conditions, plants that exhibit wide variations in sludge quantity and quality should carefully consider the applicability of anaerobic digestion as a stabilization process.

Anaerobic digesters may be either cylindrical, rectangular, or egg-shaped. The most common design (assumed in this algorithm) is a circular digester with a diameter ranging from 20 to 125 ft, and a side water depth between 20 and 40 ft. Tanks are usually constructed of reinforced concrete.

There are several common types of anaerobic digestion processes, including single-stage low-rate digestion, high-rate digestion, two-stage high-rate digestion, and others. Single-stage digesters are completely mixed and heated. In two-stage digestion, only the first digester is mixed and heated; the second stage provides gravity concentration of digested sludge solids, and decanting of supernatant liquor. Selection and design of an anaerobic digestion process requires experienced design engineers.

For this cost algorithm, it is assumed that single-stage low-rate digestion is being used with heating and mixing of digester contents. Fuel energy for heating is supplied by the methane generated during anaerobic digestion. When digestion tank requirements exceed a diameter of 125 ft or side water depths of 40 ft, two or more digesters are assumed.

Capital costs include excavation and construction of reinforced concrete tanks, purchase and installation of floating cover(s), gas circulation equipment, external heater(s) and heat exchanger(s), gas safety equipment, positive displacement pumps, internal piping, and ancillary equipment. In addition, capital costs include a two-story control building.

A-3.1.1 Process Design

Traditionally, volume requirements have been determined from empirical loading criteria, such as per capita volume allowance, as shown for low-rate digestion in the table below (Reference 4).

Sludge Type	Tank Volume (ft^3/capita)
Primary sludge only	2 to 3
Primary sludge plus waste activated sludge	4 to 6
Primary sludge plus trickling filter humus	4 to 5

Volatile solids loading rate has been suggested as a more direct method of determining reactor volume. For low-rate digestion, volatile solids loading rates range between 0.04 and 0.1 lb volatile solids/day/ft^3.

Another important consideration in sizing an anaerobic digester is solids retention time. The digester should be sized to allow adequate time for the decomposition of volatile organics. Ten days has been suggested as the minimum acceptable solids retention time for high-rate digesters operating near 95° F. Solids retention time for low-rate digestion ranges between 30 and 60 days.

A-3.1.2 Algorithm Development

The following algorithm is based on the CAPDET program. Equations used in the CAPDET algorithm for anaerobic digestion can be found in Reference 1, pages 2.19-45 through 2.19-78. Cost and requirement outputs were developed utilizing the program by varying sludge volume and solids concentration entering the digester, using the following input parameters:

- Sludge specific gravity = 1.02.
- Percent volatile solids destroyed = 50 percent.
- Effluent concentration = percent influent + 2 percent.
- Digestion operating temperature = 95° F.
- Raw sludge temperature = 70° F.
- Volatile solids in raw sludge = 60 percent.
- Cost of standard 70-ft-diameter gas circulation unit = $51,000.

- Cost of standard 1-million-Btu/hr heating unit = $64,000.

- Cost of standard 2-in-diameter gas safety equipment = $9,250 (includes accumulator with drip trap, low-pressure check valve, pressure relief and flame trap valve, flame trap, six drip traps, gas pressure gauge, waste gas burner, and gas meter).

- Cost of standard size sludge pump = $4,000 (8 gal/min at 70 ft of head).

Additional input parameters (projected 1983 values) shown on Table 1-1 were obtained from construction cost guides (2, 3). Costs of floating cover, circulation unit, heating unit, safety equipment, and sludge pump were obtained from equipment suppliers.

Equations for calculating O&M requirements such as labor and electrical power were taken directly from the CAPDET program. For capital costs, values obtained from the CAPDET program were fit to polynomial equations using multiple regression curve fits. Costs and requirements are expressed as functions of appropriate design and operating parameters. For example, capital cost is expressed as a function of digester tank volume, and O&M requirements (labor and electricity) are related to the solids processed per day. In calculating operation and maintenance requirements, it was assumed that sufficient digester gas is produced to heat the digesters, and that no supplemental natural gas is required.

A-3.2 Input Data

A-3.2.1 Daily sludge volume, SV, gal/day.

A-3.2.2 Sludge suspended solids concentration, SS, percent.

A-3.2.3 Percent volatile solids in raw sludge, PV, percent of total solids dry weight.

A-3.2.4 Raw sludge specific gravity, SSG, unitless.

A-3.2.5 Digested sludge specific gravity, SGD, unitless.

A-3.2.6 Percent volatile solids converted to methane, carbon dioxide, and water during digestion, PVR, percent.

A-3.2.7 Percent suspended solids in sludge effluent, SSE, percent.

A-3.3 Design Parameters

A-3.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-3.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-3.3.3 Raw sludge specific gravity, SSG, unitless. Default value = 1.02.

A-3.3.4 Digested sludge specific gravity, SGD, unitless. Default value = 1.03.

A-3.3.5 Percent volatile solids in raw sludge, PV, percent. Default value = 60 percent.

A-3.3.6 Percent volatile solids converted to methane, carbon dioxide, and water during digestion, PVR, percent. Default value = 50 percent.

A-3.3.7 Percent suspended solids in digested sludge effluent, SSE, percent. Default value = influent percent suspended solids + 2 percent.

A-3.4 Process Design Calculations

A-3.4.1 Calculate the volume of raw sludge to digester.

$$VRS = \frac{SV}{7.48}$$

where

VRS = Volume of raw sludge, ft^3/day.
7.48 = Conversion factor, gal/ft^3.

A-3.4.2 Calculate dry solids digested per day.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{(100)\ (2{,}000)}$$

where

TDSS = Daily dry solids digested, tons/day.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.

A-3.4.3 Calculate solids retention time.

$$TD = (PVR - 30)\ (2)$$

where

TD = Solids retention time, days.

A-3.4.4 Calculate digested sludge solids withdrawal.

$$SD = (TDSS)\ (2{,}000)\ [1 - \frac{(PV)}{(100)}\ \frac{(PVR)}{(100)}]$$

where

SD = Digested sludge solids withdrawal, lb/day.
2,000 = Conversion factor, lb/ton.

A-3.4.5 Calculate the volume of digested sludge.

$$VD = \frac{(SD)\ (100)}{(SGD)\ (62.4)\ (SSE)}$$

where

VD = Volume of digested sludge, ft^3/day.

A-3.4.6 Calculate total digestion tank volume.

$$VT = [VRS - (\frac{2}{3})\ (VRS - VD)]\ (TD)$$

where

VT = Total digestion tank volume, ft^3.

A-3.5 Process Design Output Data

A-3.5.1 Volume of raw sludge, VRS, ft^3/day.

A-3.5.2 Daily dry solids digested, TDSS, tons/day.

A-3.5.3 Solids retention time, TD, days.

A-3.5.4 Digested sludge solids withdrawal, SD, lb/day.

A-3.5.5 Volume of digested solids, VD, ft^3/day.

A-3.5.6 Total digestion tank volume, VT, ft^3.

A-3.6 Quantities Calculations

A-3.6.1 Maintenance labor requirement.

A-3.6.1.1 If TDSS $\leq$ 0.1 ton/day, maintenance labor is calculated by:

$$ML = 352$$

A-3.6.1.2 If $0.1 \leq TDSS \leq 1$ ton/day, maintenance labor is calculated by:

$$ML = 448\ (TDSS)^{0.105}$$

A-3.6.1.3 If $1 < TDSS \leq 10$ tons/day, maintenance labor is calculated by:

$$ML = 448\ (TDSS)^{0.470}$$

A-3.6.1.4 If $TDSS > 10$ tons/day, maintenance labor is calculated by:

$$ML = 200\ (TDSS)^{0.804}$$

where

ML = Annual maintenance labor requirement, hr/yr.

A-3.6.2 Operation labor requirement.

A-3.6.2.1 If $TDSS \leq 0.1$ ton/day, operation labor is calculated by:

$$OL = 608$$

A-3.6.2.2 If $0.1 < TDSS \leq 1$ ton/day, operation labor is calculated by:

$$OL = 720\ (TDSS)^{0.0734}$$

A-3.6.2.3 If $1 < TDSS \leq 10$ tons/day, operation labor is calculated by:

$$OL = 720\ (TDSS)^{0.4437}$$

A-3.6.2.4 If $TDSS > 10$ tons/day, operation labor is calculated by:

$$OL = 280\ (TDSS)^{0.8405}$$

where

OL = Operation labor requirement, hr/yr.

A-3.6.3 Electrical energy requirement.

A-3.6.3.1 If TDSS $\leq$ 8.5 tons/day, electrical energy is calculated by:

$$E = 46{,}720\ (TDSS)^{0.596}$$

A-3.6.3.2 If TDSS > 8.5 tons/day, electrical energy is calculated by:

$$E = 30{,}691\ (TDSS)^{0.800}$$

where

E = Annual electrical energy requirement, kWhr/yr.

A-3.7 Quantities Calculations Output Data

A-3.7.1 Annual maintenance labor requirement, ML, hr/yr.

A-3.7.2 Annual operation labor requirement, OL, hr/yr.

A-3.7.3 Annual electrical energy requirement, E, kWhr/yr.

A-3.8 Unit Price Input Required

A-3.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-3.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-3.8.3 Cost of operation and maintenance labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-3.8.4 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-3.9 Cost Calculations

A-3.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (ML + OL)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-3.9.2 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-3.9.3 Annual maintenance material and supply cost.

A-3.9.3.1 If $VT \leq 10{,}300\ ft^3$, annual material and supply cost is calculated by:

$$COSTMS = (3{,}677)\ \frac{MSECI}{751}$$

A-3.9.3.2 If $10{,}300 < VT \leq 20{,}000\ ft^3$, annual material and supply cost is calculated by:

$$COSTMS = [(0.17)\ (VT - 10{,}300) + 3{,}677]\ \frac{MSECI}{751}$$

A-3.9.3.3 If $20{,}000 < VT \leq 100{,}000\ ft^3$, annual material and supply cost is calculated by:

$$COSTMS = [4.1 \times 10^{-11}\ (VT)^3 - 6.4 \times 10^{-6}\ (VT)^2 + 0.2970\ (VT) + 1{,}641]\ \frac{MSECI}{751}$$

A-3.9.3.4 If $VT > 100{,}000\ ft^3$, annual material and supply cost is calculated by:

$$COSTMS = [4.3 \times 10^{-14}\ (VT)^3 - 7.4 \times 10^{-8}\ (VT)^2 + 0.046\ (VT) + 4{,}038]\ \frac{MSECI}{751}$$

where

COSTMS = Annual maintenance material and supply cost, \$/yr.

A-3.9.4 Total base capital cost.

A-3.9.4.1 If VT $\leq$ 10,300 ft^3, total base capital cost is calculated by:

$$TBCC = (395{,}000) \frac{ENRCCI}{4{,}006}$$

A-3.9.4.2 If 10,300 < VT $\leq$ 80,000 ft^3, total base capital cost is calculated by:

$$TBCC = [2.2\ (VT) + 372{,}440] \frac{ENRCCI}{4{,}006}$$

A-3.9.4.3 If VT > 80,000 ft^3, total base capital cost is calculated by:

$$TBCC = [5.9 \times 10^{-12}\ (VT)^3 - 1.14 \times 10^{-5}\ (VT)^2 + 7.5\ (VT) + 36{,}700] \frac{ENRCCI}{4{,}006}$$

where

TBCC = Total base capital cost, $.

A-3.9.5 Annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTMS$$

where

COSTOM = Annual operation and maintenance cost, $/yr

A-3.10 Cost Calculation Output Data

A-3.10.1 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-3.10.2 Annual cost of electrical energy, COSTEL, $/yr.

A-3.10.3 Annual maintenance material and supply cost, COSTMS, $/yr.

A-3.10.4 Total base capital cost of anaerobic digestion process, TBCC, $.

A-3.10.5 Annual operating and maintenance cost for anaerobic digestion process, COSTOM, $/yr.

APPENDIX A-4

AEROBIC DIGESTION USING MECHANICAL AERATORS

A-4.1 Background

Aerobic digestion is the stabilization of raw sludge under aerobic conditions, similar in principle to the activated sludge process. Sludge solids are converted to carbon dioxide, water, and ammonia through the microbial degradation of the sludge solids. Traditionally, aerobic digestion has been used at small treatment plants (less than 5 mgd), although the process has also been used at larger plants.

The advantages of aerobic digestion over anaerobic digestion include:

- Lower capital cost than anaerobic digestion.
- Easier to operate than anaerobic digestion.
- Virtually odor free operation.
- Produces a supernatant return flow which is low in BOD, SS, and ammonia nitrogen.

Disadvantages of aerobic digestion are:

- High energy consumption.
- The digested sludge has poor mechanical dewatering characteristics.
- The process is significantly affected by cold temperature, which reduces biological activity and may cause mechanical problems with surface aerators during freezing conditions.
- Methane, often used as a fuel source in anaerobic digestion, is not produced.

Aerobic digesters are usually rectangular open tanks constructed of concrete or steel. In cold weather areas, the tanks are often placed below ground to minimize heat losses. The air (oxygen) necessary for oxidation can be added to the sludge mass by mechanical surface aerators, as covered in this cost algorithm, or by air diffusors, as covered in Appendix A-5.

The following algorithm is based on the construction of rectangular reinforced concrete digesters. Capital costs include: excavation, construction of reinforced concrete tanks, purchase of mechanical aerators and ancillary equipment, and installation of all equipment.

A-4.1.1 Process Design

The selection and design of aerobic digestion units is complex. Minimum temperature, volatile solids reduction, sludge characteristics, detention time, sludge age, and other factors are involved. Typical design parameters (References 1, 4) are presented in the table below.

Design Parameter	Typical Value
Hydraulic detention time, days at 68° F:	
Activated sludge only	12 to 16
Activated sludge from plant operated without primary settling	16 to 18
Primary plus activated or trickling filter sludge	18 to 22
Solids loading, lb volatile solids/ft^3/day	0.1 to 0.2
Oxygen requirement, lb O_2/lb of volatile solids destroyed	2
Tank volume in ft^3/capita	3 to 4
Air requirement, 20 to 60 ft^3/min/1,000 ft^3	20 to 60
Energy requirements for mixing, hp/1,000 ft^3	0.5 to 1.0

A-4.1.2 Algorithm Development

The following algorithm is based on use of the CAPDET program. The CAPDET algorithm for aerobic digestion with mechanical aeration is found in Reference 1, pages 2.19-23 through 2.19-44. Costs and requirements were developed utilizing the program by varying sludge volume and solids concentration entering the aerobic digester, using the following input parameters:

- Detention time = 20 days.
- Volatile solids destroyed = 45 percent.
- Sludge specific gravity = 1.02.
- Mixed liquor solids = 12,000 mg/l.
- Solids in digested sludge = 4 percent.
- Ratio of oxygen saturation in waste to oxygen saturation in water = 0.9.
- Standard transfer efficiency = 1.68 lb O_2/hp-hr.

- Temperature in digester = 73 °F.

- Cost of standard slow speed, pier-mounted 20-hp aerator = $21,200.

Additional input parameters (projected 1983 values) shown on Table 1-1 were obtained from construction cost guides (2, 3). Cost of the standard aerator was obtained from equipment suppliers.

Capital costs, O&M costs, and O&M requirements, except for electrical energy, were obtained through use of the CAPDET program, and were fit to a polynomial equation using a multiple regression program. Electrical energy was calculated directly from the horsepower required for aeration. Costs and requirements were expressed as functions of the total aeration horsepower required.

A-4.2 Input Data

A-4.2.1 Daily sludge volume, SV, gal/day.

A-4.2.2 Sludge suspended solids concentration, SS, percent.

A-4.2.3 Sludge specific gravity, SSG, unitless.

A-4.2.4 Percent volatile solids in raw sludge, PV, percent.

A-4.2.5 Percent volatile solids converted to carbon dioxide and water during digestion, PVR, percent.

A-4.3 Design Parameters

A-4.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-4.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-4.3.3 Sludge specific gravity, SSG, unitless. Default value = 1.02.

A-4.3.4 Percent volatile solids in raw sludge, PV, percent. Default value = 60 percent.

A-4.3.5 Percent volatile solids converted to carbon dioxide and water during digestion, PVR, percent.. Default value = 45 percent.

A-4.4 Process Design Calculations

A-4.4.1 Calculate dry solids digested per day.

$$DSS = \frac{(SV)\ (SSG)\ (SS)\ (8.34)}{(100)}$$

where

DSS = Daily dry solids digested, lb/day.

A-4.4.2 Calculate daily oxygen requirement.

$$OR = \frac{(2)\ (DSS)\ (PV)\ (PVR)}{(100)\ (100)}$$

where

OR = Oxygen requirement, lb/day.

2 = Oxygen required for oxidation of volatile solids, lb O_2/lb volatile solids converted.

A-4.4.3 Calculate total horsepower required for aeration.

$$THP = \frac{(OR)}{(1.68)\ (24)}$$

where

THP = Total horsepower required, hp.
1.68 = Oxygen transfer rate, lb O_2/hp-hr.

A-4.5 Process Design Output Data

A-4.5.1 Daily dry solids digested, DSS, lb/day.

A-4.5.2 Daily oxygen requirement, OR, lb/day.

A-4.5.3 Total horsepower required, THP, hp.

A-4.6 Quantities Calculations

A-4.6.1 Calculate operation and maintenance labor requirement.

$$L = 2.3 \times 10^{-7}\ (THP)^3 - 3.4 \times 10^{-3}\ (THP)^2 + 8.47\ (THP) + 1{,}013$$

where

L = Annual operation and maintenance labor requirement, hr/yr.

A-4.6.2 Calculate electrical energy requirement.

$$E = (THP)\ (24)\ (365)\ (0.746)$$

where

E = Annual electrical energy requirement, kWhr/yr.
0.746 = Conversion factor, hp to kW.

A-4.7 Quantities Calculations Output Data

A-4.7.1 Annual operation and maintenance labor requirement, L, hr/yr.

A-4.7.2 Annual electrical energy requirement, E, kWhr/yr.

A-4.8 Unit Price Input Required

A-4.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-4.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-4.8.3 Cost of operation and maintenance labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-4.8.4 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-4.9 Cost Calculations

A-4.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-4.9.2 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-4.9.3 Annual maintenance material and supply cost.

$$COSTMS = [1.01 \times 10^{-6}\ (THP)^3 - 0.00163\ (THP)^2 + 7.257\ (THP) + 1{,}175]\ \frac{MSECI}{751}$$

where

COSTMS = Annual maintenance material and supply cost, \$/yr.

A-4.9.4 Total base capital cost.

$$TBCC = [-0.00169\ (THP)^3 + 2.07\ (THP)^2 + 1{,}564\ (THP) + 152{,}850]\ \frac{ENRCCI}{4{,}006}$$

where

TBCC = Total base capital cost, \$.

A-4.9.5 Annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTMS$$

where

COSTOM = Annual operation and maintenance cost, \$/yr.

A-4.10 Cost Calculation Output Data

A-4.10.1 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-4.10.2 Annual cost of electrical energy, COSTE, \$/yr.

A-4.10.3 Annual maintenance and material supply cost, COSTMS, \$/yr.

A-4.10.4 Total base capital cost of mechanical aerobic digestion process, TBCC, \$.

A-4.10.5 Annual operating and maintenance cost for mechanical aerobic digestion process, COSTOM, \$/yr.

APPENDIX A-5

AEROBIC DIGESTION USING DIFFUSED AERATION

A-5.1 Background

Reference is made to Appendix A-4, which briefly discusses aerobic digestion in general. Aerobic digestion using diffused aeration is similar to aerobic digestion using mechanical aerators, except for the method of introducing and mixing air (oxygen) with the digester contents. If activated sludge treatment is used at the treatment plant and aerobic digestion is considered, it is advantageous to use diffused aeration, since a common blower facility can supply air to both the digester and the activated sludge reactors. Swing arm diffusers are commonly used in both the activated sludge reactor and the aerobic digester.

The following algorithm is based on the construction of rectangular reinforced concrete digesters. Capital costs include: excavation, construction of reinforced concrete tanks, and purchase and installation of swing arm headers, diffusers, and ancillary equipment. The depth and width of the aeration tanks are fixed at 15 ft and 30 ft, respectively. Capital costs do not include the cost of blowers, associated equipment, and blower building.

A-5.1.1 Process Design

The user is referred to Appendix A-4 for major design considerations of aerobic digestion. The following table (References 1, 4) presents typical design parameters for aerobic digestion using diffused aeration.

Design Parameter	Typical Value
Hydraulic detention time, days at 68 °F:	
Activated sludge only	12 to 16
Activated sludge from plant operated without primary settling	16 to 18
Primary plus activated or trickling filter sludge	18 to 22
Solids loading, lb volatile solids/ft^3/day	0.1 to 0.20
Oxygen requirement, lb O_2/lb of volatile solids destroyed	2

Tank volume in ft^3/capita	3 to 4
Air requirement, ft^3/min/1,000 ft^3	20 to 60
Energy requirement for mixing, cfm/1,000 ft^3	20 to 30

A-5.1.2 Algorithm Development

The following algorithm is based on use of the CAPDET program. The CAPDET algorithm for aerobic digestion with diffused aeration is found in Reference 1, pages 2.19-4 through 2.19-22. Costs and O&M requirements were developed utilizing the program by varying sludge volume and solids concentration entering the aerobic digester, using the following input parameters:

- Detention time = 20 days.
- Influent volatile solids = 60 percent.
- Volatile solids destroyed = 45 percent.
- Sludge specific gravity = 1.02.
- Mixed liquor solids = 12,000 mg/l.
- Ratio of oxygen saturation in waste to oxygen saturation in water = 0.9.
- Standard transfer efficiency = 8 percent.
- Temperature in digester = 73 °F.
- Cost of standard 12.0-scfm coarse-bubble diffuser = $14.00.
- Cost of standard 550-scfm swing arm diffuser = $6,500.

Additional input parameters (projected 1983 values) shown on Table 1-1 were obtained from construction cost guides (2, 3). Costs of the standard diffusers and headers were obtained from equipment suppliers.

Equations for O&M requirements are those used in the CAPDET program, with the exception of electrial power, which is based on oxygen demand and energy requirements for oxygen transfer. Capital costs obtained from the CAPDET program were fit to polynomial equations using multiple regression curve fits.

Costs and O&M requirements were expressed as functions of the parameter most closely related to costs or requirements. For example, O&M requirements (labor and electrical energy) are related to the air supply required; capital cost is expressed as a function of the sludge volume.

A-5.2 Input Data

A-5.2.1 Daily sludge volume, SV, gal/day.

A-5.2.2 Sludge suspended solids concentration, SS, percent.

A-5.2.3 Sludge specific gravity, SSG, unitless.

A-5.2.4 Percent volatile solids in raw sludge, PV, percent.

A-5.2.5 Percent volatile solids converted to carbon dioxide and water during digestion, PVR, percent.

A-5.2.6 Hydraulic detention time, TD, days.

A-5.2.7 Efficiency of oxygen transfer from air to water, STE, percent.

A-5.2.8 Transfer rate of oxygen to water per hp-hr, TR, lb O_2/hp-hr.

A-5.3 Design Parameters

A-5.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-5.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-5.3.3 Sludge specific gravity, SSG, unitless. Default value = 1.02.

A-5.3.4 Percent volatile solids in raw sludge, PV, percent. Default value = 60 percent.

A-5.3.5 Percent volatile solids converted to carbon dioxide and water during digestion, PVR, percent. Default value = 45 percent.

A-5.3.6 Hydraulic detention time, TD, days. Default value = 20 days.

A-5.3.7 Efficiency of oxygen transfer from air to water, STE, percent. Default value = 8 percent.

A-5.3.8 Transfer rate of oxygen to water per hp-hr, TR, lb O_2/hp-hr. Default value = 1.0 lb/hp-hr.

A-5.4 Process Design Calculations

A-5.4.1 Calculate dry solids digested per day.

$$DSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{(100)}$$

where

DSS = Daily dry solids digested, lb/day.
8.34 = Density of water, lb/gal.

A-5.4.2 Calculate daily oxygen requirement.

$$OR = \frac{(2)\ (DSS)\ (PV)\ (PVR)}{(100)\ (100)}$$

where

OR = Oxygen requirement, lb/day.

2 = Oxygen required for oxidation of volatile solids, lb O_2/lb volatile solids converted.

A-5.4.3 Calculate air required to satisfy oxygen demand.

$$TAIR = \frac{(OR)\ (100)}{(STE)\ (0.56)\ (0.0176)\ (24)\ (60)}$$

where

TAIR = Total air required, scfm.

0.56 = Factor for conversion from standard transfer efficiency (oxygen to water) to transfer efficiency of oxygen to mixed liquor at 73 °F, decimal percent.

0.0176 = Conversion factor, lb O_2/ft^3 air.

A-5.5 Process Design Output Data

A-5.5.1 Daily dry solids digested, DSS, lb/day.

A-5.5.2 Daily oxygen requirement, OR, lb/day.

A-5.5.3 Daily air requirement, TAIR, scfm.

A-5.6 Quantities Calculations

A-5.6.1 Calculate operation labor requirement.

A-5.6.1.1 If TAIR $\leq$ 3,000 scfm, operation labor is calculated by:

$$OL = 62.36\ (TAIR)^{0.3972}$$

A-5.6.1.2 If TAIR > 3,000 scfm, operation labor is calculated by:

$$OL = 26.56\ (TAIR)^{0.5038}$$

where

OL = Operation labor requirement, hr/yr.

A-5.6.2 Calculate maintenance labor requirement.

A-5.6.2.1 If TAIR $\leq$ 3,000 scfm, maintenance labor is calculated by:

$$ML = 22.82\ (TAIR)^{0.4379}$$

A-5.6.2.2 If TAIR > 3,000 scfm, maintenance labor is calculated by:

$$ML = 6.05\ (TAIR)^{0.6037}$$

where

ML = Maintenance labor requirement, hr/yr.

A-5.6.3 Calculate annual electrical energy requirement.

$$E = \frac{(OR)\ (365)}{(TD)\ (1.34)}$$

where

E = Annual electrical energy requirement, kWhr/yr.
1.34 = Conversion factor, hp-hr to kWhr.

A-5.6.4 Calculate maintenance material and supply cost factor. This item includes repair and replacement costs. It is calculated as a percentage of the total base capital cost.

$$OMMP = 38\ (SV)^{-0.2602}$$

where

OMMP = Annual maintenance material and supply cost factor, percent.

A-5.7 Quantities Calculations Output Data

A-5.7.1 Annual operation labor requirement, OL, hr/yr.

A-5.7.2 Annual maintenance labor requirement, ML, hr/yr.

A-5.7.3 Annual electrical energy requirement, E, kWhr/yr.

A-5.7.4 Annual maintenance material and supply cost factor, OMMP, percent.

A-5.8 Unit Price Input Required

A-5.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-5.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-5.8.3 Cost of operation and maintenance labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-5.8.4 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-5.9 Cost Calculations

A-5.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (OL + ML)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-5.9.2 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-5.9.3 Total base capital cost.

A-5.9.3.1 If sludge suspended solids, SS, is 1 percent, total base capital cost is calculated by:

$$TBCC = [-1.987 \times 10^{-11}\ (SV)^3 + 1.7 \times 10^{-5}\ (SV)^2 + 5.737\ (SV) + 259{,}240]\ \frac{ENRCCI}{4{,}006}$$

A-5.9.3.2 If sludge suspended solids, SS, is 2 percent, total base capital cost is calculated by:

$$TBCC = [-1.603 \times 10^{-11} (SV)^3 + 1.57 \times 10^{-5} (SV)^2 + 6.178 (SV) + 271{,}910] \frac{ENRCCI}{4{,}006}$$

A-5.9.3.3 If sludge suspended solids, SS, is 3 percent, total base capital cost is calculated by:

$$TBCC = [-1.498 \times 10^{-11} (SV)^3 + 1.68 \times 10^{-5} (SV)^2 + 6.446 (SV) + 300{,}150] \frac{ENRCCI}{4{,}006}$$

where

TBCC = Total base capital cost, \$.

A-5.9.4 Annual maintenance material and supply cost.

$$COSTMS = \frac{(OMMP)\ (TBCC)}{(100)}$$

where

COSTMS = Annual maintenance material and supply cost.

A-5.9.5 Annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTMS$$

where

COSTOM = Annual operation and maintenance cost, \$/yr

A-5.10 Cost Calculation Output Data

A-5.10.1 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-5.10.2 Annual cost of electrical energy, COSTE, \$/yr.

A-5.10.3 Annual maintenance material supply cost, \$/yr.

A-5.10.4 Total base capital cost of diffused aerobic digestion process, TBCC, \$.

A-5.10.5 Annual operation and maintenance cost for diffused aerobic digestion process, COSTOM, \$/yr.

APPENDIX A-6

LIME STABILIZATION

A-6.1 Background

Lime stabilization is a process in which lime is added to raw sludge in a quantity sufficient to raise the pH of the sludge to approximately 12.0 for at least 2 hours. The lime-stabilized sludge readily dewaters with mechanical equipment (e.g., filter press, centrifuge, etc.), and is generally suitable for disposal to landfill, dedicated disposal site, or application to agricultural land (except where the existing agricultural soil already has a high pH).

A potential disadvantage of the lime stabilization method is that the mass of dry sludge solids is increased by the lime added and the chemical precipitates that result from the addition. Because of the increased sludge volume, the cost of transport and disposal/application is often greater for lime-stabilized sludge than for sludge stabilized by other methods (e.g., anaerobic digestion).

Two forms of lime are commercially available: (1) quicklime (CaO) and (2) hydrated lime ($Ca(OH)_2$). Quicklime is less expensive but must be converted to hydrated lime on site by slaking. Hydrated lime can be mixed with water and applied directly. Generally, larger treatment plants purchase quicklime, and smaller sewage treatment plants use hydrated lime. For a specific plant, a detailed economic analysis is necessary which takes into account plant size, chemical requirements, chemical costs, and labor and maintenance requirements. In this cost algorithm, the use of hydrated lime is assumed in developing the cost default values. This assumption should produce adequate cost estimates for small and medium size plants (those using up to 5 tons of lime/day), but may result in overestimating O&M costs for larger plants.

A-6.1.1 Process Design

The design of a lime stabilization system consists of two parts: (1) design of a lime handling system; and (2) design of the sludge mixing system. The design of each is briefly described below.

Design of the lime handling system depends on the form and quantities of lime received at the treatment plant. Lime can be stored in steel or concrete silos or bins. At a minimum, sufficient storage capacity to provide a 7-day supply of lime should be provided; however, a 2- or 3-week supply is desirable. In addition, the total storage volume should be at least 50 percent greater than the capacity of the delivery railcar or truck to ensure adequate lime supply between shipments.

Dry hydrated lime is delivered from storage to a dilution tank fitted directly onto the feeder. The dilution tank is agitated by either compressed air, water jets, or impeller-type mixers. From the dilution tank, the slurry is then transferred to the sludge mixing tank. Smaller treatment plants purchase and store bagged hydrated lime which is mixed with water and metered to the sludge mixing tank as required.

The mixing tank is sized based on detention time. Optimally, the mixing tank should be sized to hold the lime/sludge mixture for 30 minutes. This detention time should allow sufficient contact to raise the pH beyond 12.5. Mixing tanks can be operated in batch or continuous mode. Tank mixing is accomplished either with diffused air or mechanical mixers. Diffused air is more commonly used in lime stabilization.

The lime stabilization process in this cost algorithm includes a lime storage silo sized for 30 days storage; dual batch mixing tanks, each having a capacity to hold 0.5 hours of plant design sludge flow; and a lime feeding system. Normal costs for piping, pumps, electrical, and other accessories are included.

A-6.1.2 Algorithm Development

The following algorithm follows the basic sequence used by an engineer when designing a lime stabilization process. Dosage, contact time, labor, electrical requirements, and capital costs were obtained from information in Reference 4, pages 6-104 through 6-107. Lime costs are based on vendor quotes.

A-6.2 Input Data

A-6.2.1 Daily sludge volume, SV, gal/day.

A-6.2.2 Sludge suspended solids concentration, SS, percent.

A-6.3 Design Parameters

A-6.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-6.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-6.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated using the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-6.3.4 Daily operation period, HPD, hr/day. Default value = 8 hr/day.

A-6.3.5 Annual operation period, DPY, days/yr. Default value = 365 days/yr.

A-6.3.6 Sludge detention time in mixing tank, DT, hr/batch. Default value = 0.5 hr.

A-6.3.7 Lime dosage as a fraction of dry sludge solids mass, LD, lb of $Ca(OH)_2$/lb of dry sludge solids. Default value = 0.3. The lime dosage required is determined by the type of sludge, its chemical composition, and the solids concentration. The following tables are given to provide guidance in selecting an appropriate value.

APPROXIMATE LIME DOSE REQUIRED TO RAISE TO 12.5 THE pH OF A MIXTURE OF PRIMARY SLUDGE AND TRICKLING FILTER HUMUS AT DIFFERENT SOLIDS CONCENTRATIONS

Solids Concentration (SS) (%)	Lime Dose (LD) (lb $Ca(OH)_2$/lb dry solids)
1	0.39
2	0.32
3	0.27
4	0.23

LIME DOSE REQUIRED TO KEEP pH ABOVE 11.0 FOR AT LEAST 14 DAYS

Type of Sludge	Lime Dose (LD) (lb $Ca(OH_2)$/lb suspended solids)
Primary Sludge	0.10 - 0.15
Activated Sludge	0.30 - 0.50
Septage	0.10 - 0.30
Alum-sludge*	0.40 - 0.60
Alum sludge* Plus Primary Sludge†	0.25 - 0.40
Iron-sludge*	0.35 - 0.60

* Precipitation of primary treated effluent.
† Equal proportions by weight of each type of sludge.

A-6.3.8 Hydrated lime content of the lime product used, LC, percent. Default value = 90 percent.

A-6.4 Process Design Calculations

A-6.4.1 Calculate annual lime requirement.

$$ALR = \frac{(8.34)\ (SV)\ (SS)\ (SSG)\ (LD)\ (365)\ (100)}{(100)\ (LC)}$$

where

ALR = Weight of lime product required annually, lb/yr.

A-6.4.2 Calculate volume of lime storage silo (30 days storage assumed).

$$VLS = \frac{(ALR)}{(12)\ (30)}$$

where

VLS = Volume of lime storage required, ft^3.
12 = Months/yr.
30 = Bulk density of hydrated lime in storage silo, lb/ft^3.

A-6.4.3 Calculate combined capacity of two mixing tanks.

$$MTC = \frac{(SV)\ (DT)\ (2)\ (365)}{(HPD)\ (DPY)}$$

where

MTC = Total mixing tank capacity required, gal.
2 = Design factor.

A-6.4.4 Calculate capacity of lime feed system.

$$LFC = \frac{(ALR)\ (2.0)}{(DPY)\ (HPD)\ (0.167)}$$

where

LFC = Total lime feed system capacity required, lb/hr.

0.167 = 1/6 = Assumed 5-min period of lime feeding divided by 30-min detention period.

A-6.5 Process Design Output Data

A-6.5.1 Annual lime requirement, ALR, lb/yr.

A-6.5.2 Volume of lime storage silo, VLS, ft^3.

A-6.5.3 Combined capacity of two mixing tanks, MTC, gal.

A-6.5.4 Capacity of lime feed system, LFC, lb/hr.

A-6.6 Quantities Calculations

A-6.6.1 Calculate annual energy requirement for air mixing.

$$BER = \frac{(MTC)\ (0.03)\ (97)}{(7.48)}$$

where

BER = Annual energy requirement for air mixing, kWhr/yr.
0.03 = Blower capacity factor based on 3 cfm/100 ft^3 of tank volume.
97 = kWhr required annually per cfm of blower capacity.

A-6.6.2 Calculate total annual energy requirement.

$$E = BER\ (1.3)$$

where

E = Total annual energy requirement, kWhr/yr.

1.3 = Additional power factor for lime feeding and other minor energy requirements.

A-6.6.3 Calculate annual labor requirement.

$$L = (DPY)\ (HPD)\ (0.5 + \frac{(SV)\ (365)}{50,000,000})$$

where

L = Annual labor requirement, hr/yr.

$0.5 + \frac{(SV)\ (365)}{50,000,000}$ = Labor hour factor.

A-6.7 Quantities Calculations Output Data

A-6.7.1 Annual energy requirement for air mixing, BER, kWhr/yr.

A-6.7.2 Total annual energy requirement, E, kWhr/yr.

A-6.7.3 Annual labor requirement, L, hr/yr.

A-6.8 Unit Price Input Required

A-6.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-6.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made MSECI.

A-6.8.3 Cost of lime, LMCST, \$/ton. Default value = \$100/ton (ENRCCI/4,006).

A-6.8.4 Cost of lime storage silo(s), LSCST, $\$/ft^3$. Default value = $\$7.40/ft^3$ (ENRCCI/4,006).

A-6.8.5 Cost of mixing tanks, MTCST, including air mixing system, scrubber, and piping, \$/gal. Default value = \$0.80/gal (MSECI/751).

A-6.8.6 Cost of lime feed system, LFCST, including all accessories, \$/lb/hr. Default value = \$15/lb/hr (MSECI/751).

A-6.8.7 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-6.8.8 Cost of energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-6.9 Cost Calculations

A-6.9.1 Annual cost of lime.

$$COSTLM = \frac{(ALR)\ (LMCST)}{2,000}$$

where

ACSTLM = Annual cost of lime, \$/yr.

A-6.9.2 Cost of lime storage silo.

$$COSTLS = (VLS)\ (LSCST)$$

where

COSTLS = Cost of lime storage silo, \$.

A-6.9.3 Cost of lime feed system with appurtenances.

$$COSTLF = (LFC)\ (LFCST)$$

where

COSTLF = Cost of lime feed systems, \$.

A-6.9.4 Cost of mixing tanks with appurtenances.

$$COSTMT = (MTC)\ (MTCST)$$

where

COSTMT = Cost of mixing tanks with appurtenances, \$.

A-6.9.5 Annual cost of operation labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation labor, \$/yr.

A-6.9.6 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-6.9.7 Total base capital cost.

$$TBCC = COSTLS + COSTLF + COSTMT$$

where

TBCC = Total base capital cost, \$.

A-6.9.8 Annual maintenance material and supply cost.

$$COSTM = (TBCC)\ (0.15)$$

where

COSTM = Annual maintenance material and supply cost, \$/yr.

A-6.9.9 Annual cost of operation and maintenance.

$$COSTOM = COSTLM + COSTLB + COSTEL + COSTM$$

where

COSTOM = Annual cost of operation and maintenance, \$/yr.

A-6.10 Cost Calculations Output Data

A-6.10.1 Annual cost of lime, COSTLM, \$/yr.

A-6.10.2 Cost of lime storage silo, COSTLS, \$.

A-6.10.3 Cost of lime feed system with appurtenances, COSTLF, \$.

A-6.10.4 Cost of mixing tanks with appurtenances, COSTMT, \$.

A-6.10.5 Annual cost of operation labor, COSTLB, \$/yr.

A-6.10.6 Annual cost of electrical energy, COSTEL, \$/yr.

A-6.10.7 Annual maintenance material and supply cost, COSTM, \$/yr.

A-6.10.8 Total base capital cost, TBCC, \$.

A-6.10.9 Total annual operation and maintenance cost, COSTOM, \$/yr.

APPENDIX A-7

THERMAL CONDITIONING OF SLUDGE

A-7.1 Background

Thermal conditioning, also known as Zimpro Process®, low-pressure oxidation, and heat treatment, is a stabilization and conditioning process which prepares sludge for dewatering without the use of chemicals. The sludge is heated to temperatures from 290 to 410 °F under pressures of 150 to 400 lb/in^2, with the addition of steam and sometimes air. During treatment, the sludge is stabilized due to the hydrolysis of proteinaceous materials and destruction of cellular tissues. In addition, the high temperatures and pressures to which the sludge is subjected result in the release of bound water, enhancing dewatering.

The thermal conditioning process is most applicable to biological sludges that may be difficult to stabilize or condition by other means. However, the process is generally limited to large treatment plants (>5 mgd) due to the associated high capital and O&M costs. In addition, the process requires skilled personnel for operation and a rigorous preventative maintenance program.

A major disadvantage associated with thermal conditioning results from the high concentrations of soluble organic compounds and ammonia nitrogen in the supernatant and filtrate recycle liquor. The recycle liquor can increase the BOD load to an aeration system appreciably. In addition, the thermal conditioning system and subsequent dewatering equipment will, in almost all cases, require odor control facilities.

A-7.1.1 Process Design

The design of thermal conditioning systems is based on a number of factors such as sludge volume, percent volatile solids, detention time, and operating schedule. Process performance is a function of temperature, pressure, and feed solids concentration. Typical values are shown below.

Parameter	Value
Volatile solids destroyed	30-40 percent
Solids capture	95 percent
Effluent solids	35-50 percent
Temperature	290-410 °F
Pressure	150-400 lb/in^2g
Detention time	30-90 minutes
Steam consumption	600 lb/1,000 gal sludge

Thermal conditioning systems are generally purchased from the manufacturer as package units. The package consists of sludge feed pumps, sludge grinders, heat exchangers, reactors, boiler, gas separators, air compressors (if necessary), and decanting tank. Equipment such as heat exchangers and reactors are constructed of corrosion-resistant materials, usually stainless steel.

Capital costs in the following algorithm include purchase and installation of the above-mentioned equipment, piping, controls, wiring, a single-story building, and odor control systems. Costs do not include provisions for treatment of the supernatant and filtrate recycle streams. The streams are normally returned to the main treatment plant following preliminary treatment.

A-7.1.2 Algorithm Development

Fuel, electrical energy, and labor requirements in the following algorithm are based on information from Reference 5, pages 300-13 through 300-34, and Reference 7, pages A-224 and A-225. Base capital costs are based on Reference 7 (pages A-224 and A-225) and values obtained from equipment manufacturers. Capital costs and electrical energy were fit to equations using a multiple regression program.

A-7.2 Input Data

A-7.2.1 Daily sludge volume, SV, gal/day.

A-7.2.2 Hours per day process is operated, HPD, hr/day.

A-7.2.3 Days per year process is operated, DPY, days/yr.

A-7.3 Design Parameters

A-7.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-7.3.2 Hours per day process is operated, HPD, hr/day. Default value = 20 hr/day.

A-7.3.3 Days per year process is operated, DPY, days/yr. Default value = 365 days/yr.

A-7.4 Process Design Calculations

A-7.4.1 Sludge volume processed in gallons per minute.

$$MSV = \frac{(SV)\ (365)}{(HPD)\ (DPY)\ (60)}$$

where

MSV = Sludge volume, gal/min.

A-7.5 Process Design Output Data

A-7.5.1 Sludge volume, MSV, gal/min.

A-7.6 Quantities Calculations

A-7.6.1 Fuel requirement. Calculations for the two most commonly used fuels, fuel oil and natural gas, are shown below. Use only one fuel type for cost estimating.

A-7.6.1.1 Annual fuel oil requirement.

$$FO = (MSV)\ (5.04)\ (DPY)$$

where

FO = Annual fuel oil requirement, gal/yr.

5.04 = Fuel oil consumption factor, gal fuel oil/day/gpm of sludge feed.

A-7.6.1.2 Annual natural gas requirement.

$$NG = (MSV)\ (700)\ (DPY)$$

where

NG = Annual natural gas requirement, ft^3/yr.

700 = Natural gas consumption factor, ft^3 gas/day/gpm of sludge feed.

A-7.6.2 Annual electrical energy requirement.

$$E = [-\ 0.0315\ (MSV)^2 + 28.6\ (MSV) + 50.0]\ (DPY)$$

where

E = Annual electrical energy requirement, kWhr/yr.

A-7.6.3 Annual operation and maintenance labor requirement.

$$L = [0.141\ (MSV) + 3.60]\ (DPY)$$

where

L = Annual operation and maintenance labor requirement, hr/yr.

A-7.7 Quantities Calculations Output Data

A-7.7.1 Annual fuel requirement, FO, gal/yr, or natural gas requirement, NG, ft^3/yr.

A-7.7.2 Annual electrical energy requirement, E, kWhr/yr.

A-7.7.3 Annual operation and maintenance labor requirement, L, hr/yr.

A-7.8 Unit Price Input Required

A-7.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-7.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time analysis is made.

A-7.8.3 Unit cost of fuel oil, COSTFO, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-7.8.4 Unit cost of natural gas, COSTNG, $\$/ft^3$. Default value = $\$0.006/ft^3$ (ENRCCI/4,006).

A-7.8.5 Unit cost of electricity, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-7.8.6 Unit cost of labor, COSTL, \$/hr. Default valve = \$13.00/hr (ENRCCI/4,006).

A-7.9 Cost Calculations

A-7.9.1 Annual cost of fuel.

$$COSTFU = (FO)\ (COSTFO)$$

or

$$COSTFU = (NG)\ (COSTNG)$$

where

COSTFU = Annual cost of fuel, \$/yr.

A-7.9.2 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-7.9.3 Annual operation and maintenance labor cost.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual operation and maintenance labor cost, \$/yr.

A-7.9.4 Total base capital cost. Wet oxidation facilities are usually purchased as a complete package directly from manufacturers. Costs are largely a function of sludge volume, MSV, in gal/min.

$$TBCC = [0.229\ (MSV)^3 - 116.32\ (MSV)^2 + 30{,}264\ (MSV) + 880{,}950]\ \frac{MSECI}{751}$$

where

TBCC = Total base capital cost of wet oxidation stabilization facility, \$.

A-7.9.5 Annual maintenance material and supply cost, COSTMS, is assumed to be a function of total base capital cost, TBCC.

$$COSTMS = 0.02\ (TBCC)$$

where

COSTMS = Total annual maintenance parts and materials cost, \$/yr.

A-7.9.6 Annual operation and maintenance cost.

$$COSTOM = (COSTFU) + (COSTEL) + (COSTLB) + (COSTMS)$$

where

COSTOM = Annual operation and maintenance cost, \$/yr.

A-7.10 Cost Calculation Output Data

A-7.10.1 Annual cost of fuel, COSTFU, \$/yr.

A-7.10.2 Annual cost of electrical energy, COSTEL, \$/yr.

A-7.10.3 Annual operation and maintenance labor cost, COSTLB, \$/yr.

A-7.10.4 Total base capital cost of wet oxidation facility, TBCC, \$.

A-7.10.5 Total annual operation and maintenance cost of wet oxidation facility, COSTOM, \$/yr.

APPENDIX A-8

CENTRIFUGE DEWATERING

A-8.1 Background

Centrifuge dewatering is a process in which centrifugal force is applied to promote the separation of solids from the liquid in a sludge. Dewatering is accomplished through clarification and solids compaction. Depending upon the physical properties of the sludge (particle size and density, temperature, and sludge age), the solids concentration in the dewatered cake varies from 10 to 25 percent.

The selection and design of a centrifuge is dependent on a number of factors determined through a pilot test program. Process variables include the feed flow rate, rotational speed of the centrifuge, differential speed of the scroll, depth of the settling zone, chemical use, and the physical properties of the sludge. Design parameters are established by individual equipment manufacturers, and include maximum operating speed, feed inlet, and conveyor and bowl type. Although there are numerous types of centrifuges available, only two have found prominence in dewatering sludges: the imperforate basket and the solid bowl conveyor.

The most common type of centrifuge used in wastewater sludge management is the solid bowl, also referred to as a scroll centrifuge. Solid bowl centrifuges are classified as either high g or low g; high-g centrifuges operate above 1,400 rpm, and low-g centrifuges operate at less than 1,400 rpm. In the solid bowl type, sludge is fed at a constant flow rate into a rotating bowl where it separates into a dense cake containing the solids, and a dilute centrate stream. Centrate is usually returned to the primary clarifier or sludge thickener.

Base capital costs in this algorithm include the purchase and installation of one or more low-g solid bowl centrifuges. The number of centrifuges required is based on sludge flow, according to the following matrix:

Sludge Flow (gal/min)	Number of Centrifuges
$\leq$ 500	1
> 500 but $\leq$ 1,000	2
> 1,000 but $\leq$ 1,500	3
> 1,500 but $\leq$ 2,000	4

In addition, base capital costs include the construction of a building of sufficient area to house the units and ancillary equipment; purchase and installation of pipe; and electrical instrumentation. O&M costs include labor, electrical energy, and materials.

A-8.1.1 Algorithm Development

The following algorithm is based on capital costs and O&M costs and requirements contained in Reference 6, pages 175 through 180; Reference 7, page A-195; and from information supplied by equipment manufacturers. Costs and O&M requirements synthesized from these references were fit to equations using a multiple regression program. Costs and requirements are presented as functions of sludge volume processed per minute.

A-8.2 Input Data

A-8.2.1 Daily sludge volume, SV, gal/day.

A-8.2.2 Hours per day process is operated, HPD, hr/day.

A-8.2.3 Days per year process is operated, DPY, days/yr.

A-8.3 Design Parameters

A-8.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user or the previous unit process. No default value.

A-8.3.2 Hours per day process is operated, hr/day. Default value = 8 hr/day.

A-8.3.3 Days per year process is operated, DPY, days/yr. Default value = 365 days/yr.

A-8.4 Process Design Calculations

A-8.4.1 Sludge volume in gal/min.

$$MSV = \frac{(SV)\ (365)}{(HPD)\ (DPY)\ (60)}$$

where

MSV = Sludge volume in gal/min.

A-8.5 Process Design Output Data

A-8.5.1 Sludge volume, MSV, gal/min.

A-8.6 Quantities Calculations

A-8.6.1 Annual operation and maintenance labor requirement.

A-8.6.1.1 If MSV < 70 gal/min, labor is calculated by:

$$L = 0.028\ (MSV)^2 + 0.265\ (MSV) + 744$$

A-8.6.1.2 If 70 $\leq$ MSV < 500 gal/min, labor is calculated by:

$$L = 1.75 \times 10^{-5}\ (MSV)^3 - 0.019\ (MSV)^2 + 8.205\ (MSV) + 426$$

A-8.6.1.3 If MSV $\geq$ 500 gal/min, labor is calculated by:

$$L = [-\ 2.10 \times 10^{-7}\ (MSV)^3 + 6.6 \times 10^{-4}\ (MSV)^2 + 0.035\ (MSV) + 1{,}686]$$

where

L = Annual operation and maintenance labor requirement, hr/yr.

A-8.6.2 Annual electrical energy requirement.

A-8.6.2.1 Process energy.

A-8.6.2.1.1 If MSV < 70 gal/min, process electrical energy is calculated by:

$$PE = [-\ 5.91\ (MSV)^2 + 2{,}695\ (MSV) + 500]$$

A-8.6.2.1.2 If 70 $\leq$ MSV < 500 gal/min, process electrical energy is calculated by:

$$PE = 6.671 \times 10^{-4}\ (MSV)^3 - 0.513\ (MSV)^2 + 2{,}041\ (MSV) + 24{,}253$$

A-8.6.2.1.3 If MSV $\geq$ 500 gal/min, process electrical energy is calculated by:

$$PE = 1.493 \times 10^{-3}\ (MSV)^3 - 5.313\ (MSV)^2 + 7{,}435\ (MSV) - 1{,}557{,}500$$

where

PE = Annual process electrical energy required, kWhr/yr.

A-8.6.2.2 Annual building energy.

A-8.6.2.2.1 If MSV < 70 gal/min, building electrical energy is calculated by:

$$BE = [- 14.015 (MSV)^2 + 1,867 (MSV) + 67,917]$$

A-8.6.2.2.2 If 70 $\leq$ MSV < 500 gal/min, building electrical energy is calculated by:

$$BE = 1.748 \times 10^{-3} (MSV)^3 - 1.797 (MSV)^2 + 675.6 (MSV) + 93,530$$

A-8.6.2.2.3 If MSV $\geq$ 500 gal/min, building electrical energy is calculated by:

$$BE = [- 1.110 \times 10^{-5} (MSV)^3 + 0.033 (MSV)^2 + 118.4 (MSV) + 139,140]$$

where

BE = Annual building electrical energy required, kWhr/yr.

A-8.6.2.3 Total annual electrical energy required.

$$E = PE + BE$$

where

E = Electrical energy required, kWhr/yr.

A-8.7 Quantities Calculations Output Data

A-8.7.1 Annual operation and maintenance labor requirement, L, hr/yr.

A-8.7.2 Annual electrical energy requirement, E, kWhr/yr.

A-8.8 Unit Price Input Required

A-8.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-8.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is made.

A-8.8.3 Unit cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-8.8.4 Unit cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-8.9 Cost Calculations

A-8.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-8.9.2 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-8.9.3 Annual cost of maintenance parts and materials.

$$COSTPM = [1.92 \times 10^{-5}\ (MSV)^3 - 0.0055\ (MSV)^2 + 13.053\ (MSV) + 2{,}113]\ \frac{MSECI}{751}$$

where

COSTPM = Annual cost of parts and materials, \$/yr.

A-8.9.4 Total base capital cost.

A-8.9.4.1 If MSV < 70 gal/min, total base capital cost is calculated by:

$$TBCC = [-\ 10.538\ (MSV)^2 + 3{,}023.6\ (MSV) + 161{,}390]\ \frac{MSECI}{751}$$

A-8.9.4.2 If 70 $\leq$ MSV < 500 gal/min, total base capital cost is calculated by:

$$TBCC = [-\ 9.4 \times 10^{-4}\ (MSV)^3 - 0.5\ (MSV)^2 + 1{,}653\ (MSV) + 217{,}840]\ \frac{MSECI}{751}$$

A-8.9.4.3 If MSV $\geq$ 500 gal/min, total base capital cost is calculated by:

$$TBCC = [6.8 \times 10^{-4} (MSV)^3 - 2.5 (MSV)^2 + 3,803 (MSV) - 520,470] \frac{MSECI}{751}$$

where

TBCC = Total base capital cost, $.

A-8.9.5 Total annual operation and maintenance cost.

$$COSTOM = (COSTEL) + (COSTLB) + (COSTPM)$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-8.10 Cost Calculations Output Data

A-8.10.1 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-8.10.2 Annual cost of electrical energy, COSTEL, $/yr.

A-8.10.3 Annual cost of parts and materials, COSTPM, $/yr.

A-8.10.4 Total base capital cost for centrifuge dewatering, TBCC, $.

A-8.10.5 Total annual operation maintenance cost for centrifuge dewatering, COSTOM, $/yr.

APPENDIX A-9

BELT FILTER DEWATERING

A-9.1 Background

Belt filters have become increasingly popular in the United States, often selected as the method for dewatering sludges at new treatment plants. This popularity is due to the high dewatering capabilities and low power requirements of the process.

Belt filters employ single or double moving belts made of woven synthetic fiber to dewater sludges continuously. The belts pass over and between rollers which exert increasing pressure on the sludge as it moves with the belts. Sludges are dewatered initially through the action of capillarity and gravity, and afterwards by increasing pressure and shear force over the length of the filtration zone. The dried cake is removed from the filter belt by a flexible scraper. A second scraper and sprayed water are used to clean the belt.

Sludge conditioning is important in this process in order to achieve optimal dewatering performance. Costs obtained in this algorithm do not include conditioning. Those costs may be obtained using the algorithms in Appendices A-13, A-14, and A-15.

Process design is based on solids and hydraulic loading. However, solids loading appears to be the more critical of the two. Belt filters are purchased from the manufacturer in standard belt widths. In this algorithm, single or multiple units of 0.5-, 1-, and 2-meter widths are considered. To estimate the width of a belt filter, the loading rate (lb sludge/meter/hr) is the key design parameter, as shown in the table below.

Influent Suspended Solids (%)	1-2	3-4	5-6
Loading Rate (dry solids lb/hr/meter of belt width)	400-600	600-800	800-900

Capital costs in this algorithm include purchase and installation of one or more belt press units and ancillary equipment, and a building to house belt presses with adequate room for safe operation and maintenance. Annual O&M costs include labor, electrical energy, and parts and materials.

A-9.1.1 Algorithm Development

This algorithm is based on design and cost information obtained from Reference 6, pages 181 through 183, and information supplied by equipment manufacturers. Costs and O&M requirements obtained were fit to equations using a multiple regression program.

A-9.2 Input Data

A-9.2.1 Daily sludge volume, SV, gal/day.

A-9.2.2 Sludge suspended solids concentration, SS, percent.

A-9.2.3 Sludge specific gravity, SSG, unitless.

A-9.2.4 Sludge dry solids loading rate per meter width of the belt press, BFLR, lb/meter/hr.

A-9.2.5 Hours per day process is operated, HPD, hr/day.

A-9.2.6 Days per year process is operated, DPY, days/yr.

A-9.3 Design Parameters

A-9.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-9.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value. Be sure to include SS added by conditioning chemicals.

A-9.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated as follows:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

A-9.3.4 Sludge dry solids. Loading rate per meter width of the belt press, BFLR, lb/hr. This value is a function of suspended solids in the feed sludge. Default values are 500 for 2 percent SS, 650 for 4 percent SS, and 800 for 6 percent SS.

A-9.3.5 Hours per day process is operated, HPD, hr/day. Default value = 8 hr/day.

A-9.3.6 Days per year process is operated, DPY, days/yr. Default value = 365.

A-9.4 Process Design Calculations

A-9.4.1 Calculate dry solids dewatered per day.

$$DSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{(100)}$$

where

DSS = Dry solids dewatered per day, lb/day.
8.34 = Density of water, lb/gal.

A-9.4.2 Calculate the total width of the belt filter needed to dewater the sludge at the specified loading rate. Costs are based on the use of one or more 0.5-, 1-, and 2-meter-wide unit belt filters. The total width required is sufficient to estimate the costs regardless of the number of units used.

$$TBFW = \left[\frac{(DSS)\ (365)}{(BFLR)\ (HPD)\ (DPY)}\right]$$

where

TBFW = Total belt filter width, meters.

A-9.5 Process Design Output Data

A-9.5.1 Dry suspended solids dewatered per day, DSS, lb/day.

A-9.5.2 Total belt filter width, TBFW, meters.

A-9.6 Quantities Calculations

A-9.6.1 Annual operation and maintenance labor required.

A-9.6.1.1 If TBFW $\leq$ 0.5 meters, labor is calculated by:

$$L = 1{,}773 \left[\frac{(TBFW)}{0.5}\right]$$

A-9.6.1.2 If TBFW > 0.5 meters, labor is calculated by:

$$L = [-\ 0.34\ (TBFW)^3 + 3{,}734\ (TBFW)^2 + 441.5\ (TBFW) + 619]$$

where

L = Annual operation and maintenance labor required, hr/yr.

A-9.6.2 Annual electrical energy required.

A-9.6.2.1 If TBFW $\leq$ 0.5 meters, electrical energy is calculated by:

$$E = 22{,}065 \left[\frac{(TBFW)}{0.5}\right]$$

A-9.6.2.2 If TBFW > 0.5 meters, electrical energy is calculated by:

$$E = [-\ 5.42\ (TBFW)^3 + 234.6\ (TBFW)^2 + 16{,}020\ (TBFW) + 13{,}997]$$

where

E = Annual electrical energy required, kWhr/yr.

A-9.7 Quantities Calculations Output Data

A-9.7.1 Annual operation and maintenance labor required, L, hr/yr.

A-9.7.2 Annual electrical energy required, E, kWhr/yr.

A-9.8 Unit Price Input Required

A-9.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-9.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is made.

A-9.8.3 Cost of operation and maintenance labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-9.8.4 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-9.9 Cost Calculations

A-9.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of labor, \$/yr.

A-9.9.2 Annual cost of electrical energy, \$/yr.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy.

A-9.9.3 Annual cost of parts and materials.

A-9.9.3.1 If TBFW $\leq$ 0.5 meters, annual cost of parts and materials is calculated by:

$$COSTPM = 1{,}784 \left[\frac{(TBFW)}{0.5}\right] \frac{MSECI}{751}$$

A-9.9.3.2 If TBFW > 0.5 meters, annual cost of parts and materials is calculated by:

$$COSTPM = [-\ 0.708\ (TBFW)^3 + 30.6\ (TBFW)^2 + 2{,}371\ (TBFW) + 1{,}184] \frac{MSECI}{751}$$

where

COSTPM = Annual cost of parts and materials, \$/yr.

A-9.9.4 Total base capital cost.

A-9.9.4.1 If TBFW $\leq$ 0.5 meters, total base capital cost is calculated by:

$$TBCC = [243{,}000] \frac{MSECI}{751}$$

A-9.9.4.2 If TBFW > 0.5 meters, total base capital cost is calculated by:

$$TBCC = [-\ 158.6\ (TBFW)^3 + 5{,}496\ (TBFW)^2 + 98{,}269\ (TBFW) + 192{,}630] \frac{MSECI}{751}$$

where

TBCC = Total base capital cost, \$.

A-9.9.5 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-9.10 Cost Calculations Output Data

A-9.10.1 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-9.10.2 Annual cost of electrical energy, COSTEL , \$/yr.

A-9.10.3 Annual cost of parts and materials, COSTPM, \$/yr.

A-9.10.4 Total base capital cost, TBCC, \$.

A-9.10.5 Total annual operation and maintenance cost, COSTOM, \$/yr.

APPENDIX A-10

RECESSED PLATE FILTER PRESS DEWATERING

A-10.1 Background

Recessed plate pressure filters consist of numerous parallel plates, recessed on both sides with a filter cloth hung over the face of each plate. The number of plates is determined by sludge volume and cycle time. The process, which operates in a batch mode, uses high pressures to force water from the sludge.

The process operates by pumping conditioned sludge into the void spaces between each plate where a sludge cake forms. Pressure within the chamber builds up to approximately 225 to 250 psi, and is maintained for a 1- to 4-hour period. Filtrate is collected in drainage ports and discharged to a common drain. As solids accumulate in the press, the head loss increases with a subsequent decrease in filtrate flow. The pressure cycle ends when the chambers are completely filled, and the filtrate flow approaches zero. The plates are then opened, and the filter cake drops onto conveyors or into hoppers for removal.

In this dewatering process, sludge conditioning is imperative. Costs for conditioning are not included in this algorithm. These costs may be obtained using the algorithms in Appendices A-13, A-14, and A-15.

Due to relatively high capital and O&M costs, this dewatering process is usually considered for sludge of poor dewaterability and/or where a final cake solids content over 30 percent is desired, as necessary. Filter presses are ideal for dewatering sludges in preparation for incineration. The cyclic operation may be a disadvantage at some treatment facilities. Several manufacturers have developed new designs which have minimized or virtually eliminated cyclical operation.

In this algorithm, filter presses with a minimum total chamber volume per unit of 10 cu ft and a maximum of 450 cu ft are assumed. The number of units required is based on total chamber volume according to the following table:

Total Chamber Volume, cu ft	Number of Units
$\leq$ 450	1
> 450 but $\leq$ 900	2
> 900 but $\leq$ 1,200	3
> 1,200 but $\leq$ 1,500	4

Capital costs in this algorithm include purchase and installation of filter press units; feed pumps, including one standby unit; and building for housing the units. Operation and maintenance costs include labor, electrical energy, and maintenance materials.

A-10.1.1 Algorithm Development

The following algorithm uses total chamber volume as the variable in estimating costs and O&M requirements. Base capital and O&M costs were derived from information contained in Reference 6, pages 187 through 189. Additional cost information was supplied by equipment manufacturers.

A-10.2 Input Data

A-10.2.1 Daily sludge volume, SV, gal/day.

A-10.2.2 Sludge suspended solids concentration, SS, percent.

A-10.2.3 Sludge specific gravity, SSG, unitless.

A-10.2.4 Hours per day process is operated, HPD, hr/day.

A-10.2.5 Days per year process is operated, DPY, days/yr.

A-10.2.6 Cake solids content, CSC, percent.

A-10.2.7 Filter cycle time, FCT, hr/cycle.

A-10.3 Design Parameters

A-10.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-10.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value. Be sure to include SS added by conditioning chemicals.

A-10.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated as follows:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-10.3.4 Hours per day process is operated, HPD, hr/day. Default value = 8 hr/day.

A-10.3.5 Days per year process is operated, DPY, days/yr. Default value = 365 days per year.

A-10.3.6 Cake solids content, CSC, percent. This input value should be provided by the user, if possible, including time for cleanup between cycles. The attainable cake suspended solids concentration is in the range of 30 to 50 percent. Default value = 40 percent.

A-10.3.7 Filter cycle time, FCT, hr/cycle. This input value should be provided by the user if possible. Range is 1 to 4 hr. If not available, default cycle times are as follows:

Percent Solids	FCT, hr/cycle
2	2.5
4	2.2
6	2.0

A-10.4 Process Design Calculations

A-10.4.1 Calculate the dry sludge solids dewatered per day.

$$DSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)}{(100)}$$

where

DSS = Dry sludge solids dewatered per day, lb/day.
8.34 = Density of water, lb/gal.

A-10.4.2 Calculate the cake volume.

$$CV = \frac{(DSS)\ (100)}{(CSC)\ (71)}$$

where

CV = Cake volume, ft^3/day.
71 = Assumed weight of filter cake, lb/ft^3.

A-10.4.3 Calculate the total chamber volume required, ft^3.

$$TCV = \frac{(CV)\ (FCT)}{(HPD)}$$

where

TCV = Total chamber volume required, ft^3.

A-10.5 Process Design Output Data

A-10.5.1 Total dry solids produced per day, DSS, lb/day.

A-10.5.2 Cake volume produced per day, CV, ft^3/day.

A-10.5.3 Total chamber volume required, TCV, ft^3.

A-10.6 Quantities Calculations

A-10.6.1 Annual operation and maintenance labor requirement.

A-10.6.1.1 If TCV $\leq$ 10 ft^3, labor requirement is calculated by:

$$L = \frac{(1,455)\ (TCV)}{(10)}$$

A-10.6.1.2 If 10 < TCV $\leq$ 450 ft^3, labor requirement is calculated by:

$$L = [-\ 2.07 \times 10^{-4}\ (TCV)^2 + 0.17\ (TCV) + 1,455]$$

A-10.6.1.3 If 450 < TCV $\leq$ 900 ft^3, labor requirement is calculated by:

$$L = 3.1\ (TCV - 900) + 2,884$$

A-10.6.1.4 If TCV > 900 ft^3, labor requirement is calculated by:

$$L = [-\ 6.7 \times 10^{-3}\ (TCV)^2 + 18.96\ (TCV) - 8,696]$$

where

L = Annual labor requirement, hr/yr.

A-10.6.2 Annual electrical energy requirement.

A-10.6.2.1 If TCV $\leq$ 10 ft^3, electrical energy requirement is calculated by:

$$E = 58,000\ \frac{(TCV)}{(10)}$$

A-10.6.2.2 If TCV > 10 ft^3, electrical energy requirement is calculated by:

$$E = [- 5.49 \times 10^{-6} (TCV)^3 + 9.83 \times 10^{-3} (TCV)^2 + 583.8 (TCV) + 50,956]$$

where

E = Annual electrical energy requirement, kWhr/yr.

A-10.7 Quantities Calculations Output Data

A-10.7.1 Annual operation and maintenance labor requirement, L, hr/yr.

A-10.7.2 Annual electrical energy requirement, E, kWhr/yr.

A-10.8 Unit Price Input Required

A-10.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-10.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is made.

A-10.8.3 Unit cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-10.8.4 Unit cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-10.9 Cost Calculations

A-10.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (L) (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-10.9.2 Annual cost of electrical energy.

$$COSTEL = (E) (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-10.9.3 Annual cost of maintenance parts and materials.

A-10.9.3.1 If TCV < 10 ft^3, cost of parts and materials is calculated by:

$$COSTPM = \left[\frac{(2,880)\ (TCV)}{(10)}\right] \frac{MSECI}{751}$$

A-10.9.3.2 If TCV $\geq$ 10 ft^3, cost of parts and materials is calculated by:

$$COSTPM = [-\ 1.63 \times 10^{-5}\ (TCV)^3 + 0.0358\ (TCV)^2 + 24.9\ (TCV) + 2,452]\ \frac{MSECI}{751}$$

where

COSTPM = Annual cost of maintenance parts and materials, \$/yr.

A-10.9.4 Total base capital cost.

A-10.9.4.1 If TCV < 10 ft^3, base capital cost is calculated by:

$$TBCC = (235,320)\ \frac{MSECI}{751}$$

A-10.9.4.2 If TCV $\geq$ 10 ft^3, base capital cost is calculated by:

$$TBCC = [-\ 8.632 \times 10^{-4}\ (TCV)^3 + 1.875\ (TCV)^2 + 1,997\ (TCV) + 204,815]\ \frac{MSECI}{751}$$

where

TBCC = Total base capital cost, \$.

A-10.9.5 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-10.10 Cost Calculations Output Data

A-10.10.1 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-10.10.2 Annual cost of electrical energy, COSTEL, \$/yr.

A-10.10.3 Annual cost of parts and materials, COSTPM, \$/yr.

A-10.10.4 Total base capital cost for recessed plate pressure filter dewatering, TBCC, \$.

A-10.10.5 Total annual operation and maintenance cost for recessed plate pressure filter dewatering, COSTOM, \$/yr.

APPENDIX A-11

VACUUM FILTER DEWATERING

A-11.1 Background

Vacuum filtration is a widely used method for mechanical dewatering of wastewater sludges, though it is seldom selected now for new treatment plants. Vacuum filtration is a continuous process consisting of a rotating drum which is radially divided into compartments. The outside of the drum is covered by a woven fabric or other filter medium, a portion (about 20 to 40 percent) of which is submerged in sludge contained in a vat below the drum. Vacuum (10 to 26 inches of mercury) is alternately applied to the submerged portion of the drum. As a result, water is drawn into the drum, and a cake forms on the filter medium. As the filter rotates, the vacuum is continued, and further moisture reduction occurs as air is drawn through the cake into the drum. Before the filter cake reaches the sludge vat again, the sludge cake is broken off by blades and/or rollers. The cake drops onto a conveyor and is removed for ultimate disposal.

Chemical conditioning with lime, ferric chloride, and/or organic polyelectrolytes is usually a necessary step prior to sludge vacuum filtration. Costs obtained in this algorithm do not include conditioning. These costs may be obtained using the algorithms in Appendices A-13, A-14, and A-15.

The design of vacuum filtration systems is based on the solids loading rate which is usually determined through laboratory testing. A conservative rate of 3.5 $lb/ft^2/hr$ has been widely used in process design. Actual operating loading rates typically vary between 2 and 10 $lb/ft^2/hr$. The low values represent filtration of fresh and digested activated sludge; the high values are typical for raw primary sludge or mixed primary sludge plus trickling filter humus. Cake solids typically range from 12 to 17 percent.

Vacuum filtration facilities are generally sold as a package by various filter manufacturers. The package normally includes vacuum pumps, sludge feed pumps, filtrate pumps, sludge conditioning tanks, chemical feed pumps, and belt conveyors that transport dewatered filter cake. Capital costs in this cost algorithm include purchase and installation of one or more vacuum filters, appurtenant equipment, and construction of a building to house the units. O&M costs include labor, electricity, and parts and materials.

A-11.1.1 Algorithm Development

Cost equations in the following algorithm were developed by accessing the existing CAPDET program. The CAPDET algorithm for vacuum filtration is found in Reference 1, pages 2.65-1 through 2.65-17. Values were obtained by varying sludge volume and suspended solids concentration entering the vacuum filter.

In some cases, CAPDET was found to overestimate costs and O&M requirements when compared with data in the literature. Therefore, costs and O&M requirements are based on information provided by a number of additional cost sources, namely, Reference 4, pages 9.27 through 9.45; and Reference 6, page 185. Costs and O&M requirements were fit to an equation using a multiple regression program.

A-11.2 Input Data

A-11.2.1 Daily sludge volume, SV, gal/day.

A-11.2.2 Sludge suspended solids, SS, percent.

A-11.2.3 Sludge specific gravity, SSG, unitless.

A-11.2.4 Sludge loading rate, SLR, $lb/ft^2/hr$.

A-11.2.5 Hours per day process is operated, HPD, hr/day.

A-11.2.6 Days per week process is operated, DPW, days/yr.

A-11.3 Design Parameters

A-11.3.1 Daily sludge volume, SV, gal/day. This value must be input by the user or the previous unit process. No default value. Be sure to include volume added by conditioning chemicals.

A-11.3.2 Sludge suspended solids, SS, percent. This value must be input by the user or the previous unit process. No default value. Be sure to include solids added by conditioning chemicals.

A-11.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated as follows:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)(100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-11.3.4 Sludge loading rate, SLR, $lb/ft^2/hr$. Default value = 5 $lb/ft^2/hr$.

A-11.3.5 Hours per day process is operated, HPD, hr/day. Default value = 8 hr/day.

A-11.3.6 Days per year process is operated, DPY, days/yr. Default value = 365 days/yr.

A-11.4 Process Design Calculations

A-11.4.1 Calculate total filter area.

$$TFA = \frac{(SV)\ (SS)\ (SSG)\ (8.34)\ (365)}{(100)\ (SLR)\ (HPD)\ (DPY)}$$

where

TFA = Total filter area, ft^2.
8.34 = Density of water, lb/gal.

A-11.4.2 Calculate dry solids produced.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)\ (365)}{(100)\ (2{,}000)\ (DPY)}$$

where

TDSS = Daily dry solids produced, tons/day.

A-11.5 Process Design Output Data

A-11.5.1 Required filter area, TFA, ft^2.

A-11.5.2 Daily dry solids produced, DSS, tons/day.

A-11.6 Quantities Calculations

A-11.6.1 Filter selection. Units must be one of the following sizes, which are commercially available: 60, 85, 100, 125, 150, 200, 250, 300, 360, 430, 500, 575, 675, 750 ft^2.

A-11.6.1.1 If the total filter area is less than 750 ft^2, only one filter will be used. The total filter area (TFA) should be compared to the commercially available units (CFA), and the smallest available unit which is larger than TFA should be selected.

A-11.6.1.2 If the total filter area is greater than 750 ft^2, a minimum of two filters will be used. Selection of the correct filter size must be done by trial and error. If TFA is greater than 750 ft^2, increase the number of filters by one and calculate the unit filter area (AF). If AF $\leq$ 750, the choice will be made as follows: Select the smallest standard size which is greater than AF; if (CFA x NF) is larger than TFA by more than 10 percent, increase the number of filters by 1 and repeat the procedure; if not, AF = CFA.

A-11.6.2 Calculate total surface area of selected commercially available vacuum filter(s).

$$CTFA = (CFA)\ (NF)$$

where

CTFA = Total surface area of selected commercially available vacuum filter(s), ft^2.

A-11.6.3 Calculate housing area required for filters.

$$AB = [-\ 5.9 \times 10^{-8}\ (CTFA)^3 - 2.3 \times 10^{-5}\ (CTFA)^2 + 1.69\ (CTFA) + 1,277]$$

where

AB = Area of the building, ft^2.

A-11.6.4 Annual operation labor requirement.

A-11.6.4.1 If $0.01 \leq TDSS \leq 0.09$ tons/day, operation labor is:

$$OL = 520$$

A-11.6.4.2 If $0.09 < TDSS \leq 9$ tons/day, operation labor is calculated by:

$$OL = 1,760\ (TDSS)^{0.504}$$

A-11.6.4.3 If $9 < TDSS \leq 300$ tons/day, operation labor is calculated by:

$$OL = 1,200\ (TDSS)^{0.734}$$

where

OL = Annual operation labor requirement, hr/yr.

A-11.6.5 Annual maintenance labor requirement.

A-11.6.5.1 If $0.01 \leq TDSS \leq 0.09$ tons/day, maintenance labor is:

$$ML = 64$$

A-11.6.5.2 If $0.09 < TDSS \leq 9$ tons/day, maintenance labor is calculated by:

$$ML = 240 (TDSS)^{0.548}$$

A-11.6.5.3 If $9 < TDSS \leq 300$ tons/day, maintenance labor is calculated by:

$$ML = 136 (TDSS)^{0.808}$$

where

ML = Annual maintenance labor requirement, hr/yr.

A-11.6.6 Installation labor requirement.

A-11.6.6.1 If CFA < 400 ft^2, installation labor is calculated by:

$$IL = [544 + 0.32 (CFA)] (NF)$$

A-11.6.6.2 If CFA $\geq$ 400 ft^2, installation labor is calculated by:

$$IL = [476 + 0.48 (CFA)] (NF)$$

where

IL = Installation labor requirement, hr.

A-11.6.7 Annual electrical energy requirement.

$$E = 28,000 (DSS)^{0.933}$$

where

E = Annual electrical energy requirement, kWhr/yr.

A-11.7 Quantities Calculations Output Data

A-11.7.1 Filter area of the commercial unit selected, CFA, ft^2.

A-11.7.2 Number of filters, NF, unitless.

A-11.7.3 Total surface area of selected commercially available vacuum filter, CTFA, ft^2.

A-11.7.4 Area of building, AB, ft^2.

A-11.7.5 Annual operation labor requirements, OL, hr/yr.

A-11.7.6 Maintenance labor requirement, ML, hr/yr.

A-11.7.7 Installation labor requirement, IL, hr.

A-11.7.8 Annual electrical energy requirement, E, kWhr/yr.

A-11.8 Unit Price Input Required

A-11.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-11.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-11.8.3 Cost of standard size 300 ft^2 vacuum filter, COSTSF, \$. Default value = \$200,000 (ENRCCI/4,006).

A-11.8.4 Cost of building, construction, COSBC, \$70/ft^2 (ENRCCI/4,006).

A-11.8.5 Cost of installation labor, COSTIN, \$/hr. Default value = \$18.00/hr (ENRCCI/4,006).

A-11.8.6 Cost of operation and maintenance labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-11.8.7 Cost of electricity, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-11.9 Cost Calculations

A-11.9.1 Cost factor, expressed as a percent of standard size filter.

$$COSTR = 52 + 0.16\ (CFA)$$

where

COSTR = Cost factor, expressed as a percent of standard size filter cost.

A-11.9.2 Cost of vacuum filter. This cost includes the cost of the vacuum filter, vacuum pump, filtrate pump, filtrate fork, sludge pump, conveyor belt, electric motors, and control panel.

$$COSTEQ = \frac{(COSTSF)\ (COSTR)\ (NF)}{(100)}$$

where

COSTEQ = Purchase cost of vacuum filter and accessories, $.

A-11.9.3 Cost of filter building.

$$COSTH = (AB)\ (COSTBC)$$

where

COSTH = Cost of building, $.

A-11.9.4 Filter installation cost.

$$ICOST = (IL)\ (COSTIN)$$

where

ICOST = Filter installation cost, $.

A-11.9.5 Other equipment installation costs. This includes costs for installation of vacuum pump, filtrate pump, filtrate tank, sludge tank, sludge pump, conveyor belt, electrical panel, and piping.

$$OICOST = (0.60)\ (COSTEQ)$$

where

OICOST = Other equipment installation costs, $.

A-11.9.6 Annual cost of operation and maintenance labor.

$$COSTLB = (OL + ML)\ (COSTL)$$

where

COSTLB = Total cost of labor for operation and maintenance, $/yr.

A-11.9.7 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-11.9.8 Annual cost of parts and materials.

$$COSTPM = (COSTEQ + ICOST + OICOST)\ (0.15)$$

where

COSTPM = Annual cost of parts and materials, \$/yr.

A-11.9.9 Total base capital cost.

$$TBCC = COSTEQ + COSTH + ICOST + OICOST$$

where

TBCC = Total base capital cost.

A-11.9.10 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-11.10 Cost Calculations Output Data

A-11.10.1 Purchase cost of vacuum filter and accessories, COSTEQ, \$.

A-11.10.2 Cost of building, COSTH, \$.

A-11.10.3 Filter installation cost, ICOST, \$.

A-11.10.4 Other equipment installation costs, OICOST, \$.

A-11.10.5 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-11.10.6 Annual cost of electrical energy, COSTEL, \$/yr.

A-11.10.7 Annual cost of parts and materials, COSTPM, \$/yr.

A-11.10.8 Total base capital cost, TBCC, \$.

A-11.10.9 Annual cost of operation and maintenance, COSTOM, \$/yr.

APPENDIX A-12

SLUDGE DRYING BED DEWATERING

A-12.1 Background

Sludge drying beds are commonly used at small treatment plants, since they require less frequent operator attention, use little energy, are less sensitive to influent solids concentration, and produce a drier sludge than mechanical devices. The limitations of this process are that it requires a large land area, requires stabilized sludge to prevent nuisance odors, is sensitive to climate, and is more labor-intensive than mechanical dewatering. As a consequence of the frequent downtime and high capital and operating costs of mechanical systems, however, drying bed dewatering has become a viable option at medium and large facilities where adequate land is available. Moreover, design improvements such as the use of chemical conditioning and mechanical sludge removal have made sludge drying bed dewatering more attractive.

Although there are many types of drying beds (paved, wedge-wire, and vacuum-assisted), sand drying beds are the most common. In this process, sludge is dewatered in an open or covered bed primarily through drainage and evaporation. Water drains through the sludge into sand where it is removed through underdrains. Additional sludge drying is accomplished through evaporation; therefore, drying time is affected by climate. Areas of high rainfall and/or high humidity may have a detrimental effect on drying. Natural freezing of sludges in northern climates has been reported to improve dewaterability.

Once the sludge has achieved the required dryness, it is manually or mechanically removed using front-end loaders or truck-mounted vacuum removal systems. Periodically, sand must be replaced and graded.

Chemically conditioned sludges offset unpredictable weather conditions and variable sludge characteristics. In addition, chemical conditioning improves the drying capabilities of many sludges. Costs for conditioning are not included in this algorithm. These costs may be obtained using the algorithms in Appendices A-13, A-14, and A-15.

Drying beds were traditionally designed using per capita area criteria for sizing. Values ranged from 1.0 to 3.0 ft^2 per capita, depending on the type and solids content of the applied sludge. The currently accepted criterion for sizing drying beds is the solids loading rate. Typical requirements vary from 10 to 40 lb dry solids/ft^2/yr. In the United States, local regulatory agencies have established guidelines or standards for the minimum area of sludge drying bed required as a function of dry sludge solids applied per year (e.g., 20 lb of dry solids/ft^2/yr).

The following algorithm is based on construction of uncovered sand drying beds, using the following assumptions:

- Depth of gravel = 9 inches.
- Depth of sand = 9 inches.
- Height of concrete dividing walls = 2 ft.
- Diesel fuel consumption of front-end loader = 4 gal/hr.
- Annual sludge removal frequency = 20 times/yr.
- Sludge removal and bed preparation time = 3 hr/4,000 ft^2.

Capital costs include purchase of land, excavation and site work, installation of drain pipe and valves, construction of steel reinforced concrete dividing walls, and purchase of one or more front-end loaders. O&M costs include labor, diesel fuel, periodic replacement of sand, and replacement parts and materials.

A-12.1.1 Algorithm Development

Costs and O&M requirements in this algorithm were based on design experience and information obtained from various references. Capital costs were obtained from Reference 6, page 193, and Reference 7, page A-197. Labor, diesel, and maintenance material requirements were estimated from information in Reference 6, pages 194 and 195.

A-12.2 Input Data

A-12.2.1 Daily sludge volume, SV, gal/day.

A-12.2.2 Sludge suspended solids concentration, SS, percent.

A-12.2.3 Sludge specific gravity, SSG, unitless.

A-12.2.4 Sludge drying bed loading, DBA, lb dry solids/ft^2/yr.

A-12.3 Design Parameters

A-12.3.1 Daily sludge volume, SV, gal/day. This value must be input by the user. No default value.

A-12.3.2 Sludge suspended solids concentration, SS, percent. This value must be input by the user. No default value.

A-12.3.3 Sludge specific gravity, SSG, unitless. Default value is calculated using the following equation:

$$SSG = \frac{1}{\frac{(100) - (SS)}{100} + \frac{(SS)}{(1.42)(100)}}$$

where

SSG = Specific gravity of sludge, unitless.
1.42 = Specific gravity of sludge solids, unitless.

A-12.3.4 Sludge drying bed area, DBA, lb dry solids/ft^2/yr. This value should be input by the user, if possible, from state regulatory requirements. Most states have requirements. Default values are:

If SS = 2 percent, DBA = 15 lb dry solids/ft^2/yr.
If SS = 4 percent, DBA = 22 lb dry solids/ft^2/yr.
If SS = 6 percent, DBA = 28 lb dry solids/ft^2/yr.
If SS = 8 percent, DBA = 33 lb dry solids/ft^2/yr.

A-12.4 Process Design Calculations

A-12.4.1 Calculate dry sludge solids dewatered per year.

$$DSS = \frac{(SV)\ (365)\ (8.34)\ (SS)\ (SSG)}{(100)}$$

where

DSS = Dry sludge solids dewatered, lb/yr.
8.34 = Density of water, lb/gal.

A-12.4.2 Calculate area of sludge drying beds required.

$$A = \frac{(DSS)}{(DBA)\ (1,000)}$$

where

A = Area of sludge drying beds required in 1,000 ft^2.

A-12.5 Process Design Output Data

A-12.5.1 Dry sludge solids dewatered, DSS, lb/yr.

A-12.5.2 Area of sludge drying beds required, A, 1,000 ft^2.

A-12.6 Quantities Calculations

A-12.6.1 Calculate total land area required.

$$TLA = \frac{(1.5)\ (A)}{43.56}$$

where

TLA = Total land area required, acres.

1.5 = Factor to account for additional area required for buffer and equipment storage.

43.56 = Factor to convert 1,000 ft^2 to acres.

A-12.6.2 Calculate annual operation and maintenance labor requirement.

$$L = 6.87 \times 10^{-6} (A)^3 - 6.45 \times 10^{-3} (A)^2 + 15.3 (A) + 18$$

where

L = Annual operation and maintenance labor requirement, hr/yr.

A-12.6.3 Calculate annual diesel fuel requirement.

$$FU = 1.48 \times 10^{-5} (A)^3 - 0.018 (A)^2 + 52 (A) + 15$$

where

FU = Annual diesel fuel requirement, gal/yr.

A-12.7 Quantities Calculations Output Data

A-12.7.1 Total land area required, TLA, acres.

A-12.7.2 Annual operation and maintenance labor requirement, L, hr/yr.

A-12.7.3 Annual diesel fuel requirement, FU, gal/yr.

A-12.8 Unit Price Input Required

A-12.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-12.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is made.

A-12.8.3 Unit cost of land required, LANDCST, \$/acre. Default value = \$3,000/acre.

A-12.8.4 Unit cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-12.8.5 Unit cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-12.9 Cost Calculations

A-12.9.1 Cost of land for sludge drying bed site.

$$COSTLAND = (TLA) (LANDCST)$$

where

COSTLAND = Cost of land for sludge drying bed site, \$.

A-12.9.2 Construction cost of sludge drying beds.

$$COSTSDB = [1.52 \times 10^{-4} (A)^3 - 1.157 (A)^2 + 3{,}425 (A) + 27{,}742] \frac{ENRCCI}{4{,}006}$$

where

COSTSDB = Construction cost of sludge drying beds, \$.

A-12.9.3 Annual cost of operation and maintenance labor.

$$COSTLB = (L) (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-12.9.4 Annual cost of diesel fuel.

$$COSTDSL = (FU) (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, \$/yr.

A-12.9.5 Annual cost of maintenance parts and materials.

$$COSTPM = [- 1.61 \times 10^{-6} (A)^3 + 0.00297 (A)^2 + 32 (A) + 196] \frac{MSECI}{751}$$

where

COSTPM = Annual cost of maintenance parts and materials, \$/yr.

A-12.9.6 Total base capital cost.

$$TBCC = COSTLAND + COSTSDB$$

where

TBCC = Total base capital cost, \$.

A-12.9.7 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTDSL + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-12.10 Cost Calculations Output Data

A-12.10.1 Cost of land for sludge drying bed site, COSTLAND, \$.

A-12.10.2 Construction cost of sludge drying beds, COSTSDB.

A-12.10.3 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-12.10.4 Annual cost of diesel fuel, COSTDSL, \$/yr.

A-12.10.5 Annual cost of maintenance parts and materials, COSTPM, \$/yr.

A-12.10.6 Total base capital cost of sludge drying beds, TBCC, \$.

A-12.10.7 Total annual operation and maintenance cost of sludge drying beds, COSTOM, \$/yr.

APPENDIX A-13

CHEMICAL CONDITIONING WITH LIME

A-13.1 Background

Conditioning is defined as the pretreatment of sludge to facilitate the removal of water in subsequent treatment processes. Lime may be added to sludge to improve the effectiveness of dewatering processes. Lime is often used in conjunction with other chemicals (e.g., ferric chloride) for conditioning sludge. Note that lime conditioning is <u>not</u> equivalent to lime stabilization, a process covered in Appendix A-6. Lime enhances dewatering through the flocculation of calcium carbonate ($CaCO_3$) which provides a granular structure, thereby increasing sludge porosity and reducing sludge compressibility.

Two forms of lime are commercially available: (1) quicklime (CaO) and (2) hydrated lime ($Ca(OH)_2$). Quicklime is less expensive, but must be converted to hydrated lime on site by a process called slaking, in a lime slaking unit. Hydrated lime can be mixed with water and applied directly. Generally, larger sewage treatment plants purchase quicklime, and smaller sewage treatment plants use hydrated lime. For a specific plant, a detailed economic analysis is necessary which takes into account plant size, chemical requirements, chemical costs, and labor and maintenance requirements. In this cost algorithm, the use of hydrated lime is assumed in developing the cost default values. This assumption should produce adequate cost estimates for small and medium size plants (those using up to 5 tons of lime/day), but may result in overestimating O&M costs for larger plants.

The lime chemical conditioning process in this cost algorithm includes dry lime storage (30 days), a dry lime feeding system (belt gravimetric or volumetric), a lime-water solution mixing tank, solution feed pump, a building (or room) to house the equipment, and appurtenant piping and controls. The base capital cost derived from this algorithm is intended to include the total chemical feed system. Base annual O&M costs include labor, lime, and parts and materials. The cost of electrical energy is not included, since it is insignificant when compared with other O&M costs.

A-13.1.1 Algorithm Development

The algorithm on the following pages is based on equations used in the CAPDET program (1), pages 2.11-10 through 2.11-12, and on other references for lime conditioning. Information presented in Reference 4, pages 8-6 and 8-7, Reference 8, pages 15 through 19, and Reference 9, pages 5 through 8, form the basis for dosage equations. The cost of lime was obtained from chemical suppliers.

Costs and requirements obtained through the use of CAPDET and other references were fit to equations using a multiple regression program. Capital costs and O&M requirements are expressed as functions of lime feed capacity.

A-13.2 Input Data

A-13.2.1 Daily sludge volume, SV, gal/day.

A-13.2.2 Sludge suspended solids, SS, percent.

A-13.2.3 Sludge specific gravity, SSG, unitless.

A-13.2.4 Lime dosage as a fraction of dry sludge solids mass, LD, lb of $Ca(OH)_2$/ton of dry sludge solids.

A-13.2.5 Hours per day process is operated, HPD, hr/day.

A-13.2.6 Days per year process is operated, DPY, days/yr.

A-13.3 Design Parameters

A-13.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-13.3.2 Sludge suspended solids, SS, percent. This input value must be provided by the user. No default value.

A-13.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated as follows:

$$SSG = \frac{1}{\frac{100-SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

A-13.3.4 Lime dosage as a fraction of dry sludge solids mass, LD, lb of $Ca(OH)_2$/ton of dry sludge solids. This input value must be provided by the user. Lime dosage varies depending on the sludge characteristics, the use of other conditioning chemicals, and the type of sludge dewatering unit for which the sludge is being conditioned. The table below provides typical ranges of lime dosages for several types of sludges.

Sludge Type	Pounds of Lime Added Per Ton of Dry Sludge Solids
Raw Primary Plus Waste Biological	110 to 300
Digested Primary Plus Waste Biological	160 to 370

A-13.3.5 Hours per day process is operated, HPD, hr/day. Default value = 8 hr/day.

A-13.3.6 Days per year process is operated, DPY, days/yr. Default value = 365 days/yr.

A-13.4 Process Design Calculations

A-13.4.1 Calculate dry solids conditioned per day.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)\ (365)}{(100)\ (2,000)\ (DPY)}$$

where

TDSS = Dry solids conditioned per day, tons/day.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.

A-13.4.2 Calculate the daily lime requirement.

$$DLR = (LD)\ (TDSS)$$

where

DLR = Daily lime requirement, lb/day.

A-13.4.3 Calculate the design capacity of lime feed system.

$$LUR = \frac{(DLR)\ (24)}{(HPD)}$$

where

LUR = Design capacity of lime feed system, lb/day.

A-13.4.4 Calculate the capacity of the liquid diluted lime solution feed system, LCSF, gal/day. It is assumed that the lime solution contains 0.5 lb of $Ca(OH)_2$ per gallon.

$$LCSF = \frac{(LUR)}{(0.5)}$$

where

LCSF = Capacity of the liquid solution feed system, gal/day.

A-13.5 Process Design Output Data

A-13.5.1 Dry solids conditioned per day, TDSS, tons/day.

A-13.5.2 Daily lime requirement, DLR, lb/day.

A-13.5.3 Design capacity of lime feed system, LUR, lb/day.

A-13.5.4 Capacity of diluted lime solution feed system, LCSF, gal/day.

A-13.6 Quantities Calculations

A-13.6.1 Calculate annual labor requirement.

A-13.6.1.1 If LCSF < 90 gal/day, labor is calculated by:

$$L = 600 + 92.5\ (LCSF)^{0.2827}$$

A-13.6.1.2 If 90 $\leq$ LCSF < 35 gal/day, labor is calculated by:

$$L = 189.2\ (LCSF)^{0.2565} + 92.5\ (LCSF)^{0.2827}$$

A-13.6.1.3 If 350 $\leq$ LCSF < 1,050 gal/day, labor is calculated by:

$$L = 33.4\ (LCSF)^{0.5527} + 92.5\ (LCSF)^{0.2827}$$

A-13.6.1.4 If 1,050 $\leq$ LCSF < 10,000 gal/day, labor is calculated by:

$$L = 51.8\ (LCSF)^{0.4894} + 92.5\ (LCSF)^{0.2827}$$

A-13.6.1.5 If 10,000 $\leq$ LCSF gal/day, labor is calculated by:

$$L = 12.2\ (LCSF)^{0.647} + 92.5\ (LCSF)^{0.2827}$$

where

L = Annual labor requirement, hr/yr.

A-13.6.2 Electrical energy requirement for this system is insignificant.

A-13.6.3 Annual operation maintenance and material and supply cost factor. It is assumed that the annual O&M material and supply cost is 2 percent of the lime system construction cost.

$$OMMP = 0.02$$

where

OMMP = O&M material and supply cost factor expressed as a fraction of the lime system construction cost.

A-13.7 Quantities Calculations Output Data

A-13.7.1 Annual labor requirement, L, hr/yr.

A-13.7.2 O&M material and supply cost factor, OMMP, expressed as a fraction of the lime system capital cost.

A-13.8 Unit Price Input Required

A-13.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-13.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-13.8.3 Cost of lime, LMCST, \$/lb. Default value = \$0.05/lb (ENRCCI/4,006).

A-13.8.4 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-13.9 Cost Calculations

A-13.9.1 Capital cost of lime storage and feed system.

A-13.9.1.1 If LUR < 750 lb/day, lime system cost is calculated by:

$$CCLIME = (30{,}000)\ \frac{MSECI}{751}$$

A-13.9.1.2 If LUR $\geq$ 750 lb/day, lime system cost is calculated by:

$$CCLIME = (376)\ (LUR)^{0.6614}\ \frac{MSECI}{751}$$

where

CCLIME = Capital cost of lime storage and feed system, \$.

A-13.9.2 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-13.9.3 Annual cost of lime.

$$COSTLM = (DLR)\ (365)\ (LMCST)$$

where

COSTLM = Annual cost of lime, \$/yr.

A-13.9.4 Annual maintenance parts and material cost.

$$COSTMP = (OMMP)\ (CCLIME)$$

where

COSTMP = Annual material and supply cost, \$/yr.

A-13.9.5 Total base capital cost.

$$TBCC = CCLIME$$

where

TBCC = Total base capital cost, \$.

A-13.9.6 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTLM + COSTMP$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-13.10 Cost Calculations Output Data

A-13.10.1 Capital cost of lime storage and feed system, CCLIME, \$.

A-13.10.2 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-13.10.3 Annual cost of lime, COSTLM, \$/yr.

A-13.10.4 Annual maintenance parts and material cost, COSTMP, \$/yr.

A-13.10.5 Total base capital cost of lime conditioning, TBCC, \$.

A-13.10.6 Total annual operation and maintenance cost of lime conditioning, COSTOM, \$/yr.

APPENDIX A-14

CHEMICAL CONDITIONING WITH FERRIC CHLORIDE

A-14.1 Background

Ferric chloride may be added to sludge to improve the effectiveness of dewatering and thickening. Ferric chloride may be used alone or in conjunction with lime. Ferric chloride enhances the dewaterability of sludges through the precipitation of ferric hydroxide which enhances floc formation. In addition, the ferric hydroxide neutralizes negatively charged solids, which decreases hydrostatic repulsion and causes aggregation.

Ferric chloride is available in liquid (35 to 45 percent $FeCl_3$) or dry (crystals) forms. Liquid ferric chloride is a corrosive dark brown oily appearing solution with a weight of 11.2 to 12.4 lb/gal. Liquid form iron salts can be shipped in 3,000- to 4,000-gal bulk truckload lots, in 4,000- to 10,000-gal bulk carload lots, and 5- to 13-gal carboys. Storage tanks must be lined with corrosion-resistant material.

Dry ferric chloride is available in 18- to 40-gal steel drums. Once the drums are opened, the contents should be mixed with water and stored in solution. Heat-resistant mixing tanks must be used due to the heat generated when ferric chloride is mixed with water.

A typical ferric chloride feed system includes a storage tank for the liquid ferric chloride (e.g., 30-day storage), a mixing tank to accurately combine ferric chloride and water, a metering pump to add accurate dosages of ferric chloride to the sludge flow, a building (or room) to house equipment, and appurtenant piping and controls. The base capital cost derived from this algorithm is intended to include the total chemical feed system. Base annual O&M costs include labor, lime, and replacement parts and materials.

A-14.1.1 Algorithm Development

The algorithm on the following pages is based on equations used in the CAPDET program (1), pages 2.11-7 through 2.11-9, and from information obtained from Reference 4, pages 8-6 and 8-7; and Reference 8, pages 15 through 19. The cost of ferric chloride was quoted by chemical suppliers.

Capital costs and O&M requirements were fit to equations using a multiple regression program. Equations were developed as functions of the chemical feed capacity.

A-14.2 Input Data

A-14.2.1 Daily sludge volume, SV, gal/day.

A-14.2.2 Sludge suspended solids, SS, percent.

A-14.2.3 Sludge specific gravity, SSG, unitless.

A-14.2.4 Hours per day process is operated, HPD, hr/day.

A-14.2.5 Days per year process is operated, DPY, days/yr.

A-14.2.6 Ferric chloride dosage as a fraction of dry sludge solids mass, FCD, lb of $FeCl_3$/tons of dry sludge solids.

A-14.3 Design Parameters

A-14.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-14.3.2 Sludge suspended solids, SS, percent. This input value must be provided by the user. No default value.

A-14.3.3 Sludge specific gravity, SSG, unitless. Default value is calculated by the following equation:

$$SSG = \frac{1}{\frac{100-SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.

A-14.3.4 Hours per day process is operated, HPD, hr/day. Default value = 8 hr/day.

A-14.3.5 Days per year process is operated, DPY, days/yr. Default value = 365 days/yr.

A-14.3.6 Ferric chloride dosage as a fraction of dry sludge solids mass, FCD, lb of $FeCl_3$/ton of dry sludge solids. This input value must be provided by the user. No default value. Ferric chloride dosages vary depending on the sludge characteristics, the use of other chemical conditioning chemicals, and the type of sludge dewatering or thickening unit for which the sludge is being conditioned. Dosages are usually obtained through extensive laboratory and/or pilot plant testing. The table below provides typical ranges of ferric chloride dosages for several types of sludges.

Sludge Type	Pounds of Ferric Chloride Added Per Ton of Dry Sludge Solids
Raw Primary	40 to 120
Waste Activated	120 to 200
Anaerobically Digested, Combined	60 to 200

A-14.4 Process Design Calculations

A-14.4.1 Calculate dry solids conditioned per day.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)\ (365)}{(2{,}000)\ (100)\ (DPY)}$$

where

TDSS = Dry solids conditioned per day, tons/day.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.

A-14.4.2 Calculate the daily ferric chloride requirement.

$$DFCR = (FCD)\ (TDSS)$$

where

DFCR = Daily ferric chloride requirement, lb/day.

A-14.4.3 Calculate system design capacity expressed as equivalent iron molecules, accounting for hours per day the system is operated.

$$ISUR = \frac{(DFCR)\ (55.8)\ (24)}{(162)\ (HPD)}$$

where

ISUR = System design capacity, lb iron/day.
55.8 = Molecular weight of iron, g/mole.
162 = Molecular weight of ferric chloride, g/mole.

A-14.4.4 Calculate the capacity of the liquid chemical solution feed system. It is assumed that liquid $FeCl_3$ contains 4.11 lb of iron per gallon.

$$LCSF = \frac{(ISUR)}{(4.11)}$$

where

LCSF = Capacity of the liquid chemical solution feed system, gal/day.

A-14.5 Process Design Output Data

A-14.5.1 Dry solids conditioned per day, TDSS, tons/day.

A-14.5.2 Sludge specific gravity, SSG, unitless.

A-14.5.3 Daily ferric chloride requirement, DFCR, lb/day.

A-14.5.4 System design capacity, ISUR, lb iron/day.

A-14.5.5 Design capacity of the ferric chloride feed system, LCSF, gal/day.

A-14.6 Quantities Calculations

A-14.6.1 Calculate annual operation and maintenance labor requirement.

A-14.6.1.1 If LCSF < 90 gal/day, labor requirement is:

$$L = 600$$

A-14.6.1.2 If 90 $\leq$ LCSF < 350 gal/day, labor requirement is calculated by:

$$L = 189.2\ (LCSF)^{0.2565}$$

A-14.6.1.3 If 350 $\leq$ LCSF < 1,050 gal/day, labor requirement is calculated by:

$$L = 33.4\ (LCSF)^{0.5527}$$

A-14.6.1.4 If 1,050 $\geq$ LCSF $\leq$ 10,000 gal/day, labor requirement is calculated by:

$$L = 51.8\ (LCSF)^{0.4894}$$

A-14.6.1.5 If LCSF $\geq$ 10,000 gal/day, labor requirement is calculated by:

$$L = 12.2\ (LCSF)^{0.647}$$

where

L = Annual operation and maintenance labor requirement, hr/yr.

A-14.6.2 Electrical energy requirement for this system is insignificant.

A-14.6.3 Calculate operation and maintenance material supply cost factor. This cost factor is expressed as a percentage of the ferric chloride system capital cost.

$$OMMP = 0.02$$

where

OMMP = O&M material and supply cost factor expressed as a fraction of the ferric chloride system capital cost.

A-14.7 Quantities Calculations Output Data

A-14.7.1 Annual labor requirement, L, hr/yr.

A-14.7.2 Annual O&M material and supply cost factor, OMMP, fraction of system capital cost.

A-14.8 Unit Price Input Required

A-14.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-14.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-14.8.3 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-14.8.4 Cost of ferric chloride, FCCST, \$/lb. Default value = 0.475 \$/lb (ENRCCI/4,006).

A-14.9 Cost Calculations

A-14.9.1 Capital cost of iron salt storage and feed system.

A-14.9.1.1 If ISUR < 1,000 lb/day, ferric chloride system cost is calculated by:

$$CCFC = (67,850)\ \frac{MSECI}{751}$$

A-14.9.1.2 If 1,000 $\leq$ ISUR < 4,000 lb/day, ferric chloride cost is calculated by:

$$CCFC = (3,855)\ (ISUR)^{0.4152}\ \frac{MSECI}{751}$$

A-14.9.1.3 If 4,000 $\leq$ ISUR < 10,000 lb/day, ferric chloride system cost is calculated by:

$$CCFC = (100)\ (ISUR)^{0.8857}\ \frac{MSECI}{751}$$

A-14.9.1.4 If ISUR $\geq$ 10,000 lb/day, ferric chloride system cost is calculated by:

$$CCFC = (0.458)\ (ISUR)^{1.425}\ \frac{MSECI}{751}$$

where

CCFC = Capital cost of ferric chloride feed system, \$.

A-14.9.2 Annual cost of ferric chloride.

$$COSTFC = (DFCR)\ (DPY)\ (FCSST)$$

where

COSTFC = Annual cost of ferric chloride, \$/yr.

A-14.9.3 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual operation and maintenance labor cost, \$/yr.

A-14.9.4 Annual maintenance parts and material cost.

$$COSTMP = (OMMP)\ (CCFC)$$

where

COSTMP = Annual maintenance parts and material cost, \$/yr.

A-14.9.5 Total base capital cost.

$$TBCC = CCFC$$

where

TBCC = Total base capital cost, $.

A-14.9.6 Total annual operation and maintenance cost.

$$COSTOM = COSTFC + COSTLB + COSTMP$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-14.10 Cost Calculations Output Data

A-14.10.1 Capital cost of iron salt storage and feed system, CCFC, $.

A-14.10.2 Annual cost of ferric chloride, COSTFC.

A-14.10.3 Annual operation and maintenance labor cost, COSTLB, $/yr.

A-14.10.4 Annual maintenance parts and material cost, COSTMP, $/yr.

A-14.10.5 Total base capital cost, TBCC, $.

A-14.10.6 Total annual operation and maintenance cost, COSTOM, $/yr.

APPENDIX A-15

CHEMICAL CONDITIONING WITH POLYMERS

A-15.1 Background

Polymers may be added to sludge to improve the effectiveness of dewatering units and thickening units. Polymers may be used alone or in conjunction with other conditioning chemicals (e.g., ferric chloride). Polymers enhance particle destabilization through interparticle bridging, charge neutralization, and dehydration.

There are many types of polymers available for sludge conditioning. It is common to experiment with different types and dosages to determine the most cost-effective polymer for a specific sludge conditioning requirement.

The polymer feed system in this algorithm includes a storage tank for the polymer (e.g., 30-day storage), a mixing tank to accurately combine polymer and water, a metering pump which is controlled by sludge volume to add accurate dosages of polymer to the sludge flow, a building (or room) to house equipment, and appurtenant piping and controls. The capital cost derived from this algorithm is intended to include the total chemical feed system. O&M costs include the purchase of polymer, labor, and maintenance parts and materials. Due to their relative low costs compared with other O&M components, electrical energy costs are not included.

A-15.1.1 Algorithm Development

The algorithm on the following pages is based on values obtained using the CAPDET program (1), pages 2.11-13 through 2.11-15. Polymer dosage requirement equations are based on information presented in Reference 4, page 8-21, and Reference 8, pages 15 through 19. An average polymer cost for sludge conditioning was provided by chemical suppliers.

Costs and requirements obtained from CAPDET and other references were fit to equations using a multiple regression program. Capital costs and O&M requirements are based on polymer feed capacity.

A-15.2 Input Data

A-15.2.1 Daily sludge volume, SV, gal/day.

A-15.2.2 Sludge suspended solids, SS, percent.

A-15.2.3 Sludge specific gravity, SSG, unitless.

A-15.2.4 Polymer dosage as a fraction of dry sludge solids mass, PD, lb of polymer/ton of dry sludge solids.

A-15.2.5 Hours per day process is operated, HPD, hr/day.

A-15.2.6 Days per year process is operated, DPY, days/yr.

A-15.3 Design Parameters

A-15.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-15.3.2 Sludge suspended solids, SS, percent. This input value must be provided by the user. No default value.

A-15.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated as follows:

$$SSG = \frac{1}{\frac{100-SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-15.3.4 Polymer dosage as a fraction of dry sludge solids mass, PD, lb of polymer/ton of dry sludge solids. This input value must be provided by the user. Polymer dosages vary depending on the sludge characteristics, the use of other chemical conditioning chemicals, and the type of sludge dewatering or thickening unit for which the sludge is being conditioned. The table below provides typical ranges of polymer dosages for several types of sludges.

Sludge Type	Pounds of Polymer Added Per Ton of Dry Sludge Solids
Raw Primary	0.5 to 1.0
Waste Activated	8 to 15
Anaerobically Digested, Combined	5 to 12

A-15.3.5 Hours per day process is operated, HPD, hr/day. Default value = 8 hr/day.

A-15.3.6 Days per year process is operated, DPY, days/yr. Default value = 365 days/yr.

A-15.4 Process Design Calculations

The costing for this process is parametric and determined by the daily polymer requirement.

A-15.4.1 Calculate dry solids conditioned per day.

$$TDSS = \frac{(SV)\ (SS)\ (SSG)\ (8.34)\ (365)}{(100)\ (2{,}000)\ (DPY)}$$

where

TDSS = Dry solids conditioned per day, tons/day.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.

A-15.4.2 Calculate the daily polymer requirement.

$$DPR = (PD)\ (TDSS)$$

where
DPR = Daily polymer requirement, lb/day.

A-15.4.3 Calculate the design capacity of the polymer feed system.

$$PUR = \frac{(DPR)\ (24)}{(HPD)}$$

where

PUR = Design capacity of polymer feed system, lb/day.

A-15.4.4 Calculate the capacity of the liquid diluted polymer solution feed system. It is assumed that the solution of polymer has a concentration of 0.25 percent polymer.

$$LCSF = \frac{(PUR)\ (100)}{(0.25)\ (8.34)}$$

where

LCSF = Capacity of the liquid solution feed system, gal/day.
8.34 = Density of water, lb/gal.

A-15.5 Process Design Output Data

A-15.5.1 Dry solids conditioned per day, TDSS, tons/day.

A-15.5.2 Daily polymer requirement, DPR, lb/day.

A-15.5.3 Design capacity of polymer feed system, PUR, lb/day.

A-15.5.4 Capacity of the diluted polymer solution feed system, LCSF, gal/day.

A-15.6 Quantities Calculations

A-15.6.1 Annual operation and maintenance labor requirement.

A-15.6.1.1 If LCSF < 1,000 gal/day, annual labor is calculated by:

$$L = 16.7\ (LCSF)^{0.4894} + 46.3\ (LCSF)^{0.2827}$$

A-15.6.1.2 If 1,000 $\leq$ LCSF < 10,000 gal/day, annual labor is calculated by:

$$L = 25.9\ (LCSF)^{0.4894} + 46.3\ (LCSF)^{0.2827}$$

A-15.6.1.3 If LCSF $\geq$ 10,000 gal/day, annual labor is calculated by:

$$L = 6.1\ (LCSF)^{0.647} + 46.3\ (LCSF)^{0.2827}$$

where

L = Annual operation and maintenance labor requirement, hr/yr.

A-15.6.2 Electrical energy requirement for this system is insignificant.

A-15.6.3 Annual operation and maintenance material supply cost factor. It is assumed that the annual O&M material and supply cost is 2 percent of the polymer system construction cost.

$$OMMP = 0.02$$

where

OMMP = O&M material and supply cost factor, fraction of the polymer system construction cost.

A-15.7 Quantities Calculations Output Data

A-15.7.1 Annual operation and maintenance labor requirement, L, hr/yr.

A-15.7.2 Annual O&M parts and materials cost factor, OMMP, fraction of polymer system construction cost.

A-15.8 Unit Price Input Required

A-15.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-15.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-15.8.3 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-15.8.4 Cost of polymer, PCST, \$/lb. Default value = 2.80, \$/lb (ENRCCI/4,006).

A-15.9 Cost Calculations

A-15.9.1 Capital cost of polymer storage and feed system.

A-15.9.1.1 If PUR < 375 lb/day, the polymer system cost is calculated by:

$$CCP = 27,600 + 235\ (PUR)^{0.95}\ \frac{MSECI}{751}$$

A-15.9.1.2 If PUR $\geq$ 375 lb/day, the polymer system cost is calculated by:

$$CCP = 57,500 + 235\ (PUR)^{0.90}\ \frac{MSECI}{751}$$

where

CCP = Capital cost of polymer system, \$.

A-15.9.2 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-15.9.3 Annual cost of polymer.

$$COSTP = (DPR)\ (DPY)\ (PCST)$$

where

COSTP = Annual cost of ferric chloride, \$/yr.

A-15.9.4 Annual maintenance parts and material cost.

$$COSTMP = (OMMP) (CCP)$$

where

COSTMP = Annual maintenance parts and material cost, \$/yr.

A-15.9.5 Total base capital cost.

$$TBCC = CCP$$

where

TBCC = Total base capital cost, \$.

A-15.9.6 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTP + COSTMP$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-15.10 Cost Calculations Output Data

A-15.10.1 Capital cost of polymer system, CCP, \$.

A-15.10.2 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-15.10.3 Annual cost of polymer, COSTP, \$/yr.

A-15.10.4 Annual material and supply cost, COSTMP, \$/yr.

A-15.10.5 Total base capital cost of polymer conditioning, TBCC, \$.

A-15.10.6 Total annual operation and maintenance cost of polymer conditioning, COSTOM, \$/yr.

APPENDIX A-16

FLUIDIZED BED INCINERATION

A-16.1 Background

Fluidized bed incinerators utilize a fluidized bed of sand as a heat reservoir to promote uniform combustion of sludge. Air is injected into the bottom of the incinerator at a pressure of 3 to 5 psig to fluidize the bed. The bed temperature is controlled at approximately 1,200 to 1,400 °F using gas or fuel oil, as necessary. Combustion is controlled by varying the sludge feed and/or the air flow to the reactor vessel to completely oxidize all organic matter in the sludge.

Dewatered sludge is injected either above or directly into the fluidized sand bed. Solids remain in the sand bed until the particles are reduced to mineral ash. Ash is carried out of the top of the furnace by the upflowing exhaust gases where it is removed by air pollution control devices. Venturi scrubbers, electrostatic precipitators, and cyclones have been used to control pollutants from incinerators, as specified by federal, state, or local requirements.

Fluidized bed furnaces are reliable due to the presence of few mechanical components compared with other incineration devices. In addition, minimal pollutant emissions are produced under proper operating conditions. However, the process is complex and requires the use of trained personnel to maintain efficient operation. Since capital and O&M costs are relatively high, fluidized bed incinerators are typically limited to larger treatment plants and at locations where land disposal of sludges is limited or prohibited.

Fluidized bed incinerators are purchased as package units from manufacturers in standard sizes which begin at 6 ft in diameter and increase in 1-ft increments up to 25 ft. Size is based on numerous factors, including:

- Solids loading rate.
- Percent solids in sludge.
- Percent volatile solids.
- Sludge heat value.
- Hours per week of operation.

Base capital costs obtained with the following algorithm include purchase and installation of the incinerator, installation of controls and other ancillary equipment, and construction of a building to house the incinerator. Base capital costs do not include pollution control devices, since this cost depends upon the degree of control required. Pollution control can add between 10 and 25 percent to the base capital cost, depending on the equipment used. Heat recovery devices are not included in the costs.

Base annual O&M costs include labor, electrical energy, auxiliary and startup fuel, and replacement parts and materials.

A-16.1.1 Algorithm Development

The following algorithm is based on costs and requirements obtained by accessing the CAPDET program. Equations used in the CAPDET program are on pages 2.29-5 through 2.29-20 of Reference 1. Costs and requirements were obtained by varying sludge volume and solids concentration entering the incinerator, using the following input parameters:

- Operation hours per day = 24 hr/day.
- Operation days per year = 360 days/yr.
- Heat value of sludge = 118 Btu/lb.
- Sludge percent volatile solids = 70 percent.
- Ambient air temperature = 40 °F.
- Operating temperature = 1,100 °F.
- Detention time = 15 seconds.
- Sand-to-sludge ratio = 6 lb/lb.
- Specific weight of sand = 110 lb/ft^3.
- Cost of standard 15-ft-diameter incinerator = $1,680,000.

Additional input parameters (projected 1983 values) shown on Table 1-1 were obtained from construction cost guides (2, 3). Cost of the standard incinerator was obtained from equipment suppliers.

Fuel requirements obtained from CAPDET were determined to be too high; therefore, they were estimated using methods described in Reference 4.

Costs and requirements obtained through use of the CAPDET program or other references were fit to an equation using a multiple regression program. Other equations were used directly as they appear in CAPDET.

A-16.2 Input Data

A-16.2.1 Daily sludge volume, SV, gal/day.

A-16.2.2 Feed sludge suspended solids concentration, SS, percent.

A-16.2.3 Sludge specific gravity, SSG, unitless.

A-16.2.4 Volatile suspended solids concentration, VSS, percent.

A-16.2.5 Hours per day process is operated, HPD, hr/day.

A-16.2.6 Days per year process is operated, DPY, days/yr.

A-16.3 Design Parameters

A-16.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-16.3.2 Feed sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-16.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated using the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Specific gravity of sludge solids, unitless.

A-16.3.4 Volatile suspended solids concentration, VSS, percent. Default value = 60 percent.

A-16.3.5 Hours per day process is operated, HPD, hr/day. Default value = 24 hr/day.

A-16.3.6 Days per year process is operated, DPY, days/yr. Default value = 360 days/yr.

A-16.4 Process Design Calculations

A-16.4.1 Calculate loading rate of dry sludge solids in lb/hr.

$$LR = \frac{(SV)\ (365)\ (8.34)\ (SS)\ (SGS)}{(DPY)\ (HPD)\ (100)}$$

where

LR = Loading rate of dry sludge solids, lb/hr.
8.34 = Density of water, lb/gal.

A-16.4.2 Calculate heating value of the sludge solids.

$$HV = \frac{(LR)\ (VSS)\ (10,000)}{(100)}$$

where

HV = Heating value of the sludge, Btu/hr.

10,000 = Assumed Btu per lb of volatile solids in the sludge. This value is approximately correct for raw wastewater solids. Reduce Btu per lb by approximately 25 percent if sludge is chemically conditioned with lime or ferric chloride.

A-16.4.3 Calculate moisture content of sludge.

$$M = (100) - (SS)$$

where

M = Moisture content of sludge, percent.

A-16.4.4 Calculate sludge loading rate.

$$SL = 10^{(2.7 - 0.0222M)}$$

where

SL = Sludge loading rate, $lb/ft^2/hr$.

A-16.4.5 Calculate cross-sectional area of incinerator.

$$A = \frac{LR}{SL}$$

where

A = Cross-sectional area of incinerator, ft^2.

A-16.4.6 Compute annual auxiliary fuel supply requirement.

A-16.4.6.1 Calculate burning rate.

$$BR = 10^{(5.947 - 0.0096M)}$$

where

BR = Burning rate, $Btu/ft^2/hr$.

A-16.4.6.2 Calculate total heat input rate.

$$HIR = (BR)\ (A)$$

where

HIR = Total heat input rate, Btu/hr.

A-16.4.6.3 Calculate auxiliary fuel supply required.

$$AFS = (HIR) - (HV)$$

where

AFS = Auxiliary fuel supply required, Btu/hr.

A-16.4.6.4 Calculate fuel oil required annually.

$$FO = \frac{(AFS)\ (DPY)\ (HPD)\ (1.1)}{(144{,}000)}$$

where

FO = Annual fuel oil required, gal/yr.
1.1 = Efficiency factor, unitless.
144,000 = Btu in 1 gal of fuel oil, Btu/gal.

A-16.5 Process Design Output Data

A-16.5.1 Loading rate of dry sludge solids, LR, lb/hr.

A-16.5.2 Heating value of sludge solids, HV, Btu/hr.

A-16.5.3 Moisture content of sludge, M, percent.

A-16.5.4 Sludge loading rate, SL, $lb/ft^2/hr$.

A-16.5.5 Cross-sectional area of incinerator, A, ft^2.

A-16.5.6 Annual auxiliary fuel oil requirement, FO, gal/yr.

A-16.6 Quantities Calculations

A-16.6.1 Determine size and number of incinerators to be used. Generally, the size of commercial fluidized bed incinerators begins at 6 ft in diameter, and increases in 1-ft increments to the largest diameter of 25 ft.

A-16.6.1.1 Calculate incinerator diameter if only one incinerator is used.

$$D = (1.273\ A)^{0.5}$$

where

D = Incinerator diameter, ft.
1.273 = 4/3.1416.

If incinerator diameter, D, is equal to or less than 25 ft, use one incinerator and increase D to the next larger integer greater than 5 and less than 26. Note that this does not include standby capacity.

A-16.6.1.2 Calculate diameters of multiple incinerators if diameter, D, of one incinerator is more than 25 ft.

$$D = [(1.273)\ (A/N)]^{0.5}$$

where

D = Diameter of incinerator, ft.
1.273 = 4/3.1416.
A = Area of incinerator, ft^2.
N = Number of incinerators.

Try N = 2 first. If A/N is greater than 490 ft^2, then try successive integer values of N (i.e., 3, 4, etc.) until the ratio of A/N is less than 490 ft^2. Note that this does not include standby capacity.

A-16.6.2 Calculate area of incinerator building.

$$AB = (1{,}700 + 90\ D)\ (N)$$

where

AB = Area of incinerator building, ft^2.

A-16.6.3 Calculate annual maintenance labor requirement.

$$ML = (6)\ [(LR)\ (HPD)]^{0.58}$$

where

ML = Annual maintenance labor requirement, hr/yr.

A-16.6.4 Calculate annual operation labor requirement.

$$OL = (18)\ [(LR)\ (HPD)]^{0.54}$$

where

OL = Annual operational labor requirement, hr/yr.

A-16.6.5 Calculate annual electrical energy requirement.

$$E = (N)\ (0.88)\ (DPY)\ (HPD)\ (1.165)\ [D]^{1.9}$$

where

E = Annual electrical energy requirement, kWhr/yr.
0.88 = Conversion factor, hp to kWhr.

A-16.6.6 Annual operation and maintenance parts and material cost is expressed as a percentage of the total base capital cost of the incinerator (TBCC) to be calculated later.

$$OMMP = 0.45 \text{ percent}$$

where

OMMP = Annual O&M parts and materials cost factor, percent of base capital cost.

A-16.7 Quantities Calculations Output Data

A-16.7.1 Diameter of incinerators, D, ft.

A-16.7.2 Number of incinerators, N.

A-16.7.3 Area of incinerator building, AB, ft^2.

A-16.7.4 Annual maintenance labor requirement, ML, hr/yr.

A-16.7.5 Annual operational labor requirement, OL, hr/yr.

A-16.7.6 Annual electrical energy requirement, E, kWhr/yr.

A-16.7.7 Annual O&M parts and materials cost factor, OMMP, fraction of base capital cost.

A-16.8 Unit Price Input Required

A-16.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-16.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-16.8.3 Cost of operational labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-16.8.4 Cost of fuel oil, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-16.8.5 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-16.9 Cost Calculations

A-16.9.1 Cost of installed incinerator and appurtenances.

A-16.9.1.1 Calculate the cost of a "standard size" fluidized bed incinerator of 15-ft diameter.

$$COSTFI = \$1{,}680{,}000 \ \frac{MSECI}{751}$$

where

COSTFI = Cost of "standard size" 15-ft-diameter fluidized bed incinerator, $.

A-16.9.1.2 Calculate the cost of installed incinerator and appurtenances

$$COSTFB = (0.122)\ (D)^{0.7788}\ (N)^{0.9}\ (COSTFI)$$

where

COSTFB = Cost of installed fluidized bed incinerator, $.

A-16.9.2 Cost of incinerator building and foundation.

$$COSTIB = (AB)\ (145)\ \frac{ENRCCI}{4{,}006}$$

where

COSTIB = Cost of incinerator building and foundation, $.
145 = Last quarter 1983 cost for building, $/ft^2.

A-16.9.3 Annual cost of operation and maintenance labor.

$$COSTLB = [(OL) + (ML)]\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, $/yr.

A-16.9.4 Annual cost of fuel oil.

$$COSTDSL = (FO)\ (COSTDF)$$

where

COSTDSL = Annual cost of fuel oil, \$/yr.

A-16.9.5 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-16.9.6 Total base capital cost of fluidized bed incinerator.

$$TBCC = (COSTFB) + (COSTIB)$$

where

TBCC = Base capital cost of fluidized bed incinerator, \$.

A-16.9.7 Annual cost of maintenance parts and materials.

$$COSTMP = (TBCC)\ (0.0045)$$

where

COSTMP = Annual cost of operation and maintenance materials, \$/yr.

A-16.9.8 Total annual operation and maintenance cost.

$$COSTOM = (COSTLB) + (COSTDSL) + (COSTEL) + (COSTMP)$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-16.10 Cost Calculations Output Data

A-16.10.1 Cost of installed incinerator and appurtenances, COSTFB, \$.

A-16.10.2 Cost of incinerator building and foundation, COSTIB, \$.

A-16.10.3 Annual cost of operational labor, COSTLB, \$/yr.

A-16.10.4 Annual cost of fuel oil, COSTDSL, \$/yr.

A-16.10.5 Annual cost of electrical energy, COSTEL, \$/yr.

A-16.10.6 Annual cost of maintenance parts and materials, COSTMP, \$/yr.

A-16.10.7 Total base capital cost of fluidized bed incinerator facility, TBCC, \$.

A-16.10.8 Total annual cost of operation and maintenance for fluidized bed incinerator, COSTOM, \$/yr.

APPENDIX A-17

MULTIPLE HEARTH INCINERATION

A-17.1 Background

Multiple hearth incinerators are multi-chambered vertically mounted furnaces with hearths located above one another. Within each hearth is a set of rabble arms used to move the sludge in a spiral pattern around each hearth. Dewatered sludge is fed into the top of the incinerator and is swept radially towards the center, where the sludge drops to the second hearth. The sludge is again swept spirally to the periphery of the hearth, and passes downward to the next hearth. This pattern is continued through subsequent hearths. As the sludge moves toward the bottom, further oxidation occurs, yielding an ash which is removed from the bottom. Hot rising gases flow in a direction counter-current to the sludge flow.

Multiple hearth incineration is a two-stage process consisting of sludge drying on the upper hearths and combustion of volatile solids on the lower hearths. The process reduces dewatered sludge solids (greater than 15 percent solids) to an inert ash that is readily disposed. Auxiliary fuel is usually required for feed sludge concentrations between 15 and 30 percent solids. Feed solids greater than 50 percent solids (excluding conditioning chemicals) are typically <u>not</u> incinerated, since temperatures in excess of the refractory material and metallurgical limits of the furnace may be achieved.

Base capital costs in the following algorithm include purchase of the incinerator and ancillary equipment from the manufacturer, installation of all equipment, and construction of a building to house the incinerator. Base annual O&M costs include labor, electrical energy, auxiliary fuel, and replacement parts and materials.

A-17.1.1 Algorithm Development

The following algorithm was developed using information provided in <u>Process Design Manual for Sludge Treatment and Disposal</u> (4). Calculations used in determining fuel requirements for sludge incineration were obtained from pages 11-10 through 11-20 of this manual. Process design equations follow from the descriptions on pages 11-31 through 11-48 of Reference 4. Additional cost information used for base capital and O&M costs was obtained from Reference 7, pages A-186 and A-187, and Reference 8, pages 315 through 331. Costs and requirements were fit to equations using a multiple regression program.

A-17.2 Input Data

A-17.2.1 Daily sludge volume, SV, gal/day.

A-17.2.2 Feed sludge suspended solids concentration, SS, percent.

A-17.2.3 Sludge specific gravity, SSG, unitless.

A-17.2.4 Volatile suspended solids concentration, VSS, percent.

A-17.2.5 Hours per day process is operated, HPD, hr/day.

A-17.2.6 Days per year process is operated, DPY, days/yr.

A-17.3 Design Parameters

A-17.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-17.3.2 Feed sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-17.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated using the following equation:

$$SSG = \frac{1}{\frac{100-SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Specific gravity of sludge solids, unitless.

A-17.3.4 Volatile suspended solids concentration, VSS, percent. Default value = 60 percent.

A-17.3.5 Hours per day process is operated, HPD, hr/day. Default value = 24 hr/day.

A-17.3.6 Days per year process is operated, DPY, days/yr. Default value = 360 days/yr.

A-17.4 Process Design Calculations

A-17.4.1 Calculate loading rate of dry sludge solids in lb/hr.

$$LR = \frac{(SV)\ (365)\ (8.34)\ (SS)\ (SSG)}{(DPY)\ (HPD)\ (100)}$$

where

LR = Loading rate of dry sludge solids, lb/hr.

A-17.5 Process Design Output Data

A-17.5.1 Loading rate of dry sludge solids, LR, lb/day.

A-17.6 Quantities Calculations

A-17.6.1 Calculate annual operation and maintenance labor requirement.

$$L = [- 9.886 \times 10^{-11} (SV)^3 + 1.28 \times 10^{-6} (SV)^2 + 0.38 (SV) + 1,708]$$

where

L = Annual operation and maintenance labor requirement, hr/yr.

A-17.6.2 Calculate annual fuel oil requirement. The supplementary fuel oil (or natural gas) required for incinerator start-up and incineration is highly sensitive to the moisture content of the sludge and the Btu value of the sludge solids. It is therefore very difficult in a general cost algorithm to provide a simple formula for supplementary fuel oil requirements. Self-contained combustion without supplementary fuel is often possible with raw primary sludges which have been dewatered to a solids concentration of over 30 percent. Whenever possible, the supplementary fuel oil requirement used in the algorithm should be obtained through engineering mass balance calculations for site-specific conditions. The calculations shown in Subsections A-17.6.2.1 through A-17.6.2.9 provide a reasonable approximation based on an incinerator temperature of 1,400 °F and ambient air and sludge temperature of 60 °F.

A-17.6.2.1 Calculate heating value of the sludge.

$$HV = \frac{(LR)\ (VSS)\ (10,000)}{(100)}$$

where

HV = Heating value of the sludge, Btu/hr.

10,000 = Assumed Btu per lb of volatile solids in the sludge. This value is approximately correct for raw wastewater solids. Reduce Btu per lb by approximately 25 percent if sludge is chemically conditioned with lime or ferric chloride.

A-17.6.2.2 Calculate combustion air requirement.

$$AIR = \frac{(HV)\ (7.5)\ (2)}{(10,000)}$$

where

AIR = Combustion air requirement in lb of dry air/hr.
7.5/10,000 = Assumed lb of dry air required per 10,000 Btu.
2 = Excess air factor, unitless.

A-17.6.2.3 Calculate heat required to raise ambient air temperature (60 °F) to furnace temperature of 1,400 °F.

$$HAIR = (AIR)\ (1{,}340)\ [(0.256) + (0.013)\ (0.5)]$$

where

HAIR = Heat required to raise ambient air temperature to 1,400 °F, Btu/hr.

1,340 = Assumed difference between furnace temperature of 1,400 °F and ambient air temperature of 60 °F.

0.256 = Btu required to heat 1 lb of air in Btu/lb - °F.

0.0131 = Assumed water content of ambient air in lb water/lb air.

0.5 = Btu required to heat water in Btu/lb - °F.

A-17.6.2.4 Calculate heat required to raise sludge dry solids temperature to furnace temperature of 1,400 °F.

$$HSS = (LR)\ (0.25)\ (1{,}340)$$

where

HSS = Heat required to raise sludge solids temperature to 1,400 °F, Btu/hr.

0.25 = Btu required to heat 1 lb of solids in Btu/lb - °F.

1,340 = Assumed difference between furnace temperature of 1,400 °F and sludge temperature of 60 °F.

A-17.6.2.5 Calculate heat required to raise temperature of water (moisture content) of feed sludge.

$$HW = \left[\frac{(SV)\ (SSG)\ (8.34)}{(HPD)} - (LR)\right]\ (1{,}716)$$

where

HW = Heat required to raise sludge moisture content from 60 °F to 212 °F, evaporate water, and raise temperature of water vapor to 1,400 °F, in Btu/hr.

8.34 = Density of water, lb/gal.

1,716 = Btu required to raise 1 lb of water from 60 °F to a water vapor temperature of 1,400 °F, Btu/lb.

A-17.6.2.6 Calculate heat required to raise temperature of water formed during combustion reaction to 1,400 °F.

$$HCW = 0.0782\ (HAIR + HSS + HW)$$

where

HCW = Heat required to raise temperature of water formed during combustion reaction to 1,400 °F, Btu/hr.

0.0782 = Conversion factor.

A-17.6.2.7 Calculate heat required to compensate for radiation losses. Assume 5 percent radiation losses.

$$HL = (0.05)\ (HAIR + HSS + HW + HCW)$$

where

HL = Heat required to compensate for radiation losses, Btu/hr.

0.05 = Assumed radiation heat loss, fraction of total.

A-17.6.2.8 Calculate supplemental heat required by incinerator.

$$SH = (HAIR + HSS + HW + HCW + HL) - (HV)$$

where

SH = Supplemental heat required by incinerator, Btu/hr.

A-17.6.2.9 Calculate supplemental fuel requirement. Because the supplemental fuel also requires air for combustion and this air must be heated, and more water is formed by the reaction, the calculations in Subsections A-17.6.2.2 through A-17.6.2.8 can be carried forward through several iterations. If this is done, it will be seen that the actual supplemental heat required is approximately double the value SH determined in Subsection A-17.6.2.8 above. This approximation is used below.

$$FO = \frac{(SH)\ (DPY)\ (HPD)}{144{,}000}\ (2)\ (1.1)$$

where

FO = Fuel oil required, gal/yr.

2 = Factor to account for fuel oil combustion heat requirement.

1.1 = Factor to account for start-up fuel and inefficiencies.

144,000 = Heat content of fuel oil, Btu/gal.

A-17.6.3 Calculate annual electricity requirement.

$$E = [- 2.68 \times 10^{-8}\ (SV)^3 + 1.51 \times 10^{-3}\ (SV)^2 + 25.4\ (SV) + 189{,}400]$$

where

E = Annual electrical energy requirement, kWhr.

A-17.7 Quantities Calculations Output Data

A-17.7.1 Annual operation and maintenance labor requirement, L, hr/yr.

A-17.7.2 Annual fuel oil requirement, FO, gal/yr.

A-17.7.3 Annual electrical energy requirement, E, kWhr/yr.

A-17.8 Unit Price Input Required

A-17.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-17.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-17.8.3 Cost of operational labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-17.8.4 Cost of fuel oil, COSTFO, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-17.8.5 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-17.9 Cost Calculations

A-17.9.1 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-17.9.2 Annual cost of fuel oil.

$$COSTFUEL = (FO)\ (COSTFO)$$

where

COSTFUEL = Annual cost of fuel oil, \$/yr.

A-17.9.3 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-17.9.4 Annual cost of maintenance parts and materials.

$$COSTMP = [-\ 1.3 \times 10^{-10}\ (SV)^3 - 3.0 \times 10^{-6}\ (SV)^2 + 0.87\ (SV) + 8{,}166]\ \frac{MSECI}{751}$$

where

COSTMP = Annual cost of maintenance parts and materials, \$/yr.

A-17.9.5 Base capital cost of multiple hearth incinerator.

$$TBCC = [- 2.7 \times 10^{-3} (SV)^2 + 231.5 (SV) + 1,681,000] \frac{MSECI}{751}$$

where

TBCC = Total base capital cost of multiple hearth incinerator, $.

A-17.9.6 Annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTDSL + COSTEL + COSTMP$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-17.10 Cost Calculations Output Data

A-17.10.1 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-17.10.2 Annual cost of fuel oil, COSTFUEL, $/yr.

A-17.10.3 Annual cost of electrical energy, COSTEL, $/yr.

A-17.10.4 Annual cost of maintenance parts and materials, COSTPM, $/yr.

A-17.10.5 Total base capital cost of multiple hearth incinerator facility, TBCC, $.

A-17.10.6 Total annual operation and maintenance cost for multiple hearth incinerator, COSTOM, $/yr.

APPENDIX A-18

COMPOSTING - WINDROW METHOD

A-18.1 Background

In windrow composting, dewatered sludge is mixed with a bulking agent and spread on paved but uncovered areas in windrows with an approximately triangular or trapezoidal cross sectional area of 35 ft^2. The most economical and most commonly used bulking agents in the windrow process are previously composted sludge and sawdust. Windrows are approximately 14 ft wide, with access areas between windrows of 10 ft. Windrows are 300 ft long, or less for small plants. Sludge remains in windrows for approximately 30 days, with periodic turning to maintain aerobic conditions and to provide mixing. At the end of the composting period, the sludge is moved to a storage area for additional curing. With properly controlled operation, high temperatures achieved during composting can destroy virtually all pathogens and parasites. However, compost is a suitable medium for regrowth of bacteria, and precautions must be taken to prevent reinfection. Windrow composting may be adversely affected by cold or wet weather.

The algorithm presented below is based on the construction and operation of a windrow composting facility with the following conditions:

- Windrow and access areas are paved with asphalt; the storage area is unpaved.
- Dewatered sludge is mixed with previously composted sludge to obtain an initial solids concentration of approximately 40 percent.
- Windrows are turned mechanically once a day for the first 2 weeks, and three times per week thereafter.
- Compost mix remains in the composting area for 30 days.

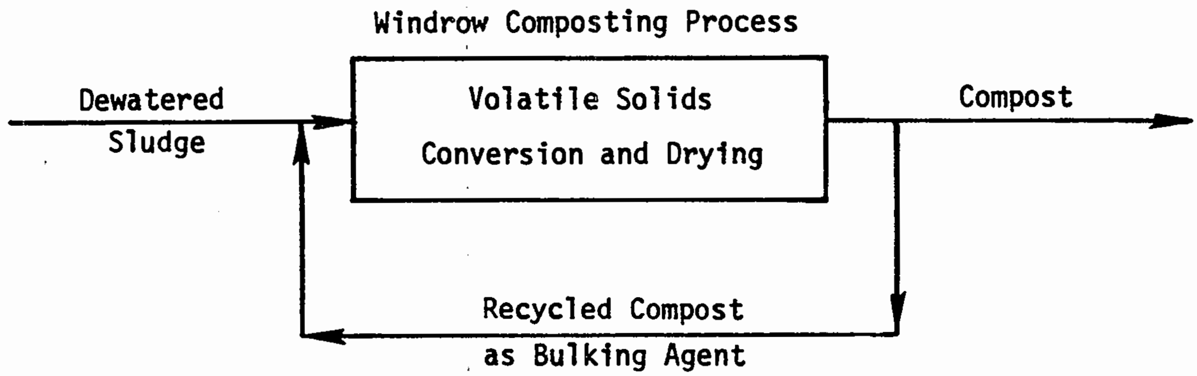
Capital costs include purchase of land, site clearing and grading, paving of composting area, purchase of windrow turning machine and front-end loader, purchase and construction of unloading and mixing structure, and construction of a maintenance and operation building. Operation and maintenance costs include operation and maintenance labor, fuel for composting and ancillary machinery, and O&M materials and supplies.

A-18.1.1 Algorithm Development

The following algorithm was developed for windrow composting using previously composted sludge as the bulking agent. Supplemental information was obtained from Reference 4, pages 12-10 through 12-12 and pages 12-16 through

12-22; and through correspondence with the Los Angeles County Sanitation District. The information obtained from references was fit to equations using a multiple regression program.

The process is shown schematically in the flow diagram below. Reference to the diagram should aid the reader in following the material balance calculations that follow. In these calculations, it is assumed that no changes occur to the recycled compost used as bulking agent, since any further conversion taking place in the recycled compost is negligible compared with the conversion of solids in the dewatered sludge.



A-18.2 Input Data

A-18.2.1 Daily dewatered sludge volume entering the composting process, SV, gal/day.

A-18.2.2 Sludge solids concentration in dewatered sludge, SS, percent dry solids.

A-18.2.3 Percent volatile solids in dewatered sludge, VSP, percent of total solids dry weight.

A-18.2.4 Percent volatile solids destroyed during composting, VSC, percent of sludge volatile solids dry weight.

A-18.2.5 Compost solids content percent, CSP, percent dry solids.

A-18.2.6 Dewatered sludge specific weight, SC, lb/yd^3.

A-18.2.7 Compost product specific weight, SR, lb/yd^3.

A-18.2.8 Mixed dewatered sludge and compost specific weight, SM, lb/yd^3.

A-18.2.9 Windrow cross section area, X, ft^2.

A-18.2.10 Windrow length, LNTH, ft.

A-18.2.11 Truck unloading and mixing area, AUM, ft^2/ton of dry solids/day.

A-18.2.12 Finished compost storage area, ACS, ft^2/ton of dry solids/day.

A-18.2.13 Fraction of total composting site area requiring clearing of brush and trees, FWB, expressed as a decimal fraction.

A-18.2.14 Fraction of total composting site requiring light grading, FRLG, expressed as a decimal fraction.

A-18.2.15 Fraction of total composting site requiring medium grading, FRMG, expressed as a decimal fraction.

A-18.2.16 Fraction of total composting site requiring extensive grading, FREG, expressed as a decimal fraction.

A-18.3 Design Parameters

A-18.3.1 Daily dewatered sludge volume entering the composting process, SV, gal/day. This input value must be provided by the user. No default value.

A-18.3.2 Sludge solids concentration in dewatered sludge, SS, percent of dewatered sludge weight. This input value should be provided by the user. However, if no value is available, default value = 20 percent.

A-18.3.3 Percent volatile solids in dewatered sludge, VSP, percent of total solids dry weight. Default value = 35 percent.

A-18.3.4 Percent volatile solids destroyed during composting, VSC, percent of sludge volatile solids dry weight. Default value = 30 percent.

A-18.3.5 Compost solids percent after composting, CSP. Default value = 65 percent.

A-18.3.6 Dewatered sludge specific weight, SC. Default value = 1,820 lb/yd^3.

A-18.3.7 Compost product specific weight, SR. Default value = 865 lb/yd^3.

A-18.3.8 Mixed dewatered sludge and compost specific weight, SM. Default value = 1,685 lb/yd^3.

A-18.3.9 Windrow cross section, X. Default value = 35 ft^2.

A-18.3.10 Windrow length, LNTH. Default value = 300 ft.

A-18.3.11 Truck unloading and mixing area, AUM. Default value = 300 ft^2/ton of dry solids/day to be composted.

A-18.3.12 Finished compost storage area, ACS. Default value = 900 ft^2/ton of dry solids/day to be composted.

A-18.3.13 Fraction of composting site requiring clearing of brush and trees, FWB. Varies significantly depending on site-specific conditions. Default value = 0.7 for composting sites.

A-18.3.14 Fraction of composting site requiring light grading, FRLG. Varies significantly depending on site-specific conditions. Default value = 0.3.

A-18.3.15 Fraction of composting site requiring medium grading, FRMG. Varies significantly depending on site-specific conditions. Default value = 0.4.

A-18.3.16 Fraction of composting site requiring extensive grading, FREG. Varies significantly depending on site-specific conditions. Default value = 0.3.

A-18.4 Process Design Calculations

A-18.4.1 Calculate daily wet weight of dewatered sludge to be composted.

$$DS = \frac{(SV)\ (8.34)}{(2{,}000)} \left[\frac{1}{\frac{100 - (SS)}{100} + \frac{(SS)}{(1.42)\ (100)}} \right]$$

where

DS = Daily wet weight of dewatered sludge, tons/day.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.
1.42 = Assumed specific gravity of sludge solids, unitless.

A-18.4.2 Calculate daily dry solids weight of dewatered sludge to be composted.

$$DSS = \frac{(SS)\ (DS)\ (2{,}000)}{100}$$

where

DSS = Daily dry solids weight of dewatered sludge, lb/day.
2,000 = Conversion factor, lb/ton.

Note: In many cases, the user will know the daily dry solids weight of dewatered sludge, DSS, prior to using the algorithm. If so, DS can be back-calculated as follows:

$$DS = \frac{(DSS)\ (100)}{(SS)\ (2{,}000)}$$

A-18.4.3 Calculate weight of volatile solids in sludge composted per day.

$$VSS = \frac{(VSP)}{(100)} \times (DSS)$$

where

VSS = Daily volatile dry solids weight, lb/day.

A-18.4.4 Calculate sludge volatile solids destroyed during composting.

$$VSD = \frac{(VSC)\ (VSS)}{100}$$

where

VSD = Sludge volatile solids destroyed during composting, lb/day.

A-18.4.5 Calculate quantity of compost produced.

A-18.4.5.1 Tons of compost produced per day.

$$CPW = \frac{(DSS - VSD)\ (100)}{(CSP)\ (2{,}000)}$$

where

CPW = Compost produced, tons/day.
2,000 = Conversion factor, lb/ton.

A-18.4.5.2 Cubic yards of compost produced per day.

$$CPV = \frac{(DSS - VSD)\ (100)}{(CSP)\ (SR)}$$

where

CPV = Compost produced, yd^3/day.

A-18.4.6 Calculate quantity of compost product mixed with dewatered sludge to obtain a solids content of 40 percent in the mixture. Note: If SS is greater than 40, then R = 0.

A-18.4.6.1 Ratio of recycled compost product to dewatered sludge.

$$R = \frac{0.40 - \frac{(SS)}{(100)}}{\frac{(CSP)}{(100)} - 0.40}$$

where

R = Lb compost product recycled/lb of dewatered sludge.

A-18.4.6.2 Weight of dewatered sludge composted per day.

$$WC = \frac{(DSS)\ (100)}{(SS)}$$

where

WC = Weight of dewatered sludge, lb/day.

A-18.4.6.3 Weight of recycled compost product.

$$WR = R \times WC$$

where

WR = Weight of recycled product compost, lb/day.

A-18.4.6.4 Volume of recycled compost product.

$$VR = \frac{WR}{SR}$$

where

VR = Volume of recycled compost product, yd^3/day.

A-18.4.7 Calculate volume of mixed dewatered sludge and recycled compost for composting in windrows.

$$VM = \frac{WC}{SC} + \frac{WR}{SR}$$

where

VM = Volume of mixed dewatered sludge and recycled compost for composting windrows, yd^3/day.

A-18.4.8 Calculate number of windrows required, based on a 30-day composting period.

$$NW = \frac{(VM)\ (27)\ (30\ days)}{(X)\ (LNTH)}$$

where

NW = Number of windrows with cross section, X, and length, LNTH.
27 = Conversion factor, ft^3/yd^3.

A-18.4.9 Calculate area covered by windrows.

$$AW = \frac{(NW)\ (LNTH)\ (14)}{43,560}$$

where

AW = Area covered by windrows, acres.
14 = Width of windrows, ft.
43,560 = Conversion factor, ft^2/acre.

A-18.4.10 Calculate total composting area.

$$AC = \frac{(NW + 1)\ [(10)\ (LNTH)]}{43,560} + AW$$

where

AC = Total composting area, acres.
10 = Distance between windrows, ft.
43,560 = Conversion factor, ft^2/acre.

A-18.4.11 Calculate unloading and mixing area.

$$AU = \frac{(DSS)\ (AUM)}{(43,560)\ (2,000)}$$

where

AU = Unloading and mixing area, acres.
43,560 = Conversion factor, ft^2/acre.
2,000 = Conversion factor, lb/ton.

A-18.4.12 Calculate finished compost storage area.

$$AS = \frac{(DSS)\ (ACS)}{(43{,}560)\ (2{,}000)}$$

where

AS = Finished compost storage area, acres.
43,560 = Conversion factor, ft^2/acre.
2,000 = Conversion factor, lb/ton.

A-18.4.13 Calculate total site area required.

$$TLAR = (1.5)\ (AC + AU + AS)$$

where

TLAR = Total site area required, acres.

1.5 = A factor to account for area required for building and buffer around the property.

A-18.4.14 Calculate housing area required.

$$HA = 1.263 \times 10^{-5}\ (DS)^3 - 0.013226\ (DS)^2 + 7.5783\ (DS) + 841$$

where

HA = Housing area, ft^2.

This equation is a multiple regression curve fit based on conceptual building areas required for sludge composting operations between 50 and 600 tons/day of dewatered sludge solids.

A-18.5 Process Design Output Data

A-18.5.1 Dewatered sludge (wet weight) to be composted, DS, tons/day.

A-18.5.2 Dry solids weight of sludge to be composted, DSS, lb/day.

A-18.5.3 Weight of compost produced, CPW, tons/day.

A-18.5.4 Volume of compost produced, CPV, yd^3/day.

A-18.5.5 Weight of compost recycled to mix with dewatered sludge, WR, lb/day.

A-18.5.6 Volume of compost recycled to mix with dewatered sludge, VR, yd^3/day.

A-18.5.7 Volume of mixed dewatered sludge and recycled compost for composting in windrows, VM, yd^3/day.

A-18.5.8 Number of windrows required, NW.

A-18.5.9 Area required for composting, AC, acres.

A-18.5.10 Unloading and mixing area, AU, acres.

A-18.5.11 Storage area, AS, acres.

A-18.5.12 Total area required, TLAR, acres.

A-18.5.13 Housing area, HA, ft^2.

A-18.6 Quantities Calculations

A-18.6.1 Calculate annual fuel requirement. Fuel for composting machines and other equipment used in the windrow process is a function of the quantity of dewatered sludge processed as follows:

$$FU = 0.00057\ (DS)^3 - 0.53\ (DS)^2 + 413\ (DS) + 15,000$$

where

FU = Annual fuel requirement, gal/yr.

This equation is a multiple regression curve fit based on fuel usage for conceptual composting operations between 50 and 600 tons/day of dewatered sludge.

A-18.6.2 Calculate operation and maintenance labor requirement. Operation and maintenance labor is a function of the quantity of dewatered sludge processed as follows:

$$L = [-\ 0.033\ (DS)^2 + 60\ (DS) + 2,020]$$

where

L= Operation and maintenance labor requirement, hr/yr.

This equation is a multiple regression curve fit based on labor requirements for conceptual composting operations between 50 and 600 tons/day of dewatered sludge.

A-18.7 Quantities Calculations Output Data

A-18.7.1 Fuel requirement, FU, gal/yr.

A-18.7.2 Operation and maintenance labor requirement, L, hr/yr.

A-18.8 Unit Price Input Required

A-18.8.1 Current Engineering News Record Construction Cost Index, ENRCCI.

A-18.8.2 Current Marshall and Swift Equipment Cost Index, MSECI.

A-18.8.3 Cost of diesel fuel, COSTDF, $/gal. Default value = $1.30/gal (ENRCCI/4,006).

A-18.8.4 Cost of operation and maintenance labor, COSTL, $/hr. Default value = $13.00/hr (ENRCCI/4,006).

A-18.8.5 Cost of land, LANDCST, $/acre. Default value = $3,000/acre (ENRCCI/4,006).

A-18.8.6 Cost of clearing brush and trees, BCRCST, $/acre. Default value = $1,500/acre (ENRCCI/4,006).

A-18.8.7 Cost of light grading earthwork, LGECST, $/acre. Default value = $500/acre (ENRCCI/4,006).

A-18.8.8 Cost of medium grading earthwork, MGECST, $/acre. Default value = $2,500/acre (ENRCCI/4,006).

A-18.8.9 Cost of extensive grading earthwork, EGECST, $/acre. Default value = $5,000/acre (ENRCCI/4,006).

A-18.8.10 Cost of paving, PVCOST, $/acre. Default value = $58,000/acre (ENRCCI/4,006) (reflects cost of bituminous concrete).

A-18.9 Cost Calculations

A-18.9.1 Total cost of land for composting site.

$$COSTLAND = (TLAR)\ (LANDCST)$$

where

COSTLAND = Total cost of land for composting site, $.

A-18.9.2 Cost of clearing brush and trees.

$$COSTCBT = (TLAR)\ (FWB)\ (BCRCST)$$

where

COSTCBT = Cost to clear brush and trees, $.

A-18.9.3 Cost of grading earthwork.

$$COSTEW = (TLAR) [(FRLG) (LGECST) + (FRMG) (MGECST) + (FREG) (EGECST)]$$

where

COSTEW = Cost of earthwork grading, \$.

A-18.9.4 Cost of paving windrow composting area.

$$COSTPV = (AC) (PVCOST)$$

where

COSTPV = Cost of paving windrow composting area, \$.

A-18.9.5 Cost of equipment. Equipment cost is a function of the quantity of dewatered sludge processed using the following equation:

$$COSTEQ = [1,560 (DS) + 450,000] \frac{MSECI}{751}$$

where

COSTEQ = Cost of equipment, \$.

This equation is a multiple regression curve fit based on equipment cost for conceptual composting operations between 5 and 600 tons/day of dewatered sludge.

A-18.9.6 Cost of unloading and mixing structure.

$$COSTUM = \left[\frac{(DSS) (AUM) (20)}{2,000}\right] \frac{ENRCCI}{4,006}$$

where

COSTUM = Cost of unloading and mixing structure, \$.
20 = Construction cost of unloading and mixing structure, \$/ft^2.
2,000 = Conversion factor, lb/ton.

A-18.9.7 Cost of operation and maintenance building.

$$COSTH = (HA) (50) \frac{ENRCCI}{4,006}$$

where

COSTH = Cost of operation and maintenance building, \$.
50 = Construction cost of operation and maintenance building, $\$/ft^2$.

A-18.9.8 Cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-18.9.9 Annual fuel cost.

$$COSTFL = (FU)\ (COSTDF)$$

where

COSTFL = Annual cost of fuel, \$/yr.

A-18.9.10 Annual cost of parts and material.

$$COSTPM = (0.18)\ (COSTEQ)\ \frac{MSECI}{751}$$

where

COSTPM = Annual parts and material cost, \$/yr.

0.18 = Annual replacement parts and materials, percent of equipment cost.

A-18.9.11 Total base capital cost.

$$TBCC = COSTLAND + COSTCBT + COSTEW + COSTPV + COSTEQ + COSTUM + COSTH$$

where

TBCC = Total base capital cost, \$.

A-18.9.12 Annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTFL + COSTPM$$

where

COSTOM = Total operation and maintenance cost, \$/yr.

A-18.10 Cost Calculations Output Data

A-18.10.1 Cost of land for composting site, COSTLAND, \$.

A-18.10.2 Cost to clear brush and trees from site, COSTCBT, \$.

A-18.10.3 Cost of grading earthwork, COSTEW, \$.

A-18.10.4 Cost of paving windrow composting area, COSTPV, \$.

A-18.10.5 Cost of composting equipment, COSTEQ, \$.

A-18.10.6 Cost of unloading and mixing structure, COSTUM, \$.

A-18.10.7 Cost of operation and maintenance building, COSTH, \$.

A-18.10.8 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-18.10.9 Annual cost of fuel, COSTFL, \$/yr.

A-18.10.10 Annual cost of parts and material, COSTPM, \$/yr.

A-18.10.11 Total base capital cost, TBCC, \$.

A-18.10.12 Annual operation and maintenance cost, COSTOM, \$/yr.

APPENDIX A-19

COMPOSTING - AERATED STATIC PILE METHOD

A-19.1 Background

Aerated static pile composting is similar in principle to windrow composting, previously discussed in Appendix A-18. However, in the aerated static pile composting process, the mixture of dewatered sludge and bulking agent remains fixed (as opposed to the periodic turning procedure used in the windrow method), and a forced ventilation system maintains aerobic conditions. A layer of previously composted sludge placed over the surface of the pile provides insulation, allowing for high temperatures throughout the pile. Because the piles do not need to be turned, and the outer layer of previously composted sludge provides insulation, static pile composting is less affected by inclement weather than windrow composting. Both digested and raw dewatered sludges have been composted by this technique.

Bulking agents used in aerated static pile composting include wood chips, rice hulls, or straw. Previously composted sludge is not a suitable bulking agent, since a porous structure must be maintained to allow movement through the pile. This algorithm assumes the use of wood chips as the bulking agent.

Composting, even with the aerated static pile method, is largely a materials handling process, and most systems in the United States use mobile equipment. Labor and bulking agent are the largest operating cost components.

The physical characteristics of the sludge and bulking agent must be defined at various stages of the process. Volatile solids and water are removed during processing, which substantially reduces the sludge weight but does not appreciably reduce the volume.

The aerated static pile process in this algorithm consists of (1) unloading and mixing, (2) aerated pile composting, (3) drying, (4) screening, and (5) storage. An area is also provided for storage of bulking agent.

1. Unloading and mixing. Dewatered sludge is delivered to the unloading and mixing structure. The structure is covered and paved. Sludge is unloaded directly onto a bed of bulking agent (wood chips). The sludge and bulking agent are then mixed with a mobile composting/mixing machine or front-end loader, depending on the size of the operation.

2. Composting. The sludge/bulking agent mixture is moved from the unloading and mixing structure to composting pads by front-end loader. Composting pads are paved but uncovered, with aeration piping and drainage collection permanently installed in trenches. One blower is

provided for each 2,400 ft^2 of composting area. Sludge is placed in the extended pile configuration and insulated with screened finished compost. Space is provided for 30 days of composting and curing.

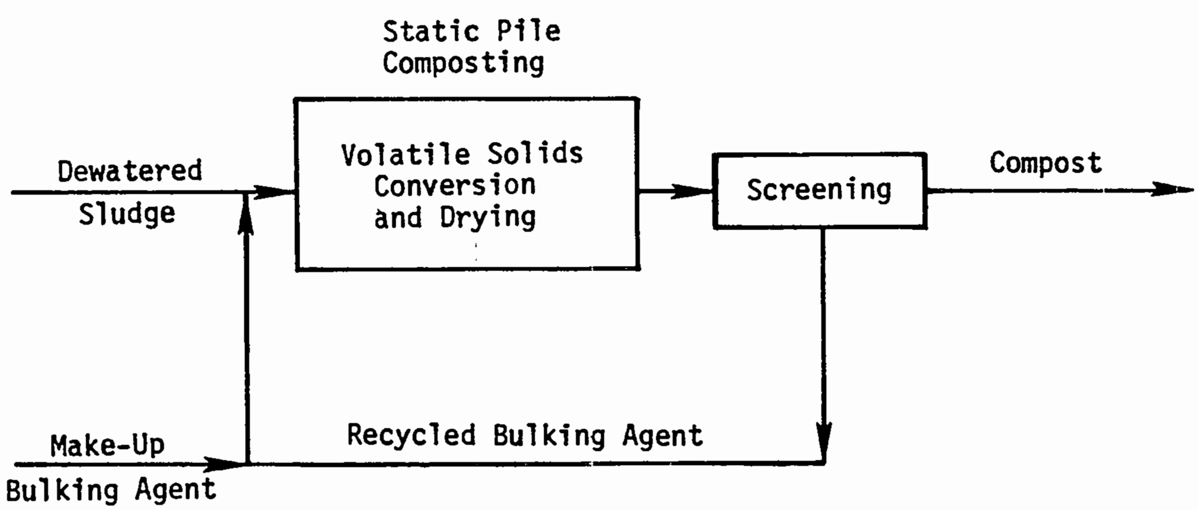
3. Drying. A covered and paved structure provides 5 days of drying time. The structure is open on both ends, similar to the unloading and mixing structure. The sludge/bulking agent mixture is moved from the composting pads to the drying area and turned to achieve at least 50 percent solids by natural drying.

4. Screening. The sludge/bulking agent mixture is moved from the drying structure by a front-end loader to a totally enclosed screening building. Screening removes about 75 percent of the bulking agent. Compost is transferred to an unpaved and uncovered storage area, and screened bulking agent is returned to the unloading and mixing structure.

A-19.1.1 Algorithm Development

Design and cost equations in the following algorithm are based on Reference 4, pages 12-22 through 12-36. Additional data for O&M requirements were taken from Reference 7, page A-181.

The process is shown schematically in the flow diagram below. Reference to the diagram should aid the reader in following the material balance calculations that follow. In these calculations, it is assumed that no changes occur to the bulking agent during composting, since any conversion of the bulking agent should be negligible compared to conversion of volatile solids in the dewatered sludge.



A-19.2 Input Data

A-19.2.1 Daily dewatered sludge volume entering the composting process, SV, gal/day.

A-19.2.2 Sludge solids concentration in dewatered sludge, SS, percent dry solids.

A-19.2.3 Volatile solids in dewatered sludge, VSP, percent of total solids dry weight.

A-19.2.4 Percent volatile solids destroyed during composting, VSC, percent of sludge volatile solids dry weight.

A-19.2.5 Compost solids content percent, CSP, percent dry solids.

A-19.2.6 Compost product specific weight, SR, lb/yd^3.

A-19.2.7 Mixed dewatered sludge and bulking agent specific weight, SM, lb/yd^3.

A-19.2.8 Bulking agent mixing ratio, BA, yd^3/ton dewatered sludge.

A-19.2.9 New bulking agent mixing ratio, NB, fraction of total BA.

A-19.2.10 New bulking agent specific weight, SNB, lb/yd^3.

A-19.2.11 Recycled bulking agent mixing ratio, RB, fraction of total BA.

A-19.2.12 Recycled bulking agent specific weight, SRB, lb/yd^3.

A-19.2.13 Bulking agent in compost product, BP, lb/day.

A-19.2.14 Truck unloading and mixing area, AUM, ft^2/ton of dry solids/day.

A-19.2.15 Composting area, AC, ft^2/ton of dry solids/day.

A-19.2.16 Drying area, AD, ft^2/ton of dry solids/day.

A-19.2.17 Finished compost storage area, ACS, ft^2/ton of dry solids/day.

A-19.2.18 Bulking agent storage area, AB, ft^2/ton of dry solids/day.

A-19.2.19 Fraction of total composting site area requiring clearing of brush and trees, FWB, expressed as a decimal fraction.

A-19.2.20 Fraction of total composting site area requiring light grading, FRLG, expressed as a decimal fraction.

A-19.2.21 Fraction of total composting site area requiring medium grading, FRMG, expressed as a decimal fraction.

A-19.2.22 Fraction of total composting site area requiring extensive grading, FREG, expressed as a decimal fraction.

A-19.3 Design Parameters

A-19.3.1 Daily dewatered sludge volume entering the composting process, SV, gal/day. This input value must be provided by the user. No default value.

A-19.3.2 Sludge solids concentration in dewatered sludge, SS. This input value should be provided by the user whenever possible. However, if no value is available, default value = 20 percent.

A-19.3.3 Percent volatile solids in dewatered sludge, VSP, percent of total solids dry weight. Default value = 35 percent.

A-19.3.4 Percent volatile solids destroyed during composting, VSC, percent of sludge volatile solids dry weight. Default value = 45 percent.

A-19.3.5 Compost product percent solids, CSP. Default value = 65 percent.

A-19.3.6 Compost product specific weight, SR. Default value = 1,000 lb/yd^3.

A-19.3.7 Mixed dewatered sludge and bulking agent specific weight, SM. Default value = 1,100 lb/yd^3.

A-19.3.8 Bulking agent mixed with dewatered sludge, BA. Default value = 2.5 yd^3/ton dewatered sludge.

A-19.3.9 New bulking agent mixing ratio, NB. Bulking agent is a function of several factors, including quantity and solids content of sludge processed, characteristics of the bulking agent, and efficiency of screening. Default value = (BA) (0.25) yd^3/ton dewatered sludge.

A-19.3.10 New bulking agent specific weight, SNB. Default value = 500 lb/yd^3.

A-19.3.11 Recycled bulking agent mixing ratio, RB. Default value = (BA) (0.75) yd^3/ton dewatered sludge.

A-19.3.12 Recycled bulking agent specific weight, SRB. Default value = 600 lb/yd^3.

A-19.3.13 Bulking agent in compost product, BP. Default value is calculated by:

$$BP = \frac{(NB)\ (SRB)\ (DSS)\ (100)}{(SS)\ (2{,}000)}$$

where

BP = Bulking agent compost product, lb/day.
2,000 = Conversion factor, lb/ton.

A-19.3.14 Truck unloading and mixing area, AUM. Default value = 300 ft^2/ton of dry solids/day to be composted.

A-19.3.15 Composting area, AC. Default value = 7,000 ft^2/ton dry solids/day to be composted.

A-19.3.16 Drying area, AD. Default value = 300 ft^2/ton dry solids/day to be composted.

A-19.3.17 Finished compost storage area, ACS. Default value = 900 ft^2/ton dry solids/day to be composted. Equivalent to approximately 9 days of storage.

A-19.3.18 Bulking agent storage area, AB. Default value = 2,000 ft^2/ton dry solids/day to be composted.

A-19.3.19 Fraction of composting site requiring clearing of brush and trees, FWB. Varies significantly depending on site-specific conditions. Default value = 0.7.

A-19.3.20 Fraction of composting site requiring light grading, FRLG. Varies significantly depending on site-specific conditions. Default value = 0.3.

A-19.3.21 Fraction of composting site requiring medium grading, FRMG. Varies significantly depending on site-specific conditions. Default value = 0.4.

A-19.3.22 Fraction of composting site requiring extensive grading, FREG. Varies significantly depending on site-specific conditions. Default value = 0.3.

A-19.4 Process Design Calculations

A-19.4.1 Calculate daily wet weight of dewatered sludge to be composted.

$$DS = \frac{(SV)\ (8.34)}{(2,000)} \left[\frac{1}{\frac{100 - (SS)}{100} + \frac{(SS)}{(1.42)\ (100)}} \right]$$

where

DS = Daily wet weight of dewatered sludge, tons/day.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.
1.42 = Assumed specific gravity of sludge solids.

A-19.4.2 Calculate daily dry solids weight of dewatered sludge to be composted.

$$DSS = \frac{(2,000)\ (SS)\ (DS)}{(100)}$$

where

DSS = Daily dry solids weight of dewatered sludge, lb/day.
2,000 = Conversion factor, lb/ton.

Note: In many cases, the user will know the daily dry solids weight of dewatered sludge, DSS, prior to using the program. If so, DS can be back-calculated as follows:

$$DS = \frac{(DSS)\ (100)}{(SS)\ (2,000)}$$

Similarly, SV can be back-calculated, using the formula in Appendix A-19.4.1.

A-19.4.3 Calculate bulking agent in compost product, BP, default value, if required.

$$BP = \frac{(NB)\ (SRB)\ (DSS)\ (100)}{(SS)\ (2,000)}$$

where

BP = Default value for BP, lb/day.
2,000 = Conversion factor, lb/ton.

A-19.4.4 Calculate weight of volatile solids in sludge composted per day.

$$VSS = \frac{(VSP)}{(100)} \times (DSS)$$

where

VSS = Daily volatile solids weight, lb/day.

A-19.4.5 Calculate volatile solids destroyed during composting.

$$VSD = \frac{(VSC)\ (VSS)}{100}$$

where

VSD = Sludge volatile solids weight destroyed during composting, lb/day.

A-19.4.6 Bulking agent required.

A-19.4.6.1 Calculate weight of bulking agent.

$$BAW = \frac{(NB)\ (SNB) + (RB)\ (SRB)}{2{,}000}\ DS$$

where

BAW = Bulking agent weight, tons/day.
2,000 = Conversion factor, lb/ton.

A-19.4.6.2 Calculate volume of bulking agent.

$$BAV = (BA)\ (DS)$$

where

BAV = Bulking agent volume, yd^3/day.

A-19.4.7 Calculate volume of mixed dewatered sludge and bulking agent to be composted.

$$MV = \frac{(DS + BAW)\ (2{,}000)}{SM}$$

where

MV = Volume of mixed sludge and bulking agent to be composted, yd^3/day.

A-19.4.8 Calculate volume of screened compost required for insulation of aerated piles.

$$SCV = \frac{(DSS)\ (2.15)}{SR}$$

where

SCV = Volume of screened compost, yd^3/day.

A-19.4.9 Quantity of compost produced.

A-19.4.9.1 Calculate weight of compost produced.

$$CPW = \frac{DSS - VSD + BP}{(CSP)\ (20)}$$

where

CPW = Compost produced, tons/day.

A-19.4.9.2 Calculate volume of compost produced.

$$CPV = \frac{(DSS - VSD + BP)\ (100)}{(CSP)\ (SR)}$$

where

CPV = Compost produced, yd^3/day.

A-19.4.10 Calculate total area required.

$$AT = (1.5)\ (DSS)\ \frac{(AUM + AC + AD + ACS + AB)}{(43{,}560)\ (2{,}000)}$$

where

AT = Total area required, acres.

1.5 = Factor to account for additional land area required for buffer, storage, etc.

A-19.4.11 Calculate housing area required.

$$HA = (0.000028735)\ (DS)^3 - (0.029885)\ (DS)^2 + (16.161)\ (DS) + 1{,}600$$

where

HA = Building area, ft^2.

This equation is a multiple regression curve fit based on conceptual building areas required for sludge composting operations between 50 and 600 tons/day of dewatered sludge solids.

A-19.5 Process Design Output Data

A-19.5.1 Dewatered sludge (wet weight) to be composted, DS, tons/day.

A-19.5.2 Dry solids weight of sludge to be composted, DSS, lb/day.

A-19.5.3 Weight of bulking agent required, BAW, tons/day.

A-19.5.4 Volume of bulking agent required, BAV, yd^3/day.

A-19.5.5 Volume of mixed sludge and bulking agent to be composted, MV, yd^3/day.

A-19.5.6 Weight of compost produced, CPW, tons/day.

A-19.5.7 Volume of compost produced, CPV, yd^3/day.

A-19.5.8 Compost recycled to insulate aerated piles, SCV, yd^3/day.

A-19.5.9 Total area required, AT, acres.

A-19.5.10 Building area required, HA, ft^2.

A-19.6 Quantities Calculations

A-19.6.1 Calculate annual fuel usage. Fuel for mixing machines and other mobile equipment used in the process is a function of the quantity of dewatered sludge processed:

$$FU = [- (0.1016)\ (DS)^2 + (222.64)\ (DS) + (7{,}744)]$$

where

FU = Annual fuel requirement, gal/yr.

This equation is a multiple regression curve fit based on fuel usage for conceptual composting operations between 50 and 600 tons/day of dewatered sludge.

A-19.6.2 Calculate annual electrical energy requirement. Electricity for aeration and screening is a function of the quantity of dewatered sludge processed:

$$EU = (DS)\ (400)$$

where

EU = Annual electrical energy requirement, kWhr/yr.

A-19.6.3 Calculate annual bulking agent required.

$$BAU = (NB)\ (DS)\ (365)$$

where

BAU = Bulking agent usage, yd^3/yr.

A-19.6.4 Calculate annual operation and maintenance labor requirement. Operation and maintenance labor is a function of the quantity of dewatered sludge processed.

$$L = [- (0.0331)\ (DS)^2 + (61.03)\ (DS) + (1,959)]$$

where

L = Operation and maintenance labor requirement, hr/yr.

This equation is a multiple regression curve fit based on labor requirements for conceptual composting operations between 50 and 600 tons/day of dewatered sludge.

A-19.7 Quantities Calculations Output Data

A-19.7.1 Annual fuel requirement, FU, gal/yr.

A-19.7.2 Annual electrical energy requirement, EU, kWhr/yr.

A-19.7.3 Annual bulking agent required, BAU, yd^3/yr.

A-19.7.4 Annual operation and maintenance labor requirement, L, hr/yr.

A-19.8 Unit Price Input Required

A-19.8.1 Current Engineering News Record Construction Cost Index, ENRCCI.

A-19.8.2 Current Marshall and Swift Equipment Cost Index, MSECI.

A-19.8.3 Cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-19.8.4 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-19.8.5 Cost of bulking agent, COSTB, $\$/yd^3$. Default value = $\$15.00/yd^3$ (ENRCCI/4,006).

A-19.8.6 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-19.8.7 Cost of land, LANDCST, \$/acre. Default value = \$3,000/acre (ENRCCI/4,006).

A-19.8.8 Cost of clearing brush and trees, BCRCST, \$/acre. Default value = \$1,500/acre (ENRCCI/4,006).

A-19.8.9 Cost of light grading earthwork, LGECST, \$/acre. Default value = \$1,000/acre (ENRCCI/4,006).

A-19.8.10 Cost of medium grading earthwork, MGECST, \$/acre. Default value = \$2,500/acre (ENRCCI/4,006).

A-19.8.11 Cost of extensive grading earthwork, EGECST, \$/acre. Default value = \$5,000/acre (ENRCCI/4,006).

A-19.9 Cost Calculations

A-19.9.1 Cost of land.

$$COSTLAND = (AT)\ (LANDCST)$$

where

COSTLAND = Total land cost for composting site, \$.

A-19.9.2 Cost of clearing brush and trees.

$$COSTCBT = (AT)\ (FWB)\ (BCRCST)$$

where

COSTCBT = Total cost to clear brush and trees, \$.

A-19.9.3 Cost of grading earthwork.

$$COSTEW = (AT)\ [(FRLG)\ (LGECST) + (FRMG)\ (MGECST) + (FREG)\ (EGECST)]$$

where

COSTEW = Cost of earthwork grading, \$.

A-19.9.4 Cost of composting pad construction. This cost includes construction of pads and purchase and installation of piping and blowers.

$$COSTCP = \left[\frac{(DSS)\ (AC)\ (3.15)}{(2,000)}\right] \frac{ENRCCI}{4,006}$$

where

COSTCP = Cost of composting pads, \$.
3.15 = Unit cost of composting pads, \$/ft^2.

A-19.9.5 Cost of equipment. Mobile equipment and screening equipment costs are a function of the quantity of dewatered sludge processed using the following equation:

$$COSTEQ = [- 5.4\ (DS)^2 + 5{,}855\ (DS) + 435{,}000]\ \frac{MSECI}{751}$$

where

COSTEQ = Total cost of equipment, $.

This equation is a multiple regression curve fit based on the 1983 cost of equipment required for composting operations.

A-19.9.6 Cost of unloading and mixing structure.

$$COSTUM = \left[\frac{(DSS)\ (AUM)\ (20)}{(2{,}000)}\right] \frac{ENRCCI}{4{,}006}$$

where

COSTUM = Cost of unloading and mixing structure, $.
20 = Unit cost of unloading and mixing structure, $\$/ft^2$.

A-19.9.7 Cost of drying structure.

$$COSTD = \left[\frac{(DSS)\ (AD)\ (20)}{(2{,}000)}\right] \frac{ENRCCI}{4{,}006}$$

where

COSTD = Cost of drying structure, $.
20 = Unit cost of drying structure, $\$/ft^2$.

A-19.9.8 Cost of operation and maintenance building.

$$COSTH = (HA)\ (50)\ \frac{(ENRCCI)}{(4{,}006)}$$

where

COSTH = Cost of operation and maintenance building, $.
50 = Unit cost of operation and maintenance building, $\$/ft^2$.

A-19.9.9 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-19.9.10 Annual cost of fuel.

$$COSTFL = (FU)\ (COSTDF)$$

where

COSTFL = Annual cost of fuel, \$/yr.

A-19.9.11 Annual cost of electrical energy.

$$COSTEL = (EU)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-19.9.12 Cost of bulking agent.

$$COSTBA = (BAU)\ (COSTB)$$

where

COSTBA = Annual cost of bulking agent, \$/yr.

A-19.9.13 Annual cost of parts and material.

$$COSTPM = (0.15)\ (COSTEQ)\ \frac{MSECI}{751}$$

where

COSTPM = Cost of parts and material, \$/yr.

0.15 = Annual cost of parts and materials is assumed to be 15 percent of equipment capital cost.

A-19.9.14 Total base capital cost.

$$TBCC = COSTLAND + COSTCBT + COSTEW + COSTCP + COSTEQ + COSTUM + COSTD + COSTH$$

where

TBCC = Total base capital cost, $.

A-19.9.15 Annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTFL + COSTEL + COSTBA + COSTPM$$

where

COSTOM = Total operation and maintenance cost, \$/yr.

A-19.10 Cost Calculations Output Data

A-19.10.1 Cost of land for composting site, COSTLAND, $.

A-19.10.2 Cost to clear brush and trees from site, COSTCBT, $.

A-19.10.3 Cost of grading earthwork, COSTEW, $.

A-19.10.4 Cost of composting pad construction, COSTCP, $.

A-19.10.5 Cost of equipment, COSTEQ, $.

A-19.10.6 Cost of unloading and mixing structure, COSTUM, $.

A-19.10.7 Cost of drying structure, COSTD, $.

A-19.10.8 Cost of operation and maintenance building, COSTH, $.

A-19.10.9 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-19.10.10 Annual cost of fuel, COSTFL, $/yr.

A-19.10.11 Annual cost of electrical energy, COSTEL, $/yr.

A-19.10.12 Annual cost of bulking agent, COSTBA, $/yr.

A-19.10.13 Annual cost of parts and material, COSTPM, $/yr.

A-19.10.14 Total base capital cost, TBCC, $.

A-19.10.15 Annual operation and maintenance cost, COSTOM, $/yr.

APPENDIX A-20

LIQUID SLUDGE TRUCK HAULING, INCLUDING SLUDGE LOADING FACILITIES

A-20.1 Background

Truck hauling is a flexible and widely used method for transporting sludge to a disposal site or other sludge management facility. Truck hauling is most applicable at small- and medium-sized treatment facilities. One advantage of truck hauling is the flexibility that it provides, since terminal points and haul routes can be changed readily at relatively low cost. Generally, truck hauling is more economical than railroad or pipeline when transporting sludges less than 150 miles. Diesel-equipped vehicles are the economic choice for larger trucks and trucks with high annual mileage operation.

Specially designed tank trucks are used for hauling liquid sludge (sludge containing less than 15 percent solids). Tank configurations and volumes vary depending on sludge loading and unloading times, haul distance, and frequency of trips. In most applications, tanker trucks for hauling liquid sludge are usually less than 6,000 gallons. Tanker dimensions and maximum load of the vehicle are limited by state law.

In the following algorithm, capital costs include purchase of specially designed tank trucks and construction of sludge loading facilities at the treatment plant. The loading facility consists of a concrete slab and appropriate piping and valving set at a height of 12 ft to load the tanker from the top. Base annual O&M costs include driver labor, operational labor, fuel, vehicle maintenance, and loading facility maintenance.

A-20.1.1 Algorithm Development

Fuel and labor requirements used for computation of O&M cost equations in this algorithm were derived from communications with truck and equipment manufacturers. Additional information used in development of cost equations was obtained from Reference 11, pages 6, 7, 31, 33, 39, 40, 42, 60, 61, 62, and 66.

A-20.2 Input Data

A-20.2.1 Daily sludge volume, SV, gal/day.

A-20.2.2 Truck loading time at treatment plant, LT, hr.

A-20.2.3 Truck unloading time at disposal site, ULT, hr.

A-20.2.4 Round trip haul time from treatment plant to disposal site, RTHT, hr.

A-20.2.5 Round trip haul distance from treatment plant to disposal site, RTHD, miles.

A-20.2.6 Work schedule for hauling, HPD, hr/day.

A-20.2.7 Number of days/yr when sludge is hauled, DPY, days/yr.

A-20.3 Design Parameters

A-20.3.1 Daily sludge volume, SV, gal/day. This input value must be furnished by the user. No default value.

A-20.3.2 Truck loading time at treatment plant, LT, hr. Default value = 0.4 hr.

A-20.3.3 Truck unloading time at disposal site, ULT, hr. Default value = 0.8 hr. See table below for guidance.

TYPICAL TRUCK UNLOADING TIME AS A FUNCTION
OF TYPE OF DISPOSAL UTILIZED

Type of Disposal	Typical Unloading Time, Hr
Landfill	0.4
Storage lagoon at disposal site	0.4
Agricultural utilization	1.0
Forest land utilization	1.5
Land reclamation utilization	1.0
Dedicated disposal site	0.6

A-20.3.4 Round trip haul time, from treatment plant to disposal site, RTHT, hr. No default value. This value must be input by user. If not available, this value can be estimated using an average mph for truck hauling, as follows:

A-20.3.4.1 Urban travel.

$$RTHT = \frac{\text{Round trip distance in miles}}{\text{25 miles/hr average speed}}$$

A-20.3.4.2 Rural travel.

$$RTHT = \frac{\text{Round trip distance in miles}}{\text{35 miles/hr average speed}}$$

A-20.3.4.3 Highway travel.

$$RTHT = \frac{\text{Round trip distance in miles}}{\text{45 miles/hr average speed}}$$

where

RTHT = Round trip haul time, hr.

A-20.3.5 Round trip haul distance from treatment plant to disposal site, RTHD, miles. No default value. If several sludge disposal sites are planned, e.g., private farmer agricultural utilization, use average distance to sites.

A-20.3.6 Daily work schedule for hauling, HPD, hr/day. Default value = 7 hr/day.

A-20.3.7 Days/yr of sludge hauling, DPY, days. Default value = 180 days/yr. See table below for guidance.

TYPICAL DAYS PER YEAR OF SLUDGE HAULING AS A FUNCTION OF TYPES OF DISPOSAL USED AND GEOGRAPHICAL REGION

Type of Disposal	Geographical Region	Typical Days/Yr of Sludge Hauling
Landfill or storage lagoon at disposal site	Northern U.S.	230
	Central U.S.	250
	Sunbelt States	260
Agricultural or land reclamation utilization	Northern U.S.	100
	Central U.S.	120
	Sunbelt States	140
Forest land utilization	Northern U.S.	160
	Central U.S.	180
	Sunbelt States	200
Dedicated disposal site	Northern U.S.	160
	Central U.S.	180
	Sunbelt States	200

A-20.4 Process Design Calculation

A-20.4.1 Number and capacity of sludge haul trucks. Liquid sludge is hauled in tanker trucks with capacities between 1,600 and 6,000 gal. The capacity of the tank trucks utilized is a function of the volume of sludge to be hauled per day and the round trip haul time. Special tanker capacities available are 1,600, 2,000, 2,500, 3,000, 4,000, and 6,000 gallons.

A-20.4.1.1 Total volume hauled per trip.

$$\text{FACTOR} = \frac{\text{SV (LT + ULT + RTHT) (365)}}{\text{HPD (DPY)}}$$

where

FACTOR = Gallons hauled per trip if only one truck were utilized.

A-20.4.1.2 Number of vehicles and capacity of each truck. The number of vehicles is calculated using FACTOR and the following matrix:

FACTOR, gal	Number, NTR, and Capacity of Tanker Trucks, CAP, Gal
<1,600	1 at 1,600
>1,600 but <2,500	1 at 2,500
>2,500 but <4,000	1 at 4,000
>4,000 but <8,000	2 at 4,000
>8,000 but <12,000	2 at 6,000
>12,000	All 6,000

If FACTOR exceeds 12,000, $\text{NTR} = \frac{\text{Factor}}{6{,}000}$ (Round to next highest integer.)

where

CAP = Capacity of tanker trucks required, gal, calculated from above matrix.

NTR = Number of trucks required. Calculated from the above matrix.

A-20.5 Process Design Output Data

A-20.5.1 Capacity of tanker trucks, CAP, gal.

A-20.5.2 Number of trucks required, NTR.

A-20.6 Quantities Calculations

A-20.6.1 Number of round trips/yr.

$$\text{NRT} = \frac{\text{SV (365)}}{\text{CAP}}$$

where

NRT = Number of round trips/yr.

A-20.6.2 Driver labor requirement

$$DT = [LT + ULT + RTHT]\ NRT$$

where

DT = Driver labor requirement, hr/yr.

A-20.6.3 Calculate annual fuel requirement. Vehicle fuel usage is a function of truck size. The following fuel usage values are typical for different capacity trucks.

Truck Capacity, CAP, gal	Fuel Consumption, FC, mpg
1,600	8
2,500	7
4,000	6
6,000	5

$$FU = \frac{(RTHD)\ (NRT)}{FC}$$

where

FU = Annual fuel requirement, gal/yr
FC = Fuel consumption rate, mpg, see table above.

A-20.7 Quantities Calculations Output Data

A-20.7.1 Number of round trips/yr, NRT.

A-20.7.2 Driver labor requirement, DT, hr/yr.

A-20.7.3 Annual fuel requirement, FU, gal/yr.

A-20.8 Unit Price Input Required

A-20.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-20.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is made.

A-20.8.3 Cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-20.8.4 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-20.9 Cost Calculations

A-20.9.1 Cost of sludge tanker trucks.

$$TTCOST = (NTR)\ (COSTSTT)\ \frac{MSECI}{751}$$

where

TTCOST = Total cost of all sludge tanker trucks, $.
COSTSTT = Cost per sludge tanker truck, obtained from the table below.

Tanker Capacity, CAP, gal	Cost of Truck, COSTSTT, 1983 $
1,600	60,000
2,500	80,000
4,000	100,000
6,000	120,000

A-20.9.2 Cost of vehicle loading area facilities. The tanker truck loading facilities are assumed to consist of a concrete slab, appropriate piping and valving to a height of 12 ft to load the tanker from the top. Cost of the loading area facilities are assumed to be a function of sludge volume, SV, in gal/yr. The relationship of SV to loading area facilties cost is graduated in a stepped manner.

$$COSTLA = (CSTLAB)\ \frac{ENRCCI}{4,006}$$

where

COSTLA = Total capital cost of loading area facilities, $.

CSTLAB = Base cost of loading area facilities, $. This is a function of the annual volume of sludge hauled, SV, in gal/yr, and can be obtained from the table below.

Annual Volume of Sludge Hauled, SV x 365, gal/yr	Base Cost of Loading Area Facilities, COSTLAB, $
100,000 to 500,000	20,000
500,000 to 1,000,000	30,000
1,000,000 to 2,000,000	40,000
2,000,000 to 4,000,000	50,000
4,000,000 to 8,000,000	60,000
8,000,000 to 12,000,000	70,000
12,000,000 to 16,000,000	80,000
16,000,000 to 20,000,000	90,000
20,000,000 and over	100,000

A-20.9.3 Annual vehicle maintenance cost. Maintenance cost per vehicle mile traveled is a function of truck capacity and initial cost of truck. The following factors are used to calculate vehicle maintenance costs.

Truck Capacity, CAP, Gal	Maintenance Cost, MCM, $/mile Traveled, 1983
1,600	0.28
2,500	0.32
4,000	0.36
6,000	0.40

$$VMC = (RTHD)\ (NRT)\ (MCM)\ \frac{(MSECI)}{(751)}$$

where

VMC = Annual vehicle maintenance cost, $.
MCM = Maintenance cost per mile traveled, $/mile from table above.

A-20.9.4 Loading area facility annual maintenance cost. For the purposes of this program, it is assumed that loading area facilities annual maintenance cost is a function of loading area facility capital cost.

$$MCOSTLA = (COSTLA)\ (0.05)$$

where

MCOSTLA = Annual maintenance cost for loading facilities, $/yr.

0.05 = Assumed annual maintenance cost factor as a function of total loading area facility capital cost.

A-20.9.5 Annual cost of operation labor

$$COSTLB = (DT)\ (COSTL)\ (1.2)$$

where

COSTLB = Annual cost of operation labor, $/yr.

1.2 = A factor to account for additional labor required at the loading facility.

A-20.9.6 Annual cost of diesel fuel.

$$COSTDSL = (FU)\ (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, \$/yr.

A-20.9.7 Total base capital cost.

$$TBCC = TTCOST + COSTLA$$

where

TBCC = Total base capital cost, \$.

A-20.9.8 Annual operation and maintenance cost.

$$COSTOM = (VMC) + (MCOSTLA) + (COSTLB) + (COSTDSL)$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-20.10 Cost Calculation Output Data

A-20.10.1 Total cost of sludge tanker trucks, TTCOST, \$.

A-20.10.2 Total capital cost of loading area facilities, COSTLA, \$.

A-20.10.3 Annual vehicle maintenance cost, VMC, \$/yr.

A-20.10.4 Annual loading facility maintenance cost, MCOSTLA, \$/yr.

A-20.10.5 Annual cost of operation labor, COSTLB, \$/yr.

A-20.10.6 Annual cost of diesel fuel, COSTDSL, \$/yr.

A-20.10.7 Total base capital cost, TBCC, \$.

A-20.10.8 Total annual operation and maintenance cost, COSTOM, \$/yr.

APPENDIX A-21

DEWATERED SLUDGE TRUCK HAULING,
INCLUDING SLUDGE LOADING FACILITIES

A-21.1 Background

Truck hauling is a commonly employed sludge transport method, particularly at small and medium treatment facilities. Truck hauling is less capital-intensive than other transport methods for hauling sludges over distances less than 150 miles. An additional benefit of this method is the flexibility that it provides when changing terminal points and haul routes.

Dewatered sludge (sludge containing more than 15 percent solids) is hauled in trucks similar to general purpose or standard highway trucks. Trucks are covered to minimize nuisances and to prevent inadvertent spillage. Standard truck capacities range from 7 to 36 yd^3; however, maximum loads are limited by state laws. Diesel-equipped vehicles are generally the most economic choice for larger trucks and trucks with high annual mileage operation.

Capital costs in the following algorithm include construction of a truck loading facility designed to accommodate the sludge volume within the operating schedule. Costs include construction of a concrete loading slab, and purchase of skip loaders and trucks. Annual O&M costs include vehicle and loading facility maintenance, driver and operational labor, and diesel fuel for vehicles.

A-21.1.1 Algorithm Development

In the following algorithm, cost and O&M requirement equations were developed from Reference 11, Pages 10, 11, 28, 30, 32, 34, 39, 41, 43, 60, 61, 62, and 66. Additional information used in cost equations was supplied by truck and equipment manufacturers.

A-21.2 Input Data

A-21.2.1 Daily sludge volume, SV, gal/day.

A-21.2.2 Truck loading time at treatment plant, LT, hr.

A-21.2.3 Truck unloading time at disposal site, ULT, hr.

A-21.2.4 Round trip haul time from treatment plant to disposal site, RTHT, hr.

A-21.2.5 Round trip haul distance from treatment plant to disposal site, RTHD, miles.

A-21.2.6 Work schedule for hauling, HPD, hr/day.

A-21.2.7 Number of days/yr when sludge is hauled, DPY, days/yr.

A-21.3 Design Parameters

A-21.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-21.3.2 Truck loading time at treatment plant, LT, hr. Default value = 0.4 hr.

A-21.3.3 Truck unloading time at disposal site, ULT, hr. Default value = 0.8 hr. See table below for guidance.

Type of Disposal	Typical Unloading Time, ULT, hr
Landfill	0.4
Storage lagoon at disposal site	0.4
Agricultural utilization	1.0
Forest land utilization	1.5
Land reclamation utilization	1.0
Dedicated disposal site	0.6

A-21.3.4 Round trip haul time from treatment plant to disposal site, RTHT, hr. No default value. This value must be input by user. If a value is not available, it can be estimated using average miles per hour for haul truck, as follows:

A-21.3.4.1 Urban travel.

$$RTHT = \frac{\text{Round trip distance in miles}}{\text{25 miles per hour average speed}}$$

A-21.3.4.2 Rural travel.

$$RTHT = \frac{\text{Round trip distance in miles}}{\text{35 miles per hour average speed}}$$

A-21.3.4.3 Highway travel.

$$RTHT = \frac{\text{Round trip distance in miles}}{\text{45 miles per hour average speed}}$$

where

RTHT = Round trip haul time, hr.

A-21.3.5 Round trip haul distance from treatment plant to disposal site, RTHD, miles. No default value. If several sludge disposal sites are planned, e.g., private farmer agricultural utilization, use average distance to sites.

A-21.3.6 Daily work schedule for hauling, HPD, hr/day. Default value = 7 hr/day.

A-21.3.7 Days/yr of sludge hauling, DPY, days/yr. Default value = 180 days per year. See table below for guidance.

TYPICAL DAYS/YEAR OF SLUDGE HAULING AS A FUNCTION OF THE TYPES OF DISPOSAL USED AND GEOGRAPHICAL REGION

Type of Disposal	Geographical Region	Typical Days/Yr of Sludge Hauling
Landfill or storage lagoon at disposal site	Northern U.S.	230
	Central U.S.	250
	Sunbelt States	260
Agricultural or land reclamation utilization	Northern U.S.	100
	Central U.S.	120
	Sunbelt States	140
Forest land utilization	Northern U.S.	160
	Central U.S.	180
	Sunbelt States	200
Dedicated disposal site	Northern U.S.	160
	Central U.S.	180
	Sunbelt States	200

A-21.4 Process Design Calculations

A-21.4.1 Annual sludge volume hauled, yd^3/yr. Trucks which haul dewatered sludge are sized in terms of yd^3 of capacity. Therefore, it is necessary to convert gal of dewatered sludge to yd^3 of dewatered sludge.

$$SVCY = \frac{(SV)\ (365)}{202}$$

where

SVCY = Sludge volume hauled, yd^3/yr.
SV = Sludge volume, gal/day.
202 = Conversion factor, gal/yd^3

A-21.4.2 Number and capacity of sludge haul trucks. Dewatered sludge is hauled in trucks with capacities between 7 and 36 yd^3. The capacity of the trucks utilized is a function of the volume of sludge to be hauled per day and the round trip hauling time. Typical capacities available are 7, 10, 15, 25, and 36 yd^3.

A-21.4.2.1 Total sludge volume hauled per day.

$$FACTOR = \frac{SVCY\ (LT + ULT + RTHT)}{(HPD)\ (DPY)}$$

where

FACTOR = Yd^3 which would have to be hauled per trip if only one truck were utilized.

A-21.4.2.2 Capacity and number of haul vehicles. Capacity and number of haul vehicles are calculated using FACTOR and the following matrix:

FACTOR, yd^3	Number, NTR, and Capacity of Trucks, CAP, yd^3
<7	1 at 7
7 to 10	1 at 10
10 to 15	1 at 15
15 to 25	1 at 25
25 to 36	1 at 36
36 to 50	2 at 25
50 to 72	2 at 36

If FACTOR exceeds 72 use:

$NTR = \frac{FACTOR}{36}$ (Round to next highest integer). CAP = 36 yd^3.

where

CAP = Capacity of truck required, yd^3.
NTR = Number of trucks required. Calculated from the above matrix.

A-21.5 Process Design Output Data

A-21.5.1 Annual sludge volume hauled, SVCY, yd^3/yr.

A-21.5.2 Capacity of truck, CAP, yd^3.

A-21.5.3 Number of trucks required, NTR.

A-21.6 Quantities Calculations

A-21.6.1 Number of round trips/yr.

$$NRT = \frac{SVCY}{CAP}$$

where

NRT = Number of round trips/yr (round to next highest integer).

A-21.6.2 Driver time.

$$DT = [LT + ULT + RTHT]\ NRT$$

where

DT = Driver time, hr/yr.

A-21.6.3 Annual fuel requirement. Vehicle fuel usage is a function of truck size. The following fuel usage values are typical for different capacity trucks.

Truck Capacity, CAP, yd^3	Fuel Consumption, FC, miles/gal
7	9
10	8
15	7
25	6
36	5

$$FU = \frac{(RTHD)\ (NRT)}{FC}$$

where

FU = Annual fuel requirement, gal/yr.
FC = Fuel consumption rate, miles/gal, see table above.

A-21.7 Quantities Calculations Output Data

A-21.7.1 Number of round trips/yr, NRT.

A-21.7.2 Driver labor requirement, DT, hr/yr.

A-21.7.3 Annual fuel requirement, FU, gal/yr.

A-21.8 Unit Price Input Required

A-21.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-21.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is made.

A-21.8.3 Cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-21.8.4 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-21.9 Cost Calculations

A-21.9.1 Cost of sludge haul trucks.

$$TCOSTTRK = (NTR)\ (COSTTRK)\ \frac{MSECI}{751}$$

where

TCOSTTRK = Total cost of dewatered sludge haul trucks, \$.
COSTTRK = Cost per truck, obtained from the table below.

Truck Capacity, CAP, yd^3	Cost of Truck, COSTTRK, 1983 \$
7	65,000
10	98,000
15	130,000
25	171,000
36	214,000

A-21.9.2 Cost of vehicle loading facilities. Truck loading facilities are assumed to consist of a concrete slab, one or more skip loaders to load the trucks, and miscellaneous improvements such as drainage, lighting, etc. Cost of the truck loading facilities are assumed to be a function of sludge volume in yd^3/yr (SVCY). The relationship of SVCY to loading area facilities cost is graduated in a stepped manner and depends upon the number of loading vehicles required.

$$COSTLA = (COSTLAB)\ \frac{ENRCCI}{4,006}$$

where

COSTLA = Total capital cost of loading area facilities, \$.

COSTLAB = Base cost of loading area facilities, $. This is a function of the annual volume of sludge hauled, SVCY, and can be obtained from the table below.

Annual Volume of Sludge Hauled, SVCY, yd^3	Base Cost of Loading Area Facilities, COSTLAB, $
500 to 2,500	40,000
2,500 to 5,000	45,000
5,000 to 10,000	50,000
10,000 to 20,000	80,000
20,000 to 40,000	90,000

Annual Volume of Sludge Hauled, SVCY, yd^3	Base Cost of Loading Area Facilities, COSTLAB, $
40,000 to 60,000	100,000
60,000 to 80,000	150,000
80,000 to 100,000	185,000
100,000 and over	220,000

A-21.9.3 Annual vehicle maintenance cost. Maintenance cost per vehicle mile traveled is a function of truck capacity and initial cost of the truck. The following factors are used to calculate vehicle maintenance costs.

Truck Capacity, CAP, yd^3	Maintenance Cost, MCM, $/mile Traveled, 1983
7	0.26
10	0.32
15	0.37
25	0.45
36	0.53

$$VMC = (RTHD)\ (NRT)\ (MCM)\ \frac{MSECI}{751}$$

where

VMC = Annual maintenance cost, $/yr.
MCM = Maintenance cost/mile travelled, $/mile, from table above.

A-21.9.4 Annual maintenance cost for loading area facilities. For the purposes of this program, it is assumed that loading area facilities annual maintenance cost is a function of loading area facilities capital cost.

$$MCOSTLA = (COSTLA)\ (0.05)$$

where

MCOSTLA = Annual maintenance cost for loading area facilities, $/yr.

0.05 = Assumed annual maintenance cost factor as a function of total loading area facilities capital cost.

A-21.9.5 Annual cost of operational labor.

$$COSTLB = (DT)\ (COSTL)\ (1.2)$$

where

COSTLB = Annual cost of operational labor, $/yr.

1.2 = A factor to account for additional labor required at loading facility.

A-21.9.6 Annual cost of diesel fuel.

$$COSTDSL = (FU)\ (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, $/yr.

A-21.9.7 Total base capital cost.

$$TBCC = TCOSTTRK + COSTLA$$

where

TBCC = Total base capital cost, $.

A-21.9.8 Annual operation and maintenance cost.

$$COSTOM = (VMC) + (MCOSTLA) + (COSTLB) + (COSTDSL)$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-21.10 Cost Calculation Output Data

A-21.10.1 Total cost of dewatered sludge haul trucks, TCOSTTRK, $.

A-21.10.2 Total capital cost of loading area facilities, COSTLA, $.

A-21.10.3 Annual vehicle maintenance cost, VMC, $/yr.

A-21.10.4 Annual loading facility maintenance cost, MCOSTLA, $/yr.

A-21.10.5 Annual cost of operation labor, COSTLB, $/yr.

A-21.10.6 Annual cost of diesel fuel, COSTDSL, $/yr.

A-21.10.7 Total base capital cost, TBCC, $.

A-21.10.8 Total annual operation and maintenance cost, COSTOM, $/yr.

APPENDIX A-22

LIQUID SLUDGE TRANSPORT BY RAIL

A-22.1 Background

Rail transport of liquid sludge can be a cost-effective and energy-efficient operation. The use of this means of liquid sludge transport is, however, limited for several reasons, which include:

- The operation requires fixed terminal points. In order to make rail hauling a truly viable option, generally both the treatment plant and the disposal site must be located close to the railhead.
- There is an ongoing administrative burden. Because of its more labor intensive nature and because contractual agreements are made with the railroad company, a higher administrative cost is associated with a rail haul operation than with some other forms of sludge transportation.
- Operations are more vulnerable to labor disputes and strikes.
- There is a potential risk of spills due to the possibility of leaking valves and derailment.
- In the event of an unforeseen requirement for terminal point relocation, the choices will be severely limited.

Despite these drawbacks, when geographic and economic conditions are suitable, the use of rail hauling can be a viable option. However, use of rail transport for small quantities of sludges or over short distances is not economical when compared with other transport alternatives.

The physical operation of a liquid sludge rail hauling system is simple. Liquid sludge is pumped from a storage containment directly into tank cars. The cars are then transported to the disposal site (or possibly to a receiving point for another form of transportation) where they are unloaded, usually by gravity flow. Loading and unloading facilities and labor requirements are generally provided by the wastewater treatment authority. Tank cars themselves and their maintenance are usually contracted for, since the amortization on the purchase of a tank car can be at a considerably higher cost than that of leasing.

Capital costs obtained using the following algorithm include: loading and unloading rail sidings and switches; site work and buildings at loading and unloading facilities; and pumps and piping for loading tank cars. Rail cars are assumed to discharge by gravity into the unloading storage facility.

O&M costs include: railroad haul fees; rail tank car lease; facility operation and maintenance labor; facility operation and maintenance supplies; electrical energy; and rail maintenance.

A-22.1.1 Algorithm Development

Cost and O&M requirement equations for the following algorithm were obtained from information presented in Reference 11, pages 21, 50, 52, 60, 61, and 62. Rail hauling rates for bulk liquids were quoted by the Southern Pacific Transportation Company. Factors for rate adjustment due to regional variations included in the algorithm are based on Reference 11, page 68.

A-22.2 Input Data

A-22.2.1 Daily sludge volume, SV, gal/day.

A-22.2.2 Sludge specific gravity, SSG, unitless.

A-22.2.3 Round trip haul distance, RTHD, miles.

A-22.3 Design Parameters

A-22.3.1 Daily sludge volume, SV, gal/day. This input value must be furnished by the user. No default value.

A-22.3.2 Sludge specific gravity, SSG, unitless. This valuve should be provided by the user. If not available, default value is calculated with the following equation:

$$SSG = \frac{1}{\frac{100-SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-22.3.3 Round trip haul distance, RTHD, miles. Typical values range from 40 to 640 miles. No default value.

A-22.4 Process Design Calculations

A-22.4.1 Wet weight of sludge transported per year.

$$TS = \frac{(SV)\ (SSG)\ (8.34)\ (365)}{(2,000)}$$

where

TS = Wet weight of sludge transported per year, tons/yr.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.

A-22.4.2 Carloads per year. A standard 20,000-gal capacity railroad tank car is assumed in the cost estimate.

$$CLPY = \frac{(SV)\ (365)}{20,000}$$

where

CLPY = Carloads/yr.

A-22.4.3 Total load and unload time, obtained using the following table:

Daily Sludge Volume, SV (gal/day)	Total Load and Unload Time, TLUT (Hr)
20,500	10
41,000	11
205,500	12
410,000	14
2,055,000	38

where

TLUT = Total load and unload time, hr.

A-22.4.4 Transit time, obtained using the following table:

RTHD (Miles)	Transit Time, TRANST (Hr)
40	96
80	96
160	144
320	168
640	192

where

TRANST = Transit time, hr.

A-22.4.5 Total round trip time.

$$TRTT = TLUT + TRANST$$

where

TRTT = Total round trip time, hr.

A-22.4.6 Number of rail tank cars required.

$$NRTCR = \frac{(CLPY)\ (TRTT)}{(365)\ (24)}$$

where

NRTCR = Number of rail tank cars required.

A-22.5 Process Design Output Data

A-22.5.1 Wet weight of sludge transported per year, TS, tons/yr.

A-22.5.2 Carloads per year, CLPY.

A-22.5.3 Total load and unload time, TLUT, hr.

A-22.5.4 Transit time, TRANST, hr.

A-22.5.5 Total round trip time, TRTT, hr.

A-22.5.6 Number of rail tank cars required, NRTCR.

A-22.6 Quantities Calculations

A-22.6.1 Annual operation and maintenance labor requirement, obtained from the table below:

Daily Sludge Volume, SV (gal/day)	Annual Labor Required, L (hr/yr)
20,500	4,254
41,000	4,384
205,500	9,340
410,000	11,000
2,055,000	29,700

where

L = Operation and maintenance labor requirement, hr/yr.

A-22.6.2 Annual electrical energy requirement, obtained from the table below:

Daily Sludge Volume, SV (gal/day)	Annual Electrical Energy Requirement, E (kWhr/yr)
20,500	35,000
41,000	40,000
205,500	90,000
410,000	140,000
2,055,000	480,000

where

E = Annual electrical energy requirement, kWhr/yr.

A-22.7 Quantities Calculations Output Data

A-22.7.1 Annual operation and maintenance labor requirement, L, hr/yr.

A-22.7.2 Annual electrical energy requirement, E, kWhr/yr.

A-22.8 Unit Price Input Required

A-22.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-22.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-22.8.3 Region of country, REGION, NC = north central and central, NE = northeast, SE = southeast, SW = southwest, and WC = west coast. Default value = NC.

A-22.8.4 Railroad mileage credit (for shipper supplied railroad cars), RRMC, $/mile. Default value = $0.25/mile (ENRCCI/4,006).

A-22.8.5 Annual full maintenance rail tank car lease rate, ARTCLR, $/yr. Default = $9,000/yr (ENRCCI/4,006).

A-22.8.6 Cost of labor, COSTL, $/hr. Default value = $13.00/hr (ENRCCI/4,006).

A-22.8.7 Cost of electrical energy, COSTE, $/kWhr. Default value = $0.09/kWhr (ENRCCI/4,006).

A-22.9 Cost Calculations

A-22.9.1 Railroad facilities construction cost. The facilities include storage equal to one day's sludge production; loading pumps and piping sized to fill 1, 2, 10, 20, and 100 unit car trains in 1.5, 2, 3, and 15 hr, respectively; loading and unloading rail sidings and switches; and loading and unloading buildings and site work. Costs for storage at the unloading area can be obtained using algorithms presented in Appendices A-32 through A-34. Rail cars discharge by gravity into the unloading storage facilities.

Railroad facility construction costs are obtained using the following table:

Daily Sludge Volume, SV (gal/day)	Total Railroad Facilities Construction Cost, CRFCC* ($)
20,500	304,000
41,000	341,000
205,500	646,000
410,000	951,000
2,055,000	1,954,000

* 1983 value.

The construction cost should be updated using the Engineering News Record Construction Cost Index.

$$TRFCC = (CRFCC)\left(\frac{ENRCCI}{4,006}\right)$$

where

TRFCC = Railroad facilities construction cost, $.

A-22.9.2 Annual railway haul cost.

A-22.9.2.1 Calculate the point-to-point railroad haul cost.

$$RRHC = [(TS)\ (RR)\ (RFACT)]\ \frac{ENRCCI}{4,006}$$

where

RRHC = Railroad haul cost, $/yr.

RR = Unadjusted rail rate, $/ton. Rail rates should be obtained from the following table:

Round Trip Haul Distance, RTHD (Miles)	Unadjusted Rail Rate, RR, $/Ton of Sludge Hauled
40	3.55
80	5.10
160	6.90
320	11.00
640	21.10

RFACT = Regional cost adjustment factor which varies according to region of the United States. Values should be obtained from the following:

If REGION = NC, RFACT = 1.0
If REGION = NE, RFACT = 1.25
If REGION = SE, RFACT = 0.75
If REGION = SW, RFACT = 0.90
If REGION = WC, RFACT = 1.10

A-22.9.2.2 Calculate the railroad mileage cost credit (for shipper supplied railway tank cars).

$$RRMCC = (RTHD)\ (CLPY)\ (RRMC)$$

where

RRMCC = Railroad mileage cost credit, $/yr.

A-22.9.2.3 Calculate the total rail tank car lease cost.

$$TRTCLC = (NRTCR)\ (ARTCLR)$$

where

TRTCLC = Total rail tank car lease cost, $/yr.

A-22.9.2.4 Calculate the total annual railway haul cost.

$$TARHC = RRHC - RRMCC + TRTCLC$$

where

TARHC = Total annual railway haul cost, $/yr.

A-22.9.3 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of labor, $/yr.

A-22.9.4 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-22.9.5 Annual operation and maintenance supply cost, obtained from table below:

Daily Sludge Volume, SV (gal/day)	Unadjusted O&M Supply Cost, OMS ($/yr)
20,500	800
41,000	1,230
205,500	3,780
410,000	6,140
2,055,000	16,900

$$COSTMS = (OMS)\ \frac{MSECI}{751}$$

where

COSTMS = Annual operation and maintenance supply cost, \$/yr.

A-22.9.6 Annual rail maintenance cost, obtained from table below, \$/yr.

Daily Sludge Volume, SV (gal/day)	Unadjusted Rail Maintenance Cost, RM ($/yr)
20,500	2,800
41,000	4,200
205,500	5,600
410,000	11,100
2,055,000	27,800

$$COSTRM = (RM)\ \frac{MSECI}{751}$$

where

COSTRM = Annual rail maintenance cost, \$/yr.

A-22.9.7 Total facilities operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTMS + COSTRM$$

where

COSTOM = Total annual facilities operation and maintenance cost, $/yr.

A-22.9.8 Annual railway haul and facilities operation and maintenance cost.

$$TARHFOM = TARHC + COSTOM$$

where

TARHFOM = Annual railway haul and facilities O&M cost, $/yr.

A-22.10 Cost Calculation Output Data

A-22.10.1 Annual railway haul cost, TARHC, $/yr.

A-22.10.2 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-22.10.3 Annual cost of electrical energy, COSTEL, $/yr.

A-22.10.4 Annual operation and maintenance supply cost, COSTMS, $/yr.

A-22.10.5 Annual rail maintenance cost, COSTRM, $/yr.

A-22.10.6 Total annual facilities operation and maintenance cost, COSTOM, $/yr.

A-22.10.7 Total base capital cost of railroad facilities, TRFCC, $.

A-22.10.8 Total annual railway haul and facilities O&M cost, TARHFOM, $/yr.

APPENDIX A-23

BARGE TRANSPORTATION OF LIQUID SLUDGE FOR OCEAN DISPOSAL

A-23.1 Background

The use of self-propelled and/or towed barges for the ocean disposal of liquid sludge has been practiced for many years. Several considerations are important in the evaluation of any sludge barge transport system. These include but are not limited to:

- Design and operation of shore facilities.
- Design and operation of the barge(s).
- Tugboat contracting (when required).
- Course, especially when inland waterways must be navigated.
- Round trip haul time and distance.

In many cases, particularly when the treatment facility is not located immediately adjacent to a waterway, sludge storage facilities are required near the loading dock. Tanks similar in design to unheated digesters are commonly used for this purpose. The size of these storage tanks is dependent upon the sludge generation and handling rates, and an assumed design contingency factor. Other shore facilities include pumps, piping and docking facilities.

The design and number of barges required for an efficient ocean disposal operation is highly variable, dependent on such factors as sludge generation rate, available storage capacity, operating schedule and haul distance. In general, larger barges can travel at faster speeds and reduce transit times, thus making them more economical for larger operations. On the other hand, barges this large may not be practical for smaller treatment plants. A thorough cost analysis, optimizing all variables, should be conducted whenever the purchase of a barge(s) is contemplated.

Small- and medium-size treatment plants (e.g., those which generate less than 2,000 wet tons of sludge annually) generally do not produce enough sludge to make barge haul/ocean disposal a cost-effective alternative. However, certain municipalities on the east coast (i.e., New York and New Jersey) combine sludges through inter-facility pumping for storage at a common site, or through transporter-arranged multiple pickups of sludge along the disposal route. In this way, smaller treatment plants achieve lower costs through economy of scale.

For many treatment plants, full-service contracts for barge hauling services are the most cost-effective option. If, however, a treatment plant does utilize its own barge(s), tugboat services are usually contracted. Because of high capital and maintenence costs, only very large plants generally own the motive power unit(s) (tugboat or power barge). For purposes of this algorithm, it is assumed that barges are owned and tug services are contracted.

Capital costs obtained using this cost algorithm include the following:

- Purchase of one or more barges.

- Construction of barge loading and docking facility (includes sludge storage).

- Purchase and installation of sludge pumps and piping needed to fill barges.

Annual operation and maintenance costs consist of the following:

- Tugboat rental.
- Barge maintenance.
- Barge loading and sludge storage facility operation and maintenance.
- Annual incidental costs for permits, monitoring, and administration.

A-23.1.1 Algorithm Development

The following algorithm was developed from information on barge transportation of sludge presented in Reference 11, pages 14, 15, 18, 19, 35, 36, 37, 38, 45, 46, 48, 49, 60, and 61. Supporting information was provided from a draft ocean disposal model developed by the Scientex Corporation for EPA. Current values for barge costs, capacities, and fuel requirements supplied by manufacturers were also used.

A-23.2 Input Data

A-23.2.1 Daily sludge volume, SV, gal/day.

A-23.2.2 Round trip barge hauling distance, RTHD, miles.

A-23.2.3 Average barge speed, BRSP, mph.

A-23.2.4 Barge downtime per trip for loading, docking, idle time, etc., DT, hr/trip.

A-23.2.5 Days of separate sludge storage required at loading facility, STDAYS, days.

A-23.2.6 Hours required to fill barge at loading facility, FILLHRS, hr.

A-23.3 Design Parameters

A-23.3.1 Daily sludge volume, SV, gal/day. This input value must be furnished by the user. No default value.

A-23.3.2 Roundtrip haul distance, RTHD, miles. This input value must be furnished by the user, and should include the distance covered while actually releasing sludge to the ocean.

A-23.3.3 Average barge speed, BRSP, mph. Range of barge speed is approximately 2 to 10 mph. Default value = 3 mph.

A-23.3.4 Barge downtime per trip for loading, docking, idle time, etc., DT, hr/trip. Default value = 8 hr/trip.

A-23.3.5 Days of separate sludge storage required at loading facility, STDAYS, days. Default value = 2 days.

A-23.3.6 Hours required to fill barge at loading facility, FILLHRS, hr. Default value = 4 hr.

A-23.4 Process Design Calculations

A-23.4.1 Calculate annual sludge weight, liquid tons/yr.

$$TT = \frac{(SV) \times (365) \times (8.6)}{(2,000)}$$

where

TT = Total quantity of sludge barged, liquid tons/yr.

8.6 = Assumed weight of sludge, lb/gal (based on sludge specific gravity of 1.03).

2,000 = Conversion factor, lb/ton.

A-23.4.2 Calculate barge hours per trip.

$$HOURS = \frac{RTHD}{BRSP} + DT$$

where

HOURS = Barge hr/trip.

A-23.4.3 Calculate required barge capacity, BRCAP.

$$BRCAP = \frac{(TT)\ (HOURS)}{(365)\ (24)\ (0.8)}$$

where

BRCAP = Total barge capacity required, tons, assuming year-around, 24-hr/day operation.

365 = Days/yr.

24 = Hr/day.

0.8 = Utilization factor.

A-23.4.4 Calculate barge size and number required, using table below. Standard barge sizes range from 1,500 to 7,500 ton capacity.

Required Barge Capacity, BRCAP, tons	Barge Size BRSIZE, tons	Number of Barges NBR
0 - 1,500	1,500	1
1,501 - 3,000	3,000	1
3,001 - 4,500	4,500	1
4,501 - 6,000	6,000	1
6,001 - 7,500	7,500	1
7,501 - 9,000	4,500	2
9,001 - 12,000	6,000	2
12,001 - 15,000	7,500	2
15,001 - 18,000	6,000	3
18,001 - 22,500	7,500	3

where

BRSIZE = Barge size required, tons.
NBR = Number of barges required.

A-23.4.5 Calculate barge trips per year.

$$TP = \frac{TT}{BRSIZE}$$

where

TP = Number of trips annually.

A-23.4.6 Calculate annual tugboat time required.

$$TUGTIME = \frac{(RTHD)\ (TP)}{(BRSP)}$$

where

TUGTIME = Annual hours of tugboat use.

A-23.4.7 Calculate volume of liquid sludge tanks at barge loading facility.

$$STVOL = (SV)\ (STDAYS)$$

where

STVOL = Volume of liquid sludge storage tanks at barge loading facility, gal.

A-23.4.8 Calculate capacity of pumps and piping to fill barge(s).

$$PUMPIN = \frac{(NBR)\ (BRSIZE)\ (233)}{(60)\ (FILLHRS)}$$

where

PUMPIN = Capacity of loading pumps and piping, gal/min.

233 = Gal of sludge/liquid ton, assuming a sludge specific gravity of 1.03.

60 = Conversion factor, min/hr.

A-23.4.9 Calculate size of loading dock in terms of number of barges to be docked simultaneously.

$$DOCK = NBR$$

where

DOCK = Size of dock in terms of number of barges.

A-23.5 Process Design Output Data

A-23.5.1 Annual sludge weight, TT, liquid tons/yr.

A-23.5.2 Barge hours per trip, HOURS.

A-23.5.3 Total barge capacity required, BRCAP, tons.

A-23.5.4 Size of each barge, BRSIZE, liquid tons.

A-23.5.5 Number of barges required, NBR.

A-23.5.6 Annual number of barge trips, TP, number/yr.

A-23.5.7 Annual tugboat time required, TUGTIME, hr/yr.

A-23.5.8 Volume of liquid sludge storage tanks, STVOL, gal.

A-23.5.9 Capacity of pumps and pipes to fill barge(s), PUMPIN, gal/min.

A-23.5.10 Size of loading dock, DOCK, in terms of number of barges.

A-23.6 Unit Price Input Required

A-23.6.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is prepared.

A-23.6.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is prepared.

A-23.6.3 Cost of 3,000 liquid ton capacity barge, BRCOST, \$. Default value = \$1,950,000 (MSECI/751).

A-23.6.4 Cost of sludge storage tanks, STCOST, \$/gal. Default value = \$0.40/gal storage capacity (ENRCCI/4,006).

A-23.6.5 Cost of sludge pumps and piping to fill barge(s), PUMPCOST, \$/gal/min. Default value = \$160/gal/min (ENRCCI/4,006).

A-23.6.6 Cost of docking facilities for barge(s), DOCKCOST, \$/barge. Default value = \$500,000 (ENRCCI/4,006).

A-23.6.7 Cost of tugboat rental, TUGCOSTHR, \$/hr. Default value = \$350/hr (MSECI/751).

A-23.7 Cost Calculations

A-23.7.1 Total barge capital cost. Capital cost of barges is calculated based on the capital cost of a 3,000-liquid-ton-capacity barge.

$$\text{TBRCOST} = (\text{BRCOST})\ (\text{NBR})\ \frac{\text{BRSIZE}}{3{,}000}^{0.6}$$

where

TBRCOST = Total barge capital cost, \$.
0.6 = Constant reflecting economy of scale for various size barges.

A-23.7.2 Total barge loading and sludge storage facilities capital cost.

$$\text{FACCOST} = [(\text{STVOL})\ (\text{STCOST})] + [(\text{PUMPIN})\ (\text{PUMPCOST})] + [(\text{DOCK})\ (\text{DOCKCOST})]$$

where

FACCOST = Total capital cost of barge loading and sludge storage facilities, \$.

A-23.7.3 Annual tugboat rental cost

$$\text{TUGCOST} = (\text{TUGTIME})\ (\text{TUGCOSTHR})$$

where

TUGCOST = Tugboat rental cost, \$/yr.

A-23.7.4 Annual barge maintenance cost.

$$BROMCOST = TBRCOST\ (0.12)$$

where

BROMCOST = Annual barge maintenance cost, \$/yr.
0.12 = Annual O&M cost as a percentage of barge capital cost.

A-23.7.5 Annual barge loading and sludge storage facilities operation and maintenance cost.

$$FACOMCOST = FACCOST\ (0.10)$$

where

FACOMCOST = Annual barge facilities operation and maintenance cost, \$/yr.

0.10 = Annual O&M cost as a percentage of barge facilities capital cost.

A-23.7.6 Annual incidental costs for permits, monitoring, and administration.

$$INCCOST = TT\ (0.22)$$

where

INCCOST = Annual incidental costs, \$/yr
0.22 = Cost/liquid ton for incidental costs, \$/ton.

A-23.7.7 Total base capital cost.

$$TBCC = TBRCOST + FACCOST$$

where

TBCC = Total base capital cost, \$.

A-23.7.8 Annual operation and maintenance cost

$$COSTOM = TUGCOST + BROMCOST + FACOMCOST + INCCOST$$

where

COSTOM = Total annual O&M cost, $/yr.

A-23.8 Cost Calculations Output Data

A-23.8.1 Total barge capital cost, TBRCOST, $.

A-23.8.2 Total barge loading and sludge storage facilities capital cost, FACCOST, $.

A-23.8.3 Annual tugboat rental cost, TUGCOST, $/yr.

A-23.8.4 Annual barge maintenance cost, BROMCOST, $/yr.

A-23.8.5 Annual barge facility operation and maintenance cost, FACOMCOST, $/yr.

A-23.8.6 Annual permit, monitoring, and administration cost, INCCOST, $/yr.

A-23.8.7 Total base capital cost, TBCC, $.

A-23.8.8 Total annual operation and maintenance cost, COSTOM, $/yr.

APPENDIX A-24

LONG-DISTANCE PIPELINE TRANSPORT OF LIQUID SLUDGE

A-24.1 Background

Pipelines have been successfully used for transporting liquid sludge (i.e., usually less than 10 percent solids by weight), from very short distances up to distances of 10 miles or more. Liquid sludge pumping through pipelines is generally best accomplished with sludge containing 3 percent solids or less.

The principles applied in liquid sludge pipeline and water pipeline design are quite similar. Unlike water, however, laminar flow is common in sludges with higher solids concentrations. Also, there is a tendency for the organic sludge solids to adhere to the inside of pipelines during pumping. These conditions often result in friction losses that are higher than those experienced in water pipelines. In the following alogorithm, this phenomenon has been taken into account by applying a "K" factor to an otherwise unmodified Hazen-Williams formula. This "K" factor, which is a function of both sludge solids content and sludge type, is discussed in more detail in Subsection A-24.3.4. Pipelines with coated interiors (e.g., glass or cement mortar linings) are often used as a means of reducing friction loss. Because dried sludge can "cake" on interior pipe walls, flushing pipelines with clean water or treated effluent is also commonly practiced as means of reducing friction loss due to such "caking." In addition, flushing has been used as a means for preventing sludge solids from settling and hardening in dormant pipelines.

Cost considerations for this algorithm include: pipeline and pumping station construction costs and O&M labor, materials, and energy requirements. Large variations in construction costs are associated with certain route-specific variables such as the number of river crossings or the fraction of pipeline length requiring excavation of rock. In order to obtain the best results, the user is encouraged to obtain or plot a viable pipeline route on a suitable scale map and input the most accurate design parameter values possible. Cost of right-of-way acquisition is not included in this algorithm.

A-24.1.1 Algorithm Development

The following algorithm is based on common engineering principles used when designing a pipeline transport system. Sources of information on sludge pipeline transport were Reference 4, pages 14-1 through 14-2, and Reference 8, pages 41 through 46. Cost equations are based on Reference 11, pages 24, 54 through 58, and 69 through 71; and Reference 12, pages 4-1 through 4-28.

A-24.2 Input Data

A-24.2.1 Daily sludge volume, SV, gpd.

A-24.2.2 Pipeline length, PL, ft.

A-24.2.3 Hazen-Williams friction coefficient, C.

A-24.2.4 Coefficient to adjust for increased head loss due to sludge solids content, K.

A-24.2.5 Elevation at the start of the pipeline, PSELEV, ft.

A-24.2.6 Maximum elevation in the pipeline, ELEVMX, ft.

A-24.2.7 Hours per day of pumping, HPD, hr.

A-24.2.8 Fraction of pipeline length that requires rock excavation, ROCK.

A-24.2.9 Fraction of pipeline length that does not involve rock excavation, but is greater than 6 ft deep, DEPTH.

A-24.3 Design Parameters

A-24.3.1 Pipeline velocity is 3 ft/sec maximum.

A-24.3.2 Pipeline friction loss, PFL, function of pipe diameter, velocity, and "C" value selected.

A-24.3.3 Hazen-Williams friction coefficient, C. Default value = 90.

A-24.3.4 Coefficient, K, to adjust for increased head loss due to sludge solids content. No default value. Pipeline friction losses may be much higher for transporting sewage sludge than for transporting water, depending upon such factors as the sludge concentration (percent solids by weight) and the type of sludge (raw primary, digested, etc.). The user is cautioned that the K factors provided in the table below are highly simplified and may give inaccurate results for pipeline friction loss. An elaborate method for design engineering calculations is provided in Section 14.1.2 of Reference 4.

K FACTORS FOR VARIOUS SLUDGE CONCENTRATIONS
AND TWO TYPES OF SLUDGE

Solids Concentration Percent by Weight	K Factor: Digested Sludge	K Factor: Untreated Primary Sludge
1.0	1.05	1.20
2.0	1.10	1.60
3.0	1.25	2.10
4.0	1.45	2.70
5.0	1.65	3.40
6.0	1.85	4.30
7.0	2.10	5.70
8.0	2.60	7.20

A-24.3.5 Number of 2- or 4-lane highway crossings, NOH. Default value = 1.

A-24.3.6 Number of divided highway crossings, NODH. Default value = 0.

A-24.3.7 Number of railroad tracks (2 rails/track) crossed, NRC. Default value = 2.

A-24.3.8 Number of small rivers crossed, NOSR. Default value = 0.

A-24.3.9 Number of large rivers crossed, NOLR. Default value = 0.

A-24.4 Process Design Calculations

A-24.4.1 Calculate pipeline diameter.

$$PD = 12\left[\frac{SV}{63{,}448\ (HPD)}\right]^{1/2}$$

(Round to next highest even integer.)

where

PD = Pipeline diameter, inches.
63,488 = Conversion factor =

$$\frac{3.1416}{4}\left[\frac{(3\ ft/sec)\ (7.48\ gal/ft^3)\ (86{,}400\ sec/day)}{(24\ hr/day)}\right]$$

Note: Pipeline is assumed to be flowing full.

A-24.4.2 Calculate head loss due to pipeline friction.

$$PFL = K \left[\frac{SV\ (24)}{(HPD)\ (PD)^{2.63}\ (C)\ (16.892)} \right]^{1.852}$$

where

PFL = Head loss due to pipe friction, ft/ft.

K = Coefficient to adjust for increased head loss due to sludge solids content.

24 = Conversion factor, hr/day.

2.63 = Hazen-Williams constant.

C = Hazen-Williams friction coefficient.

$$16.892 = \frac{646{,}000\ \text{gal/day/cfs}}{(24)\ (2.31)\ (12)^{2.63}}$$

A-24.4.3 Head required due to elevation difference.

$$HELEV = ELEVMX - PSELEV$$

where

HELEV = Head required due to elevation difference, ft.

A-24.4.4 Total Pumping head required.

$$H = [(PL)\ (PFL) + HELEV]$$

where

H = Total pumping head required, ft.

A-24.4.5 Number of pumping stations.

$$NOPS = \frac{(H)}{HAVAIL}$$

If the decimal ending for the NOPS resultant is greater than or equal to 0.25, then round up to the next higher interger. If it is less than 0.25, round down. Thus, if NOPS is 2.35, use 3 pump stations. If NOPS = 2.10, use 2 pump stations.

where

NOPS = Number of pumping stations.

HAVAIL = Head available from each pumping station, ft. This is a function of the type of pump, sludge flow rate, and whether or not pumps are placed in series. Obtain this value from the table below.

Pipe Diameter, PD (Inches)	Head Available, HAVAIL (Ft)
4 & 6	450
8	260
10 & 12	230
14 & 16	210
18 & 20	200

A-24.4.6 Total horsepower required for pump stations.

$$HP = \frac{(H)\ (SV)\ (33{,}000)}{(HPD)\ (60)\ (0.50)\ (8.34)}$$

where

HP = Total pumping horsepower required, hp.
33,000 = Conversion factor, hp to ft-lb/min.
60 = Conversion factor, min/hr.
0.50 = Assumed pump efficiency.
8.34 = Density of water, lb/gal.

A-24.4.7 Horsepower required per pump station.

$$HPS = \frac{HP}{NOPS}$$

where

HPS = Horsepower required per pump station, hp.

A-24.5 Process Design Output Data

A-24.5.1 Pipe diameter, PD, inches.

A-24.5.2 Head loss due to pipe friction, PFL, ft/ft of pipe.

A-24.5.3 Head required due to elevation change, HELEV, ft.

A-24.5.4 Total pumping head required, H, ft.

A-24.5.5 Number of pumping stations, NOPS.

A-24.5.6 Total pumping horsepower required, HP, hp.

A-24.5.7 Horsepower required per pump station, HPS, hp.

A-24.6 Quantities Calculations

A-24.6.1 Electrical energy requirement.

$$E = \left[\frac{(0.0003766)\ (1.2)\ (H)}{(0.5)\ (0.9)}\right] \frac{(SV)\ (365)\ (8.34)}{1,000}$$

where

E = Electrical energy, kWhr/yr.
0.0003766 = Conversion factor, kWhr/1,000 ft-lb.
8.34 = Density of water, lb/gal.
1.2 = Assumed specific gravity of sludge.
0.5 = Assumed pump efficiency.
0.9 = Assumed motor efficiency.

A-24.6.2 Operation and maintenance labor requirement.

$$L = (NOPS)\ (LPS) + (PL)\ (0.02)$$

where

L = Annual operation and maintenance labor, hr/yr.

0.02 = Assumed maintenance hr/yr per ft of pipeline, hr/ft.

LPS = Annual labor per pump station, hr/yr. This is a function of pump station horse power, HPS, as shown below.

Pump Station Horsepower, HPS	Annual O&M Labor, LPS (Hr)
25	700
50	720
75	780
100	820
150	840
200	870
250	910
300	940
350	980

A-24.7 Quantities Calculations Output Data

A-24.7.1 Electrical energy requirement, E, kWhr/yr.

A-24.7.2 Operation and maintenance labor requirement, L, hr/yr.

A-24.8 Unit Price Input Required

A-24.8.1 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-24.8.2 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-24.8.3 Unit cost of electricity, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-24.8.4 Unit cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-24.9 Cost Calculations

A-24.9.1 Cost of installed pipeline.

$$\text{COSTPL} = (1 + 0.7\ \text{ROCK})\ (1 + 0.15\ \text{DEPTH})\ \text{PL}\ (\text{COSTP})\ \frac{\text{ENRCCI}}{4{,}006}$$

where

COSTPL = Cost of installed pipeline, \$.

0.7 = Assumed fraction of pipeline length that requires rock excavation.

0.15 = Assumed fraction of pipeline length that does not require rock excavation, but is greater than 6 ft deep.

COSTP = Pipeline cost per unit length, \$/ft. This cost is obtained from the following table.

Pipeline Diameter, PD (Inches)	Installed Cost, COSTP, (\$/ft, 1983)
4	21.10
6	22.80
8	25.30
10	27.90
12	30.40
14	35.50
16	38.90
18	43.10
20	50.70

A-24.9.2 Cost of pipeline crossings.

$$COSTPC = [NOH\ (19{,}000) + NODH\ (38{,}000) + NRC\ (14{,}000) + NOSR\ (85{,}000) + NOLR\ (\$340{,}000)]\ \frac{ENRCCI}{4{,}006}$$

where

COSTPC = Cost of pipe crossings, $.

A-24.9.3 Cost of pump stations.

$$COSTPS = NOPS\ [165{,}000 + 2{,}700\ (HPS-25)]\ \frac{MSECI}{751}$$

where

COSTPS = Construction cost of all pump stations.

Note: If HPS is less than 25 hp, then, for this calculation, let HPS = 25 hp.

A-24.9.4 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Total annual cost of electricity, $/yr.

A-24.9.5 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, $/yr.

A-24.9.6 Cost of pumping station replacement parts and materials.

$$COSTPM = NOPS\ (PS)\ \left(\frac{MSECI}{751}\right)$$

where

COSTPM = Annual cost of pumping station replacement parts and materials, \$/yr.

PS = Annual cost of parts and supplies for a single pumping station, \$/yr. This cost is a function of pumping station horse power as shown below.

Pump Station Horsepower, HPS	Annual Parts and Supplies Cost, PS, (\$/Yr)
25	1,080
50	1,130
75	1,270
100	1,380
150	1,500
200	1,590
250	2,840
300	2,960
350	3,110

A-24.9.7 Total base capital cost.

TBCC = COSTPL + COSTPC + COSTPS

where

TBCC = Total base capital cost, \$.

A-24.9.8 Total annual operation and maintenance cost.

COSTOM = COSTEL + COSTLB + COSTPM

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-24.10 Cost Calculations Output Data

A-24.10.1 Cost of installed pipeline, COSTPL, \$.

A-24.10.2 Cost of pipeline crossings, COSTPC, \$.

A-24.10.3 Cost of pump stations, COSTPS, \$.

A-24.10.4 Annual cost of electrical energy, COSTEL, \$/yr.

A-24.10.5 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-24.10.6 Cost of pumping station replacement parts and materials, COSTPM, $/yr.

A-24.10.7 Total base capital cost, TBCC, $.

A-24.10.8 Annual operation and maintenance cost, COSTOM, $/yr.

APPENDIX A-25

OCEAN OUTFALL DISPOSAL

A-25.1 Background

Ocean outfalls provide a means for both transportation and disposal of sludge, but are of limited applicability for most facilities, since they require close proximity to the ocean. In addition, regulatory constraints limit their use as a method of sludge disposal.

Ocean disposal of liquid sludge is typically accomplished using a pipeline and outfall system identical to that used for ocean disposal of wastewater. A manifold or multiple-point diffuser is commonly employed at the end of the outfall pipeline to facilitate the dilution of the liquid sludge with seawater. In virtually all ocean outfalls, only one pump station is required unless the onshore pipeline length is excessive. The ocean outfall system presented in this algorithm consists of one pump station, both land and submarine pipelines, and a diffuser section at the point of discharge. If a long overland pipeline is necessary to carry sludge to the beginning of the coastal outfall, the user should use the "Long Distance Pipeline Transport of Liquid Sludge" algorithm (Appendix A-24) to calculate the cost of this pipeline.

Pipeline design is broken down into three different types of construction environments: onshore pipeline, nearshore pipeline, and offshore pipeline. Costs used for these three types vary due to the differing materials used and degrees of difficulty associated with pipeline construction in each environment.

Capital costs for ocean outfalls vary over a wide range, depending on site-specific conditions. The use of this algorithm will provide only a very rough estimate of costs. Cost considerations for the operation and maintenance of an ocean outfall system basically consist of pump power (electrical) requirements and pump and pipeline maintenance requirements.

A-25.1.1 Algorithm Development

Design equations in the following algorithm were developed using common engineering principles applicable to the design of a pipeline transport system. However, construction and O&M costs are significantly higher than pipeline transport costs due to the conditions under which construction and maintenance occur. Cost curves were developed using the following unpublished documents by R. L. Michel of EPA: Evaluation of Ocean Outfall Cost Data (January 5, 1982); Order of Magnitude Equations for Estimating Costs of Ocean Outfalls (January 26, 1982); and Ocean Outfall Cost Factors (March 17, 1982).

A-25.2 Input Data

A-25.2.1 Daily sludge volume, SV, gal/day.

A-25.2.2 Hours per day of pumping, HPD, hr.

A-25.2.3 Hazen-Williams friction coefficient, C.

A-25.2.4 Coefficient to adjust for increased head loss due to sludge solids content, K.

A-25.2.5 Onshore pipeline length, ONPL, ft.

A-25.2.6 Offshore (past the surf zone) pipeline length, OFPL, ft.

A-25.2.7 Nearshore (in the surf zone) pipeline length, NSPL, ft.

A-25.2.8 Diffuser pipeline length, NDPL, ft.

A-25.3 Design Parameters

A-25.3.1 Daily sludge volume, SV, gal/day. This input value must be furnished by the user. No default value.

A-25.3.2 Hours per day of pumping, HPD, hr. Default value = 20 hr.

A-25.3.3 Hazen-Williams friction coefficient, C. Default value = 90.

A-25.3.4 Coefficient, K, to adjust for increased head loss due to sludge solids content. No default value. Pipeline friction losses may be much higher for transporting sewage sludge than for transporting water, depending upon such factors as the sludge concentration (percent solids by weight) and the type of sludge (raw primary, digested, etc.). The user is cautioned that the K factors provided in the table below are highly simplified and may give inaccurate results for pipeline friction loss. An elaborate method for design engineering calculations is provided in Section 14.1.2 of Reference 4.

K FACTORS FOR VARIOUS SLUDGE CONCENTRATIONS
AND TWO TYPES OF SLUDGE

	K Factor	
Solids Concentration Percent by Weight	Digested Sludge	Untreated Primary Sludge
1.0	1.05	1.20
2.0	1.10	1.60
3.0	1.25	2.10
4.0	1.45	2.70
5.0	1.65	3.40

	K Factor	
Solids Concentration Percent by Weight	Digested Sludge	Untreated Primary Sludge
6.0	1.85	4.30
7.0	2.10	5.70
8.0	2.60	7.20

A-25.3.5 Onshore pipeline length, ONPL, ft. No default value.

A-25.3.6 Offshore pipeline length, OFPL, ft. No default value.

A-25.3.7 Nearshore pipeline length, NSPL, ft. No default value.

A-25.3.8 Diffuser pipeline length, NDPL, ft. No default value.

A-25.3.9 Pipeline velocity is 3 ft/sec maximum for all segments (i.e., onshore, nearshore, offshore, and diffuser).

A-25.3.10 Pipeline friction loss is a function of pipe diameter in all segments (i.e., onshore, nearshore, offshore, and diffuser).

A-25.3.11 Head due to elevation difference is assumed to be negligible; therefore, equal to zero.

A-25.4 Process Design Calculations

A-25.4.1 Calculate minimum pipeline diameter, based on flow velocity of 3 ft/sec.

$$PD = 12\left[\frac{SV}{63{,}448\ (HPD)}\right]^{0.5}$$

where

PD = Pipeline diameter, inches.

63,448 = Conversion factor =

$$\frac{3.1416}{4}\left[\frac{(3\ ft/sec)\ (7.48\ gal/ft^3)\ (86{,}400\ sec/day)}{24\ hr/day}\right]$$

Increase PD to next largest standard pipe diameter of 6 inches or more (i.e., 6, 8, 10, 12, 15, 18, 21, 24, 27, 30, 36, 42, or 48 inches).

A-25.4.2 Calculate head loss due to pipe friction per foot of pipeline length.

$$PFL = K\left[\frac{SV\ (24)}{(HPD)\ PD^{2.63}\ (C)\ (405)}\right]^{1.852}$$

A-25.4.3 Calculate total pipeline length, TPL, ft.

$$TPL = ONPL + OFPL + NSPL + NDPL$$

where

TPL = Total pipeline length, ft.

A-25.5 Process Design Output Data

A-25.5.1 Pipe diameter, PD, inches.

A-25.5.2 Headloss due to pipe friction, PFL, feet per foot of pipe.

A-25.5.3 Total pipeline length, TPL, ft.

A-25.6 Quantities Calculations

A-25.6.1 Annual electrical energy requirement.

$$E = \left[\frac{(0.0003766)\ (1.2)\ (TPL)\ (PFL)}{(0.5)\ (0.9)}\right] \frac{(SV)\ (365)\ (8.34)}{(1{,}000)}$$

where

E = Annual electrical energy requirement, kWhr/yr.
0.0003766 = Conversion factor, kWhr/1,000 ft-lb.
1.2 = Assumed specific gravity of sludge.
8.34 = Density of water, lb/gal.
0.5 = Assumed pump efficiency.
0.9 = Assumed motor efficiency.

A-25.6.2 Annual operation and maintenance labor requirement.

$$L = (TPL)\ (0.077) + (LPS)$$

where

L = Annual operation and maintenance labor, hr/yr.
0.077 = Assumed maintenance hr/yr per ft of pipeline.
LPS = Pump station operation and maintenance labor, hr.

This is a function of pumping station capacity as shown following:

Pump Station Capacity (gal/day)	Annual O&M Labor, LPS (hr)
180,000	700
400,000	720
720,000	780
1,160,000	820
1,580,000	840
2,020,000	870
2,880,000	910
3,600,000	940
4,320,000	980

A-25.7 Quantities Calculation Output Data

A-25.7.1 Annual electrical energy requirement, E, kWhr/yr

A-25.7.2 Annual operation and maintenance labor requirement, L, hr/yr.

A-25.8 Unit Price Input Required

A-25.8.1 Current Engineering News Record Construction Cost Index, ENRCCI. No default value.

A-25.8.2 Unit cost of electricity, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-25.8.3 Unit cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-25.9 Cost Calculations

A-25.9.1 Total installed cost of pipeline.

A-25.9.1.1 Cost of onshore pipeline.

$$COSTONPL = ONPL\ (COSTONP)\ \left(\frac{ENRCCI}{4{,}006}\right)$$

where

COSTONPL = Cost of installed onshore pipeline, \$.

COSTONP = Onshore pipeline cost unit per length, \$/ft. This cost is obtained from the table presented below.

Pipe Diameter (inches)	Onshore Pipeline Installed Cost, COSTONP ($/ft)
6	22.80
8	25.30
10	27.90
12	38.90
16	50.70
20	67.40
24	89.60
30	119.20
36	158.50
42	210.80
48	280.40
54	372.90

A-25.9.1.2 Cost of offshore pipeline.

$$COSTOFPL = OFPL\ (COSTOFP)\ \left(\frac{ENRCCI}{4{,}006}\right)$$

where

COSTOFPL = Cost of installed offshore pipeline, $.

OFPL = Offshore pipeline length, ft.

COSTOFP = Offshore pipeline per cost unit length, $/ft. This cost is obtained from the following table:

Pipe Diameter (inches)	Offshore Pipeline Installed Cost, COSTOFP ($/ft)
6	324
8	326
10	329
12	333
16	342
20	354
24	369
30	396
36	429
42	468
48	513
54	564

A-25.9.1.3 Cost of nearshore pipeline.

$$\text{COSTNSPL} = \text{NSPL (COSTNSP)} \left(\frac{\text{ENRCCI}}{4{,}006}\right)$$

where

COSTNSPL = Cost of installed nearshore (surf zone) pipeline, \$.

COSTNSP = Nearshore pipeline cost per unit length, \$/ft. This cost is obtained from the following table:

Pipe Diameter (inches)	Nearshore Pipeline Installed Cost, COSTNSP (\$/ft)
6	567
8	686
10	795
12	898
16	1,084
20	1,256
24	1,420
30	1,640
36	1,850
42	2,050
48	2,240
54	2,420

A-25.9.1.4 Cost of diffuser pipeline.

$$\text{COSTNDPL} = \text{NDPL (COSTNDP)} \left(\frac{\text{ENRCCI}}{4{,}006}\right)$$

where

COSTNDPL = Cost of installed diffuser pipeline, \$.

NDPL = Diffuser pipeline length, ft.

COSTNDP = Diffuser pipeline cost per unit length, \$/ft. This cost is obtained from the table presented below.

Pipe Diameter (inches)	Diffuser Pipeline Installed Cost, COSTNDP ($/ft)
6	404
8	406
10	409
12	413
16	422
20	434
24	449
30	476
36	509
42	548
48	593
54	644

A-25.9.1.5 Total cost of outfall pipeline.

TCOSTPL = COSTONPL + COSTOFPL + COSTNSPL + COSTNDPL

where

TCOSTPL = Total installed cost of outfall pipeline, $.

A-25.9.2 Cost of pump station.

$$\text{COSTPS} = \text{COSTIPS}\ \left(\frac{\text{ENRCCI}}{4{,}006}\right)$$

where

COSTPS = Construction cost of pump station, $.

COSTIPS = Cost of individual pump station, $, as obtained from the following table:

Pump Station Capacity (gpd)	Pump Station Construction Cost, COSTIPS ($)
180,000	80,000
400,000	96,300
720,000	120,000
1,160,000	149,000
1,580,000	183,000
2,020,000	208,000
2,880,000	260,000
3,600,000	313,000
4,320,000	365,000

A-25.9.3 Annual cost of electrical energy required.

$$COSTEL = E\ (COSTE)$$

where

COSTEL = Total annual cost of electricity, $/yr.

A-25.9.4 Annual cost of operation and maintenance labor.

$$COSTLB = L\ (COSTL)$$

where

COSTLB = Total cost of operation and maintenance labor, $/yr.

A-25.9.5 Annual cost of pumping station parts and materials.

$$COSTPM = PS\ \left(\frac{ENRCCI}{4,006}\right)$$

where

COSTPM = Annual cost of pumping station parts and materials, $/yr.

PS = Annual cost of parts and supplies for a single pumping station, $/yr. This cost is a function of pumping station capacity as shown in the following table:

Pump Station Capacity (gal/day)	Annual Parts and Material, PS ($/yr)
180,000	1,080
400,000	1,130
720,000	1,270
1,160,000	1,380
1,580,000	1,500
2,020,000	1,590
2,880,000	2,840
3,600,000	2,960
4,320,000	3,110

A-25.9.6 Total base capital cost.

$$TBCC = TCOSTPL + COSTPS$$

where

TBCC = Total base capital cost, $.

A-25.9.7 Total annual operation and maintenance cost.

$$COSTOM = COSTEL + COSTLB + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-25.10 Cost Calculations Output Data

A-25.10.1 Total installed cost of outfall pipeline, TCOSTPL, $.

A-25.10.2 Cost of pump station, COSTPS, $.

A-25.10.3 Annual cost of electrical energy, COSTEL, $/yr.

A-25.10.4 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-25.10.5 Annual cost of pumping station parts and materials, COSTPM, $/yr.

A-25.10.6 Total base capital cost, TBCC, $.

A-25.10.7 Total annual operation and maintenance cost, COSTOM, $/yr.

APPENDIX A-26

LAND APPLICATION TO CROPLAND

A-26.1 Background

Use of municipal wastewater treatment plant sludge as a source of fertilizer nutrient to enhance crop production is widespread in the United States. Hundreds of communities, both large and small, have developed successful agricultural utilization programs. These programs benefit the municipality generating the sludge by providing an environmentally acceptable means of sludge disposal, while providing the participating farmer with a substitute or supplement for conventional fertilizers.

A major advantage of agricultural utilization is that the municipality usually does not have to purchase land. Furthermore, the land utilized for sludge application is kept in production, and its value for future uses is not impaired.

Sludge application rates for agricultural utilization (dry unit weight of sludge applied per unit of land area per year) are usually low, i.e., in the range of 3 to 10 tons/acre/year, depending on the physical characteristics of the sludge and soil and the types of crops grown. Sludges can be applied by surface spreading or subsurface injection. Surface application methods include spreading by specially equipped farm tractors, tank wagons, special applicator vehicles equipped with flotation tires, tank trucks, and portable or fixed irrigation systems.

Sludge is usually applied only once a year to each application site. Relatively large land areas may thus be needed, requiring the cooperation of many individual land owners. In addition, the scheduling of sludge transport and application around agricultural planting, harvesting, etc., plus adverse climatic conditions, may require careful management. If the farms accepting sludge are numerous and widespread, an expensive and complicated sludge distribution system may be required.

It is important to note that this cost algorithm assumes that the sludge application vehicles at the application site are <u>not</u> the same vehicles which transported the sludge from the treatment plant to the application site. In many cases, however, the <u>same</u> vehicle is used to both transport the sludge and apply it to the application site. If the same vehicle is used for sludge transport and application, then the user should use zero for the cost of the on-site sludge application vehicle, COSTPV (Subsection A-26.8.6), since the cost of that vehicle has already been included in the previous sludge hauling process.

The user should note that this cost algorithm does include calculations for the costs of land, lime addition, and site grading. In many cases of agricultural sludge utilization, all or some of these costs are not applicable to the municipality, since they are either unnecessary or paid for by the farmer. If so, the user of this unit process cost algorithm simply uses zero cost, where appropriate, in Subsections A-26.8.1, A-26.8.2, and A-26.8.5.

O&M costs include labor, diesel for the operation of vehicles, vehicle maintenance, and site maintenance.

A-26.1.1 Algorithm Development

Capital costs and O&M requirements in this algorithm were based on information obtained from equipment manufacturers. Additional information was obtained from Reference 13, pages 6-1 through 6-46.

A-26.2 Input Data

A-26.2.1 Daily sludge volume, SV, gpd.

A-26.2.2 Sludge suspended solids concentration, SS, percent.

A-26.2.3 Sludge specific gravity, SSG, unitless.

A-26.2.4 Average dry solids application rate, DSAR, tons of dry solids/acre/yr.

A-26.2.5 Annual sludge application period, DPY, days/yr.

A-26.2.6 Daily sludge application period, HPD, hr/day.

A-26.2.7 Fraction of farmland area needed in addition to actual sludge application area, e.g., buffer zones, unsuitable soil or terrain, changes in cropping patterns, etc., FWWAB.

A-26.2.8 Fraction of food chain crop growing area requiring lime addition to raise pH to 6.5, FRPH.

A-26.2.9 Fraction of food chain crop growing area requiring light grading for drainage control, FRLG.

A-26.3 Design Parameters

A-26.3.1 Daily sludge volume, SV, gpd. This input value must be provided by the user. No default value.

A-26.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-26.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not provided, default value is calculated using the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed specific gravity of sludge solids, unitless.

A-26.3.4 Average dry solids application rate, DSAR, tons of dry solids/acre/yr. This value normally ranges from 3 to 10 for typical food chain crop growing sites depending upon crop grown, soil conditions, climate, and other factors. Default value = 5 tons/acre/yr.

A-26.3.5 Annual sludge application period, DPY, days/yr. This value normally ranges from 100 to 140 days/yr depending upon climate, cropping patterns, and other factors. See table below for typical values. Default value = 120 days/yr.

TYPICAL DAYS PER YEAR OF FOOD CHAIN CROP SLUDGE APPLICATION

Geographic Region	Typical Days/Yr of Sludge Application
Northern U.S.	100
Central U.S.	120
Sunbelt States	140

A-26.3.6 Daily sludge application period, HPD, hr/day. This value normally ranges from 5 to 7 hr/day depending upon equipment used, proximity of application sites, and other factors. Default value = 6 hr/day.

A-26.3.7 Fraction of farmland area needed in addition to actual sludge application area, e.g., buffer zones, unsuitable soil or terrain, changes in cropping patterns, etc., FWWAB. Default value = 0.4.

A-26.3.8 Fraction of food chain crop growing area requiring lime addition to raise pH to 6.5, FRPH. Depending upon the natural pH of local soils, this fraction can vary from 0 to 1. Default value = 0.5.

A-26.3.9 Fraction of food chain crop growing area requiring light grading for drainage control, FRLG. Depending upon local conditions at the sludge application sites this fraction can vary from 0 to 1. Default value = 0.3.

A-26.4 Process Design Calculations

A-26.4.1 Calculate dry solids applied to land per year.

$$TDSS = \frac{(SV)\ (8.34)\ (SS)\ (SSG)\ (365)}{(2{,}000)\ (100)}$$

where

TDSS = Dry solids applied to land, tons/yr.
8.34 = Density of water, lb/gal.
2,000 = Conversion factor, lb/ton.

A-26.4.2 Sludge application area required.

$$SDAR = \frac{(TDSS)}{(DSAR)}$$

where

SDAR = Farm area required for sludge application, acres.

A-26.4.3 Hourly sludge application rate.

$$HSV = \frac{(SV)\ (365)}{(DPY)\ (HPD)}$$

where

HSV = Hourly sludge application rate, gal/hr.

A-26.4.4 Capacity of on-site mobile sludge application vehicles. It is assumed that the sludge has already been transported to the private farm sludge application sites by a process such as a large haul vehicle, etc. The on-site mobile application vehicles accept the sludge from the transport vehicle, pipeline, or on-site storage facility, and proceed to the sludge application area to apply the sludge. Typical on-site mobile sludge application vehicles at farm sites have capacities ranging from 1,600 to 4,000 gal, in the following increments: 1,600, 2,200, 3,200, and 4,000 gal.

A-26.4.4.1 Capacity and number of on-site mobile sludge application vehicles. The capacity and number of on-site mobile sludge application vehicles required is determined by comparing the hourly sludge volume, HSV, with the vehicle sludge handling rate, VHRCAP. See table below.

HSV (Gal/Hr)	Vehicle Capacity CAP (Gal) Number of Each Capacity, NOV 1,600	2,200	3,200	4,000
0 - 3,456	1	-	-	-
3,456 - 4,243	-	1	-	-
4,243 - 5,574	-	-	1	-
5,574 - 6,545	-	-	-	1
6,545 - 8,500	-	2	-	-
8,500 - 11,200	-	-	2	-
11,200 - 13,100	-	-	-	2
13,100 - 19,600	-	-	-	3
19,600 - 26,000	-	-	-	4

Above 26,000 gal/hr, the number of 4,000-gal capacity vehicles required is calculated by:

$$NOV = \frac{HSV}{6,545}$$ (round to the next highest integer)

where

NOV = Number of on-site sludge application vehicles.

A-26.4.4.2 Average round trip on-site cycle time for mobile sludge application vehicles.

$$CT = \frac{(LT) + (ULT) + (TT)}{0.75}$$

where

CT = Average round trip on-site cycle time for mobile sludge application vehicle, min.

LT = Load time, min, varies with vehicle size (see table below).

ULT = Unload time, min, varies with vehicle size (see table below).

TT = On-site travel time to and from sludge loading facility to sludge application area, min (assumed values are shown in table below).

0.75 = An efficiency factor.

Vehicle Capacity, CAP (Gal)	LT (Min)	ULT (Min)	TT (Min)	CT (Min)
1,600	6	8	5	25
2,200	7	9	5	28
3,200	8	10	5	31
4,000	9	11	5	33

A-26.4.4.3 Single vehicle sludge handling rate. The actual hourly sludge throughput rates for an on-site mobile sludge application vehicle is dependent upon the vehicle tank capacity, the cycle time, and an efficiency factor.

$$VHRCAP = \frac{(CAP)\ (60)\ (0.9)}{(CT)}$$

where

VHRCAP = Single vehicle sludge handling rate, gal/hr.
CAP = Vehicle tank capacity, gal.
0.9 = Efficiency factor.

The table below shows VHRCAP values for typical size vehicles.

Vehicle Capacity, CAP (Gal)	VHRCAP (Gal/Hr)
1,600	3,456
2,200	4,243
3,200	5,574
4,000	6,545

A-26.5 Process Design Output Data

A-26.5.1 Dry solids applied to land, TDSS, tons/yr.

A-26.5.2 Sludge application area required, SDAR, acres.

A-26.5.3 Hourly sludge application rate, HSV, gal/hr.

A-26.5.4 Capacity of on-site mobile sludge application vehicle, CAP, gal.

A-26.5.5 Number of on-site mobile sludge application vehicles, NOV.

A-26.5.6 Cycle time for on-site mobile sludge application vehicle, CT, min.

A-26.5.7 Single vehicle sludge handling rate, VHRCAP, gal/hr.

A-26.6 Quantities Calculations

A-26.6.1 Total land area required. For virtually all sludge to food chain crop applications, a larger land area is required than that needed only for sludge application/disposal (SDAR). The additional area may be required for changes in cropping patterns, buffer zones, on-site storage, wasted land due to unsuitable soil or terrain, and/or land available in the event of unforeseen future circumstances. In any case, the additional land area required is site specific and varies significantly, e.g., from 10 to 100 percent of the SDAR.

$$TLAR = (1 + FWWAB)\ (SDAR)$$

where

TLAR = Total land area required for food chain application site, acres.

A-26.6.2 Lime addition required for soil pH adjustment to a value of at least 6.5.

$$TLAPH = (FRPH)\ (SDAR)$$

where

TLAPH = Total land area requiring lime addition, acres.

A-26.6.3 Light grading required. Typical agricultural land used for growing food chain crops is usually already graded to even slopes. However, when sludge is added to the soil, additional light grading may be necessary to improve drainage control and minimize runoff of sludge solids. Obviously, this need is site specific.

$$TLARLG = (FRLG)\ (SDAR)$$

where

TLARLG = Total land area requiring light grading, acres.

A-26.6.4 Annual operation labor requirement.

$$L = \frac{8\ (NOV)\ (DPY)}{0.7}$$

where

L = Annual operation labor requirement, hr/yr.
8 = Hr/day assumed.
0.7 = Efficiency factor.

A-26.6.5 Annual diesel fuel requirement for on-site mobile sludge application vehicles.

$$FU = \frac{(HSV)\ (HPD)\ (DPY)\ (DFRCAP)}{(VHRCAP)}$$

where

FU = Annual diesel fuel usage, gal/yr.

DFRCAP = Diesel fuel consumption rate (gal/hr); for specific capacity vehicle, see table below.

GALLONS OF FUEL PER HOUR FOR VARIOUS CAPACITY SLUDGE APPLICATION VEHICLES

Vehicle Capacity, CAP (Gal)	DFRCAP (Gal/Hr)
1,600	3.5
2,200	4
3,200	5
4,000	6

A-26.7 Quantities Calculations Output Data

A-26.7.1 Total land area required, TLAR, acres.

A-26.7.2 Total land area requiring lime addition, TLAPH, acres.

A-26.7.3 Total land area requiring light grading, TLARLG, acres.

A-26.7.4 Annual operation labor required, L, hr/yr.

A-26.7.5 Annual diesel fuel usage, FU, gal/yr.

A-26.8 Unit Price Input Required

A-26.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-26.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-26.8.3 Cost of land, LANDCST, \$/acre. Default value = zero. It is assumed that application of sludge is to privately owned farm land.

A-26.8.4 Cost of lime addition, PHCST, \$/acre. Default value = \$60/acre (ENRCCI/4,006); assumes 2 tons of lime/acre requirement.

A-26.8.5 Cost of light grading earthwork, LGEWCST, \$/acre. Default value = \$1,000/acre (ENRCCI/4,006).

A-26.8.6 Cost of on-site mobile sludge application vehicle, COSTPV, \$.

A-26.8.7 Cost of operation labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-26.8.8 Cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-26.9 Cost Calculations

A-26.9.1 Cost of land.

$$COSTLAND = (TLAR)\ (LANDCST)$$

where

COSTLAND = Cost of land, \$.

A-26.9.2 Cost of lime addition to adjust pH of soil.

$$COSTPHT = (TLAPH)\ (PHCST)$$

where

COSTPHT = Cost of lime addition, \$.

A-26.9.3 Cost of light grading earthwork.

$$COSTEW = (TLARLG)\ (LGEWCST)$$

where

COSTEW = Cost of earthwork grading, \$.

A-26.9.4 Cost of on-site mobile sludge application vehicles. Note: If same vehicle is used both to transport sludge to the site and to apply sludge to the land, then COSTMAV = zero.

$$COSTMAV = (NOV)\ (COSTPV)\ \frac{MSECI}{751}$$

where

COSTMAV = Cost of on-site mobile sludge application vehicles, $.
COSTPV = Cost/vehicle, obtained from the table below.

COST OF ON-SITE MOBILE SLUDGE APPLICATION VEHICLES (1983)

Vehicle Capacity, CAP (Gal)	Cost Per Vehicle, COSTPV (1983 $)
1,600	85,000
2,200	95,000
3,200	120,000
4,000	140,000

A-26.9.5 Annual cost of operation labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation labor, $/yr.

A-26.9.6 Annual cost of diesel fuel.

$$COSTDSL = (FU)\ (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, $/yr.

A-26.9.7 Annual cost of maintenance for on-site mobile sludge application vehicles.

$$VMC = \left[\frac{(HSV)\ (HPD)\ (DPY)\ (MCSTCAP)}{(VHRCAP)}\right] \frac{MSECI}{751}$$

where

VMC = Annual cost of vehicle maintenance, $/yr.

MCSTCAP = Maintenance cost, $/hr of operation; for specific capacity of vehicle, see table below.

HOURLY MAINTENANCE COST FOR VARIOUS CAPACITIES OF SLUDGE APPLICATION VEHICLES

Vehicle Capacity, CAP (Gal)	Maintenance Cost, MCSTCAP ($/Hr)
1,600	4.85
2,200	5.31
3,200	5.96
4,000	7.16

A-26.9.8 Annual cost of maintenance for land application site (other than vehicles) including monitoring, recordkeeping, etc.

$$SMC = [(TLAR)\ (12)]\ \frac{ENRCCI}{4,006}$$

where

SMC = Annual cost of maintenance (other than vehicles), $/yr.
12 = Annual maintenance cost, $/acre.

A-26.9.9 Total base capital cost.

$$TBCC = COSTLAND + COSTPHT + COSTEW + COSTMAV$$

where

TBCC = Total base capital cost, $.

A-26.9.10 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTDSL + VMC + SMC$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-26.10 Cost Calculations Output Data

A-26.10.1 Cost of land for sludge application site, COSTLAND, $.

A-26.10.2 Cost of lime addition for pH adjustment, COSTPHT, $.

A-26.10.3 Cost of light grading earthwork, COSTEW, $.

A-26.10.4 Cost of on-site mobile sludge application vehicles, COSTMAV, $.

A-26.10.5 Annual cost of operation labor, COSTLB, $/yr.

A-26.10.6 Annual cost of diesel fuel, COSTDSL, $/yr.

A-26.10.7 Annual cost of vehicle maintenance, VMC, $/yr.

A-26.10.8 Annual cost of site maintenance, SMC, $/yr.

A-26.10.9 Total base capital cost of sludge to cropland program using on-site mobile sludge application vehicles, TBCC, $.

A-26.10.10 Base annual operation and maintenance cost for sludge to cropland program using on-site mobile sludge application vehicles, COSTOM, $/yr.

APPENDIX A-27

LAND APPLICATION TO NON-FOOD CHAIN CROPS (OTHER THAN FOREST LAND)

A-27.1 Background

In terms of cost of sludge transport, storage, and application, there appears to be little difference between costs for land application to non-food chain crops (other than forest land) and land application to food chain crops. Therefore, the user is directed to either the cost algorithm for land application to food chain crops (Appendix A-26) or land application to forest land (Appendix A-29), as appropriate, along with the selected sludge transport and sludge treatment processes required.

Non-food chain crops are those crops which are not directly or indirectly consumed by humans. Examples of such crops are cotton used for fiber, horticultural specialization, ornamental floriculture, turf grasses, flax, and seed production. Note that tobacco and animal fodder are considered food chain crops. Also included among non-food chain crops are timber land, tree farms, and other non-food tree growing operations; these are covered under a separate process algorithm entitled, "Land Application to Forest Land Sites" (Appendix A-29).

One difference between application of sewage sludge to non-food chain crops is that it may be easier to obtain public acceptance and regulatory agency approval for a program of sludge application to non-food chain crops. There will be less concern for the potential contamination of crops by heavy metal buildup and/or pathogens.

A second potential difference between application of sewage sludge to non-food chain crops and food chain crops is that it may be possible to apply sludge with higher metal content for a longer period of years to certain non-food chain crops without adversely affecting plant health (e.g., avoiding phytotoxic conditions). This potential difference, however, is plant species-specific, and it is beyond the scope of this cost model to evaluate such site- and crop-specific variations.

In summary, for cost purposes, there appears to be little tangible difference between land application of sludge to food chain crops and non-food chain crops (other than forest land), so no separate cost algorithm is provided for non-food chain crops (other than forest land).

APPENDIX A-28

SLUDGE APPLICATION TO MARGINAL LAND FOR LAND RECLAMATION

A-28.1 Background

The application of municipal sewage sludge to disturbed or marginal land to enhance land reclamation has been successfully demonstrated in Pennsylvania and other states. The city of Philadelphia applies most of its sludge (as compost) to the reclamation of mining lands in Pennsylvania.

Sludge application for land reclamation is usually a one-time application, i.e., sludge is not applied again to the same land area at periodic intervals in the future. Where this is true, the project must have a continuous supply of new disturbed land upon which to apply sludge in future years. This additional disturbed land can be created by ongoing mining or mineral processing operations, or may consist of presently existing large areas of disturbed land which are gradually reclaimed. In either case, an arrangement is necessary with the land owner to allow for future sludge application throughout the life of the sludge application project. For this reason, this cost algorithm does not generate the total land area required as do the other land application cost algorithms, but instead generates the annual land area required.

This cost algorithm estimates only the cost of sludge application at the reclamation site using on-site sludge application vehicles. It is assumed that the sludge is transported to the site by one of the transportation processes that appears in this manual (transportation algorithms are provided in Appendices A-20 through A-25). Typically, the on-site sludge application vehicles will obtain sludge from a large "nurse" truck, or an interim on-site sludge storage facility. However, if the same truck is used to both haul and apply the sludge, do not add the cost of on-site application trucks. (COSTMAV in Section A-28.9.5 of this algorithm equals zero.)

Sludge application rates (dry tons/acre) for reclaiming disturbed or marginal land vary widely depending on such factors as sludge characteristics, soil characteristics, environmental considerations (principally the need for ground water protection), and the type of vegetative cover planned. Investigation is required to determine the acceptable sludge application rate for a specific site(s). Application rates ranging from 10 to 180 dry tons/acre are reported in the literature, but rates less than 100 dry tons/acre are more common.

Disturbed or marginal lands often require extensive grading, soil pH adjustment by lime addition, scarifying, and vegetation seeding. Usually, the land owner pays for the cost of these operations. However, there are provisions for including these costs in the cost algorithm, if desired.

A-28.1.1 Algorithm Development

Concepts for sludge application in this algorithm are based on Reference 13, pages 8-1 through 8-24. Fuel, labor, and capital costs were derived from information supplied by equipment manufacturers and from Reference 14, pages 60 through 61 and pages 86 through 87.

A-28.2 Input Data

A-28.2.1 Daily sludge volume, SV, gpd.

A-28.2.2 Sludge suspended solids concentration, SS, percent.

A-28.2.3 Sludge specific gravity, SSG, unitless.

A-28.2.4 Average dry solids application rate, DSAR, tons of dry solids/acre. In reclaiming marginal land, sludge is typically only applied once, not annually as is done with other land application methods.

A-28.2.5 Annual sludge application period, DPY, days/yr.

A-28.2.6 Daily sludge application period, HPD, hr/day.

A-28.2.7 Fraction of land reclamation site area used for purposes other than sludge application, e.g., buffer zone, internal roads, sludge storage, waste land, etc., FWWAB.

A-28.2.8 Fraction of land reclamation site area requiring addition of lime for adjustment of soil pH to a value of 6.5, FRPH.

A-28.2.9 Fraction of land area requiring light grading, FRLG.

A-28.2.10 Fraction of land requiring medium grading, FRMG.

A-28.2.11 Fraction of land requiring extensive grading, FREG.

A-28.3 Design Parameters

A-28.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-28.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-28.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not provided, default value is calculated using the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity
1.42 = Assumed sludge solids specific gravity.

A-28.3.4 Average dry solids application rate, DSAR, tons of dry solids/acre. This value normally ranges from 10 to 100 for typical land reclamation sites depending upon sludge quality, soil conditions, and other factors. Default value = 25 tons/acre.

A-28.3.5 Annual sludge application period, DPY, days/yr. This value normally ranges from 100 to 180 days/yr for land reclamation sites depending upon climate, soil conditions, planting seasons, and other factors. Default value = 140 days/yr.

A-28.3.6 Daily sludge application period, HPD, hr/day. This value normally ranges from 5 to 8 hr/day depending upon equipment used, site size, and other factors. Default value = 7 hr/day.

A-28.3.7 Fraction of land reclamation site area used for purposes other than sludge application, FWWAB. Varies significantly depending upon site specific conditions. Default value = 0.3 for land reclamation sites.

A-28.3.8 Fraction of land reclamation site area requiring addition of lime to raise soil pH to value of 6.5, FRPH. Typically, strip mining spoils have a low soil pH, and substantial lime addition may be required. Default value = 1.0 for land reclamation sites.

A-28.3.9 Fraction of land reclamation site requiring light grading, FRLG. Varies significantly depending upon site specific conditions. Default value = 0.1.

A-28.3.10 Fraction of land reclamation site requiring medium grading, FRMG. Varies significantly depending upon site specific conditions. Default value = 0.3.

A-28.3.11 Fraction of land reclamation site requiring extensive grading, FREG. Varies significantly depending upon site specific conditions. Typically, a land reclamation site requires significant heavy grading. Default value = 0.6.

A-28.4 Process Design Calculations

A-28.4.1 Calculate dry solids applied to land per year.

$$TDSS = \frac{(SV)\ (8.34)\ (SS)\ (SSG)\ (365)}{(2,000)\ (100)}$$

where

TDSS = Dry solids applied to land, tons/yr.

A-28.4.2 Sludge disposal area required, not including area which is used for purposes other than sludge disposal, e.g., buffer zone, roads, waste area, etc. Since sludge is typically applied only once to marginal land for reclamation purposes, the sludge disposal area required represents the annual new land area which must be located each year.

$$SDAR = \frac{(TDSS)}{(DSAR)}$$

where

SDAR = Site area required only for sludge disposal, acres/yr.

A-28.4.3 Hourly sludge application rate.

$$HSV = \frac{(SV)\ (365)}{(DPY)\ (HPD)}$$

where

HSV = Hourly sludge application rate, gal/hr.

A-28.4.4 Capacity of on-site mobile sludge application vehicles. It is assumed that the sludge has already been transported to the land reclamation site by a previous unit process, e.g., large haul vehicle. The on-site mobile application vehicles accept the sludge from a transport vehicle, pipeline, or on-site storage facility, and proceed to the sludge application area to apply the sludge. Typical on-site mobile sludge application vehicles at land reclamation sites have capacities ranging from 1,600 to 4,000 gal, in the following increments: 1,600, 2,200, 3,200, and 4,000 gal.

A-28.4.4.1 Capacity and number of on-site mobile sludge application vehicles. The capacity and number of on-site mobile sludge application vehicles required is determined by comparing the hourly sludge volume, HSV, with the vehicle sludge handling rate, VHRCAP. See table below.

	Vehicle Number of Each Capacity, NOV Capacity, Gal, CAP			
HSV (Gal/Hr)	1,600	2,200	3,200	4,000
0 - 3,456	1	-	-	-
3,456 - 4,243	-	1	-	-
4,243 - 5,574	-	-	1	-
5,574 - 6,545	-	-	-	1
6,545 - 8,500	-	2	-	-
8,500 - 11,200	-	-	2	-

HSV (Gal/Hr)	Vehicle Number of Each Capacity, NOV Capacity, Gal, CAP 1,600	2,200	3,200	4,000
11,200 - 13,100	-	-	-	2
13,100 - 19,600	-	-	-	3
19,600 - 26,000	-	-	-	4

Above 26,000 gal/hr, the number of 4,000-gal capacity vehicles is calculated by:

$$NOV = \frac{HSV}{6,545} \text{ (round to the next highest integer)}$$

where

NOV = Number of on-site sludge application vehicles.

A-28.4.4.2 Average round trip on-site cycle time for mobile sludge application vehicles.

$$CT = \frac{(LT) + (ULT) + (TT)}{0.75}$$

where

CT = Average round trip on-site cycle time for mobile sludge application vehicle, min.

LT = Load time, min, varies with vehicle size (see table below).

ULT = Unload time, min, varies with vehicle size (see table below).

TT = On-site travel time to and from sludge loading facility to sludge application area, min (assumed values are shown in table below).

0.75 = An efficency factor.

Vehicle Capacity (Gal)	LT (Min)	ULT (Min)	TT (Min)	CT (Min)
1,600	6	8	5	25
2,200	7	9	5	28
3,200	8	10	5	31
4,000	9	11	5	33

A-28.4.4.3 Single vehicle sludge handling rate. The actual hourly sludge throughput rates for an on-site mobile sludge application vehicle is dependent upon the vehicle tank capacity, the cycle time, and an efficiency factor.

$$VHRCAP = \frac{(CAP)\ (60)\ (0.9)}{(CT)}$$

where

VHRCAP = Single vehicle sludge handling rate, gal/hr.
CAP = Vehicle tank capacity, gal.
CT = Cycle time, min.
0.9 = Efficiency factor.

The table below shows VHRCAP values for typical size vehicles.

Vehicle Capacity (Gal)	VHRCAP (Gal/Hr)
1,600	3,456
2,200	4,243
3,200	5,574
4,000	6,545

A-28.5 Process Design Output Data

A-28.5.1 Dry solids applied to land, TDSS, tons/yr.

A-28.5.2 Sludge disposal area required, SDAR, acres/yr.

A-28.5.3 Hourly sludge application rate, HSV, gal/hr.

A-28.5.4 Capacity of on-site mobile sludge application vehicle, CAP, gal.

A-28.5.5 Number of on-site mobile sludge application vehicles, NOV.

A-28.5.6 Cycle time for on-site mobile sludge application vehicle, CT, min.

A-28.5.7 Single vehicle sludge handling rate, VHRCAP, gal/hr.

A-28.6 Quantities Calculations

A-28.6.1 Total land area required per year. For virtually all land reclamation sites a larger land area is required than that needed only for sludge application/disposal (SDAR). The additional area may be required for buffer zones, on-site roads, on-site storage, wasted land due to unsuitable terrain, etc. In any case, the additional land area required for land reclamation sites is usually not significant, since they are typically located far from population centers.

$$TLAR = (1 + FWWAB)\ (SDAR)$$

where

TLAR = Total land area required for land reclamation sites, acres/yr.

A-28.6.2 Lime addition required for soil pH adjustment to a value of pH = 6.5.

$$TLAPH = (FRPH)\ (SDAR)$$

where

TLAPH = Total land area which must have lime applied for pH control, acres/yr.

A-28.6.3 Earthwork required. Usually a potential land reclamation site will require extensive grading to smooth out contours, provide drainage control, etc. The extent of grading required is very site specific, and can represent a significant portion of the total site preparation cost when the terrain is rough.

$$TLARLG = (FRLG)\ (TLAR)$$
$$TLARMG = (FRMG)\ (TLAR)$$
$$TLAREG = (FREG)\ (TLAR)$$

where

TLARLG = Total land area requiring light grading, acres/yr.
TLARMG = Total land area requiring medium grading, acres/yr.
TLAREG = Total land area requiring extensive grading, acres/yr.

A-28.6.4 Number of monitoring wells required. Virtually all regulatory agencies require that ground water quality monitoring wells be installed as a condition of land reclamation site permitting. The number and depth of monitoring wells required varies as a function of site size, ground water conditions, and regulatory agency requirements. In this algorithm, it is assumed that even the smallest land reclamation site must have one ground water quality monitoring well, and one additional monitoring well for each 200 acres/yr of total site area (TLAR) above 50 acres/yr.

$$NOMWR = 1 + \frac{(TLAR) - 50}{200} \quad \text{(increase to next highest integer)}$$

where

NOMWR = Number of monitoring wells required/yr.

A-28.6.5 Operation labor requirement.

$$L = \frac{8\ (NOV)\ (DPY)}{0.7}$$

where

L = Operation labor requirement, hr/yr.
8 = Hr/day assumed, hr.
0.7 = Efficiency factor.

A-28.6.6 Diesel fuel requirements for on-site mobile sludge application vehicles.

$$FU = \frac{(HSV)\ (HPD)\ (DPY)\ (DFRCAP)}{(VHRCAP)}$$

where

FU = Diesel fuel usage, gal/yr.

DFRCAP = Diesel fuel consumption rate for certain capacity vehicle, see table below, gal/hr.

GALLONS OF FUEL PER HOUR FOR VARIOUS CAPACITY SLUDGE APPLICATION VEHICLES

Vehicle Capacity (CAP), Gal	DFRCAP, Gal/Hr
1,600	3.5
2,200	4
3,200	5
4,000	6

A-28.7 Quantities Calculations Output Data

A-28.7.1 Total land area required, TLAR, acres/yr.

A-28.7.2 Total land area which must have lime added for soil pH adjustment, TLAPH, acres/yr.

A-28.7.3 Total land area requiring light grading, TLARLG, acres/yr.

A-28.7.4 Total land area requiring medium grading, TLARMG, acres/yr.

A-28.7.5 Total land area requiring extensive grading, TLAREG, acres/yr.

A-28.7.6 Number of monitoring wells required per year, NOMWR.

A-28.7.7 Annual operation labor requirement, L, hr/yr.

A-28.7.8 Annual diesel fuel usage, FU, gal/yr.

A-28.8 Unit Price Input Required

A-28.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-28.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-28.8.3 Cost of land, LANDCST, \$/acre. Typically, the land used for reclamation is not purchased by the municipality. Default value = zero.

A-28.8.4 Cost of lime addition, PHCST, \$/acre. Default value = \$120/acre (ENRCCI/4,006), based on 4 tons of lime/acre.

A-28.8.5 Cost of light grading earthwork, LGEWCST, \$/acre. Default value = \$1,000/acre (ENRCCI/4,006).

A-28.8.6 Cost of medium grading earthwork, MGEWCST, \$/acre. Default value = \$2,000/acre (ENRCCI/4,006).

A-28.8.7 Cost of extensive grading earthwork, EGEWCST, \$/acre. Default value = \$5,000/acre (ENRCCI/4,006).

A-28.8.8 Cost of monitoring well, MWCST, \$/well. Default value = \$5,000 (ENRCCI/4,006).

A-28.8.9 Cost of operational labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-28.8.10 Cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-28.9 Cost Calculations

A-28.9.1 Annual cost of land.

$$COSTLAND = (TLAR)\ (LANDCST)$$

where

COSTLAND = Annual cost of land for land reclamation site, \$/yr.

A-28.9.2 Annual cost of lime addition to adjust pH of the soil.

$$COSTPHT = (TLAPH)\ (PHCST)$$

where

COSTPHT = Annual cost of lime addition for pH adjustment, $/yr.

A-28.9.3 Annual cost of grading earthwork.

$$COSTEW = (TLARLG)\ (LGEWCST) + (TLARMG)\ (MGEWCST) + (TLAREG)\ (EGEWCST)$$

where

COSTEW = Cost of earthwork grading, $/yr.

A-28.9.4 Annual cost of monitoring wells.

$$COSTMW = (NOMWR)\ (MWCST)$$

where

COSTMW = Cost of monitoring wells, $/yr.

A-28.9.5 Cost of on-site mobile sludge application vehicles.

$$COSTMAV = [(NOV)\ (COSTPV)]\ \frac{MSECI}{751}$$

where

COSTMAV = Cost of on-site mobile sludge application vehicles, $.
COSTPV = Cost/vehicle, obtained from the table below.

COST OF ON-SITE MOBILE SLUDGE APPLICATION VEHICLES (1983)

Vehicle Capacity, Gal	COSTPV, 1983 $
1,600	85,000
2,200	95,000
3,200	120,000
4,000	140,000

A-28.9.6 Annual cost of operation labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation labor, \$/yr.
COSTL = Cost of labor, \$/hr.

A-28.9.7 Annual cost of diesel fuel.

$$COSTDSL = (FU)\ (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, \$/yr.

A-28.9.8 Annual cost of maintenance of on-site mobile sludge application vehicles.

$$VMC = \left[\frac{(HSV)\ (HPD)\ (DPY)\ (MCSTCAP)}{(VHRCAP)}\right] \frac{MSECI}{751}$$

where

VMC = Annual cost of vehicle maintenance, \$/yr.

MCSTCAP = Maintenance cost, \$/hr of operation; for specific capacity of vehicle, see table below.

HOURLY MAINTENANCE COST FOR VARIOUS CAPACITIES OF SLUDGE APPLICATION VEHICLES

Vehicle Capacity, Gal	MCSTCAP, \$/Hr
1,600	4.85
2,200	5.31
3,200	5.96
4,000	7.16

A-28.9.9 Annual cost of maintenance of land reclamation site (other than vehicles) for monitoring, recordkeeping, etc.

$$SMC = [(TLAR)\ (12)]\ \frac{ENRCCI}{4{,}006}$$

where

SMC = Annual cost of land reclamation site maintenance (other than vehicles), \$/yr.

12 = Annual maintenance cost, \$/acre.

A-28.9.10 Total base capital cost.

$$TBCC = COSTMAV$$

where

TBCC = Total base capital cost, $.

A-28.9.11 Total annual operation, maintenance, land, and earthwork cost.

$$COSTOM = COSTLB + COSTDSL + VMC + SMC + COSTLAND + COSTPHT + COSTEW + COSTMW$$

where

COSTOM = Annual operation, maintenance, land, and earthwork cost, $/yr.

A-28.10 Cost Calculations Output Data

A-28.10.1 Annual cost of land for reclamation site, COSTLAND, $/yr.

A-28.10.2 Annual cost of lime addition for pH adjustment, COSTPHT, $/yr.

A-28.10.3 Annual cost of grading earthwork, COSTEW, $/yr.

A-28.10.4 Annual cost of monitoring wells, COSTMW, $/yr.

A-28.10.5 Cost of on-site mobile sludge application vehicles, COSTMAV, $.

A-28.10.6 Annual cost of operation labor, COSTLB, $/yr.

A-28.10.7 Annual cost of diesel fuel, COSTDSL, $/yr.

A-28.10.8 Annual cost of vehicle maintenance, VMC, $/yr.

A-28.10.9 Annual cost of site maintenance, SMC, $/yr.

A-28.10.10 Total base capital cost of land reclamation sites using on-site mobile sludge application vehicles, TBCC, $.

A-28.10.11 Total annual operation, maintenance, land, and earthwork cost for land reclamation site using on-site mobile sludge application vehicles, COSTOM, $/yr.

APPENDIX A-29

LAND APPLICATION TO FOREST LAND SITES

A-29.1 Background

The application of municipal sewage sludge to forest land has been successfully demonstrated in the states of Washington, Michigan, and South Carolina. The city of Seattle is beginning a full-scale program. Commercial timber and fiber production lands, as well as federal and state forests, are potential application sites for properly managed programs.

This cost algorithm estimates only the cost of sludge application at the forest site using specially designed on-site liquid sludge application vehicles. It is assumed that the sludge is transported to the site by one of the transportation processes appearing in Appendices A-20 through A-25. Typically, the on-site liquid sludge application vehicles will obtain sludge from a large "nurse" truck, or an on-site sludge storage facility.

Sludge application rates (dry tons/acre) for forest land vary widely, depending on such factors as sludge characteristics, tree maturity, tree species, soil characteristics, etc. Investigation is required to determine the acceptable sludge application rate for a specific site. Unlike cropland application which usually involves annual sludge application, forest land sludge application to a specific site is often done at multi-year intervals, e.g., every 5 years.

Forest land sites are usually less accessible to sludge application vehicles than cropland, and on-site clearing and grading of access roads is often an initial capital cost. Provisions for estimating the cost of clearing brush and trees and grading rough access roads are included in this cost algorithm. These costs are often paid by the land owner.

This cost algorithm assumes that liquid sludge is applied by means of specially designed tanker trucks equipped with a spray "cannon" having a range of approximately 100 ft.

While provision is made in the cost algorithm for including land costs, the municipality generally will not purchase or lease the application site, and land cost will be zero.

Base capital costs include (where appropriate) the cost of land, clearing brush and trees, grading, monitoring wells, and mobile sludge application vehicles. Base annual O&M costs include labor, diesel fuel for vehicles, vehicle maintenance, and site maintenance.

A-29.1.1 Algorithm Development

Information utilized in the process design calculations for this algorithm was derived from Reference 13, pages 7-1 through 7-20, and Reference 15. Cost equations are based on Reference 14, pages 60, 61, 86, and 87; Reference 15; and information supplied by equipment manufacturers.

A-29.2 Input Data

A-29.2.1 Daily sludge volume, SV, gpd.

A-29.2.2 Sludge suspended solids concentration, SS, percent.

A-29.2.3 Sludge specific gravity, SSG, unitless.

A-29.2.4 Average dry solids application rate, DSAR, tons of dry solids/acre.

A-29.2.5 Annual sludge application period, DPY, days/yr.

A-29.2.6 Daily sludge application period, HPD, hr/day.

A-29.2.7 Frequency of sludge application to forest land at dry solids application rate, i.e., period between application of sludge to same forest land area, FR, yr.

A-29.2.8 Fraction of forest land site area used for purposes other than sludge application, e.g., buffer zone, internal roads, sludge storage, waste land, etc., FWWAB.

A-29.2.9 Fraction of forest land site area requiring clearing of brush and trees to allow access by application vehicle, FWB.

A-29.2.10 Fraction of land area requiring grading of access roads to allow travel by sludge application vehicle, FRG.

A-29.3 Design Parameters

A-29.3.1 Daily sludge volume, SV, gpd. This input value must be provided by the user. No default value.

A-29.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-29.3.4 Average dry solids application rate, DSAR, tons of dry solids/acre. This value normally ranges from 20 to 40 for typical forest land sites depending upon tree species, tree maturity, soil conditions, and other factors. Default value = 20 tons/acre/yr.

A-29.3.5 Annual sludge application period, DPY, days/yr. This value normally ranges from 130 to 180 days/yr for forest land sites depending upon climate, soil conditions, and other factors. Default value = 150 days/yr.

A-29.3.6 Daily sludge application period, HPD, hr/day. This value normally ranges from 5 to 8 hr/day depending upon equipment used, site size, and other factors. Default value = 7 hr/day.

A-29.3.7 Frequency of sludge application to forest land at dry solids application rate (DSAR), i.e., period between application of sludge to some forest land area, FR, yr. This value varies depending upon tree species, tree maturity, whether trees are grown for commercial purposes, and other factors. Default value = 5 yr.

A-29.3.8 Fraction of forest land site area used for purposes other than sludge application, FWWAB. Varies significantly depending upon site specific conditions. Default value = 0.2 for forest land sites.

A-29.3.9 Fraction of forest land site area requiring clearing of brush and trees to allow access by application vehicle, FWB. Varies significantly depending upon site specific conditions. Default value = 0.05 for forest land sites.

A-29.3.10 Fraction of forest land site requiring extensive grading of access roads to allow travel by sludge application vehicle, FRG. Varies significantly depending upon site specific conditions. Default value = 0.05 for forest land sites.

A-29.4 Process Design Calculations

A-29.4.1 Annual dry solids applied to land.

$$TDSS = \frac{(SV)\ (8.34)\ (SS)\ (SSG)\ (365)}{(2,000)\ (100)}$$

where

TDSS = Annual dry solids applied to land, tons/yr.

A-29.4.2 Sludge disposal area required, <u>not</u> including forest land area which is used for purposes other than sludge disposal, e.g., buffer zone, roads, waste area, etc.

$$SDAR = \frac{(TDSS)\ (FR)}{(DSAR)}$$

where

SDAR = Site area required only for sludge disposal, acres.

A-29.4.3 Hourly sludge volume which must be applied.

$$HSV = \frac{(SV)\ (365)}{(DPY)\ (HPD)}$$

where

HSV = Hourly sludge volume during application period, gal/hr.

A-29.4.4 Capacity of on-site mobile sludge application vehicles. It is assumed that the sludge has already been transported to the forest land sludge application site by a transport process such as truck hauling. The on-site mobile application vehicles accept the sludge from a large nurse truck, on-site storage facility, etc., and proceed to the sludge application area to apply the sludge. Typical on-site mobile sludge application vehicles at forest land sites are especially modified tank trucks equipped with a sludge cannon to spray the sludge at least 100 ft through a 240-degree horizontal arc. The application vehicle is modified to handle steep slopes, sharp turn radius, and doze through small trees and brush. Such vehicles can negotiate much rougher terrain, e.g., logging roads, than conventional road tanker trucks. Because of the special conditions encountered in forest land sludge application, it is assumed that the largest on-site sludge application vehicle feasible has a capacity of 2,200 gal of sludge. Only two capacity increments are included in this program, i.e., 1,000 gal and 2,200 gal.

A-29.4.4.1 Capacity and number of on-site mobile sludge application vehicles. The capacity and number of on-site mobile sludge application vehicles required is determined by comparing the hourly sludge volume, HSV, with the vehicle sludge handling rate, VHRCAP. See table below.

	Vehicle Number of Each Capacity, NOV Capacity, CAP, (Gal)	
HSV (Gal/Hr)	1,000	2,200
0 - 1,317	1	-
1,317 - 2,528	-	1
2,528 - 5,056	-	2
5,056 - 7,584	-	3

Above 7,584 gal/hr, the number of 2,200-gal capacity vehicles is calculated by:

$$NOV = \frac{HSV}{2{,}528} \quad \text{(round to next highest integer)}$$

where

NOV = Number of on-site sludge application vehicles.

A-29.4.4.2 Average round trip on-site cycle time for mobile sludge application vehicles.

$$CT = \frac{(LT) + (ULT) + (TT)}{0.75}$$

where

CT = Average round trip on-site cycle time for mobile sludge application vehicle, min.

LT = Load time, min, varies with vehicle size (see table below).

ULT = Unload time, min, varies with vehicle size (see table below).

TT = On-site travel time to and from sludge loading facility to sludge application area, min. (Assumed values are shown in table below.)

0.75 = An efficiency factor.

Vehicle Capacity, CAP (Gal)	LT (Min)	ULT (Min)	TT (Min)	CT (Min)
1,000	6	8	10	32
2,200	7	9	10	35

A-29.4.4.3 Single vehicle sludge handling rate. The actual hourly sludge throughput rates for an on-site mobile sludge application vehicle is dependent upon the vehicle tank capacity, the cycle time, and an efficiency factor.

$$VHRCAP = \frac{(CAP)\ (60)\ (0.9)}{(CT)}$$

where

VHRCAP = Single vehicle sludge handling rate, gal/hr.
CAP = Vehicle tank capacity, gal.
0.9 = Efficiency factor.

The table below shows VHRCAP values for typical size vehicles.

Vehicle Capacity, CAP (Gal)	VHRCAP (Gal/Hr)
1,000	1,317
2,200	2,528

A-29.5 Process Design Output Data

A-29.5.1 Annual sludge quantity, TDSS, tons of dry solids/yr.

A-29.5.2 Sludge disposal area required, SDAR, acres.

A-29.5.3 Capacity of on-site mobile sludge application vehicle, CAP, gal.

A-29.5.4 Number of on-site mobile sludge application vehicles, NOV.

A-29.5.5 Cycle time for on-site mobile sludge application vehicle, CT, min.

A-29.5.6 Single vehicle sludge handling rate, VHRCAP, gal/hr.

A-29.6 Quantities Calculations

A-29.6.1 Total land area required. For virtually all forest land sites a larger land area is required than that needed only for sludge application/disposal (SDAR). The additional area may be required for buffer zones, on-site roads, on-site storage, wasted land due to unsuitable soil or terrain, etc. In any case, the additional land area required is site specific and varies significantly, e.g., from 10 to 50 percent of the SDAR.

$$TLAR = (1 + FWWAB) (SDAR)$$

where

TLAR = Total land area required for forest land site, acres.

A-29.6.2 Clearing of brush and trees required. Often a forest land site will require clearing brush and trees in access road areas to allow access to the sludge application vehicle.

$$TLAWB = (FWB)\ (TLAR)$$

where

TLAWB = Total land area with brush and trees to be cleared, acres.

A-29.6.3 Earthwork required. Often a forest land site will require grading of access roads for the sludge application vehicles, provide drainage control, etc. The extent of grading required is site-specific.

$$TLARG = (FRG)\ (TLAR)$$

where

TLARG = Total land area requiring grading, acres.

A-29.6.4 Number of monitoring wells required. Virtually all regulatory agencies require that ground water quality monitoring wells be installed as a condition of forest land site permitting. The number and depth of monitoring wells required varies as a function of site size, ground water conditions, and regulatory agency requirements. In this algorithm, it is assumed that even the smallest forest land site must have one ground water quality monitoring well, and one additional monitoring well for each 200 acres of total site area (TLAR) above 50 acres.

$$NOMWR = 1 + \frac{(TLAR) - 50}{200} \quad \text{(increase to next highest integer)}$$

where

NOMWR = Number of monitoring wells required.

A-29.6.5 Annual operation labor requirement.

$$L = \frac{8\ (NOV)\ (DPY)}{0.7}$$

where

L = Annual operation labor requirement, hr/yr.
8 = Hr/day assumed.
0.7 = Efficiency factor.

A-29.6.6 Annual diesel fuel requirement for on-site mobile sludge application vehicles.

$$FU = \frac{(HSV)\ (HPD)\ (DPY)\ (DFRCAP)}{(VHRCAP)}$$

where

FU = Annual diesel fuel usage, gal/yr.

DFRCAP = Diesel fuel consumption rate for certain capacity vehicle, see table below, gal/hr.

GALLONS OF FUEL PER HOUR FOR VARIOUS CAPACITY SLUDGE APPLICATION VEHICLES

Vehicle Capacity, CAP (Gal)	DFRCAP (Gal/Hr)
1,000	3
2,200	4

A-29.7 Quantities Calculations Output Data

A-29.7.1 Total land area required, TLAR, acres.

A-29.7.2 Total land area with brush and trees to be cleared, TLAWB, acres.

A-29.7.3 Total land area requiring grading, TLARG, acres.

A-29.7.4 Number of monitoring wells required, NOMWR.

A-29.7.5 Annual operation labor requirement, L, hr/yr.

A-29.7.6 Annual diesel fuel usage, FU, gal/yr.

A-29.8 Unit Price Input Required

A-29.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-29.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-29.8.3 Cost of land, LANDCST, $/acre. Usually the forest land is not purchased by the municipality. Default value = zero.

A-29.8.4 Cost of clearing brush and trees, BCLRCST, $/acre. Default value = $1,000/acre (ENRCCI/4,006).

A-29.8.5 Cost of grading earthwork, GEWCST, $/acre. Default value = $1,500/acre (ENRCCI/4,006).

A-29.8.6 Cost of monitoring well, MWCST, \$/well. Default value = \$5,000 (ENRCCI/4,006).

A-29.8.7 Cost of operational labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-29.8.8 Cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-29.9 Cost Calculations

A-29.9.1 Cost of land for forest land application site.

$$COSTLAND = (TLAR)\ (LANDCST)$$

where

COSTLAND = Cost of land for forest land site, \$.

A-29.9.2 Cost of clearing brush and trees.

$$COSTCBT = (TLAWB)\ (BCLRCST)$$

where

COSTCBT = Cost of clearing brush and trees, \$.

A-29.9.3 Cost of grading earthwork.

$$COSTEW = (TLARG)\ (GEWCST)$$

where

COSTEW = Cost of earthwork grading, \$.

A-29.9.4 Cost of monitoring wells.

$$COSTMW = (NOMWR)\ (MWCST)$$

where

COSTMW = Cost of monitoring wells, \$.

A-29.9.5 Cost of on-site mobile sludge application vehicles.

$$COSTMAV = [(NOV)\ (COSTPV)]\ \frac{MSECI}{751}$$

where

COSTMAV = Cost of on-site mobile sludge application vehicles, \$.
COSTPV = Cost/vehicle, obtained from the table below.

COST OF ON-SITE MOBILE SLUDGE APPLICATION VEHICLES (1983)

Vehicle Capacity, CAP (Gal)	COSTPV (1983 \$)
1,000	120,000
2,200	150,000

A-29.9.6 Annual cost of operation labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation labor, \$/yr.

A-29.9.7 Annual cost of diesel fuel.

$$COSTDSL = (FU)\ (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, \$/yr.

A-29.9.8 Annual cost of maintenance of on-site mobile sludge application vehicles.

$$VMC = \left[\frac{(HSV)\ (HPD)\ (DPY)\ (MCSTCAP)}{(VHRCAP)}\right] \frac{MSECI}{751}$$

where

VMC = Annual cost of vehicle maintenance, \$/yr.

MCSTCAP = Maintenance cost, \$/hr of operation for specific capacity of vehicle; see table below.

HOURLY MAINTENANCE COST FOR VARIOUS CAPACITIES OF FOREST LAND SLUDGE APPLICATION VEHICLES

Vehicle Capacity, CAP (Gal)	MSCTCAP ($/Hr)
1,000	6.10
2,200	7.30

A-29.9.9 Annual cost of maintenance for forest land site (other than vehicles) including monitoring, recordkeeping, etc.

$$SMC = [(TLAR)\ (12)]\ \frac{ENRCCI}{4{,}006}$$

where

SMC = Annual cost of forest land site maintenance (other than vehicles), $/yr.

12 = Annual maintenance cost, $/acre.

A-29.9.10 Total base capital cost.

$$TBCC = COSTLAND + COSTCBT + COSTEW + COSTMW + COSTMAV$$

where

TBCC = Total base capital cost, $.

A-29.9.11 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTDSL + VMC + SMC$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-29.10 Cost Calculations Output Data

A-29.10.1 Cost of land for forest land site, COSTLAND, $.

A-29.10.2 Cost of clearing brush and trees, COSTCBT, $.

A-29.10.3 Cost of grading earthwork, COSTEW, $.

A-29.10.4 Cost of monitoring wells, COSTMW, $.

A-29.10.5 Cost of on-site mobile sludge application vehicles, COSTMAV, $.

A-29.10.6 Annual cost of operation labor, COSTLB, $/yr.

A-29.10.7 Annual cost of diesel fuel, COSTDSL, $/yr.

A-29.10.8 Annual cost of vehicle maintenance, VMC, $/yr.

A-29.10.9 Annual cost of site maintenance, SMC, $/yr.

A-29.10.10 Total base capital cost of forest land application site using on-site mobile sludge application vehicles, TBCC, $.

A-29.10.11 Total annual operation and maintenance cost for forest land application site using on-site mobile sludge application vehicles, COSTOM, $/yr.

APPENDIX A-30

LAND APPLICATION TO DEDICATED DISPOSAL SITE

A-30.1 Background

A dedicated land disposal (DLD) site has as its exclusive or primary purpose the land spreading of sludge. Typically, the agency which is implementing the project owns the site(s) or has a long-term lease. This cost algorithm assumes that the land is purchased. It is virtually always the case that sludge application rates (tons/acre/yr) are much higher for DLD sites than for the other land application options (cropland, forest land, etc.). Since the higher sludge application rates may pose a greater potential danger to surface and ground water quality, the site(s) is more carefully designed, managed, and monitored than sites where other land application options are employed. DLD site design and operation are focused upon containing within the site any environmentally detrimental sludge constituents.

This cost algorithm estimates only the cost of sludge application at the DLD site using on-site sludge application vehicles. It is assumed that the sludge is brought to the DLD site by a transport process, e.g., truck hauling, pipeline transport, etc. (Algorithms for transport of sludge appear in Appendices A-20 through A-25.) If the same vehicle is used for both the transport and application of sludge to the site, do not add the cost of the on-site application trucks to the total base capital cost in this algorithm.

Sludge is often applied to DLD sites throughout the year, operations halting only during inclement weather. As a result, a layer of sludge may be applied to the same land as often as 10 to 50 times a year. Sludge application rates vary widely, depending on site-specific conditions. Application rates ranging from 20 to 200 tons of dry solids/acre/yr are reported in the literature, but rates from 30 to 100 tons of dry solids/acre/yr are more common.

A substantial buffer zone is usually required around the sludge application area by regulatory agencies. Buffer zone widths are typically 300 to 1,000 ft.

Land preparation and improvement costs (e.g., grading, drainage control, fencing, roads, etc.) are usually capital costs borne by the municipality, and are included in the cost algorithm. The economic feasibility of a DLD site is usually determined by the availability of a suitable site within reasonable distance of the treatment plant, and the cost of the land.

In addition to the purchase of land and site improvements, the total base capital cost in this algorithm includes installation of monitoring wells and purchase of on-site mobile sludge application vehicles. Base annual O&M costs include labor, diesel for the operation of vehicles, vehicle maintenance, and site maintenance.

A-30.1.1 Algorithm Development

Design equations in the following algorithm are based on Reference 13, pages 9-1 through 9-45. Information received from equipment manufacturers was used to develop capital and O&M costs. Additional cost information was obtained from Reference 14, pages 60 through 61 and pages 86 through 87.

A-30.2 Input Data

A-30.2.1 Daily sludge volume, SV, gpd.

A-30.2.2 Sludge suspended solids concentration, SS, percent.

A-30.2.3 Sludge specific gravity, SSG, unitless.

A-30.2.4 Average dry solids application rate, DSAR, tons of dry solids/acre/yr.

A-30.2.5 Annual sludge application period, DPY, days/yr.

A-30.2.6 Daily sludge application period, HPD, hr/day.

A-30.2.7 Fraction of dedicated disposal site area used for purposes other than sludge application, e.g., buffer zone, internal roads, sludge storage, waste land, etc., FWWAB.

A-30.2.8 Fraction of dedicated disposal site area requiring clearing of brush and trees, FWB.

A-30.2.9 Fraction of land area requiring light grading, FRLG.

A-30.2.10 Fraction of land requiring medium grading, FRMG.

A-30.2.11 Fraction of land requiring extensive grading, FREG.

A-30.3 Design Parameters

A-30.3.1 Daily sludge volume, SV, gpd. This input value must be provided by the user. No default value.

A-30.3.2 Sludge suspended solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-30.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated with the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed sludge solids specific gravity.

A-30.3.4 Average dry solids application rate, DSAR, tons of dry solids/acre/yr. This value normally ranges from 30 to 100 for typical dedicated disposal sites depending upon climate, soil conditions, and other factors. Default value = 60 tons/acre/yr.

A-30.3.5 Annual sludge application period, DPY, days/yr. This value normally ranges from 150 to 250 days/yr for dedicated disposal sites depending upon climate, soil conditions, and other factors. Default value = 200 days/yr.

A-30.3.6 Daily sludge application period, HPD, hr/day. This value normally ranges from 5 to 8 hr/day depending upon equipment used, site size, and other factors. Default value = 7 hr/day.

A-30.3.7 Fraction of dedicated disposal site area used for purposes other than sludge application, FWWAB. Varies significantly depending upon site specific conditions. Default value = 0.4 for dedicated disposal sites.

A-30.3.8 Fraction of dedicated disposal site area requiring clearing of brush and trees, FWB. Varies significantly depending upon site specific conditions. Default value = 0.7 for dedicated disposal sites.

A-30.3.9 Fraction of dedicated disposal site requiring light grading, FRLG. Varies significantly depending upon site specific conditions. Default value = 0.3.

A-30.3.10 Fraction of dedicated disposal site requiring medium grading, FRMG. Varies significantly depending upon site specific conditions. Default value = 0.4.

A-30.3.11 Fraction of dedicated disposal site requiring extensive grading, FREG. Varies significantly depending upon site specific conditions. Default value = 0.3.

A-30.4 Process Design Calculations

A-30.4.1 Annual dry solids applied to land.

$$TDSS = \frac{(SV)\ (8.34)\ (SS)\ (SSG)\ (365)}{(2{,}000)\ (100)}$$

where

TDSS = Annual dry solids applied, tons/yr.

A-30.4.2 Sludge disposal area required, not including dedicated site disposal area which is used for purposes other than sludge disposal, e.g., buffer zone, roads, waste area, etc.

$$SDAR = \frac{(TDSS)}{(DSAR)}$$

where

SDAR = Site area required only for sludge disposal, acres.

A-30.4.3 Hourly sludge application rate.

$$HSV = \frac{(SV)\ (365)}{(DPY)\ (HPD)}$$

where

HSV = Hourly sludge application rate, gal/hr.

A-30.4.4 Capacity of on-site mobile sludge application vehicles. It is assumed that the sludge has been transported to the dedicated sludge disposal site by a process such as large haul vehicle, pipeline, etc. The on-site mobile application vehicles accept the sludge from the large nurse truck, on-site storage facility, etc., and proceed to the sludge application area to apply the sludge. Typical on-site mobile sludge application vehicles at dedicated disposal sites have capacities ranging from 1,600 to 4,000 gal, in the following increments: 1,600, 2,200, 3,200, and 4,000 gal.

A-30.4.4.1 Capacity and number of on-site mobile sludge application vehicles. The capacity and number of on-site mobile sludge application vehicles required is determined by comparing the hourly sludge volume, HSV, with the vehicle sludge handling rate, VHRCAP. See table below.

	Vehicle Number of Each Capacity, NOV Capacity, CAP (Gal)			
HSV (Gal/Hr)	1,600	2,200	3,200	4,000
0 - 3,456	1	-	-	-
3,456 - 4,243	-	1	-	-
4,243 - 5,574	-	-	1	-
5,574 - 6,545	-	-	-	1
6,545 - 8,500	-	2	-	-
8,500 - 11,200	-	-	2	-
11,200 - 13,100	-	-	-	2
13,100 - 19,600	-	-	-	3
19,600 - 26,000	-	-	-	4

Above 26,000 gal/hr, the number of 4,000-gal capacity vehicles required is calculated by:

$$NOV = \frac{HSV}{6,545} \text{ (round to the next highest integer)}$$

where

NOV = Number of on-site sludge application vehicles.

A-30.4.4.2 Average round trip on-site cycle time for mobile sludge application vehicles.

$$CT = \frac{(LT) + (ULT) + (TT)}{0.75}$$

where

CT = Average round trip on-site cycle time for mobile sludge application vehicle, min.

LT = Load time, min, varies with vehicle size (see table below).

ULT = Unload time, min, varies with vehicle size (see table below).

TT = On-site travel time to and from sludge loading facility to sludge application area, min. (assumed values are shown in table below).

0.75 = An efficiency factor.

Vehicle Capacity, CAP (Gal)	LT (Min)	ULT (Min)	TT (Min)	CT (Min)
1,600	6	8	5	25
2,200	7	9	5	28
3,200	8	10	5	31
4,000	9	11	5	33

A-30.4.4.3 Single vehicle sludge handling rate. The actual hourly sludge throughput rates for an on-site mobile sludge application vehicle is dependent upon the vehicle tank capacity, the cycle time, and an efficiency factor.

$$VHRCAP = \frac{(CAP)\ (60)\ (0.9)}{(CT)}$$

where

VHRCAP = Single vehicle sludge handling rate, gal/hr.
CAP = Vehicle tank capacity, gal.
CT = Cycle time, min.
0.9 = Efficiency factor.

The table below shows VHRCAP values for typical size vehicles.

Vehicle Capacity, CAP (Gal)	VHRCAP (Gal/Hr)
1,600	3,456
2,200	4,243
3,200	5,574
4,000	6,545

A-30.5 Process Design Output Data

A-30.5.1 Annual dry solids applied to land, TDSS, tons/yr.

A-30.5.2 Sludge disposal area required, SDAR, acres.

A-30.5.3 Hourly sludge application rate, HSV, gal/hr.

A-30.5.4 Capacity of on-site mobile sludge application vehicle, CAP, gal.

A-30.5.5 Number of on-site mobile sludge application vehicles, NOV.

A-30.5.6 Cycle time for on-site mobile sludge application vehicle, CT, min.

A-30.5.7 Single vehicle sludge handling rate, VHRCAP, gal/hr.

A-30.6 Quantities Calculations

A-30.6.1 Total land area required. For virtually all dedicated disposal sites a larger land area is required than that needed only for sludge application/disposal (SDAR). The additional area may be required for buffer zones, on-site roads, on-site storage, and wasted land due to unsuitable soil or terrain. In addition, the owner may have to purchase more land than actually needed due to the size of land parcels available. In any case, the additional land area required is site specific and varies significantly, e.g., from 10 to 100 percent of the SDAR.

$$TLAR = (1 + FWWAB) (SDAR)$$

where

TLAR = Total land area required for dedicated disposal site, acres.

A-30.6.2 Clearing of brush and trees required. Often a potential dedicated disposal site will contain brush and trees which must be cleared prior to site grading.

$$TLAWB = (FWB)\ (TLAR)$$

where

TLAWB = Total land area with brush and trees to be cleared, acres

A-30.6.3 Earthwork required. Usually a potential dedicated disposal site will require grading to smooth out contours, provide drainage control, etc. The extent of grading required is very site specific, and can represent a significant portion of the total land cost when the terrain is rough.

$$TLARLG = (FRLG)\ (TLAR)$$
$$TLARMG = (FRMG)\ (TLAR)$$
$$TLAREG = (FREG)\ (TLAR)$$

where

TLARLG = Total land area requiring light grading, acres.
TLARMG = Total land area requiring medium grading, acres.
TLAREG = Total land area requiring extensive grading, acres.

A-30.6.4 Number of monitoring wells required. Virtually all regulatory agencies require that ground water quality monitoring wells be installed as a condition of dedicated disposal site permitting. The number and depth of monitoring wells required varies as a function of site size, ground water conditions, and regulatory agency requirements. In this algorithm, it is assumed that even the smallest dedicated disposal site must have two ground water quality monitoring wells, and one additional monitoring well for each 40 acres of total site area (TLAR) above 40 acres.

$$NOMWR = 2 + \frac{(TLAR) - 40}{40} \quad \text{(increase to next highest integer)}$$

where

NOMWR = Number of monitoring wells required.

A-30.6.5 Annual operation labor requirement.

$$L = \frac{8\ (NOV)\ (DPY)}{0.7}$$

where

L = Annual operation labor requirement, hr/yr.
8 = Hr/day assumed.
0.7 = Efficiency factor.

A-30.6.6 Annual diesel fuel requirements for on-site mobile sludge application vehicles.

$$FU = \frac{(HSV)\ (HPD)\ (DPY)\ (DFRCAP)}{(VHRCAP)}$$

where

FU = Annual diesel fuel usage, gal/yr.

DFRCAP = Diesel fuel consumption rate for certain capacity city vehicle, see table below, gal/hr.

GALLONS OF FUEL PER HOUR FOR VARIOUS CAPACITY SLUDGE APPLICATION VEHICLES

Vehicle Capacity, CAP (Gal)	DFRCAP (Gal/Hr)
1,600	3.5
2,200	4
3,200	5
4,000	6

A-30.7 Quantities Calculations Output Data

A-30.7.1 Total land area required, TLAR, acres.

A-30.7.2 Total land area with brush and trees to be cleared, TLAWB, acres.

A-30.7.3 Total land area requiring light grading, TLARLG, acres.

A-30.7.4 Total land area requiring medium grading, TLARMG, acres.

A-30.7.5 Total land area requiring extensive grading, TLAREG, acres.

A-30.7.6 Number of monitoring wells required, NOMWR.

A-30.7.7 Annual operation labor requirement, L, hr/yr.

A-30.7.8 Annual diesel fuel usage, FU, gal/yr.

A-30.8 Unit Price Input Required

A-30.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-30.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-30.8.3 Cost of land, LANDCST, $/acre. Default value = $3,000/acre.

A-30.8.4 Cost of clearing brush and trees, BCLRCST, $/acre. Default value = $1,000/acre (ENRCCI/4,006).

A-30.8.5 Cost of light grading earthwork, LGEWCST, $/acre. Default value = $1,000/acre (ENRCCI/4,006).

A-30.8.6 Cost of medium grading earthwork, MGEWCST, $/acre. Default value = $2,000/acre (ENRCCI/4,006).

A-30.8.7 Cost of extensive grading earthwork, EGEWCST, $/acre. Default value = $5,000/acre (ENRCCI/4,006).

A-30.8.8 Cost of monitoring well(s), MWCST, $/well. Default value = $5,000 (ENRCCI/4,006).

A-30.8.9 Cost of operational labor, COSTL, $/hr. Default value = $13.00/hr (ENRCCI/4,006).

A-30.8.10 Cost of diesel fuel, COSTDF, $/gal. Default value = $1.30/gal (ENRCCI/4,006).

A-30.9 Cost Calculations

A-30.9.1 Cost of land for dedicated disposal site.

$$COSTLAND = (TLAR)\ (LANDCST)$$

where

COSTLAND = Cost of land for dedicated disposal site, $.

A-30.9.2 Cost of clearing brush and trees.

$$COSTCBT = (TLAWB)\ (BCLRST)$$

where

COSTCBT = Cost of clearing brush and trees, $.

A-30.9.3 Cost of grading earthwork.

$$COSTEW = (TLARLG)\ (LGEWCST) + (TLARMG)\ (MGEWCST) + (TLAREG)\ (EGEWCST)$$

where

COSTEW = Cost of grading earthwork, $.

A-30.9.4 Cost of monitoring wells.

$$COSTMW = (NOMWR)\ (MWCST)$$

where

COSTMW = Cost of monitoring wells, $.

A-30.9.5 Cost of on-site mobile sludge application vehicles.

$$COSTMAV = [(NOV)\ (COSTPV)]\ \frac{MSECI}{751}$$

where

COSTMAV = Cost of on-site mobile sludge application vehicles, $.
COSTPV = Cost of vehicle, obtained from the table below.

COST OF ON-SITE MOBILE SLUDGE APPLICATION VEHICLES (1983)

Vehicle Capacity, CAP (Gal)	COSTPV, 1983 $
1,600	85,000
2,200	95,000
3,200	120,000
4,000	140,000

A-30.9.6 Cost of miscellaneous site improvements, including fencing, drainage structures, lighting, buildings, etc. Obviously, this cost is highly variable depending upon site conditions. For the purpose of this program, the cost of these miscellaneous improvements have been made a function of total dedicated land disposal site size (TLAR).

$$MISCST = [(TLAR)\ (2{,}500)]\ \frac{ENRCCI}{4{,}006}$$

where

MISCST = Cost of miscellaneous site improvements, $.
2,500 = Cost of miscellaneous site improvements, $/acre.

A-30.9.7 Annual cost of operation labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation labor, $/yr.

A-30.9.8 Annual cost of diesel fuel.

$$COSTDSL = (FU)\ (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, $/yr.

A-30.9.9 Annual cost of maintenance for on-site mobile sludge application vehicles.

$$VMC = \left[\frac{(HSV)\ (HPD)\ (DPY)\ (MCSTCAP)}{(VHRCAP)}\right] \frac{MSECI}{751}$$

where

VMC = Annual cost of vehicle maintenance, $/yr.

MCSTCAP = Maintenance cost, $/hr of operation, for specific capacity of vehicle; see table below.

HOURLY MAINTENANCE COST FOR VARIOUS CAPACITIES OF SLUDGE APPLICATION VEHICLES

Vehicle Capacity, CAP (Gal)	MCSTCAP, $/hr
1,600	4.85
2,200	5.31
3,200	5.96
4,000	7.16

A-30.9.10 Annual cost of maintenance for dedicated disposal site (other than vehicles) including monitoring, recordkeeping, etc.

$$SMC = [(TLAR)\ (100)] \frac{ENRCCI}{4,006}$$

where

SMC = Annual cost of site maintenance (other than vehicles) for dedicated disposal, $/yr.

100 = Annual maintenance cost, $/acre.

A-30.9.11 Total base capital cost.

$$TBCC = COSTLAND + COSTCBT + COSTEW + COSTMW + COSTMAV + MISCST$$

where

TBCC = Total base capital cost, $.

A-30.9.12 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTDSL + VMC + SMC$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-30.10 Cost Calculations Output Data

A-30.10.1 Cost of land for dedicated disposal site, COSTLAND, $.

A-30.10.2 Cost of clearing brush and trees, COSTCBT, $.

A-30.10.3 Cost of grading earthwork, COSTEW, $.

A-30.10.4 Cost of monitoring wells, COSTMW, $.

A-30.10.5 Cost of on-site mobile sludge application vehicles, COSTMAV, $.

A-30.10.6 Cost of miscellaneous site improvements, MISCST, $.

A-30.10.7 Annual cost of operation labor, COSTLB, $/yr.

A-30.10.8 Annual cost of diesel fuel, COSTDSL, $/yr.

A-30.10.9 Annual cost of vehicle maintenance, VMC, $/yr.

A-30.10.10 Annual cost of site maintenance, SMC, $/yr.

A-30.10.11 Total base capital cost of dedicated land disposal site using on-site mobile sludge application vehicles, TBCC, $.

A-30.10.12 Annual operation and maintenance cost for dedicated land disposal site using on-site mobile sludge application vehicles, COSTOM, $/yr.

APPENDIX A-31

LAND DISPOSAL TO SLUDGE LANDFILL

A-31.1 Background

This process algorithm covers sludge landfills owned and operated by the sludge generating agency for the exclusive purpose of disposing of dewatered sewage sludge. Many municipalities dispose of their sewage sludge to landfills operated by other private or public entities. In these cases the municipality usually pays a disposal (tipping) fee to the landfill owner based upon cost per unit weight or volume of sludge. This process algorithm does not cover landfill disposal to another entity.

Sludge landfilling is defined as a disposal method involving the burial of sludge, i.e., the application of sludge on the land and subsequent burial by applying a layer of cover soil over the sludge. Cover is usually applied daily. Not included in this process are sludge to land applications by spreading where the sludge is spread on the soil surface or injected in the top soil layer, e.g., dedicated land disposal site, application to food chain crops, etc. These land application processes are covered in Appendices A-26 through A-30.

Sludge landfill methods in use are:

- Narrow trenching, which is defined as sludge disposal to trenches less than 10 ft wide.
- Wide trenching, which is defined as sludge disposal to trenches more than 10 ft wide.
- Codisposal with municipal refuse in a conventional municipal refuse landfill. As previously noted, this disposal method is not included in this process.

For the purpose of this algorithm, it is assumed that the sludge landfill methods involving trenching are conducted on a site owned by the agency which generates the sludge. In addition to the purchase of land, the base capital cost obtained using this algorithm includes site improvements (brush clearing, grading, etc.), installation of monitoring wells, purchase of excavation vehicles, and purchase of earth-moving vehicles. Total base annual cost includes operation labor, diesel fuel for machinery, machinery maintenance, and site maintenance.

Note that this process cost algorithm does not include any costs for transporting sludge from the treatment plant(s) to the landfill site, nor any costs involved in the treatment of sludge, e.g., stabilization, dewatering, etc. Costs for these processes may be obtained using the algorithms in other appendices.

From a regulatory viewpoint, a sludge landfill may be considered similar to a hazardous waste disposal site. In many instances there will be required ground water quality protection improvements, such as liners, leachate collection systems, etc., as well as surface water quality protection improvements, such as surface drainage control/collection structures. In a general cost program such as this one, it is impossible to take into account all of these types of site-specific variables. The user is particularly cautioned that this algorithm does not include the cost of liners or leachate collection systems.

A-31.1.1 Algorithm Development

Capital costs of equipment in this algorithm were obtained from manufacturers. O&M requirements were provided by Caterpillar Performance Handbook, Reference 16, pages 28-1 through 28-40. Additional information was obtained from Reference 4, pages 19-3 through 19-25, and Reference 17, pages 5-1 through 10-32.

A-31.2 Input Data

A-31.2.1 Daily sludge volume, SV, gpd.

A-31.2.2 Site life, SL, yr.

A-31.2.3 Trench width, TW, ft. Assume vertical side-walls for trenches.

A-31.2.4 Trench depth, TD, ft. Assume 2 ft of soil cover for top 2 ft of each trench.

A-31.2.5 Trench spacing, TS, ft. This is the horizontal distance between the edges of trenches.

A-31.2.6 Annual sludge application period, DPY, days/yr.

A-31.2.7 Daily sludge application period, HPD, hr/day.

A-31.2.8 Fraction of landfill site used for purposes other than sludge trenching, e.g., buffer zones, internal roads, cover soil storage, etc., FWWAB.

A-31.2.9 Fraction of raw landfill disposal site requiring clearing of brush and trees, FWB.

A-31.2.10 Fraction of raw landfill disposal site requiring grading, FRG.

A-31.3 Design Parameters

A-31.3.1 Daily sludge volume to be landfilled, SV, gpd. This input value must be provided by the user. No default value.

A-31.3.2 Landfill site life, SL, yr. Default value = 20 yr.

A-31.3.3 Trench width, TW, ft. Default value = 10 ft (assume vertical sidewalls for trenches).

A-31.3.4 Trench depth, TD, ft. Default value = 10 ft.

A-31.3.5 Trench spacing, i.e., distance between edges of trenches, TS, ft. Default value = 15 ft.

A-31.3.6 Annual sludge application period, DPY, days/yr. Default value = 240 days.

A-31.3.7 Daily sludge application period, HPD, hr/day. Default value = 7 hr/day.

A-31.3.8 Fraction of raw landfill site used for purposes other than sludge trenching, FWWAB. Default value = 0.3.

A-31.3.9 Fraction of raw landfill disposal site requiring clearing of brush and trees, FWB. Default value = 0.7.

A-31.3.10 Fraction of raw landfill disposal site requiring initial grading, FRG. Default value = 0.7.

A-31.4 Process Design Calculations

A-31.4.1 Calculate total volume of sludge to be landfilled during site life.

$$TSV = \frac{(SV)\ (SL)\ (365)}{(202)}$$

where

TSV = Total sludge volume to be landfilled over site life, yd^3.
202 = Conversion factor, gal/yd^3.

A-31.4.2 Calculate total trench volume required during site life.

$$TV = \frac{(TSV)\ (TD)}{(TD - 2)}$$

where

TV = Total trench volume required during site life, yd^3.
2 = Assumed depth of cover soil in trench, ft.

A-31.4.3 Calculate area of landfill site required only for sludge disposal, i.e., not including additional area required for buffer zone, on-site roads, etc.

$$SDAR = \frac{(3)\ (TV)\ (TS + TW)}{(TD)\ (TW)\ (4{,}840)}$$

where

SDAR = Area of landfill required only for sludge disposal, acres.
3 = Conversion factor, ft/yd.
4,840 = Conversion factor, yd^2/acre.

A-31.4.4 Calculate required hourly capacity of earth excavation digging machine(s).

$$EVR = \frac{(TV)}{(SL)\ (DPY)\ (HPD)\ (0.70)}$$

where

EVR = Average earth excavation rate requirement for digging machine(s), yd^3/hr.

0.70 = Efficiency factor.

A-31.4.5 Calculate required hourly capacity of earth-moving and cover material application machine(s).

$$EMR = \frac{(TV)\ (2)}{(SL)\ (DPY)\ (HPD)\ (TD)\ (0.5)}$$

where

EMR = Average earth-moving and cover material application rate requirement for earth-moving machine(s), yd^3/hr.

2 = Assumed depth of cover material, ft.

0.5 = An efficiency factor.

A-31.4.6 Size and number of earth excavation machines. It is assumed that this machine is a backhoe for smaller landfill sites and an excavator for larger landfill sites. The size and number of earth excavation machines is determined by comparing the required hourly capacity of the earth excavation machine, EVR, with standard excavation rates for various size earth excavation machines. See table below.

NUMBER OF EARTH-EXCAVATING MACHINES OF EACH CAPACITY, NOVEX

Required Excavation Rate, EVR, Yd^3/Hr	Capacity of Excavating Machines, CAPEX (Yd^3/Hr)						
	20	50	100	150	200	250	300
0 - 20	1	-	-	-	-	-	-
20 - 50	-	1	-	-	-	-	-
50 - 100	-	-	1	-	-	-	-
100 - 150	-	-	-	1	-	-	-
150 - 200	-	-	-	-	1	-	-
200 - 250	-	-	-	-	-	1	-
250 - 300	-	-	-	-	-	-	1
300 - 400	-	-	-	-	2	-	-
400 - 500	-	-	-	-	-	2	-

Above 600 yd^3/hr, the number of 300 yd^3/hr excavators needed is calculated by:

$$NOVEX = \frac{EVR}{300} \quad \text{(round to the next highest integer)}$$

where

NOVEX = Number of earth excavation machines required.
CAPEX = Capacity of excavating machine(s), yd^3/hr.

A-31.4.7 Size and number of earth-moving and cover application machines. It is assumed that for smaller landfills, a front-end loader equipped with a backhoe will do both excavation and cover application, thus eliminating the need for separate earth-moving and cover application equipment. For larger landfills, it is assumed that a separate earth-moving and cover application machine(s) will be used. The size and number of earth-moving and cover application machines is determined by comparing the required hourly capacity for the earth-moving machine(s), EMR, with standard rates for various size earth-moving machines. See table below.

NUMBER OF EARTH-MOVING MACHINES OF EACH CAPACITY, NOVMV

Required Earth-Moving Rate, EMR, Yd^3/Hr	Capacity of Earth-Moving Machines, CAPMV (Yd^3/Hr)						
	10	25	50	75	100	200	300
0 - 10	0	0	0	0	0	0	0
10 - 25	-	1	-	-	-	-	-

Required Earth-Moving Rate, EMR, Yd^3/Hr	Capacity of Earth-Moving Machines, CAPMV (Yd^3/Hr)						
	10	25	50	75	100	200	300
25 - 50	-	-	1	-	-	-	-
50 - 75	-	-	-	1	-	-	-
75 - 100	-	-	-	-	1	-	-
100 - 200	-	-	-	-	-	1	-
200 - 300	-	-	-	-	-	-	1
300 - 400	-	-	-	-	-	2	-
400 - 600	-	-	-	-	-	-	2

Above 600 yd^3/hr, the number of 300 yd^3/hr earth-moving machines needed is calculated by:

$$NOVMV = \frac{EMR}{300} \quad \text{(round to the next highest integer)}$$

where

NOVMV = Number of earth-moving machines required.
CAPMV = Capacity of earth-moving machine(s), yd^3/hr.

A-31.5 Process Design Output Data

A-31.5.1 Total volume of sludge to be landfilled over site life, TSV, yd^3.

A-31.5.2 Total trench volume required during site life, TV, yd^3.

A-31.5.3 Sludge disposal area required, SDAR, acres.

A-31.5.4 Average earth excavation rate requirement for digging machine(s), EVR, yd^3/hr.

A-31.5.5 Average earth-moving and cover application rate requirement for earth-moving and cover application machine(s), EMR, yd^3/hr.

A-31.5.6 Number of earth excavation machines required, NOVEX.

A-31.5.7 Capacity of earth excavation machine(s) required, CAPEX, yd^3/hr.

A-31.5.8 Number of earth-moving and cover application machines required, NOVMV.

A-31.5.9 Capacity of earth-moving machine(s) required, CAPMV, yd^3/hr.

A-31.6 Quantities Calculations

A-31.6.1 Total land area required. For virtually all sludge landfill sites a larger land area is required than that needed only for sludge application/disposal (SDAR). The additional area may be required for buffer zones, on-site roads, on-site storage, wasted land due to unsuitable soil or terrain. In addition, the agency may have to purchase more land than actually needed due to the size of land parcels available. In any case, the additional land area required is site-specific and varies significantly, e.g., from 10 to 100 percent of the SDAR.

$$TLAR = (1 + FWWAB)\ (SDAR)$$

where

TLAR = Total land area required for landfill site, acres.

A-31.6.2 Clearing of brush and trees required. Often a potential landfill site will contain brush and trees which must be cleared prior to site grading.

$$TLAWB = (FWB)\ (TLAR)$$

where

TLAWB = Total land area with brush and trees to be cleared, acres.

A-31.6.3 Earthwork required. Usually a potential landfill site will require grading to smooth out contours, provide drainage control, etc. The extent of grading required is very site-specific, and can represent a significant portion of the total site development cost when the terrain is rough.

$$TLARG = (FRG)\ (TLAR)$$

where

TLARG = Total land area requiring grading, acres.

A-31.6.4 Number of monitoring wells required. Virtually all regulatory agencies require that ground water quality monitoring wells be installed as a condition of landfill site permitting. The number and depth of monitoring wells required varies as a function of site size, ground water conditions, and regulatory agency requirements. In this algorithm, it is assumed that even the smallest landfill site must have two ground water quality monitoring wells, with one additional monitoring well for each 50 acres of total site area (TLAR) over 20 acres.

$$NOMWR = 2 + \frac{(TLAR) - 20}{50} \quad \text{(increase to next highest integer)}$$

where

NOMWR = Number of monitoring wells required.

A-31.6.5 Annual operation labor requirement.

$$L = \frac{8\ (NOVEX + NOVMV)\ (DPY)}{0.7}$$

where

L = Annual operation labor requirement, hr/yr.
8 = Hr/day assumed.
0.7 = Efficiency factor.

A-31.6.6 Annual diesel fuel requirement for on-site earth excavation and earth-moving machines.

$$FU = \frac{[(EVR) + (EMR)]\ (HPD)\ (DPY)\ [(NOVEX)\ (DFREX) + (NOVMV)\ (DFRMV)]}{[(NOVEX)\ (CAPEX) + (NOVMV)\ (CAPMV)]}$$

where

FU = Annual diesel fuel usage, gal/yr.

DFREX = Diesel fuel consumption rate for specific capacity (CAPEX) excavating machine(s) to be used, gal/hr; use table below.

DFRMV = Diesel fuel consumption rate for specific capacity (CAPMV) earth-moving machine(s) to be used, gal/hr; use table below.

GALLONS OF FUEL/HOUR FOR VARIOUS CAPACITY
EARTH-HANDLING MACHINES

Machine Capacity, CAPEX or CAPMV, As Appropriate, Yd^3/Hr	DFREX or DFRMV, As Appropriate, Gal/Hr
10	2
25	3
50	4
75	5
100	6
150	8
200	10
250	12
300	14

A-31.7 Quantities Calculations Output Data

A-31.7.1 Total land area required, TLAR, acres.

A-31.7.2 Total land area with brush and trees to be cleared, TLAWB, acres.

A-31.7.3 Total land area requiring grading, TLARG, acres.

A-31.7.4 Number of monitoring wells required, NOMWR.

A-31.7.5 Annual operation labor requirement, L, hr/yr.

A-31.7.6 Annual diesel fuel usage, FU, gal/yr.

A-31.8 Unit Price Input Required

A-31.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-31.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-31.8.3 Cost of land, LANDCST, \$/acre. Default value = \$3,000/acre.

A-31.8.4 Cost of clearing brush and trees, BCLRCST, \$/acre. Default value = \$1,000/acre (ENRCCI/4,006).

A-31.8.5 Cost of initial site grading earthwork, GEWCST, \$/acre. Default value = \$1,500/acre (ENRCCI/4,006).

A-31.8.6 Cost of monitoring well(s), MWCST, \$/well. Default value = \$5,000/well (ENRCCI/4,006).

A-31.8.7 Cost of operation labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-31.8.8 Cost of diesel fuel, COSTDF, \$/gal. Default value = \$1.30/gal (ENRCCI/4,006).

A-31.9 Cost Calculations

A-31.9.1 Cost of land.

$$COSTLAND = (TLAR)\ (LANDCST)$$

where

COSTLAND = Cost of land for landfill site, \$.

A-31.9.2 Cost of clearing brush and trees.

$$COSTCBT = (TLAWB)\ (BCLRCST)$$

where

COSTCBT = Cost of clearing brush and trees, $.

A-31.9.3 Cost of grading earthwork.

$$COSTEW = (TLARG)\ (GEWCST)$$

where

COSTEW = Cost of grading earthwork, $.

A-31.9.4 Cost of monitoring wells.

$$COSTMW = (NOMWR)\ (MWCST)$$

where

COSTMW = Cost of monitoring wells, $.

A-31.9.5 Cost of on-site earth excavation equipment.

$$TOTCOSTEV = [(NOVEX)\ (COSTEV)]\ \frac{MSECI}{751}$$

where

TOTCOSTEV = Cost of earth excavation equipment, $.

COSTEV = Cost per earth excavation machine, $, obtained from table below.

Capacity of Earth-Excavating Machine(s), CAPEX, Yd^3/Hr	COSTEV, 1983 $
20	80,000
50	120,000
100	175,000
150	255,000
200	320,000
250	410,000
300	480,000

A-31.9.6 Cost of on-site earth-moving and cover soil application equipment.

$$TOTCOSTMV = [(NOVMV)\ (COSTMV)] \frac{MSECI}{751}$$

where

TOTCOSTMV = Total cost of earth-moving and cover soil application equipment, $.

COSTMV = Cost per earth-moving machine, $, obtained from table below.

Capacity of Earth-Moving Machine(s), CAPMV, Yd^3/Hr	COSTMV, 1983 $
10	75,000
25	90,000
50	115,000
75	150,000
100	170,000
200	320,000
300	450,000

A-31.9.7 Cost of miscellaneous site improvements, including fencing, drainage structures, lighting, buildings, etc. Obviously, this cost is highly variable depending upon site conditions. For the purpose of this program, the cost of these miscellaneous improvements have been made a function of total landfill site size (TLAR).

$$MISCST = [(TLAR)\ (1{,}000)] \frac{ENRCCI}{4{,}006}$$

where

MISCST = Cost of miscellaneous site improvements, $.
1,000 = Cost of miscellaneous site improvements, $/acre.

A-31.9.8 Annual cost of operation labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation labor, $/yr.

A-31.9.9 Annual cost of diesel fuel.

$$COSTDSL = (FU)\ (COSTDF)$$

where

COSTDSL = Annual cost of diesel fuel, \$/yr.

A-31.9.10 Annual cost of maintenance of on-site earth excavation and earth-moving machines.

$$VMC = \left[\frac{(EVR + EMR)\ (HPD)\ (DPY)\ [(NOVEX)\ (MCSTEX) + (NOVMV)\ (MCSTMV)]}{[(NOVEX)\ (CAPEX) + (NOVMV)\ (CAPMV)]}\right] \frac{MSECI}{751}$$

where

VMC = Total annual machine maintenance cost, \$/yr.

MCSTEX = Maintenance cost, \$/hr of operation, for the specific-capacity (CAPEX) excavating machine(s) to be used; see table below.

MCSTMV = Maintenance cost, \$/hr of operation, for specific-capacity earth-moving machine(s) to be used, see table below.

HOURLY MAINTENANCE COSTS FOR VARIOUS CAPACITIES OF EARTH-EXCAVATING AND MOVING MACHINES

Machine Capacity, CAPEX or CAPMV, As Appropriate, Yd^3/Hr	MCSTEX or MCSTMV, As Appropriate, (1983 \$/Hr)
10	4
25	5
50	7
75	9
100	11
150	13
200	16
250	18
300	20

A-31.9.11 Annual cost for maintenance of landfill site (other than machines), e.g., monitoring, recordkeeping, etc.

$$SMC = [(TLAR)\ (100)]\ \frac{ENRCCI}{4,006}$$

where

SMC = Annual cost of landfill site maintenance (other than vehicles), \$/yr.

100 = Annual maintenance cost, \$/acre.

A-31.9.12 Total base capital cost.

TBCC = COSTLAND + COSTCBT + COSTEW + COSTMW + TOTCOSTEV + TOTCOSTMV + MISCST

where

TBCC = Total base capital cost, \$.

A-31.9.13 Total annual operation and maintenance cost.

COSTOM = COSTLB + COSTDSL + VMC + SMC

where

COSTOM = Annual operation and maintenance cost, \$/yr.

A-31.10 Cost Calculations Output Data

A-31.10.1 Cost of land for landfill site, COSTLAND, \$.

A-31.10.2 Cost of clearing brush and trees, COSTCBT, \$.

A-31.10.3 Cost of grading earthwork, COSTEW, \$.

A-31.10.4 Cost of monitoring wells, COSTMW, \$.

A-31.10.5 Cost of on-site earth excavation equipment, TOTCOSTEV, \$.

A-31.10.6 Cost of on-site earth-moving and cover soil application equipment, TOTCOSTMV, \$.

A-31.10.7 Cost of miscellaneous site improvements, MISCST, \$.

A-31.10.8 Annual cost of operation labor, COSTLB, \$/yr.

A-31.10.9 Annual cost of diesel fuel, COSTDSL, \$/yr.

A-31.10.10 Annual cost of machinery maintenance, VMC, \$/yr.

A-31.10.11 Annual cost of site maintenance, SMC, \$/yr.

A-31.10.12 Total base capital cost of sludge landfill site using on-site earth-excavating and moving equipment, TBCC, $.

A-31.10.13 Annual operation and maintenance cost for sludge landfill site using on-site earth-excavating and moving equipment, COSTOM, $/yr.

APPENDIX A-32

SLUDGE STORAGE - FACULTATIVE LAGOONS

A-32.1 Background

Facultative sludge lagoons have been used extensively in sludge management systems. In order to minimize severe odor problems often encountered in facultative lagoons, it is generally advisable to store only stabilized sludges (e.g., anaerobically digested sludges) in facultative lagoons.

Facultative sludge lagoons consist of an aerobic surface layer, usually from 1 to 3 ft deep, a deeper anaerobic zone below, and a sludge storage zone on the bottom. Both the aerobic and anaerobic zones are biologically active with anaerobic stabilization providing substantial reduction of organic material. Dissolved oxygen is supplied to the aerobic zone by (1) surface aerators, (2) algae photosynthesis, and (3) surface transfer from the atmosphere. Sludge accumulates in the lagoons and must be periodically removed.

The key to successful operation of a facultative sludge lagoon is to maintain proper organic loading. Lagoons have operated successfully at maximum annual organic loadings of 20 lb volatile solids/1,000 ft^2/day. Loadings as high as 40 lb volatile solids/1,000 ft^2/day have been used successfully for several months during warm weather.

Typically, surface aerators in facultative lagoons assist in providing oxygen to the aerobic zone. In addition, surface aerators prevent the buildup of scum on the surface, and provide distribution of solids in the anaerobic zone. In this design, two floating brush type aerator-mixers are used in each lagoon, and at least two lagoons are specified for each plant. The lagoons are unlined, constructed of compacted soil with a crest width of 15 ft and 3:1 side slopes. The recommended maximum lagoon surface area is 4 acres or about 175,000 ft^2. Typical liquid depth is 12 ft, which gives a volume of about 523,000 ft^3/acre of surface area.

The following algorithm is based on the construction and operation of a facultative lagoon with design conditions as mentioned above. Base capital costs include purchase of land, excavation and construction of the lagoon, and purchase and installation of aerators. Base annual O&M costs include labor, electrical energy, and replacement parts and materials. Costs do not include provisions for the removal of sludge from the lagoons.

A-32.1.1 Algorithm Development

Typical design parameters used in this process algorithm were discussed above. Base capital costs and annual O&M requirements were obtained from in-house documents provided by Culp/Wesner/Culp Consulting Engineers.

A-32.2 Input Data

A-32.2.1 Daily sludge volume input to lagoon, SV, gal/day.

A-32.2.2 Sludge solids concentration, SS, percent.

A-32.2.3 Sludge specific gravity, SSG, unitless.

A-32.2.4 Percent volatile solids in sludge, VSP, percent of dry solids.

A-32.2.5 Volatile solids destroyed during storage, VSDP, percent of volatile solids.

A-32.2.6 Lagoon loading rate, LL, lb VSS/1,000 ft^2/day.

A-32.2.7 Thickened sludge solids content in lagoon, TSC, percent.

A-32.2.8 Lagoon liquid depth, LD, ft.

A-32.3 Design Parameters

A-32.3.1 Daily sludge volume input to lagoon, SV, gal/day. This input value must be provided by the user. No default value.

A-32.3.2 Sludge solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-32.3.3 Sludge specific gravity, SSG, unitless. This value should be provided by the user. If not available, default value is calculated with the following equation:

$$SSG = \frac{1}{\frac{100 - SS}{100} + \frac{(SS)}{(1.42)\ (100)}}$$

where

SSG = Sludge specific gravity, unitless.
1.42 = Assumed specific gravity of sludge solids.

A-32.3.4 Volatile solids concentration, VSP, expressed as a percent of the dry solids weight. Default value = 35 percent.

A-32.3.5 Volatile solids destroyed during storage, VSDP, expressed as a percent of the volatile solids. Default value = 40 percent.

A-32.3.6 Lagoon loading, LL. Default value = 20 lb volatile solids/1,000 ft^2/day.

A-32.3.7 Thickened sludge solids content in lagoon, TSC. Default value = 6 percent.

A-32.3.8 Lagoon liquid depth, LD. Default value = 12 ft.

A-32.4 Process Design Calculations

A-32.4.1 Calculate dry solids input to lagoon per day.

$$DSS = \frac{(SV)\ (8.34)\ (SSG)\ (SS)}{(100)}$$

where

DSS = Sludge dry solids input to lagoon, lb/day.
8.34 = Density of water, lb/gal.

A-32.4.2 Calculate volatile solids input to lagoon per day.

$$VSS = \frac{(VSP)}{100} \times DSS$$

where

VSS = Volatile solids input to lagoon, lb/day.

A-32.4.3 Calculate the volatile solids destroyed.

$$VSD = \frac{(VSS)\ (VSDP)}{(100)}$$

where

VSD = Volatile solids destroyed, lb/day.

A-32.4.4 Calculate lagoon surface area required.

$$TLSA = \frac{(VSS)\ (1{,}000)}{LL}$$

where

TLSA = Total lagoon surface area, ft^2.
1,000 = Conversion factor for lagoon loading rate.

A-32.4.5 Calculate number of lagoons. Maximum surface area of each lagoons is 4 acres and a minimum of two lagoons are required.

$$NOL = \frac{TLSA}{(43{,}560)\ (4)}$$

where

NOL = Number of lagoons; if NOL less than 2, use 2.
43,560 = Conversion factor, ft^2/acre.
4 = Maximum surface area of each lagoon, acres.

A-32.4.6 Calculate area of each lagoon.

$$LSA = \frac{TLSA}{NOL}$$

where

LSA = Area of each lagoon, ft^2.

A-32.4.7 Calculate total area required.

$$AT = \frac{(TLSA)\ 2.0}{43,560}$$

where

AT = Total area, acres.

2.0 = Factor to account for land area between lagoons, buffer space, storage area, sloping sides of lagoon, etc.

A-32.4.8 Calculate total effective lagoon volume.

$$TLV = (TLSA)\ (LD)$$

where

TLV = Total effective lagoon volume, ft^3.

A-32.4.9 Calculate accumulation rate of sludge in lagoons.

$$SAL = \frac{(DSS - VSD)\ (100)}{(TSC)\ (62.4)}$$

where

SAL = Sludge accumulation rate, ft^3/day.
62.43 = Density of water, lb/ft^3.

A-32.5 Process Design Output Data

A-32.5.1 Sludge dry solids input to lagoon, DSS, lb/day.

A-32.5.2 Volatile solids input to lagoon, VSS, lb/day.

A-32.5.3 Volatile solids destroyed, VSD, lb/day.

A-32.5.4 Total lagoon surface area, TLSA, ft^2.

A-32.5.5 Number of lagoons, NOL.

A-32.5.6 Total area required, AT, acres.

A-32.5.7 Thickened sludge accumulation rate in lagoons, SAL, ft^3/day.

A-32.6 Quantities Calculations

A-32.6.1 Annual electrical energy required.

$$E = (NOL)\ (EUL)$$

where

E = Annual electrical energy required, kWhr/yr.

EUL = Electrical energy usage for each lagoon, kWhr/yr, determined from the following table:

1,000 ft^2 of Surface Area/Lagoon	Electrical Energy Usage,* EUL (kWhr/yr)
< 44	33,000
44 - 88	50,000
88 - 132	66,000
132 - 176	100,000

* Assumes that aerators operate 12 hr/day.

A-32.6.2 Annual operation and maintenance labor requirement, determined from the following table:

Total Lagoon Volume, TLV (ft^3)	O&M Labor, L (hr/yr)
200,000	1,600
500,000	1,700
1,000,000	1,800
5,000,000	1,900
10,000,000	2,100
20,000,000	3,000

where

L = Total labor, hr/yr (determined from above matrix).
TLV = Total lagoon volume, ft^3.

A-32.7 Quantities Calculations Output Data

A-32.7.1 Annual electrical energy requirement, E, kWhr/yr.

A-32.7.2 Annual operation and maintenance labor requirement, L, hr/yr.

A-32.8 Unit Price Input Required

A-32.8.1 Current Engineering News Record Construction Cost Index at time analysis is made, ENRCCI.

A-32.8.2 Current Marshall and Swift Equipment Cost Index at time analysis is made, MSECI.

A-32.8.3 Cost of land, LANDCST, \$/acre. Default value = \$3,000/acre.

A-32.8.4 Cost of electrical energy, COSTE, \$/kWhr. Default value = \$0.09/kWhr (ENRCCI/4,006).

A-32.8.5 Cost of labor, COSTL, \$/hr. Default value = \$13.00/hr (ENRCCI/4,006).

A-32.9 Cost Calculations

A-32.9.1 Cost of land for lagoon storage site.

$$\text{COSTLAND} = (\text{AT})\ (\text{LANDCST})$$

where

COSTLAND = Cost of land, \$.

A-32.9.2 Construction cost of lagoons.

$$\text{COSTLG} = (\text{LG})\ \frac{\text{ENRCCI}}{4{,}006}$$

where

COSTLG = Construction cost of lagoons, \$.

LG = Unadjusted construction cost of lagoons, a function of total lagoon volume, is determined from the following table:

Total Effective Lagoon Volume, TLV (ft^3)	Construction Cost, LG ($1,000)
200,000	35
500,000	68
1,000,000	120
2,000,000	200
5,000,000	450
10,000,000	870
20,000,000	1,700

A-32.9.3 Cost of aeration/mixing equipment.

$$COSTAM = (AM)\ (NOL)\ \frac{MSECI}{751}$$

where

COSTAM = Cost of aeration/mixing equipment, $.

AM Unadjusted purchase and installation cost for aeration-mixing equipment, a function of lagoon surface area, is determined from the following table:

Lagoon Surface Area, LSA (1,000 ft^2)	Purchase and Installation Cost, AM ($1,000)
< 44	35
44 - 88	40
88 - 132	45
132 - 176	50

A-32.9.4 Annual cost of operation and maintenance labor.

$$COSTLB = (TL)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, $/yr.

A-32.9.5 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, $/yr.

A-32.9.6 Annual cost of replacement parts and materials.

$$COSTPM = (0.02)\ (COSTLG)$$

where

COSTPM = Annual cost of replacement parts and materials, $/yr.

0.02 = Annual replacement parts and materials are estimated at 2 percent of total construction cost of lagoons.

A-32.9.7 Total base capital cost.

$$TBCC = COSTLAND + COSTLG + COSTAM$$

where

TBCC = Total base capital cost.

A-32.9.8 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-32.10 Cost Calculations Output Data

A-32.10.1 Cost of land for lagoon storage site, COSTLAND, $.

A-32.10.2 Construction cost of lagoons, COSTLG, $.

A-32.10.3 Cost of aeration/mixing equipment, COSTAM, $.

A-32.10.4 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-32.10.5 Annual cost of electrical energy, COSTEL, $/yr.

A-32.10.6 Annual cost of replacement parts and materials, COSTPM, \$/yr.

A-32.10.7 Total base capital cost for lagoon storage process, TBCC, \$.

A-32.10.8 Total annual operation and maintenance cost for lagoon storage process, COSTOM, \$/yr.

APPENDIX A-33

SLUDGE STORAGE - ENCLOSED TANK

A-33.1 Background

Storage tanks are usually mixed to maintain a homogeneous mixture, unless they are used for thickening or decanting. All enclosed tanks should be equipped to handle the odorous and potentially toxic and explosive gases that may be generated during storage.

The following algorithm may be used to obtain costs for either aboveground or buried tanks. Aboveground tanks are constructed of reinforced concrete, whereas buried tanks are constructed of steel. Additional design assumptions include the following:

- Hydraulic mixing by recirculation pumping to prevent solids settling and to provide homogeneous conditions in the tank.

- Low-pressure gas connection to anaerobic digester or other process. The costs of gas handling and treatment are not included.

- Flame traps at all connections above the liquid level.

- Vacuum relief.

Base capital costs include the installation and construction of tanks and appurtenances as specified above. Costs do not include sludge transfer facilities or costs for transporting sludge to and from the storage tanks. Base annual O&M costs include labor, electrical energy, and replacement parts and materials.

A-33.1.1 Algorithm Development

Capital costs and O&M requirements in this algorithm were obtained from information supplied by manufacturers and from past facility designs. Additional information was obtained from in-house documents provided by Culp/Wesner/Culp Consulting Engineers.

A-33.2 Input Data

A-33.2.1 Daily sludge volume, SV, gal/day.

A-33.2.2 Number of storage days required at daily sludge flow, SD, days.

A-33.2.3 Mixing energy, ME, hp/1,000 ft^3 of tank volume.

A-33.2.4 Total dynamic head at mixing pump, TDH, ft.

A-33.2.5 Mixing pump efficiency, EF, dimensionless.

A-33.2.6 Type of storage tank: below-ground steel tank storage, BGS, or aboveground reinforced concrete storage, AGS.

A-33.3 Design Parameters

A-33.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-33.3.2 Number of storage days required at daily sludge volume, SD, days. This input value must be provided by the user. No default value.

A-33.3.3 Mixing energy, ME, hp/1,000 ft^3 of tank volume. Default value = 0.3 hp/1,000 ft^3 of tank volume.

A-33.3.4 Total dynamic head, TDH, ft. TDH is a function of tank depth and friction loss in the piping, pipe fittings, and pump. Default value = 25 ft.

A-33.3.5 Mixing pump efficiency, EF. Default value = 0.7.

A-33.3.6 Type of storage desired: below-ground storage, BGS, or aboveground storage, AGS. Default value = AGS.

A-33.4 Process Design Calculations

A-33.4.1 Calculate storage tank volume.

$$TV = (SV)\ (SD)$$

where

TV = Tank volume, gal.

A-33.4.2 Calculate mixing power required.

$$MP = \frac{(TV)\ (ME)}{(7.48)\ (1{,}000)}$$

where

MP = Mixing power, hp.

7.48 = Conversion factor, gal/ft^3.

1,000 = Conversion factor to convert mixing energy, ME, from hp/1,000 ft^3 to hp/ft^3.

A-33.4.3 Calculate mixing pump capacity.

$$MC = \frac{(MP)\ (33{,}000)}{(EF)\ (TDH)\ (8.34)}$$

where

MC = Mixing pump capacity, gal/min.
33,000 = Conversion factor, hp to ft-lb/min.
8.34 = Density of water, lb/gal.

A-33.5 Process Design Output Data

A-33.5.1 Storage tank volume, TV, gal.

A-33.5.2 Mixing power required, MP, hp.

A-33.5.3 Mixing pump capacity, MC, gal/min.

A-33.6 Quantities Calculations

A-33.6.1 Annual electrical energy requirement. Electrical energy for mixing is a function of sludge tank volume and related mixing power.

$$E = (MP)\ (0.7457)\ (8{,}760)$$

where

E = Annual electrical energy requirement, kWhr/yr.
0.7457 = Conversion factor, hp to kW.
8,760 = Hours per year of operation, hr/yr.

A-33.6.2 Annual operation and maintenance labor requirement. Operation and maintenance labor is a function of storage tank volume.

Storage Tank Volume, TV (1,000 gal)	O&M Labor, L (hr/yr)
10	700
50	1,000
100	1,200
500	1,800
1,000	2,000

where

L = Total labor, hr/yr.

A-33.7 Quantities Calculations Output Data

A-33.7.1 Annual electrical energy requirement, E, kWhr/yr.

A-33.7.2 Annual operation and maintenance labor requirement, L, hr/yr.

A-33.8 Unit Price Input Required

A-33.8.1 Current Engineering News Record Construction Cost Index, ENRCCI.

A-33.8.2 Current Marshall and Swift Equipment Cost Index, MSECI.

A-33.8.3 Cost of electrical energy, COSTE, $/kWhr. Default value = $0.09/kWhr (ENRCCI/4,006).

A-33.8.4 Cost of labor, COSTL, $/hr. Default value = $13.00/hr (ENRCCI/4,006).

A-33.9 Cost Calculations

If aboveground storage is specified, proceed to Subsection A-33.9.2.

A-33.9.1 Construction cost of below-ground storage tanks.

$$\text{COSTBGS} = (\text{BGS})\,\frac{\text{ENRCCI}}{4,006}$$

where

COSTBGS = Construction cost of below-ground storage, $.

BGS = Unadjusted cost of below-ground storage, $. This value should be obtained from the following table:

Capacity, TV (1,000 gal)	Dimensions (ft) Length	Width	Depth	Construction Cost, BGS ($1,000)
10	11	11	12	49
50	18	18	20	80
100	26	26	20	137
500	58	58	20	330
1,000	82	82	20	616

A-33.9.2 Construction cost of aboveground storage tanks. If below-ground storage is specified, proceed to Subsection A-33.9.3.

$$\text{COSTAGS} = (\text{AGS})\,\frac{\text{ENRCCI}}{4,006}$$

where

COSTAGS = Cost of aboveground storage, $.

AGS = Unadjusted cost of aboveground storage, $. This value should be obtained from the following table:

Capacity, TV (1,000 gal)	Dimensions (ft)		Construction Cost, AGS ($1,000)
	Diameter	Height	
10	12	12	35
50	19.6	24	70
100	23.5	32	106
500	52	32	200
1,000	74	32	313

A-33.9.3 Cost of hydraulic mixing by recirculation.

$$COSTHM = (HM)\left(\frac{MSECI}{751}\right)$$

where

COSTHM = Cost of hydraulic mixing pump station, $.

HM = Unadjusted cost of hydraulic mixing pump station, $. This value should be obtained from the following table:

Mixing Pump Capacity, MC (gal/min)	Construction Cost, HM ($1,000)
20	17.3
100	23.5
350	31.2
500	35.5
700	42.3
2,000	55.0
3,500	70.5
5,000	87.0
10,000	125.0

A-33.9.4 Annual cost of operation and maintenance labor.

$$COSTLB = (L)(COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, \$/yr.

A-33.9.5 Annual cost of electrical energy.

$$COSTEL = (E)\ (COSTE)$$

where

COSTEL = Annual cost of electrical energy, \$/yr.

A-33.9.6 Annual cost of replacement parts and materials.

$$COSTPM = (0.03)\ (COSTHM)$$

where

COSTPM = Annual cost of replacement parts and material, \$/yr.

0.03 = Annual cost of replacement parts and materials, expressed as a percentage of pump capital cost.

A-33.9.7 Total base capital cost.

$$TBCC = COSTBGS\ (\text{or } COSTAGS) + COSTHM$$

where

TBCC = Total base capital cost.

A-33.9.8 Total annual operation and maintenance cost.

$$COSTOM = COSTLB + COSTEL + COSTPM$$

where

COSTOM = Total annual operation and maintenance cost, \$/yr.

A-33.10 Cost Calculations Output Data

A-33.10.1 Construction cost of buried storage tank, COSTBGS, \$.

A-33.10.2 Construction cost of aboveground storage tank, COSTAGS, \$.

A-33.10.3 Cost of hydraulic mixing pump station, COSTHM, \$.

A-33.10.4 Annual cost of operation and maintenance labor, COSTLB, \$/yr.

A-33.10.5 Annual cost of electrical energy, COSTEL, \$/yr.

A-33.10.6 Annual cost of replacement parts and materials, COSTPM, \$/yr.

A-33.10.7 Total base capital cost of sludge storage tank, TBCC, \$.

A-33.10.8 Total annual operation and maintenance cost of sludge storage tank, COSTOM, \$/yr.

APPENDIX A-34

UNCONFINED PILE STORAGE OF DEWATERED SLUDGE

A-34.1 Background

The term "dewatered sludge" covers a wide range of sludge solids concentrations, ranging from approximately 15 percent solids to more than 60 percent solids. In addition, the extent to which the dewatered sludge has been stabilized varies greatly, ranging from anaerobically digested sludge with high volatile solids content (e.g., 50 percent) to cured composted sludge with low volatile solids content (e.g., below 20 percent). Because of the wide range of characteristics defined by the term dewatered sludge, adequate storage of such sludge is achieved through the use of a number of techniques, e.g., enclosed tanks and hoppers, unconfined piles, or lagoons.

Dry sludge (e.g., over 50 percent solids), such as is often produced by heat drying, air drying, and temperature conversion processes, is easily stored using dry materials handling techniques. Dry sludge at treatment plants or land application sites is usually stored in unconfined piles. In high rainfall areas the unconfined piles may be covered (e.g., with plastic sheets) and drainage control provided (e.g., storage site grading and runoff collection structures). One or more skip loaders can be used to build the unconfined piles and load sludge haul vehicles.

Dewatered sludge which is relatively high in moisture content (e.g., 15 to 40 percent solids), and still high in volatile organic matter, is difficult to store in unconfined piles for a period of more than a few days. Odors develop from decomposition of the organic matter and the unconfined piles rapidly lose their shape. Rainfall accelerates the erosion process. Long-term storage for such "wet" sludge is usually done in sludge lagoons, or occasionally in confined structures. Cost algorithms for facultative sludge storage lagoons and/or sludge storage tanks are presented in Appendices A-32 and A-33, respectively.

This process covers the cost of unconfined storage of dry or composted sludge (e.g., over 50 percent solids) in built-up piles. Costs include a concrete slab, drainage control structures, and one or more skip loaders to build the unconfined piles and load sludge haul vehicles. This type of storage facility is generally provided at treatment plants where long-term storage of dry sludge is necessary. When dry sludge is stored for short interim periods at a land application site, the sludge is often simply dumped on the ground in an area where no concrete slab or permanent drainage control structures are constructed.

A-34.1.1 Algorithm Development

Construction costs in the following algorithm were based on information obtained from construction cost guides (2, 3). O&M requirements are based on design equations and additional information provided in Reference 4, pages 15-56 through 15-58.

A-34.2 Input Data

A-34.2.1 Daily sludge volume, SV, gal/day.

A-34.2.2 Dewatered sludge solids concentration, SS, percent. If SS is less than 40 percent, it is normally not feasible to use unconfined pile storage.

A-34.2.3 Period of storage required, SP, days.

A-34.2.4 Storage pile cross section area, X, ft^2.

A-34.3 Design Parameters

A-34.3.1 Daily sludge volume, SV, gal/day. This input value must be provided by the user. No default value.

A-34.3.2 Dewatered sludge solids concentration, SS, percent. This input value must be provided by the user. No default value.

A-34.3.3 Period of storage required, SP, days. Default value = 180 days.

A-34.3.4 Storage pile cross section area, X, ft^2. Default value = 32 ft^2. Algorithm assumes an equilateral triangle cross section.

A-34.4 Process Design Calculation

A-34.4.1 Calculate volume of dewatered sludge to be stored.

$$SVCY = \frac{(SV)\ (SP)}{(202)}$$

where

SVCY = Sludge volume to be stored, yd^3.
202 = Conversion factor, gal/yd^3.

A-34.4.2 Calculate storage area required in acres.

$$TA = \frac{(SVCY)\ (27)\ (2)}{(3)^{0.25}\ (X)^{0.5}\ (43{,}560)}$$

where

TA = Storage area required, acres.
27 = Conversion factor, ft^3/yd^3.
2 = Factor to account for spacing between storage piles.
X = Storage pile cross-sectional area, ft^2.
43,560 = Conversion factor, ft^2/acre.

A-34.5 Process Design Output Data

A-34.5.1 Volume of dewatered sludge to be stored, SVCY, yd^3.

A-34.5.2 Storage area required, TA, acres.

A-34.6 Quantities Calculations

A-34.6.1 Number of skip loaders required. For all but very large treatment plants, one skip loader will suffice to build the storage piles and load the sludge haul vehicles. This algorithm assumes that the number of skip loaders is a function of daily sludge volume generated and that the skip loader can handle 30 yd^3/hr of dewatered sludge (two steps: building piles and loading into vehicle).

$$NSL = \frac{(SVCY)}{(SP)\ (30)\ (8)\ (0.8)}$$

where

NSL = Number of skip loaders required (round to next highest integer).
30 = Skip loader sludge handling capacity, yd^3/hr.
8 = Hours in working day.
0.8 = An efficiency factor.

A-34.6.2 Annual diesel fuel requirement. Fuel requirement for the skip loader is a function of the hr/yr that the skip loader(s) is in use, which is a function of the yd^3 of dewatered sludge to be handled.

$$FU = \frac{(SVCY)\ (3)\ (365)}{(SP)\ (30)}$$

where

FU = Annual fuel usage, gal/yr.
3 = Annual fuel consumption rate for skip loader, gal/hr.
365 = Days/yr.
30 = Skip loader sludge handling capacity, yd^3/hr.

A-34.6.3 Annual operation and maintenance labor requirement. Annual operation and maintenance labor requirement is assumed to be a function of the yd^3 of dewatered sludge handled.

$$L = \frac{(SVCY)\ (365)}{(SP)\ (30)\ (0.7)}$$

where

L = Annual operation and maintenance labor requirement, hr.
365 = Days/yr.
30 = Sludge handling rate, yd^3/hr.
0.7 = Efficiency factor.

A-34.7 Quantities Calculations Output Data

A-34.7.1 Number of skip loaders required, NSL.

A-34.7.2 Annual diesel fuel requirement, FU, gal/yr.

A-34.7.3 Annual operation and maintenance labor requirement, L, hr/yr.

A-34.8 Unit Price Input Required

A-34.8.1 Current Engineering News Record Construction Cost Index, ENRCCI, at time cost analysis is made.

A-34.8.2 Current Marshall and Swift Equipment Cost Index, MSECI, at time cost analysis is made.

A-34.8.3 Cost of skip loader, COSTSL, $. Default value = $45,000 (MSECI/751).

A-34.8.4 Cost of concrete slab, COSTS, $/acre. Default value = $80,000/acre (ENRCCI/4,006).

A-34.8.5 Cost of drainage control structures, COSTD, $/acre. Default value = $20,000/acre (ENRCCI/4,006).

A-34.8.6 Cost of land, LANDCST, $/acre. Default value = $3,000/acre (ENRCCI/4,006).

A-34.8.7 Cost of Diesel Fuel, COSTDF, $/gal. Default value = $1.30/gal (ENRCCI/4,006).

A-34.8.8 Cost of labor, COSTL, $/hr. Default value = $13.00/hr (ENRCCI/4,006).

A-34.9 Cost Calculations

A-34.9.1 Capital cost of skip loaders.

$$TCOSTSL = (NSL)\ (COSTSL)$$

where

TCOSTSL = Capital cost of skip loaders required, $.

A-34.9.2 Cost of concrete slab.

$$TCOSTS = (TA)\ (COSTS)$$

where

TCOSTS = Cost of concrete slab, $.

A-34.9.3 Cost of drainage control structures.

$$TCOSTD = (TA)\ (COSTD)$$

where

TCOSTD = Cost of drainage control structures, $.

A-34.9.4 Cost of land.

$$COSTLAND = (TA)\ (1.2)\ (LANDCST)$$

where

COSTLAND = Total cost of land required, $.

1.2 = Factor to account for additional land required for buffer space, equipment storage, etc.

A-34.9.5 Annual cost of diesel fuel.

$$COSTFL = (FU)\ (COSTDF)$$

where

COSTFL = Annual cost of diesel fuel, $/yr.

A-34.9.6 Annual cost of operation and maintenance labor.

$$COSTLB = (L)\ (COSTL)$$

where

COSTLB = Annual cost of operation and maintenance labor, $/yr.

A-34.9.7 Annual skip loader maintenance cost.

$$SLMC = (TCOSTSL)\ (0.10)$$

where

SLMC = Annual skip loader maintenance cost, $.
0.10 = Estimated annual maintenance cost of 10 percent of purchase price.

A-34.9.8 Total base capital cost.

$$TBCC = TCOSTSL + TCOSTS + TCOSTD + COSTLAND$$

where

TBCC = Total base capital cost, $.

A-34.9.9 Total annual operation and maintenance cost.

$$COSTOM = COSTFL + COSTLB + SLMC$$

where

COSTOM = Total annual operation and maintenance cost, $/yr.

A-34.10 Cost Calculations Output Data

A-34.10.1 Capital cost of skip loaders required, TCOSTSL, $.

A-34.10.2 Cost of concrete slab, TCOSTS, $.

A-34.10.3 Cost of drainage control structures, TCOSTD, $.

A-34.10.4 Cost of land, COSTLAND, $.

A-34.10.5 Annual cost of diesel fuel, COSTFL, $/yr.

A-34.10.6 Annual cost of operation and maintenance labor, COSTLB, $/yr.

A-34.10.7 Annual cost of skip loader maintenance, SLMC, $/yr.

A-34.10.8 Total base capital cost of unconfined pile storage, TBCC, $.

A-34.10.9 Total annual operation and maintenance cost of unconfined pile storage, COSTOM, $/yr.

APPENDIX A-35

REFERENCES

1. Harris, R. W., M. J. Culinane, Jr., and P. T. Sun, eds. Process Design and Cost Estimating Algorithms for the Computer Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems (CAPDET). Final Report. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, and Environmental Protection Agency, Washington, D.C., Office of Water Program Operations, January 1982. 729 pp. (Available from NTIS as PB82-190455.)

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3. McGraw-Hill's 1983 Dodge Guide to Public Works and Heavy Construction Costs. Annual Edition No. 15. McGraw-Hill Information Systems Company, Princeton, New Jersey, 1982.

4. Process Design Manual for Sludge Treatment and Disposal. Technology Transfer Series. EPA-625/1-79-011, Center for Environmental Research Information, Cincinnati, Ohio, September 1979. 1135 pp. (Available from NTIS as PB80-200546.)

5. Zimpro Environmental and Energy Systems. Sludge Management Systems Manual. Rothschild, Wisconsin, 1984. 158 pp.

6. Process Design Manual for Dewatering Municipal Wastewater Sludges. EPA-625/1-82-014, Center for Environmental Research Information, Cincinnati, Ohio, October 1982. 222 pp.

7. Innovative and Alternative Technology Assessment Manual. Technical Report. EPA-430/9-78-009, EPA/MCD-53, Environmental Protection Agency, Washington, D.C., Municipal Construction Division, February 1980. 471 pp. (Available from NTIS as PB81-103277.)

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11. Ettlich, W. Transport of Sewage Sludge. EPA-600/2-77-216, Culp/Wesner/Culp, El Dorado Hills, California, for Municipal Environmental Research Laboratory, Cincinnati, Ohio, Wastewater Research Division, December 1977. 98 pp. (Available from NTIS as PB-278 195.)

12. Construction Costs for Municipal Wastewater Conveyance Systems: 1973-1979. Technical Report, EPA-430/9-81-003, Environmental Protection Agency, Washington, D.C., Office of Water Program Operations, February 1982. 124 pp. (Available from NTIS as PB82-160482.)

13. Process Design Manual for Land Application of Municipal Sludge. Technology Transfer, EPA-625/1-83-016, Center for Environmental Research Information, Cincinnati, Ohio, October 1983. 436 pp.

14. Reed, S. C., R. W. Crites, R. E. Thomas, and A. B. Hais. Cost of Land Treatment Systems. EPA-430/9-75-003, EPA/MCD-10-R, Environmental Protection Agency, Washington, D.C., Municipal Construction Division, September 1979. 145 pp. (Available from NTIS as PB80-182900.)

15. Gorte, J. K. Cost of Forest Land Disposal of Sludge. Ph.D. Dissertation. Michigan State University, East Lansing, 1980. 204 pp.

16. Caterpillar Tractor Company, Caterpillar Performance Handbook. Edition 6. Peoria, Illinois, January 1976. 662 pp.

17. Process Design Manual: Municipal Sludge Landfills. EPA-625/1-78-010, Environmental Research Information Center, Cincinnati, Ohio, October 1978. 331 pp. (Available from NTIS as PB-299 675.)

APPENDIX B

ANNOTATED BIBLIOGRAPHY OF SOURCES OF COST INFORMATION IN THE TECHNICAL LITERATURE

B.1 Introduction

This section contains an annotated bibliography of selected cost information literature sources for sludge management processes. The sources of information and the sludge management processes covered in each source are summarized in Table B-1. In addition, this table presents the year of publication and the base year of the cost estimates.

In order to utilize the cost estimate information contained in the technical literature, the reader should be aware of the inherent difficulties in comparing costs from different sources. Part of these difficulties stem from the varying methods that authors use in presenting their cost estimates. The reader should therefore take the following factors into consideration, since they influence capital construction and operation and maintenance costs from different literature sources.

(1) Different cost estimating base years. Cost estimates with a base year of 1980 cannot be directly compared to cost estimates with a base year of 1984. However, this problem can be overcome by using apropriate cost indexes such as the Engineering News Record Construction Cost Index.

(2) Different assumptions for certain basic cost factors, such as labor, electricity, fuel, hours per day of operation, days per year of operation, etc.

(3) Inclusion or exclusion of land costs. If land costs are included, the cost per acre may vary widely.

(4) Inclusion or exclusion of administrative and overhead costs. If administrative/overhead costs are included, the percent cost may vary widely. This factor primarily affects annual O&M cost estimates.

(5) Inclusion or exclusion of engineering fees, legal fees, administrative costs, and interest during construction as part of the project construction cost. These factors can easily add 30 to 40 percent to project costs. In some rare cases, cost estimates will not include that portion paid by EPA construction grant funds.

(6) Geographic location. Construction, labor, electricity, etc., costs vary from region to region. Costs in Oregon may be one-third less than in New York City for similar projects.

TABLE B-1

SUMMARY OF SELECTED COST INFORMATION SOURCES FROM THE TECHNICAL LITERATURE

SOURCE	Year of Publication	Base Year of Cost Estimates	Thickening: Gravity	Thickening: Dissolved Air Flotation	Stabilization: Aerobic Digestion, Diffused Air	Stabilization: Aerobic Digestion, Mechanical Air	Stabilization: Anaerobic Digestion	Stabilization: Heat Treatment	Stabilization: Lime Stabilization	Incineration: Fluidized Bed	Incineration: Multiple Hearth	Dewatering: Chemical Conditioning	Dewatering: Belt Pressure Filter	Dewatering: Centrifugation	Dewatering: Filter Press	Dewatering: Sludge Drying Bed	Dewatering: Vacuum Filter	Composting: Composting, Aerated Pile	Composting: Composting, Windrow	Transport: Truck Haul of Liquid Sludge	Transport: Truck Haul of Dewatered Sludge	Transport: Rail Haul of Liquid Sludge	Transport: Barge Hauling and Ocean Disposal	Transport: Pipeline Including Pumping	Transport: Ocean Outfall	Application or Disposal to Land: Cropland Application	Application or Disposal to Land: Marginal/Disturbed Land Application	Application or Disposal to Land: Forest Land Application	Application or Disposal to Land: Dedicated Disposal Site Application	Application or Disposal to Land: Sludge Landfill Disposal	Storage: Facultative Lagoons	Storage: Enclosed Tanks	Storage: Unconfined Piles
Anderson, K., et al. Cost of Landspreading and Hauling Sludge from Municipal Wastewater Treatment Plants, EPA 530/SW-619.	1977	1974												X		X	X			X	X					X					X		
CH$_2$M-Hill. Initial Analysis of Candidate Systems and Preliminary Site Identification: LA/OMA Project.	April 1977	1976	X	X			X			X	X	X		X	X	X	X		X	X	X	X	X	X			X	X	X	X			
Clarke et al. Digested Sludge Dewatering Experiences at Orange County, California.	May 1981	1979												X																			
Cosulich, W. F. Incineration of Sludge and Refuse with Waste Heat Recovery	July 1979	1977		X							X			X																		X	
Gorte, J. K. Cost of Forest Land Disposal of Sludge.	1980	1979																		X		X	X	X				X					
Gumerman et al. Design Manual Dewatering Municipal Wastewater Sludges, EPA-625/1-82-014.	Oct. 1982	April 1982					X				X			X	X	X	X				X									X	X "Dewatering Lagoon"		

TABLE B-1 (continued)

SOURCE	Year of Publication	Base Year of Cost Estimates	Thickening: Gravity	Thickening: Dissolved Air Flotation	Stabilization: Aerobic Digestion, Diffused Air	Stabilization: Aerobic Digestion, Mechanical Air	Stabilization: Anaerobic Digestion	Stabilization: Heat Treatment	Stabilization: Lime Stabilization	Incineration: Fluidized Bed	Incineration: Multiple Hearth	Dewatering: Chemical Conditioning	Dewatering: Belt Pressure Filter	Dewatering: Centrifugation	Dewatering: Filter Press	Dewatering: Sludge Drying Bed	Dewatering: Vacuum Filter	Composting: Composting, Aerated Pile	Composting: Composting, Windrow	Transport: Truck Haul of Liquid Sludge	Transport: Truck Haul of Dewatered Sludge	Transport: Rail Haul of Liquid Sludge	Transport: Barge Hauling and Ocean Disposal	Transport: Pipeline Including Pumping	Transport: Ocean Outfall	Application or Disposal to Land: Cropland Application	Application or Disposal to Land: Marginal/Disturbed Land Application	Application or Disposal to Land: Forest Land Application	Application or Disposal to Land: Dedicated Disposal Site Application	Application or Disposal to Land: Sludge Landfill Disposal	Storage: Facultative Lagoons	Storage: Enclosed Tanks	Storage: Unconfined Piles
LaConde et al. Process Design Manual - Land Application of Municipal Sludge, EPA-625/1-83-016.	Oct. 1983	Mid-1980																		X	X			X									
Leininger et al. Trade-Offs in Sludge Thickening and Transport/Reuse Systems.	Nov. 1980	1978	X	X										X							X			X									
McDonald et al. Sludge Management and Energy Independence.	Feb. 1981	Aug. 1979	X								X		X				X	X Method Not Defined								X	Specific Method Not Defined						
Municipality of Metropolitan Seattle. Sludge Disposal and Reuse Cost-Effectiveness Evaluation.	Dec. 1982	1983		X			X				X		X	X	X			X		X	X		X				X	X			X		
Murphy, et al. Operation and Maintenance Costs for Municipal Wastewater Facilities, EPA-430/9-81-004.	Sept. 1981	First Quarter 1981																															
Hese et al. Composting and Disposal of Industrial Wastewater Sludge.	Jan. 1980										X							X	X														

TABLE B-1 (continued)

SOURCE	Year of Publication	Base Year of Cost Estimates	Thickening		Stabilization					Incineration		Dewatering						Composting		Transport						Application or Disposal to Land					Storage		
			Gravity	Dissolved Air Flotation	Aerobic Digestion, Diffused Air	Aerobic Digestion, Mechanical Air	Anaerobic Digestion	Heat Treatment	Lime Stabilization	Fluidized Bed	Multiple Hearth	Chemical Conditioning	Belt Pressure Filter	Centrifugation	Filter Press	Sludge Drying Bed	Vacuum Filter	Composting, Aerated Pile	Composting, Windrow	Truck Haul of Liquid Sludge	Truck Haul of Dewatered Sludge	Rail Haul of Liquid Sludge	Barge Hauling and Ocean Disposal	Pipeline Including Pumping	Ocean Outfall	Cropland Application	Marginal/Disturbed Land Application	Forest Land Application	Dedicated Disposal Site Application	Sludge Landfill Disposal	Facultative Lagoons	Enclosed Tanks	Unconfined Piles
Otoski, R. M. Cost of Lime Stabilization and Ultimate Disposal of Municipal Wastewater Sludges, EPA-600/2-81-076.	June 1981	April 1980							X																								
Rimkus et al. Solids Handling Systems for Six Different Disposal Options.	April 1980	1977					X												X							X							
U.S. Environmental Protection Agency. Process Design Manual for Sludge Treatment and Disposal, EPA-625/1-79-011.	Sept. 1979	Varies; see column	X '77	X '77	X '77		X '75 '77	X '77	X '78		X '78	X '75	X '76	X '75	X '75	X '77	X '75	X '75	X '76												X '78		
U.S. Environmental Protection Agency. Innovative and Alternative Technology Assessment Manual, EPA 430/9-78-009.	Feb. 1980	Sept. 1976 2475		X	X	X	X	X	X '78 2672	X	X	X	X '77	X '78 2829	X	X	X	X	X	X	X	X		X		X (Combined)	X (Combined)	X (Combined)	X (Combined)	X '78	X	X	
Wallis, I. G. Ocean Outfall Construction Costs.	May 1979	ENR = 3,200																							X								

(7) Pollution control standards which must be met. Obviously, more stringent air and water quality emission standards usually result in higher construction and O&M costs.

(8) Many cost estimates are presented on a present worth or amortized basis. It is necessary to know what interest rates, facility life, etc., assumptions were used.

(9) Size of the sample (i.e., number of facilities) used as a basis for the cost estimates given. Generally, the larger the sample, the greater the range of costs reported.

(10) Different methods of presenting cost information versus project size. Referring specifically to municipal wastewater sludge, costs may be presented as a function of population served, treatment plant size in mgd, raw wet sludge volume in mgd, stabilized wet sludge volume in mgd, tons of dry sludge solids, tons of wet sludge, etc.

B.2 Annotated Bibiliography

The following annotated bibliography is organized in the same sequence as Table B-1. The reader should search for the sludge management process of interest on Table B-1, find the corresponding literature which has cost information on the subject process, and read the annotated reference in order to find out the types of information that the source contains.

Anderson, R. K., B. W. Weddle, T. Hillmer, and A. Geswein. Cost of Land Spreading and Hauling Sludge from Municipal Wastewater Treatment Plant. EPA-530/SW-619, U.S. Environmental Protection Agency, Office of Solid Waste Management Programs. October 1977. 157 pp.

This report is an analysis of the 1974 cost of disposing of municipal wastewater treatment sludge by land spreading. The study is based on a survey of 24 small communities.

Costs were evaluated for land spreading both liquid sludge and dewatered sludge. Average 1974 costs, including dewatering (if done), transport, and land application were as follows:

1. Liquid sludge followed by land application - $32/dry ton.
2. Vacuum filtration followed by land application - $87/dry ton.
3. Sludge drying beds followed by land application - $87/dry ton.

Survey results varied widely, and it is difficult to utilize this 1974 cost information in estimating costs in 1984 and later.

CH$_2$M Hill. Initial Analysis of Candidate Systems and Preliminary Site Identification: LA/OMA Project. Newport Beach, California, April 1977. 291 pp.

The Los Angeles/Orange County Metropolitan Area (LA/OMA) project was designed to develop a long-term plan to reuse or dispose of residual solids resulting from wastewater treatment in the Los Angeles-Orange County metropolitan area.

The study included preliminary costs, energy consumption factors, environmental and social concerns, implementation capability, process reliability and flexibility, and effects on public health, land use, and growth. The preliminary cost estimates (both capital and O&M costs) are based on third quarter 1976 (ENR = 2,800). All cost estimates are "order of magnitude" estimates, and are approximate, without benefit of detailed engineering data, plans, or specifications (+50 percent above; -30 percent below actual costs). Seventeen representative sludge management schemes were investigated. These schemes combined various methods of sludge thickening, stabilization, dewatering, drying, incineration, transport, and disposal/reuse methods. While the report is specific to the greater Los Angeles/Orange County area of southern California, it contains cost information which may be helpful to other major urban areas.

Clarke, W. N., W. Fox, and W. R. Howard. Digested Sludge Dewatering Experiences at Orange County, California. J. Water Pollut. Control Fed., 53:530-535, 1981.

The County Sanitation Districts of Orange County (CSDOC) collects, treats, and disposes of 195 mgd of wastewater, 25 percent of which is industrial. Sludge is stabilized by anaerobic sludge digestion, then dewatered in centrifuges, air-dried, and sold to a contractor for use as a soil supplement, or disposed to a sanitary landfill.

CSDOC conducted a cost evaluation to determine whether primary and secondary sludges should be dewatered separately or whether they should be combined prior to treatment. In both cases, it was assumed that polymer would be added to improve dewatering. No cost curves are presented.

The article contains representative operating costs (1980) for six centrifuges on line (four actual operating, two spares), in cost/dry ton processed. Costs include cost for polymers, electricity, and equipment maintenance, as follows:

- Maintenance costs - $2.20/dry metric ton.
- Electrical costs - $2.20/dry metric ton.

- Polymer costs - \$10.09/dry metric ton for primary digested sludge, and \$21.91/dry metric ton for combination of 70 percent digested primary sludge, 30 percent digested waste activated sludge.

Cosulich, W. F. Incineration of Sludge and Refuse with Waste Heat Recovery. J. Water Pollut. Control Fed., 51:1934-1938, 1979.

This article describes development of an incineration project to co-burn refuse and wastewater sludge at Glen Cove, New York.

Co-burning systems evaluated were:

- Pyrolysis (heat value - 350 Btu/ft^3) - Small capacity makes pyrolysis systems economically unfeasible.
- Fluidized bed incineration - Preliminary cost figures indicate no economic advantage.
- Stoker-fired incinerator - Designed with 30-min detention time.

The proposed stoker-fired incinerator system consists of flotation thickeners, aerated storage tanks, centrifuges for dewatering, and a refuse incinerator (250 tons/day). The estimated heat value was determined to be 4,550 Btu/lb. Estimated project cost for this system in 1977 was \$30 million.

Gorte, J. K. Cost of Forest Land Disposal of Sludge. Ph.D. Dissertation. Michigan State University, East Lansing, 1980. 204 pp.

This doctoral dissertation evaluates economics of sludge application to forest land. Technologies available for application, costs, and sensitivity of costs to changes in variables are tested. A simple simulation model (SLUDGE) was used for cost estimating various methods, and incorporates transportation, land application, and ground monitoring cost elements.
Conclusions of the study:

- Transportation is the largest component of disposal cost.
- For any mode of transportation, increasing haul distance causes transport cost to escalate.
- Rail and barge transport costs are fairly competitive with each other, and these methods (if feasible) are less expensive to handle long-distance transport of large sludge volumes than trucks.

- Pipeline transport of liquid sludge is the most cost-effective means of moving large volumes of sludge long distances.

- Spray irrigation is a cheaper liquid sludge application method than either surface or subsurface vehicular application.

- Transportation and application of dewatered sludge are less expensive than transportation and application of liquid sludge, on a per dry ton basis. The cost of dewatering sludge must be weighed against this disposal cost advantage.

This dissertation contains interesting cost information, but is based upon many grossly simplifying assumptions which decrease its usefulness for estimating "real life" costs at specific treatment plants.

Gumerman, R. C., and B. E. Burris. Process Design Manual for Dewatering Municipal Wastewater Sludges. EPA 625/1-82-014. Culp/Wesner/Culp, Santa Ana, California. October 1982. 221 pp.

This manual is a review of municipal wastewater sludge dewatering process technology, to facilitate the selection and design of a dewatering process. Included are discussions of sludge characteristics, dewatering processes, their performance capabilities and operational variables, chemical conditioning, cost and energy considerations, and case study information.

Dewatering processes discussed are basket centrifuge, low G and high G solid bowl centrifuge, belt filter press, vacuum filter, fixed-volume and variable-volume recessed plate filter press, drying bed, sludge lagoon, and gravity/low-pressure devices.

Construction and O&M cost curves are presented for nine dewatering processes. Construction costs are for installed equipment, and include all concrete structures, housing, pipes and valves, electrical and instrumentation equipment, and installation labor. O&M requirements and costs are presented for labor, building electrical, process electrical, diesel fuel, and maintenance materials.

Cost analyses were made for three sizes of sludge handling systems: 1, 5, and 50 tons/day of dry sludge solids (approximately equal to 1, 5, and 50 mgd wastewater treatment capacity). Costs are updated to April 1982, and are increased by 40 percent to account for engineering, contingencies, contractor's overhead and profit, legal fiscal and administrative, and interest during construction. Land costs were included at $2,000/acre. Capital costs were amortized at 10 percent for 20 years. Trucks, composting equipment, and front-end loaders were amortized at 10 percent over 8 years.

LaConde, K. V., C. J. Schmidt, H. Van Lam, T. Boston, and T. Dong. Process Design Manual for Land Application of Municipal Sludge. EPA-625/1-83-016, SCS Engineers, Long Beach, California, October 1983. 434 pp.

This is a design manual which details the planning and design of municipal wastewater sludge application to cropland, forest land, marginal (disturbed) land, and dedicated disposal sites. Cost information is limited, but includes cost tables for sludge transport trucks, pipelines, and land application site improvements (e.g., fences, grading, etc.). Cost estimates are based on mid-1980 costs.

Leininger, K. V., P. L. Nehm, and J. W. Schellpfeffer. Trade-Offs in Sludge Thickening and Transport/Reuse Systems. J. Water Pollut. Control Fed., 52:2771-2779, 1980.

This study was specific to the Madison, Wisconsin, solids reuse program. Present treatment in Madison is accomplished by a 50-mgd sewage treatment plant, consisting of primary treatment, activated sludge, gravity thickener, and two-stage anaerobic digestion. The proposed solids handling scheme was thickening, digestion, transport, and land application. Two alternative thickening methods were examined: flotation thickening and centrifugation thickening. A third variable was to vary the digestion time.

Cost curves were developed for sludge thickening, digestion, transport, and reuse facilities. Curves were derived for both capital and annual operation and maintenance cost, based on 1978 dollars. Capital costs were annualized using a 6.625 percent rate.

The study concluded that additional thickening by flotation or centrifugation was not cost effective for Madison, Wisconsin. Continuation of the existing gravity thickening process was the most economical alternative prior to agricultural reuse.

Otoski, R. M. Lime Stabilization and Ultimate Disposal of Municipal Wastewater Sludges. EPA 600/2-81-076. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, June 1981. 191 pp.

This report demonstrates the successful use of lime in stabilizing sludge from 28 municipal wastewater treatment plants in New England and New York. In general, lime stabilization was found to be an attractive alternative for treatment plants with wastewater flows of less than 6 mgd due to two factors. First, process costs are operation and maintenance (O&M) intensive rather than capital intensive. Second, the costs of chemicals, the major portion of the total cost, shows little economy of scale.

Cost curves, including both construction and O&M costs, are presented for a batch operation for sewage plant flows between 1 and 5 mgd. In addition, cost curves for converting and using existing lime-conditioning equipment for operation in lime stabilization are presented.

McDonald, G. C., T. Quinn, and A. Jacobs. Sludge Management and Energy Independence. J. Water Pollut. Control Fed., 53:190-200, 1981.

Monroe County, New York (pop. 430,000) utilizes activated sludge for treatment of municipal wastewater. The treatment plant processes an average of 90 mgd.

Sludge treatment consists of thickening of primary and secondary solids by gravity, dewatering by five vacuum filters, followed by incineration in three multiple-hearth furnaces. The generated ash is pumped into lagoons for disposal. The municipality processes 60 tons of dry solids daily.

Three alternatives were developed for disposal of the sludge:

- Direct land application.
- Composting to produce a soil conditioner.
- Thermal reduction techniques.

The alternatives were screened on the basis of equivalent annual cost over a 20-year planning period.

The most cost-effective sludge management alternative was determined to be replacement of four vacuum filters with continuous belt filter presses; modification of two multiple-hearth furnaces for starved air combustion, with provision for the addition of refuse-derived fuel to the two large furnaces, and addition of waste heat boilers and steam turbines for electrical power generation.

The sludge handling system was evaluated, assuming a total dewatering capacity of 180 tons/day, and a furnace capacity of 181 tons/day.

Municipality of Metropolitan Seattle. Sludge Disposal and Reuse Cost-Effectiveness Evaluation, Technical Memorandum. Seattle, Washington, December 1982. 113 pp.

The City of Seattle developed detailed studies of alternative methods to manage the sludge generated by its sewage treatment plants. Evaluations included alternative methods (and costs) for in-plant sludge processing, transportation, and reuse/disposal.

The following eight disposal and reuse alternatives were evaluated:

1. Agricultural use.
2. Composting.
3. Dry sludge product.
4. Incineration.
5. Landfilling.
6. Ocean disposal.
7. Silviculture.
8. Soil improvement.

In addition to costs, each alternative was evaluated in terms of energy use, air emissions, soil impacts, ground water impacts, surface water impacts, public health impacts, wildlife impacts, land availability, land use impacts, community acceptance, agency acceptance, proven experience, flexibility, federal and state legislation, and implementability.

Cost estimates are specific to the City of Seattle, but their methods of development may be of interest to other large urban areas.

Murphy, R. S., M. W. Hall, and W. H. Huang. Operation and Maintenance Costs for Municipal Wastewater Facilities. EPA-430/9-81-004, Sage Murphy & Associates, Denver, Colorado, September 1981. 136 pp.

This report summarizes O&M cost data for more than 900 wastewater treatment plants and almost 500 sewage conveyance systems. Included is information on administrative costs, sludge handling costs, and staffing. Data were obtained from a 1978 EPA report on individual wastewater treatment plants. In addition, technical literature was reviewed. The data represent costs reported during the period from 1973 to 1978. Only facilities with secondary or higher levels of treatment are included. Lagoonal treatment systems were excluded. Cost information is updated using indexes and is expressed as First Quarter 1981 dollars (unless noted).

In general, sludge management O&M costs are expressed in dollars per year versus treatment plant wastewater flow in mgd. O&M cost categories include labor, power, utilities, chemicals, and administration. Relatively little specific information is presented for individual sludge treatment and disposal/reuse processes.

Nese, P. A., J. Galandak, and J. A. Frederick. Composting and Disposal of Industrial Wastewater Sludge. J. Water Pollut. Control Fed., 52:183-191, 1980.

This article summarizes sludge management alternative plans prepared by the Linden Roselle Sewerage Authority, New Jersey, for its treatment plant and two adjacent sewerage agencies. Alternatives evaluated were:

- Pyrolysis.
- Land application of digested sludge to cropland.
- Composting followed by land application.

The study is very specific to the treatment plants studied, but contains interesting cost information pertinent to the processes considered. The sludge was too high in metal content for use on agricultural land. Other (1979 base year) cost estimates were:

- Composting - $123/dry ton.
- Pyrolysis - $169/dry ton.

Rimkus, R. R., E. W. Knight, and G. E. Sernel. Solids Handling Systems for Six Different Disposal Options. J. Water Pollut. Control Fed., 52:740-749, 1980.

The Metropolitan Sanitary District of Greater Chicago (MSDGC), which serves 5.5 million people, collects 700 tons/day of organic solids. In 1977, MSDGC generated 867 tons/day of dry sludge solids.

The disposal management options which were considered by MSDGC are:

1. Nu Earth giveaway - digested, dried sludge.

2. Heat-dried fertilizer sale - gravity settling, vacuum filtration, drying.

3. Heated digestion followed by land application (to Fulton County). Secondary solids and a small amount of primary solids are digested anaerobically for 14 days, pumped into barges, and taken to a land reclamation site (strip mine).

4. Heated digestion followed by lagoon aging and free distribution. Digested solids are stored in large holding basins, dewatered, trucked, and applied to land.

5. Heated digestion followed by lagooning and solids disposal. Removal is accomplished on a competitive bid basis.

6. Composting followed by free distribution.

Comparative costs shown below are for solids stabilization, processing, and disposal. These costs do not include capital costs, only O&M and transport/ distribution costs.

Method	$/Dry Metric Ton Distributed
Nu Earth	69
Heat-Dried Fertilizer	209
Fulton County	207
Lagoon Solids Distribution	72
Contract Lagoon Cleanout	78
Composting	234-308

Wallis, I. G. Ocean Outfall Construction Costs. J. Water Pollut. Control Fed., 51:951-957, 1979.

This article provides cost and design information on 36 outfalls on the west coast of the United States, three in Hawaii, and one in Puerto Rico. The ENR index was used to convert all costs to a common basis (ENR is 3,200). Data on installed and projected ocean outfalls were obtained from three sources: outfall owners, consulting engineers, and contractors.

It was concluded that the two major factors influencing unit construction cost are construction conditions and the diameter of the outfall. The outfall length was a less significant factor.

Local conditions which were found to affect cost significantly are seabed conditions, ease of site access, haulage distances, available hydraulic head, attitude and commitments of contractors at time of bids, and degree of protection against turbulent water conditions.

While the unit cost relationships presented here can give an approximate estimate of the projected cost of constructing an outfall, a detailed estimate based on a specific outfall design and local circumstances is needed to obtain an accurate estimate.

U.S. Environmental Protection Agency, Center for Environmental Research Information. Process Design Manual for Sludge Treatment and Disposal. EPA-625/1-79-011, Cincinnati, Ohio, September 1979. 1135 pp.

This excellent design manual deserves a place on every treatment plant design engineer's shelf. It contains a wealth of design information for virtually every sludge treatment process. However, it is weak in its coverage of sludge transport and recycle/disposal options.

Cost information is scattered throughout the manual. Base years for cost data vary from 1975 to 1978.

U.S. Environmental Protection Agency, Municipal Construction Division. Innovative and Alternative Technology Assessment Manual; Technical Report. EPA-430/9-78-009, Washington, D.C., February 1980. 471 pp.

This manual was prepared to provide guidance in applying for Innovative and Advanced (I and A) construction grant increases from 75 to 85 percent. Appendices to the manual summarize wastewater treatment and sludge management processes, including cost curves for construction and O&M cost estimating. The base year for cost estimates is 1976.

Typical of basic cost factors used are the following:

- ENR index = 2,475 (September 1976).
- Labor, including fringe benefits = $7.50/hr.
- Electrical power = $0.02/kWhr.
- Fuel oil = $0.37/gal.
- Gasoline = $0.60/gal.
- Land cost = $1,000/acre.

Sludge processes included in the manual are as follows:

- Centrifugal dewatering.
- Centrifugal thickening.
- Composting, static pile.
- Composting, windrow.
- Filter press.
- Dewatered sludge truck transport.
- Dewatered sludge rail transport.
- Digestion, aerobic.
- Digestion, two-stage anaerobic.
- DAF thickening.
- Drying beds.
- Belt press filter.
- Heat treatment of sludge.
- Incineration, fluidized bed.
- Incineration, multiple hearth.
- Lagoon, facultative.
- Land application of sludge.
- Lime stabilization.
- Liquid sludge transport by pipeline.
- Liquid sludge transport by rail.
- Liquid sludge transport by truck.
- Polymer addition.

- Sludge landfill - area method.
- Sludge landfill - trench method.
- Sludge pumping.
- Sludge storage.
- Vacuum filtration.

APPENDIX C

U.S. CUSTOMARY TO METRIC CONVERSION FACTORS

U.S. Customary Unit			Metric Unit	
Name	Symbol	Multiplier	Name	Symbol
Acre	acre	4.047×10^3	Square meter	m^2
		0.047	Hectare	ha
British thermal unit	Btu	1.055	Kilojoule	kJ
Cubic feet per day	ft^3/day	1.889×10^{-4}	Cubic meters per second	m^3/s
Cubic feet per gallon	ft^3/gal	7.482	Unit cubic meter	m^3/m^3
		7.482×10^{-3}	Cubic meters per liter	m^3/L
Cubic feet per hour	ft^3/hr	7.867×10^{-6}	Cubic meters per second	m^3/sec
Cubic feet per million gallons	ft^3/Mgal	7.482	Milliliters per cubic meter	mL/m^3
Cubic feet per minute	ft^3/min	4.719×10^{-4}	Cubic meters per second	m^3/sec
Cubic feet per minute per 1,000 cubic feet	ft^3/min/ 1,000 ft^3	1.667×10^{-2}	Liters per cubic meter per second	L/m^3/sec
Cubic feet per minute per 1,000 gallons	ft^3/min/ 1,000 gal	0.1247	Liters per cubic meter per second	L/m^3/sec
Cubic feet per pound	ft^3/lb	6.243×10^{-2}	Cubic meters per kilogram	m^3/kg
Cubic feet per second	ft^3/sec	2.832×10^{-2}	Cubic meters per second	m^3/sec

APPENDIX C (continued)

U.S. Customary Unit			Metric Unit	
Name	Symbol	Multiplier	Name	Symbol
Cubic feet per second per acre	ft^3/acre/sec	6.997×10^{-6}	Cubic meters per square meter per second	m^3/m^2/sec
Cubic feet per second per square mile	ft^3/mi^2/sec	1.093×10^{-8}	Cubic meters per square meter per second	m^3/m^2/sec
Cubic foot	ft^3	2.832×10^{-2}	Cubic meter	m^3
		28.32	Liter	L
Cubic inch	in^3	16.39×10^{-6}	Cubic meter	m^3
		16.39	Milliliter	mL
Cubic yard	yd^3	0.7646	Cubic meter	m^3
Cycles per day	cycle/day	1,440	Hertz	Hz
Degrees Fahrenheit	° F	0.5556 (° F - 32)	Degrees Centigrade	° C
Feet per day	ft/day	2.032×10^{-3}	Meters per second	m/sec
Feet per hour	ft/hr	8.467×10^{-5}	Meters per second	m/sec
Feet per minute	ft/min	5.08	Millimeters per second	mm/sec
Foot	ft	0.3048	Meter	m
		0.3048×10^{-3}	Kilometer	km
Foot-pounds per inch	ft-lb/in	1.659	Joules per meter	J/m

APPENDIX C (continued)

U.S. Customary Unit			Metric Unit	
Name	Symbol	Multiplier	Name	Symbol
Foot-pounds per second	ft-lb/sec	1.355	Watt	W
Gallon	gal	3.785×10^{-3}	Cubic meter	m^3
		3.785	Liter	L
Gallons per day	gal/day	4.381×10^{-5}	Liters per second	L/sec
		3.785×10^{-3}	Cubic meters per day	m^3/day
Gallons per day per acre	gal/day/acre	1.083×10^{-11}	Cubic meters per square meter per second	m^3/m^2/sec
		9.353	Liters per hectare per day	L/ha/day
Gallons per day per mile	gal/day/mi	2.72×10^{-11}	Cubic meters per meter per second	m^3/m/sec
Gallons per day per square foot	gal/day/ft^2	4.715×10^{-7}	Meters per second	m/sec
Gallons per day per 1,000 square feet	gal/day/1,000 ft^2	4.074×10^{-2}	Liters per square meter per day	L/m^2/day
Gallons per hour	gal/hr	1.051×10^{-6}	Cubic meters per second	m^3/sec
Gallons per mile	gal/mi	2.352	Milliliter per meter	mL/m
Gallons per minute	gal/min	6.308×10^{-5}	Cubic meters per second	m^3/sec
Gallons per pound	gal/lb	8,344	Milliliter per kilogram	mL/kg
Gallons per ton	gal/ton	4.173	Milliliter per kilogram	mL/kg

APPENDIX C (continued)

U.S. Customary Unit			Metric Unit	
Name	Symbol	Multiplier	Name	Symbol
Gallons per year	gal/yr	1.599×10^{-2}	Liters per second	L/sec
Hectare	ha	1×10^{4}	Square meter	m^2
Horsepower	hp	745.7	Watt	W
Horsepower-hour	hp-hr	2.685	Megajoule	MJ
Horsepower per 1,000 cubic feet	hp/1,000 ft^3	1,475.907	Killowatts per cubic meter	kW/m^3
Horsepower per 1,000 gallons	hp/1,000 gal	197.3	Kilowatts per cubic meter	kW/m^3
Inch	in	2.54×10^{-2}	Meter	m
		25.40	Millimeter	mm
Kilowatt	kW	3.6×10^{6}	Joules per hour	J/hr
		1.3596	Horsepower	hp
Kilowatt-hour	kWhr	3.6	Megajoule	MJ
Kilowatt-hours per day	kWhr/day	41.67	Watt	W
Kilowatt-hours per gallon	kWhr/gal	951.1	Megajoules per cubic meter	MJ/m^3
Kilowatt-hours per million gallons	kWhr/Mgal	951.1	Joules per cubic meter	J/m^3
Kilowatt-hours per pound	kWhr/lb	7.936×10^{-3}	Megajoules per kilogram	MJ/kg
Kilowatt-hours per ton	kWhr/ton	3.969	Kilojoules per kilogram	kJ/kg

APPENDIX C (continued)

U.S. Customary Unit			Metric Unit	
Name	Symbol	Multiplier	Name	Symbol
Kilowatt-hours per year	kWhr/yr	15.2096	Kilowatts per year	kW/yr
Mile	mi	1.609	Kilometer	km
Miles per hour	mi/hr	0.4469	Meters per second	m/sec
		1.609	Kilometers per hour	km/hr
Million gallons	Mgal	3.785×10^{3}	Cubic meter	m^3
		3.785	Megaliter	ML
Million gallons per day	Mgal/day (MGD)	4.383×10^{-2}	Cubic meters per second	m^3/sec
Million gallons per day per acre	Mgal/acre	1.083×10^{-5}	Meters per second	m/sec
		9.353	Megaliters per hectare per day	ML/ha/day
Parts per million	ppm	1.0	Milligrams per liter	mg/L
Pound (mass)	lb	0.4536	Kilogram	kg
Pound-foot	lb-ft	1.356	Newton-meter	Nm
Pounds per acre per day	lb/acre/day	1.297×10^{-9}	Kilograms per square meter per second	kg/m^2/sec
		1.121	Kilograms per hectare per day	kg/ha/day
Pounds per cubic foot	lb/ft^3	16.02	Kilograms per cubic meter	kg/m^3

APPENDIX C (continued)

U.S. Customary Unit			Metric Unit	
Name	Symbol	Multiplier	Name	Symbol
Pounds per cubic foot per hour	$lb/ft^3/hr$	4.449×10^{-3}	Kilograms per cubic meter per second	$kg/m^3/sec$
Pounds per 1,000 cubic feet	$lb/1{,}000\ ft^3$	16.02	Grams per cubic meter	g/m^3
Pounds per cubic yard	lb/yd^3	0.5933	Kilograms per cubic meter	kg/m^3
Pounds per day	lb/day	5.25	Milligrams per second	mg/sec
Pounds per day per acre	lb/day/acre	0.1121	Grams per square meter per day	$g/m^2/day$
Pounds per day per cubic foot	$lb/day/ft^3$	16.02	Kilograms per cubic meter per day	$kg/m^3/day$
Pounds per day per square foot	$lb/day/ft^2$	56.51	Milligrams per square meter per second	$mg/m^2/sec$
Pounds per gallon	lb/gal	0.1198	Kilograms per liter	kg/L
Pounds per hour	lb/hr	0.1260	Kilograms per second	kg/sec
Pounds per hour per square foot	$lb/hr/ft^2$	4.882	Kilograms per square meter per hour	$kg/m^2/hr$
Pounds per hour per cubic foot	$lb/hr/ft^3$	57.67	Kilograms per liter per second	kg/L/sec
Pounds per horsepower-hour	lb/hp-hr	2.957	Kilograms per kilowatt-hour	kg/kWhr
Pounds per million gallons	lb/Mgal	0.1198	Grams per cubic meter	g/m^3
Pounds per pound	lb/lb	1,000	Grams per kilogram	g/kg

APPENDIX C (continued)

U.S. Customary Unit			Metric Unit	
Name	Symbol	Multiplier	Name	Symbol
Pounds per square foot	lb/ft^2	4.883	Kilograms per square meter	kg/m^2
Pounds per square inch (force)	psi	6,895	Pascal	Pa
Pounds per 1,000 cubic feet	$lb/1,000\ ft^3$	16.02	Grams per cubic meter	g/m^3
Pounds per 1,000 gallons	lb/1,000 gal	0.1198	Grams per cubic meter	g/m^3
Pounds per year per acre	lb/yr/acre	1.121	Kilograms per hectare per year	kg/ha/yr
Pounds per year per cubic foot	$lb/yr/ft^3$	16.02	Kilograms per cubic meter per year	$kg/m^3/yr$
Pounds per year per square foot	$lb/yr/ft^2$	4.882	Kilograms per square meter per year	$kg/m^2/yr$
Square foot	ft^2	9.29×10^{-2}	Square meter	m^2
Square inch	in^2	6.452×10^{-2}	Square meter	m^2
Square mile	mi^2	2.59	Square kilometer	km^2
Square yard	yd^2	0.836	Square meter	m^2
Tons per acre	ton/acre	0.2242	Kilograms per square meter	kg/m^2
Tons per cubic yard	ton/yd^3	1.187	Megagrams per cubic meter	Mg/m^3
Watt-hour	Whr	3.6	Joule	J
Yard	yd	0.9144	Meter	m

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