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MIUS WASTEWATER TECHNOLOGY EVALUATION

hudmius

MODULAR INTEGRATED UTILITY SYSTEMS

improving community utility services by supplying electricity, heating, cooling, and water/ processing liquid and solid wastes/ conserving energy and natural resources/ minimizing environmental impact

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

A modular integrated utility system wastewater-treatment process is described. Research in the field of wastewater treatment is reviewed, treatment processes are specified and evaluated, and recommendations for system use are made. The treatment processes evaluated are in the broad categories of preparatory, primary, secondary, and tertiary treatment; physical-chemical processing; dissolved-solids removal; disinfection; sludge processing; and separate systems. Capital, operating, and maintenance costs are estimated, and extensive references are given.

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PREFACE

The Department of Housing and Urban Development (HUD) is conducting the Modular Integrated Utility System (MIUS) Program devoted to development and demonstration of the technical, economic, and institutional advantages of integrating the systems for providing all or several of the utility services for a community. The utility services include electric power, heating and cooling, potable water, liquid-waste treatment, and solid-waste management. The objective of the MIUS concept is to provide the desired utility services consistent with reduced use of critical natural resources, protection of the environment, and minimized cost. The program goal is to foster, by effective development and demonstration, early implementation of the integrated utility system concept by the organization, private or public, selected by a given community to provide its utilities.

Under HUD direction, several agencies are participating in the HUD-MIUS Program, including the Atomic Energy Commission, the Department of Defense, the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Bureau of Standards (NBS). The National Academy of Engineering is providing an independent assessment of the program.

This publication is one of a series developed under the HUD-MIUS Program and is intended to further a particular aspect of the program goals.

COORDINATED TECHNICAL REVIEW

Drafts of technical documents are reviewed by the agencies participating in the HUD-MIUS Program. Comments are assembled by the NBS Team, HUD-MIUS Project, into a Coordinated Technical Review. The draft of this publication received such a review and all comments were resolved.

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SUMMARY

Specifically, wastewater-treatment processes were reviewed for applicability to modular integrated utility systems. A set of criteria was established to evaluate the various processes. This set of criteria included low maintenance requirements, low labor costs, trouble-free and economical operation, minimum land use, odor control, prevention of health and nuisance problems, and minimum sludge disposal.

To begin the evaluation and to establish the basis for sizing the equipment, published data on the approximate wastewater flow and composition characteristics were reviewed. The flow from each household was estimated, and the household functions were categorized for the initial demonstration. The results of the review showed the capabilities of the various collection systems to be about equal for application to an integrated utility system. Site-specific features, however, could make one system more advantageous when evaluated on an individual basis.

Approximately 80 wastewater-treatment processes were then reviewed and evaluated for potential modular integrated utility system use. These processes were classified in the following broad categories: preparatory treatment, primary treatment, secondary treatment, tertiary treatment, physical-chemical treatment, dissolved-salt removal, disinfection, sludge handling, and separate systems. After evaluation, the processes that offered the most potential for early integrated utility system demonstration projects were selected. The selection of processes is not static, in that the selected processes are not the only ones that may be applicable to the system in the future. Work is being done in all areas of wastewater treatment, and the development of more advanced processes is expected. A definition of capital, operating, and maintenance cost was based on an extensive literature search made by the NASA Lyndon B. Johnson Space Center Urban Systems Project Office.

INTRODUCTION

In concept, a modular integrated utility system (MIUS) provides all necessary utilities and affords maximum waste recycling and energy conservation. As conditions warrant, these utilities include power generation; heating; air-conditioning; solid-waste collection, processing, and disposal; water treatment; and wastewater treatment. An MIUS can be small enough to serve office buildings and apartment complexes or large enough to serve communities. Thus, the makeup of the MIUS and the selection of the MIUS components can vary widely. Because of its integrated nature (integration of utilities and waste processing), the MIUS is compatible with the reuse of treated wastewater in some form, the use of compact systems, the reduction of manpower requirements, and the use of waste produced by other MIUS processes when compared to a series of comparably sized conventional systems.

This paper is intended to be an evaluation of the wastewater-treatment state of the art as applicable to an MIUS and is written in a manner reflecting Webster's definition of "evaluate"; that is, an attempt is made to determine the worth of the various processes and process groupings for MIUS applications. Because the reader may possess only a limited understanding of the integration or the interconnected aspects of an MIUS, this type of approach has been chosen rather than presenting a survey of the processes and allowing the reader to make the evaluation.

The opinions presented herein are those of the NASA Lyndon B. Johnson Space Center Urban Systems Project Office (USPO) and are based on an 18-month review of the various processes used in several MIUS application studies, which included garden and high-rise apartment buildings, shopping centers, hospitals, office buildings, and a community mixture. However, background information for each process evaluation is referenced in the applicable process description or evaluation section. Because the size of the wastewater-treatment systems may vary, depending on the size of the area served, this discussion is generally limited to processes and systems adaptable to a capacity of 946 m^3/day (250 000 gal/day) or less and thus encompasses early MIUS applications only.

Wastewater flow and composition, collection systems, treatment processes and systems, treatment process efficiency, and MIUS water reuse economics are discussed, and conclusions are presented. For reasons of scope reduction, the process in which the water is used and collected within the buildings has been divorced from the

MIUS in this document. However, the water use and collection process is important and must be considered in an MIUS design.

This document has been written with the assumption that the reader has a working understanding of wastewater-treatment processes such as those presented in Weber's "Physicochemical Processes for Water Quality Control" (ref. 1) or in similar wastewater-treatment textbooks (refs. 2 to 4). However, when the clarification of significant processes, process elements, or other terminology is deemed necessary, descriptions are presented in this report. The use of specific nomenclature for some equipment or processes is intended to clarify or to aid identification rather than to be an endorsement of the product.

The author realizes that new technology will change the conclusions of this document, that some processes may be slighted and others perhaps overemphasized, and that each decision is open to criticism. However, the author believes that the information contained in this document is worth the attempt put forth.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

CRITERIA FOR MIUS EQUIPMENT

In general, many of the criteria for low-maintenance, low-labor, trouble-free, economical wastewater-treatment equipment are the same as the criteria for any small wastewater-treatment system. However, in an MIUS, the wastewater is treated for reuse rather than for disposal. As a minimum, the water will be reused for cooling tower supply and lawn irrigation. Each different use has associated with it a different set of water quality criteria. Highly disinfected water is required for use in an area of high population density. Tertiary treated water is required as a maximum criterion, especially for discharge into natural streams in some locations. The MIUS wastewater-treatment system should be designed for flow diversion at different points to provide the minimum water quality required for a particular water reuse.

Other criteria for an early MIUS application include (1) minimum-land-use processes, (2) minimum open-air processes for odor control, (3) preventive measures for all health and nuisance problems, and (4) minimum land use for sludge disposal. Any additional criteria for specific processes are defined in the evaluation section for each process described.

WASTEWATER FLOW AND COMPOSITION

Estimations of the amount of wastewater and the constituents in the wastewater to be treated by the MIUS are of prime consideration in the treatment plant design. Because the water is used for a variety of activities, such as bathing and laundry, the water characteristics are actually a summation of water flows and compositions from each water use function. The water use functions considered for the MIUS apartment complex were (1) domestic use (kitchen, laundry, bathing, toilet, cleaning), (2) exterior use (lawn irrigation, carwashing, swimming pool), and (3) MIUS process use (cooling towers, boilers).

Flow

General information about the per capita flow in waste-treatment designs can be found in references 2, 3, and 5 to 7. Most of these works contain information that is a summation of more specific work. Because the MIUS will be built for small numbers of users, a knowledge of the general per capita water use for cities would not be sufficient to determine accurate flow rates. Therefore, individual research articles (refs. 8 to 23) were reviewed in an effort to make this determination.

Table I is a presentation of the volume and the percent breakdown of water use by function as determined in the study performed in 300 residences by Gilbert Associates (ref. 15). This study disclosed that residences averaged approximately 0.757 m^3/day (200 gal/day) per house and 0.606 m^3/day (160 gal/day) per apartment, for a composite average of 0.681 m^3/day (180 gal/day).

The effect of family income on per capita use in a study of 13 Illinois communities is shown in figure 1 (ref. 14). Differences in water use related to property evaluation were measured by Dunn and Larson (ref. 13). However, their study indicated that water use is most directly related to occupation, followed closely by income, property value, education, and family size, respectively. Dunn and Larson attempted to measure the influence of each of these variables.

Wolff indicated that differences in potable water use arose from differences in lot size (ref. 11). To differentiate between household use and exterior use, he compared water use during a hot, dry day to use during a rainy day. Wolff also estimated the average apartment waterflow at 0.693 m^3/day (183 gal/day). Hudson showed that per capita water use has increased uniformly from 1939 to 1958 (ref. 10). Haney and Hamann (ref. 8) also broke down the per capita use into daily functional use as did Reid (ref. 9).

On the basis of total per capita daily use, variations in each functional use were estimated to be from 0.114 to 0.379 m^3/day (30 to 100 gal/day) by the U.S. Public Health Service (ref. 15). The Federal Water Quality Administration (FWQA) found that both the Johns Hopkins University and the Public Health Service studies revealed that the average per capita consumption of water was inversely proportional to the number of people in the dwelling. The Public Health Service determined that domestic water use, not including lawn watering, fits the general formula $Q = 88 + 26P$, where Q is the daily volume of water used per household expressed in gallons and P is the number of persons per household. This finding is documented by the FWQA in reference 5. However, for their report, the FWQA used the model of $Q = 55 + 50P$ for the "average" home consisting of an average house (3 bedrooms, 111.5 to 148.6 square meters (1200 to 1600 square feet) of living area, 1-1/2 baths having a shower and tub combination in the full bath and a shower in the half bath, a dishwasher, an automatic clothes washer, and a garbage disposal) and an average family (2 adults and 2 children). No true evaluation of the effects of all variables that determine average water usage has ever been accomplished, and, from the review of the research articles mentioned, no exact formula for flow rates that could be devised for specific areas and conditions was evident. However, tables II to V contain data on water use functions as determined by the referenced studies.

For this initial MIUS apartment unit demonstration, the formula $Q = 52 + 50P$ has been used with the breakdown shown in table VI, where kitchen water use is allocated as 0.0568 m^3/day (15 gal/day) to the dishwasher and 0.0038 m^3/day (1 gal/day) plus 0.0114 m^3/day (3 gal/day) per person to the sink. The reduction from 0.208 m^3/day (55 gal/day) per house in the FWQA estimate to 0.197 m^3/day (52 gal/day) per apartment in the MIUS complex for the household load is based on a 0.0114-m^3/day (3 gal/day) reduction in miscellaneous cleaning in an MIUS apartment having an estimated 79 square meters (850 square feet) of living area compared to the maximum 148.6-square-meter (1600 square foot) house with a laundry used in reference 5. The laundry will probably be separate from the individual apartment in the MIUS apartment complex; however, for water use estimation, the number of onsite loads per day is considered equal to one washing machine use per apartment per day.

After the per capita daily flow and the functional daily flows were chosen, the functional hourly hydrographs (fig. 2) were constructed by using the available published data (ref. 6) and USPO engineering data and estimates. Once a composite hydrograph was generated (fig. 3), the literature (refs. 11 and 22 to 25) was reviewed again for published composite hourly hydrographic data from small and large systems for both wastewater requirements and potable water demands so that the proposed MIUS apartment unit hydrograph could be compared to the measured data. From figure 4, it can be seen that the proposed MIUS hydrograph is in good general agreement with the short-sewerline wastewater hydrograph from Audubon Woods, Ohio. Flow variations are damped and peak loads are delayed in the longer sewer runs from a larger system as shown by the Indianola, Iowa, flow. Figure 5 shows that both the measured apartment and Baltimore city water demands agree generally with the proposed MIUS apartment demand.

After the maximum and minimum flow variations were examined, including infiltration from various sources, a study of apartment units (ref. 26) was used to estimate the maximum flow in the MIUS. The values chosen are 1.50 and 0.75 of the average flow for the maximum and minimum daily domestic flow, respectively.

General Wastewater Composition

Because of the short-sewerline runs experienced in the MIUS apartment complex, little natural reduction in biological oxygen demand (BOD) is anticipated; therefore, the oxygen-demand characteristics will probably be slightly greater than for normal domestic sewage. Other contaminants should be little changed, however. Because data on wastewater loadings (refs. 8, 16 to 19, 21, and 27) are highly variable, a numerical average was used for the wastewater characteristics shown in table VII, which is the basis for the average MIUS apartment unit calculations. Swimming pool backflush and cooling tower blowdown will be added to domestic flow and composition in the specific quantities and qualities calculated for the specific site, but will not be discussed in detail in this document.

Conclusions

The following conclusions were gained from this review of wastewater flow and composition.

1. Per capita flow is directly related to
   - a. Family size
   - b. Type of dwelling
   - c. Size and valuation of property
   - d. Education level of household
   - e. Occupation of head of household
   - f. Age of each occupant
   - g. Income level of household

2. Per capita daily flow from individual houses can vary from less than 0.076 cubic meter (20 gallons) to as high as 0.757 cubic meter (200 gallons) (ref. 21).

3. Per capita daily flow variations from small groups of dwellings range from 0.151 to 0.341 cubic meter (40 to 90 gallons) (ref. 27). Variation for an MIUS application is estimated as 0.75 and 1.50 times the average flow.

WASTEWATER COLLECTION SYSTEMS

One of the most significant capital cost parameters in the deployment of utility systems for a community involves the collection of wastewater. Analysis of the cost of wastewater disposal systems shows that the major capital cost is related to the collection and not to the treatment process. The primary reason for this situation is directly related to the manner in which these wastes are transported.

Collection System Types

Collection system types include three major processes: conventional gravity collection, vacuum sewage collection, and pressure sewer collection.

<u>Conventional gravity collection</u>.- Gravity-flow sewer systems were used in the Roman Empire. These same system concepts are still being used today and represent the

"conventional" mode of wastewater collection. The conventional gravity collection system uses a gradually sloping piping installation to convey the wastewater by gravity flow. By this means, a network of collection piping is developed that eventually reaches a maximum predetermined depth (4.9 to 7.3 meters (16 to 24 feet) in some cases). Pumping stations are then used to elevate the flow stream, and, subsequently, gravity flow resumes. The major disadvantage inherent in this method is the inordinate expense involved in deep trenching and in laying the larger diameter pipes that are frequently required. The principal advantage offered by the conventional system is that it uses gravity as its primary energy source and that it requires little maintenance. Conventional systems have been employed in the MIUS apartment baseline.

Vacuum sewage collection.- Although patents for municipal vacuum sewage collection were recorded in 1892, only recently has serious interest in this concept again been shown. As a result of this renewed interest, commercially available systems have been produced. The vacuum sewage collection system uses either standard water closets or low-water-consuming vacuum toilets. Wastewater in the system is transported by means of an applied vacuum of 50 662 to 60 795 N/m^2 (0.5 to 0.6 atmosphere). The principal advantages offered by the application of the vacuum concept are (1) that piping can follow the ground profile and thus reduce the cost of installation by eliminating the need for deep gravity-flow-type trenching; (2) that smaller, less expensive pipe can be used because of the "force main" nature of the flow; and (3) that any leakage due to line breakage will occur inwardly and the breakage will be quickly discernible. Additional treatment expenses can be eliminated if vacuum toilets are used because of a sizable reduction in wastewater flow. If a community installation is considered, using local MIUS options, the costs are further reduced because the large interceptors to a central treatment site are precluded. Principal disadvantages of the system are (1) that utility code revisions usually are required, (2) that mechanical systems rather than gravity systems are involved and thus operating costs are increased, and (3) that more maintenance is required and thus maintenance costs are increased. Many land-based vacuum sewage collection systems are currently being operated in Europe and some in North America.

Pressure sewer collection.- The concept of using pressure instead of gravity flow to transport wastewater to a treatment system was first proposed in 1954 as a solution to the combined-sewer overflow problem. This concept involves including a pressure sewer within a combined sewer to produce a storm sewer. This approach was recently investigated by the American Society of Civil Engineers under a Federal grant. The conclusion from the investigation was that the pressure sewer concept, as a solution to the combined-sewer overflow problem, was limited by technical and economic difficulties, but that the pressure sewer concept did have potential for certain areas that were difficult or impossible to serve by gravity systems. Several areas of potential application can be projected including (1) serving homes with fixtures below the grade of the sewer system, (2) serving homes originally serviced by septic tanks by tying into new sewer districts, (3) serving a few homes in a new sewer district to keep the entire gravity system at a shallow elevation, (4) serving an entire neighborhood by pumping to an existing gravity system at higher elevations, (5) serving lakeside and waterfront properties by pumping uphill to protect the reservoir. Advantages of the pressure sewer systems include shallow pipeline installation (just below the frostline for the region) and the use of smaller pipes. Disadvantages include the requirement for more electrical power for pumping, the use of mechanical equipment such as grinders and pumps, and the increase in system maintenance. More detailed information about combined-sewer separation and pressure sewer systems may be found in references 28 and 29.

Collection System Evaluation for MIUS

Unless the MIUS apartment complex has special problems such as hillside location or soil limitations to deep sewage, all the systems discussed are viable choices for the MIUS. The vacuum system used in conjunction with a vacuum toilet has the potential for significant water reduction.

TREATMENT PROCESSES

The basic function of any wastewater-treatment process is to hasten the natural process of purification. Most U.S. treatment facilities remove less than 95 percent of the impurities. Because of potential reuse profiles, various levels of purification may be required in the MIUS. An MIUS system should identify processes that are capable of removing more than 99 percent of most normally measured parameters. Thus, an advanced system is contemplated using several processes in series to achieve the desired contaminant reduction.

Historically, the processes used for the treatment of wastewater have been classified as primary, secondary, and tertiary. However, this classification breakdown was thought to be too broad for the purpose of this document. Therefore, preparatory, primary, secondary, tertiary, physical-chemical, dissolved-solids removal, and sludge treatments were chosen for discussion in this report.

Preparatory Activity

The preparatory steps considered include the use of racks and screens, grit chambers, skimmers, and comminutors for solids reduction. In addition, equalization storage, preaeration, and raw wastewater pumping are discussed.

Process description.- Generally, the preparatory activities are placed at the entrance to the treatment system to remove coarse solids, floating solids, grease, and similar substances that would damage or impair the operation of equipment used downstream and to condition the water in some manner to effect a more efficient or uniform treatment by the remaining processes in the treatment system. Equipment and equipment functions used in the preparatory processes are shown in table VIII. Details on the operation of this equipment have been presented in many wastewater-treatment manuals and, therefore, will not be discussed here. Particularly suggested for additional reading are references 2 and 30 to 32.

Process evaluation for MIUS.- Based on the criteria outlined earlier in this report for MIUS equipment, the following process evaluation applies to small MIUS units.

Racks and screens: Normally, an MIUS installation with short-sewer runs and few manholes will have little or no large debris to remove and, therefore, will not require the use of racks and screens unless specific site evaluation recommends this type of equipment.

Grit chambers: Because short-sewer runs have little measurable infiltration of gritty material, the requirement for grit chambers is reduced. These chambers would not be used in the MIUS unless special circumstances warrant. If used, a grit baffle could be incorporated into the equalization basin.

Skimmers: Skimmers should be used to remove oil, grease, and similar substances.

Comminutors: The use of comminutors will generally be determined by the type of installation. If screens are used in the primary stage, comminutors would usually be omitted. However, they could be included in a total physical-chemical system. A review of the specific wastewater characteristics with and without comminution should be made for each installation if this form of pretreatment is to be considered.

Equalization storage: The use of a flow equalization process reduces the diurnal variations in hydraulic and contaminant loads and thus optimizes the sizing and operation of any of the biological and physical-chemical processes that follow in the MIUS. Therefore, an equalization storage process should be part of the MIUS wastewater-treatment system. In addition, the storage basin can provide recycle storage for the treatment plant in case of system upset or influent storage in case of power failure.

Preaeration: The equalization basin should be aerated to prevent odors.

Raw wastewater pumping: Raw wastewater pumping should be incorporated, when necessary, in the MIUS concept. The necessity for raw wastewater pumping will depend on the final design of the MIUS treatment system and may be eliminated if vacuum or pressure sewage systems are used or if topography and design enable gravity flow of the wastewater through the treatment plant.

Primary Treatment

The primary treatment processes considered are sedimentation, flotation, chemical addition, and straining.

Process description.- Primary treatment is designed to remove a substantial amount of suspended matter but little or no colloidal and dissolved matter from the wastewater stream (ref. 33). In general, primary treatment is a physical process; however, chemicals may be added to improve removal capacities or rates. Table IX is a list of the common primary treatment operations and their functions.

Sedimentation: Particles in suspension as the water enters an area of quiescence can be divided into two general classifications, granular and flocculent sediment (ref. 34). Granular particles settle rapidly and at a constant velocity, independently and without change in size. These particles (sand, silt, etc.) would be captured in a grit chamber if used. Flocculent particles (organic matter etc.) tend to cluster during settling, changing in size, shape, and density. Flocculent settling can be classified into four types: (1) discrete settling region, (2) hindered settling region, (3) zone settling region, and (4) compression region. Whether chemicals are added or not, all settling systems must operate in a manner that takes advantage of the settling phenomenon shown schematically in figure 6. Standard settling basins, tube settlers, and a Lamella separator are described in the following paragraphs.

Basic design considerations for standard settling basins have evolved to reflect the settling characteristics of domestic wastewater. Wastewaters vary greatly; however, except in unusual circumstances, the following general practices will provide for an adequate basin design.

1. Detention time - Normally, primary sedimentation tanks are designed for a settling time of 90 to 150 minutes at average sewage flow. Settling times of 30 to 60 minutes can be used if the primary treatment is followed by biological treatment.

2. Surface-loading rate - For untreated wastewater, the surface-loading rate may range from 24.4 to 48.9 $m^3/day/m^2$ (600 to 1200 $gal/day/ft^2$) (ref. 3). For the MIUS with flow equalization and additional treatment following, a value of 48.9 $m^3/day/m^2$ (1200 $gal/day/ft^2$) appears appropriate. Table X is a list of the detention times for various loading rates and tank depths.

3. Weir rate - Maximum weir loads ranging from 124.2 to 186.3 $m^3/day/m$ (10 000 to 15 000 gal/day/ft) have been suggested, but, in practice, good clarification is achieved at much higher weir loads. Weir rates appear to have less effect on removal efficiency than do surface-loading rates (ref. 35).

4. Tank shapes - Both rectangular and circular tanks, made of concrete or field erectable steel, are available in various sizes from numerous manufacturers. No significant advantage to either shape is apparent. Design of the plant might be the most influential aspect in the choice of tank shape.

The use of any of several designs of tube settlers can either increase the capacity of standard clarifiers or reduce the required basin size for new clarifiers. Detailed discussions of the tube settler concept have been presented in references 36 to 39. Results of testing with tube settlers have shown that surface-loading rates as high as 203.7 $m^3/day/m^2$ (5000 $gal/day/ft^2$) may be achieved without loss in removal efficiency of the primary clarifiers (ref. 30).

The Lamella separator process (refs. 40 to 42) takes advantage of the short vertical-settling distance concept used in the tube settler, but the unit is designed in a manner that permits concurrent water-sludge flow. The separator is more applicable to water treatment than to wastewater treatment. However, the Lamella thickener is used for wastewater treatment. The water is introduced to the settling tank at about the interface of the hindered and zone settling regions (fig. 6). The settling system is combined with a vibrating sludge-thickener section. Flow-through time is reduced to approximately 8 minutes, and surface-loading-rate equivalents of 407.5 m^3/day/m^2 (10 000 gal/day/ft^2) have been achieved.

Flotation: Flotation is the opposite of sedimentation. Small gas bubbles are introduced to the liquid in some manner. These bubbles attach to the particles and are buoyed to the surface. The surface particles then are skimmed. The following flotation methods have been applied to wastewater.

1. Air flotation - Air is introduced directly to the water. This technique has not been particularly effective for domestic wastewater.

2. Dissolved-air flotation - All or part of the flow is pressurized to 275 790 to 344 738 N/m^2 (40 to 50 psi), and compressed air is added to the liquid. The pressure is retained for a short period to allow the air to be dissolved in the water. When the pressure is released, the bubbled air comes out of solution and performs the floating process.

3. Vacuum flotation - In this process, the water is saturated with air at atmospheric pressure, then a partial vacuum is applied, usually at a pressure of approximately 33 437 N/m^2 (0.33 atmosphere). The pressure change forces the gas-saturated water to release part of the gas, which floats the particles to the surface.

Chemical addition: Numerous chemicals, both inorganic (such as aluminum and ferric salts) and organic polyelectrolytes (such as Calgon ST-266), can be and have been used to enhance flotation and settling. Vendor aid and testing are suggested when attempting to use chemical addition in a specific wastewater stream.

Straining: Fine straining of the solids suspended in the wastewater stream is another method that can be incorporated as a primary treatment. The primary considerations in design are self-cleaning provisions, screen spacing, and simplicity. Various methods for separating solids from liquids have been attempted. The method most often used has been the rotating drum, such as the Hydrocylonics Rotostrainer, and the inclined screen, such as the Bauer Hydrosive or the Siemag Claritower.

Screen spacing can be varied from approximately 0.025 to 0.152 centimeter (0.010 to 0.060 inch), depending on the desired flow rates and removal efficiencies.

Process evaluation for MIUS.- The evaluation of primary processes in a small MIUS is most significantly influenced by the size and the simplicity of operation. In many instances, items produced by several manufacturers are basically the same but incorporate different requirements, which, after a detailed examination, may indicate an advantage to one manufacturer. The detailed investigation and selection of a specific unit is a part of good engineering practice for a specific site design. The following evaluation is by generic type of process only.

Sedimentation: The Lamella thickener process, which is based on a modified tube settler concept, is the most favorable sedimentation technique because it combines rapid flow-through and rapid settling with a simple sludge thickener. Only minimal operator attention is required for this process. The tube settlers would be superior to standard basins in the MIUS because of their reduced size and would be adequate for the MIUS. Standard basins would be less desirable because of the larger size required for longer detention times.

Flotation: The potential for flotation in an MIUS is inherent in the available test data: 12 minutes of retention time is equal to 4 hours of conventional clarifier time in tests on combined-sewage flow (ref. 43). Small flotation systems, however, are apparently not adequate for wastewater treatment. The lack of data precludes an evaluation of operational reliability and operator attention required. For these reasons, flotation is not seriously considered for MIUS application currently.

Chemical addition: The processes most suited for the MIUS apparently are not as affected by chemical addition as those less suited for the MIUS. The addition of chemicals is not foreseen for primary treatment enhancement in early MIUS treatment system designs.

Straining: Tube settling reduces clarifier detention times from hours to minutes, and straining reduces detention times from minutes to seconds. The removal efficiencies of straining are comparable to the efficiencies of short-term settling and make straining feasible for use in an MIUS, especially if it is followed by biological treatment.

Secondary Treatment

The discussion of secondary treatment processes is limited to aerobic techniques.

Process description.- Secondary treatment has been defined as the treatment of wastewater by biological methods after primary treatment by sedimentation (ref. 33). For the purposes of this paper, the definition will be limited to the three generic aerobic techniques for biological oxidation of wastewater impurities: activated sludge, trickling filter, and rotating biological disk. As discussed here, all the processes can be continued in some manner to include not only the biological oxidation of organic material but the conversion of ammonia nitrogen to nitrate. A clarifier is considered as a final step in all processes.

Activated sludge: The activated-sludge process is extremely flexible and can be adapted to almost any type of biodegradable waste. Certain limits of temperature and hydrogen-ion concentration (pH) are required, but, within these known limits, the process is an efficient treatment device when operating properly. However, proper operation is difficult to achieve and maintain. The reasons for the adaptability of the activated-sludge processes are, at the same time, the reasons for the operational difficulty. The following reasons have been identified in references 44 to 49.

1. The biomass is a heterogeneous mass of bacteria and other micro-organisms that have differing growth patterns.

2. The various strains of micro-organisms have been shown to make preferential use of the food supply.

3. The food supply found in wastewater is also heterogeneous and fluctuant.

To produce a good effluent with a high degree of BOD removal, a proper mixture of micro-organisms, food supply, and oxygen must be maintained. In the activated-sludge process, this balance is achieved by a partial recycling of the sludge from the clarifier to an aeration tank. Various attempts have been made to control the mixing of the micro-organisms and the food supply as well as to control the biomass/food ratio, and much research has been performed to find the best controlling parameter. Parameters studied include solids retention time, sludge volume index, mixed liquor concentration, suspended solids count, sludge age, biomass composition, and mean cell-residence time. The various methods for mixing biomass and food supply are listed in table XI and schematically defined in figures 7 to 11.

With a mass of empirical data (refs. 24, 25, and 50 to 61), many attempts have been made to model the activated-sludge process (refs. 62 to 81). Two general conclusions have been drawn from the work done to this point (refs. 69 and 75).

1. A mathematical model can be developed for a specific activated-sludge unit on the basis of data obtained from operation of that unit.

2. No single mathematical simulation exists for all activated-sludge units.

Attempts to improve the stability of the activated-sludge process have led to various modifications of the equipment design. The approximate detention times of the major process modifications are summarized in table XI. The removal efficiencies of the various processes are essentially equal (table XI). The contact times, however, have a significant effect on the size of the treatment unit. Another form of activated-sludge processing, the oxidation ditch or pond, was not considered for a small MIUS installation.

Trickling filter: The relationship of micro-organisms, oxygen, and food supply required in the activated-sludge process is similar to that in the trickling filter process. Although the theory of operation is not completely understood (refs. 82 and 83), it has, with certain variations, led to several mathematical investigations (refs. 84 to 86). Although each model produced had limitations when checked against the performance of an operating unit, two models proved more accurate than the others, and a proposed modification to one model led to repeatable data on the unit investigated (refs. 85 to 87). The various options in the trickling filter design are presented in table XII. These design options apparently have little effect on the ultimate efficiency of the unit if operated correctly for maximum removal (ref. 82). Advantages and disadvantages arise from each design combination. Design selection must be based on individual applications.

Rotating biological disk: The rotating biological disk process is similar to the trickling filter process in that both use fixed-film biological reactors. The few differences in the rotating biological disk are important, however. First, the biomass is passed through the wastewater to provide intimate contact between the micro-organisms and the wastewater. Then, the biomass is regularly and uniformly exposed to air to achieve maximum removal efficiency, excess available oxygen, and constant wetting. Recirculation is not normally used. Because of the simplicity of the system, extremely uniform and detailed investigations have been performed to determine its capabilities for treating wastewater (refs. 88 to 94).[1]

Process evaluation for MIUS.- Inherently, secondary treatment processes are dependent on micro-organisms for purifying water; therefore, given a properly functioning unit, the removal efficiencies will be similar for each process. This similarity can be seen in reviewing the referenced literature. The evaluation for MIUS can thus be reduced to an evaluation of process cost, size, and simplicity; simplicity determines the relative ease of attaining and maintaining satisfactory operation. The following conclusions were drawn from the evaluation.

Activated sludge: The major problems in using an activated-sludge system are the long detention times required in many configurations and the degree of recycled-sludge control required for efficient operation. Because secondary treatment will not be used exclusively in the MIUS, the degree of treatment increase that might be achieved using an activated-sludge process rather than a trickling filter or a rotating biological disk does not appear to warrant the increased complexity it entails. Employee supervision or cost of automating the systems would be increased with relatively little benefit to the quality of the day-to-day effluent. Therefore, the activated-sludge system is not considered the prime candidate for the MIUS.

Trickling filter: As in any treatment system, satisfactory operation of trickling filters depends on cleanliness and operational supervision. The simplest filters require little supervision if covered to prevent fly hatch and odor. However, the best performing filters are recirculating systems, which require more supervision to maintain efficient operation. The use of high packing towers and recirculation would increase pumping costs. Compared to the activated-sludge systems, the trickling filter is more amenable to small MIUS designs and should be considered a more likely choice.

Rotating biological disk: Many of the disadvantages of the activated-sludge and trickling filter systems are overcome in the rotating biological disk system. This

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[1] Unpublished data from Ronald L. Antonie, Autotrol Corp., Milwaukee, Wisconsin, May 1973.

system does not require recycling of the sludge or monitoring of sludge age, mixed liquor concentration, and so forth; therefore, operator supervision is reduced. Because no area in the system is oxygen deficient, anaerobic conditions and resulting odors do not exist in this process. The biomass is always kept wet; thus, fly-hatch problems are prevented. From the results of a detailed test program (ref. 88), the following conclusions were formulated and are directly applicable to an MIUS.

1. The rotating biological disk is a compact, highly efficient means of removing BOD, suspended solids, and ammonia nitrogen from domestic wastewater.

2. Process design and equipment simplicity result in very low maintenance requirements.

3. Simple operation, low maintenance, and low power consumption make the process well suited to package plant applications.

Because of these reasons, the rotating biological disk is the most highly rated secondary treatment system suggested for MIUS application.

Tertiary Treatment

The tertiary treatment processes discussed consist of physical, chemical, and biological processes.

Process description.- Generally, the term tertiary treatment refers to two classes of pollutant-removal processes: (1) processes to remove organics, suspended solids, or nutrients, or any combination of the three, below the levels achievable by using secondary treatment and (2) processes to remove dissolved solids (desalting) (ref. 95). Although the removal of dissolved solids and the independent physical-chemical treatment processes are discussed in separate sections of this report, these processes are a part of tertiary treatment. Many of the tertiary treatment processes are identical to the physical-chemical processes except for chemical dosages, detention times, and effluent qualities. Processes common to both techniques are given detailed review in this section. Other less developed techniques are discussed briefly in applicable subsections. The 14 processes discussed as part of a tertiary treatment system are listed in table XIII. These processes can be categorized as physical, chemical, and biological.

Physical processes: The physical processes, which include filtration, flotation, land application, air stripping (refs. 96 to 98), sorption, and gas-phase separation, are discussed in the following paragraphs.

Filtration is defined as the process of passing a liquid through a medium for the purpose of removing suspended or colloidal matter. This discussion includes several processes that are applicable to MIUS installations but does not include activated-carbon filtration, which is used primarily as an adsorption process and is discussed as a chemical process. The general classifications of removal systems to be discussed are rapid sand filters, other single-medium filters, multimedia filters, and microscreens. Other filtration processes are mentioned at the end of this subsection.

1. Rapid sand filters (refs. 99 to 107): In both sand and mixed-media filters, the filtration process is subject to a large number of variables, each of which must be considered when selecting the best possible filter for the design situation. These variables include the following.

   a. Media grain size, shape, and density

   b. Composition

   c. Head loss characteristics

   d. Flow rate

   e. Bed depth

   f. Influent characteristics

Cleaning of a rapid sand filter is generally done with backflushing or with a moving bed as in the case of a single-medium filter described in reference 100. The cleaning can be performed by manual actuation, by automatic time recycling, or, usually, automatically in response to back-pressure buildup. Sand filtration removal analyses have been performed many times under many conditions (refs. 99 to 104). The sand filter has been characterized and modeled extensively also (refs. 105 to 107). The merits and shortcomings of the rapid sand filter are therefore quite well understood; generally, when used properly, it is one of the most useful low-cost water-clarification techniques available.

2. Other single-medium filters: Several types of media other than sand (generally silica sand) have been used to perform the same function. These other media include garnet sand, anthracite coal, polyvinyl chloride (PVC)

pellets, and activated carbon. Their filtration mechanisms are similar to that of silica sand.

3. Multimedia filters: Several dual-media and multimedia filters have been designed and tested (refs. 97, 99, 101, 103, and 108). As the name suggests, these filters are composed of a series of layers of differing material; materials used include anthracite coal, silica sand, activated carbon, garnet sand, and spherical resin beads. The density of the material determines its layer position in the filter with the most dense material on the bottom. The influent end layer has the least dense material, and this material usually is of large grain size. These larger media particles blind (clog) less easily than small particles and increase the filter cycle time. For instance, PVC pellets have been useful in the filtration of highly turbid wastewater when used as the top layer of a four-layer filter system (ref. 108). At Lake Tahoe, the large-scale use of multimedia filters has been successful for more than 6 years (ref. 97).

4. Microscreens: A simple form of filtration is accomplished by using microscreens or microstrainers. In this process, finely woven stainless steel fabric is used as the filter medium (refs. 109 to 113). The fabric apertures are several micrometers in size, and the fabric is stretched onto a slowly rotating, constantly backflushed drum, which provides a large flow filtration area with small head loss. Microscreens have been used in treating wastewater, surface water, and storm water, but have been used most often to polish secondary treatment effluent. Microscreens are not a substitute for sand or multimedia filters.

Although some information and test results on single-medium and multimedia filters are contradictory, the following statements represent the general consensus on these filters.

1. Two systems interact to filter the influent: the filter medium and the previously retained influent suspension.

2. Removal efficiency, without chemical additions, depends primarily on grain size.

3. Small grains in the top layer of the filter will cause matting, which reduces the effectiveness of the remaining layers.

4. Effluent clarity can be improved by the use of coagulants, such as hydrated aluminum sulfate (alum), at

dosages of 1 to 10 mg/liter, and polyelectrolytes, such as Calgon ST-270, at dosages of 0.05 to 0.5 mg/liter.

Several other filtration techniques have been applied to wastewater treatment. Some of these techniques are (1) ultrafiltration (refs. 30 and 114 to 117), (2) slow sand filtration (refs. 3 and 4), (3) diatomite filtration (ref. 3), and (4) upflow filtration (ref. 118). These processes are considered to be nonapplicable to the MIUS either because they are impractical for design constraints, such as a slow sand filtration process, or because the process has not achieved a status of tested, commercial, available equipment, such as the ultrafiltration process. For more information on these techniques, refer to the references listed after each process.

The flotation process considered here is the same as the flotation process discussed earlier under primary treatment. Only the influent quality and the point in the tertiary treatment sequence differ from primary treatment section comments.

As used here, land application is any technique involving the assimilative capacity of the land or vegetation on the land for water and water pollutants. Land application is grouped into three categories: irrigation, overland flow, and infiltration-percolation. Additional information on land application techniques may be found in references 119 to 129.

1. Irrigation is the application of water to land to meet the needs of the local vegetation by either surface flooding or spraying. A large amount of land is required for this process, and the high salt concentrations in wastewater may prevent the irrigation of many crops. Health hazards are not severe if adequate disinfection is used. Drift should be minimized in spray irrigation.

2. The overland flow method involves spraying onto grassland slopes so that the water can flow extensively through the vegetation. This method can be used on relatively impermeable soil and is a very-low-cost substitute for advanced treatment systems. However, further research is required to define its phosphorus removal efficiency, loading rates, and applicability to cold climates.

3. Infiltration-percolation involves the application of large volumes of wastewater to the land so that the water can infiltrate the soil and percolate deep into the soil through soil pores. The limitations in using this process include the availability of high-porosity soil and the

possibility of ground-water degradation through overnitrogenation or anoxia with conversion of sulfates to hydrogen sulfide.

Air stripping of ammonia in wastewater can be achieved under the proper conditions (refs. 96 to 98 and 130). The following two conditions add significantly to the usefulness of this process.

1. High-pH ammonia is favorable for achieving ammonium ion equilibrium (85 percent at pH 10 and 98 percent at pH 11).

2. A high temperature for both air and water reduces the amount of air required for stripping a given amount of ammonia from the wastewater.

To be economical, the first condition requires lime as a coagulant in the chemical clarification process, which would precede the air-stripping process. The high calcium content in turn leads to potentially high scale formation as the calcium combines with the carbon dioxide in the air. The corrosiveness of the high-pH water also requires careful selection of tower materials. Both countercurrent and crosscurrent towers have been studied and mathematically modeled with most of the significant design parameters included in the model (ref. 98). Four potential problems exist in the air-stripping process: (1) scaling by calcium carbonate, (2) biological activity within the tower, (3) significantly reduced removal efficiency under cold air and water conditions, and (4) air pollution potential near the tower.

The sorption of phosphate in water by contact with activated alumina with subsequent regeneration of the alumina using nitric acid has been demonstrated (ref. 131). Differing results were reported when both alumina and fly ash were used (ref. 132). Sorption using synthetic resins is also being investigated, but process definition and optimization have not been done in any sorption systems.

The gas-phase separation method requires the passing of wastewater through tubes made of a selective permeable gas-phase material, preferably ammonia. The ammonia passes through the membrane and is removed by airflow passing over the outside of the tube. This process is in early stages of testing.

Chemical processes: The chemical processes, which include chemical clarification, carbon adsorption, electrochemical treatment, nutrient oxidation, and specific ion exchange, are discussed in the following paragraphs.

Chemical clarification can be used for the removal of suspended solids, organics, and phosphates in a wastewater stream. Included under the term chemical clarification as it applies to the MIUS are four distinct processes: (1) chemical addition, (2) rapid or flash mixing, (3) flocculation, and (4) settling. Interest in chemical clarification has increased recently because of the phosphorus removal capability of the process. Together with carbon adsorption and filtration, chemical clarification provides an alternative to biological treatment. This approach is discussed in the section entitled "Physical-Chemical Treatment." The two main considerations in chemical clarification are choice of equipment and techniques and choice of chemicals. Selections include choices between wet- or dry-chemical metering techniques, mixing basin shapes and types, various detention times, and different flocculation techniques. The choices of solids-separation equipment are essentially the same as those outlined in the discussion of sedimentation and flotation in the section entitled "Primary Treatment." The choice of chemicals usually is limited to alum, lime, or various iron salts with or without the use of polymer addition. The choice between chemicals is based on the suitability of the coagulant to a particular wastewater, the availability and cost of the coagulant, and the interface of the sludge treatment and disposal techniques with the chemical sludge. If the removal of phosphorus is desired in a municipal system of primary and secondary treatment only, chemical coagulants can be added in the primary clarifier (refs. 133 and 134). Results of chemical clarification studies in which different types of coagulants were used and compared are presented in references 135 to 147.[2] The coagulants (alum, lime, iron salts, and polyelectrolytes) are discussed briefly in the following paragraphs.

1. When added to water, alum reacts with bicarbonates to form aluminum hydroxide. Aluminum hydroxide forms a gelatinous precipitate that sweeps suspended matter out of the water and forms a low-solids-content sludge. The alkalinity required for proper precipitation is approximately 0.5 mg/liter for each 1 mg/liter of alum. With less alkalinity, lime is usually added as required.

2. Lime has been used as a coagulant alone or with iron salts or polyelectrolytes. Lime has been added to solutions ranging from pH 9.5 to pH 12.5. Because lime reacts with both carbonates and bicarbonates, the amount of

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[2] For more information, refer to Water Reclamation Research Center Comprehensive Monthly Reports, Dallas Water Utilities Department and Texas A. & M. University.

lime required varies with the alkalinity of the wastewater. The calcium carbonate formed acts as the coagulant, which produces a rather dense sludge. One advantage to the high-lime treatment is the production of a disinfected sludge. The recalcining of the sludge in a furnace for lime reuse reduces the coagulant loss and cost. Various application techniques, doses, detention times, and stages of recarbonation have been used.

3. The iron salts include ferrous sulfate, ferric chloride, and ferric sulfate.

a. Ferrous sulfate, generally added together with lime, produces a ferrous hydroxide that is subsequently oxidized to ferric hydroxide by the dissolved oxygen. Insoluble ferric hydroxide forms as a heavy gelatinous flow and sludge. Approximately 0.4 mg/liter of alkalinity per 1 mg/liter of ferrous sulfate is generally required for good precipitation.

b. Ferric chloride, with or without lime, forms a ferric hydroxide precipitate for sweeping the particulates out of the wastewater.

c. Ferric sulfate, with or without lime, also forms a ferric hydroxide precipitate as in item 3b.

4. Polyelectrolytes, natural or synthetic, are often added to the water stream in small amounts to facilitate coagulation.

The application of carbon adsorption for potable water purification has been practiced for years. Taste- and odor-producing organics have been the primary target of such treatment. To economically use carbon treatment for the relatively large amounts of organic pollutants present in wastewater, continuous replenishment of carbon and efficient use of carbon capacity are required. Both granular- and powdered-carbon configurations have been studied. Granular systems include packed- or fixed-bed and expanded-upflow-bed configurations. Powdered-carbon application variations result from the fact that carbon can be introduced into the treatment scheme at many points. Granular-carbon systems were initially preferred because the carbon could be regenerated and reused economically. However, powdered-carbon regeneration was found practical, and this fact has recently spurred more research in powdered activated-carbon (PAC) systems.

1. Granular activated-carbon beds include two basic configurations that have been used to bring wastewater pollutants into contact with the carbon. These

configurations are (1) fixed- or packed-bed systems using either pressure upflow or downflow patterns or gravity-flow patterns, and (2) expanded-bed upflow systems. Packed-bed and expanded-bed systems (refs. 148 to 154) have been found to be essentially equivalent in organics-removal capacity. Suspended solids are better removed by the packed bed, but the solids-removal capacity of the packed bed is not equivalent to that of a sand or mixed-media filter. The frequent backwashing of the packed bed and higher back pressures make the packed bed less economical to operate than expanded beds. In both beds, the capacity of the carbon to absorb organics appears to be enhanced by biological growth. The biological growth can be either aerobic or anaerobic, but aerobic cultures appear more viable. In addition, the potential for hydrogen sulfide generation from anaerobic bacteria is precluded by proper aeration. Air injection permitting expanded-bed aerobic operation at lower waterflow rates appears to be an efficient treatment process. Granular-carbon regeneration is required for economical carbon treatment, and many researchers have attempted to find the best process for regeneration. Thermal techniques (refs. 155 to 158) are used most often, but research on chemical regeneration (ref. 159) has been done.

2. The value of powdered activated carbon as a wastewater-treatment process has been demonstrated in several test programs (refs. 160 to 162).[3] With the advent of reasonable carbon regeneration systems, powdered carbon will become a viable concept. Such regeneration systems appear to be near realization (refs. 163 to 165). A unique system for carbon production by the pyrolysis of sludge has been proved technically feasible at an Orange County, California, treatment facility.[3]

Electrochemical treatment involves the combination of direct-current, sacrificial electrodes and an electrolyte to remove contaminants by chemical reaction, precipitation, or flotation (refs. 2 and 166). The electrochemical treatment process has been applied to various types of waste including that from papermills, tanneries, slaughterhouses, and domestic sewage systems. However, no detailed reports and costs for this process exist at this time; thus, a detailed comparison of electrochemical treatment with other techniques is prevented.

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[3] Private communication from Yukio Nakamura, NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 1973.

The chemical oxidation of ammonia can be achieved by using chlorine. The nutrient oxidation process is further discussed under "Chlorine" with references in the section of this report entitled "Disinfection."

Specific ion exchange has been used in industry for years; and, recently, ion exchange has been used to remove nutrients in domestic wastewater treatment. Studies of the removal of ammonia, nitrates, and phosphates from wastewater streams can be found in the following references: phosphates, references 166 to 168; ammonia, references 169 to 171; nitrates, references 168 and 172 to 175.

From a cost-competitive standpoint, resin and metal sorbents seem to have a marginal capacity for phosphorus removal. After further research, the cost may be reduced. Several ammonia removal schemes appear to be cost competitive, especially in low-temperature applications and if the methanol required for denitrification remains scarce. The problem of the regeneration brine stream must be faced, but flow schemes to provide for land dispersal of the nutrient-rich brine streams have been developed (ref. 168).

Biological processes: The biological processes, which include algae uptake, biological digestion, nitrification, and denitrification, are discussed in the following paragraphs.

Attempts to remove nutrients using algae in a controlled area have been made in numerous locations. This process is the same as algae uptake that occurs randomly in a lake or stream having nutrients available. The controlled attempts have had various degrees of success, but the principle appears to be sound (refs. 176 and 177).

Nutrient removal or conversion can occur in all activated-sludge and similar systems if the conditions are correctly adjusted. Various comments about the biological digestion process are made in the discussions of the activated-sludge, trickling filter, and rotating biological disk methods contained in the section entitled "Secondary Treatment." The specifics of luxury uptake of phosphates are discussed in references 178 to 180. In addition to these references, techniques involving the addition of metal salts to biological processes can be found in references 181 and 182.[4]

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[4] Description of the El Lago, Texas, Advanced Wastewater Treatment Plant, March 1974, Harris County Water Control and Improvement District No. 50.

Nitrification is the process of biological conversion of ammonia to ammonium nitrite followed by further oxidation to ammonium nitrate. This biological conversion is produced by a group of micro-organisms distinctly different from the heterogeneous group that degrades organic matter. The nitrifiers have a much slower cell growth and require cell-residence times in a biological process of approximately 10 days. If cell residence is extended to that time in an activated-sludge process, nitrification will occur simultaneously with organic matter degradation. The trickling filter and rotating disk processes inherently produce biomasses with very long cell-residence times, and these systems always produce ammonia nitrification. Biological denitrification is performed anaerobically by using a readily oxidizable organic carbon source and short detention times. The anaerobic growth media have included plastic rings, sand, gravel, activated carbon, coal, and rotating biological reactors (refs. 94 and 183 to 186). Methanol is the usual carbon source; however, initial testing has begun using a wet oxidation process supernatant fluid as the carbon source.[5]

<u>Process evaluation for MIUS</u>.- Obviously, tertiary treatment includes a wide variety of processes. Like all the processes widely used in wastewater treatment, most tertiary treatment processes are effective when operated correctly. Thus, in an evaluation, the processes are matched to the limitations and requirements of the MIUS as stated earlier. In addition, specific limitations may reduce the process usefulness; for example, the use of ferrous ions for chemical coagulation has proved very satisfactory. However, the inexpensive ferrous ion source of spent pickle liquor from the acid processing of steel is available only where the pickle liquor is near the MIUS site and thus is not general to all MIUS's. In this evaluation, therefore, the use of ferrous ions is not considered because it is only practical in a few specific cases.

Physical methods: The physical methods considered include filtration, flotation, land application, air stripping, sorption, and gas-phase separation. Flotation was evaluated in the section entitled "Primary Treatment."

The general process of filtration is a requirement if really clear, clean treated wastewater is to be achieved. The manner of filtration is the remaining consideration.

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[5] Private communication from Darwin Wright, Environmental Protection Agency, April 17, 1974.

1. Rapid sand filters have been and will continue to be effective in the removal of particulate material from water. Small grains are required for high removal efficiencies, however; this requirement leads to more frequent backflushing because influent-side surface loadings of the suspended solids cause rapid back-pressure buildup. In sand or any other single medium, the smallest or most easily clogged particles move to the inlet side of the filter because of the backflushing operation. This movement is the single largest disadvantage to sand or any other single-medium filter. Systems having pressure-triggering backflush have been widely used, however, and have proved to be very reliable.

2. All media used in other types of single-medium filters have worked well, but no single one has proved superior to another except in specific applications that are not general to the MIUS. An example of a substitution is the use of coal or carbon for sand where no silica can be allowed in the effluent stream.

3. The use of multimedia filters reduces the problem of surface matting or clogging due to small grain size. The use of large, low-density material at the filter inlet and very small, high-density material at the outlet produces clear effluent with long filtration runs, without excessive lead-pressure buildup.

4. To achieve the desired clarity of the MIUS effluent, microscreens cannot be used as a replacement for other filtration means. They are, however, useful tools for moderate filtration and could be used in conjunction with sand or multimedia filters for final polishing in an MIUS total physical-chemical treatment scheme.

All forms of land application appear to be useful processes; however, in small MIUS projects, land is expected to be very limited and surrounded by a high population density. Therefore, land application of wastewater should not be given primary consideration for an MIUS.

The air-stripping technique has not worked as well as expected in full-sized-plant operation. Air stripping can only be practically applied when lime is used as the coagulant and with warm water and air. Calcium-carbonate-filled mist and ammonia air contamination are not desired in densely populated areas. Even though waste heat from the MIUS power system could be used to provide warm air and water for the process, lime may not be the best MIUS choice for a coagulant because of the potential problems involved. These problems are described in the following subsection.

The probability for incorporation of air stripping into an MIUS is reduced because of the many negative aspects.

At the current state of development, sorption processes and gas-phase separation are not recommended for MIUS.

Chemical processes: Chemical clarification, carbon adsorption, electrochemical treatment, and specific ion exchange are evaluated in the following paragraphs. Nutrient oxidation using chlorine is discussed in the section entitled "Disinfection."

As with filtration, chemical clarification is necessary to economically achieve the high-quality effluent values which may be desired for an MIUS wastewater-treatment system. The removal capabilities are almost equivalent for all the major coagulants used. For a small tertiary treatment system, however, lime is the least likely choice because dosage, which is based on pH, is essentially the same for any wastewater contamination. Thus, when lime is used as the coagulant, more coagulant is needed for the same removal than would be needed with other coagulant choices. For small plants in which recalcining is uneconomical, again, lime appears to be a less than optimum choice. The choice of a coagulant is affected by applicability of the coagulant to the specific conditions of an MIUS site.

To produce an effluent of high quality, having low chemical oxygen demand (COD), color, or odor, some method of polishing the water to remove residual contaminants must be applied. As the last traces of contaminants are removed, the processes become more costly in regard to the amount of contaminants removed.

The most common polishing process is the granular activated-carbon column process, which is preferred currently over the use of PAC systems. As more emphasis is placed on PAC systems, this condition may change. Ultimately, if PAC can be generated onsite as an MIUS waste product, powdered carbon would become the preferable and the most economical process. In using carbon columns, the upflow, aerated, expanded-bed system is potentially the most trouble-free and the least expensive process.

The electrochemical process has not been developed and tested sufficiently to provide the background information required for serious early MIUS consideration. Specific ion exchange affords good wastewater treatment if the brine can be used as a fertilizer for the MIUS green area. Testing of the specific application should be done, but the process should be seriously considered for both phosphorus and ammonia removal.

Biological treatment: Biological treatments considered include algae uptake, biological digestion, nitrification, and denitrification.

Removal of nutrients by the use of algae and algae harvesting is feasible for large MIUS applications but not for the small MIUS concept because of the large-surface-area, shallow ponds required to make the process efficient.

If secondary treatment is designed into the MIUS wastewater system, modifications for luxury uptake of phosphate or coagulant addition could be contemplated as a shortcut to complete physical-chemical treatment, but additional testing of specific wastewater streams is required if biological digestion is used.

Whether biological uptake of phosphorus is attempted or not, nitrification should be used with all secondary treatment processes because of the economics involved. If nitrification is used, denitrification may also be used. The denitrification systems have not been defined sufficiently to choose the most economical system. All contact systems found in the literature appear suitable for performing denitrification.

Physical-Chemical Treatment

Many physical and chemical separation and conversion processes have been studied for use in municipal and industrial wastewater treatment. Among these processes are adsorption, coagulation, chemical oxidation, solvent extraction, ion exchange, distillation, freezing, reverse osmosis (RO), ultrafiltration, electrodialysis, flotation, and foam separation. This extensive investigation, however, revealed a basic physical-chemical system that consists of a few promising, easily operated processes: chemical clarification, coagulant addition and settling, granular-carbon adsorption, and filtration.

In general, the effluent quality of a physical-chemical plant consisting of chemical clarification, carbon adsorption, and filtration is superior to that of a secondary biological plant but inferior to that of a tertiary biological plant. There are indications, however, that physical-chemical treatment can be made equal to or superior to tertiary treatment if high lime application is used to raise the pH to 11.5. At this pH, hydrolysis of the organic material in the water occurs and conditions the organic matter so that it is readily adsorbed on activated carbon. An extremely high level of BOD removal has been reported using this hydrolysis technique (ref. 146).

All the processes used in complete physical-chemical plants are described in the discussions of tertiary treatment, dissolved-solids removal, disinfection, and sludge handling; therefore, no further discussion will be provided here. However, references dealing with total physical-chemical systems composed of the various processes mentioned previously include 96, 97, 137, 138, 140, 146, and 147.

Dissolved-Solids Removal

The following dissolved-solids-removal processes are included in this review: (1) freeze concentration, (2) reverse osmosis, (3) electrodialysis, (4) ion exchange, and (5) distillation.

Process description.- Many of the processes described in the following paragraphs are used to remove wastewater constituents other than dissolved solids. Though the removal of other contaminants will be mentioned, the primary reason for using these processes is to remove ionic constituents from the wastewater stream. All the processes have operational constraints that require large amounts of engineering and control effort and therefore are costly to install and operate. Great care must be taken to ensure that a requirement for these processes is justified before the processes are included in the design of a treatment system. Although several of these processes have been widely used for many years, each new application must be carefully evaluated before initiation to provide confidence that the process will work economically with a given waste stream when the degree of pretreatment during previous processing is considered.

Freeze concentration: The concept of freeze concentration was developed primarily as a means of converting saline water to freshwater. However, when ice crystals form in aqueous solutions, the crystal formed is pure water excluding all other impurities as well. Several advantages are inherent in the freeze process (refs. 187 to 189).

1. Energy consumption is low because of the direct-contact heat transfer.

2. Capital cost is low because the use of low temperatures and pressures requires only inexpensive materials and structures.

3. Little pretreatment of water is required; however, some level of suspended-solids removal is probably required.

4. Almost any dissolved impurity, whether ionic or gaseous, is removed.

5. Operational costs are low because of low energy consumption, absence of fouling or scaling problems, and little, if any, need for component replacements.

Although freeze concentration is being used in industry, a complete test program for use with wastewater is required.

Reverse osmosis: The RO process has been tested more often than any other dissolved-solids-removal system for potential use in wastewater treatment. The process was first developed for the desalination of brackish waters to supplement or provide potable water. However, if the water is pretreated properly, dissolved solids can be removed from wastewater easily. Three basic types of membranes have been developed: tubular, spiral wound, and hollow fiber. Each membrane has advantages and disadvantages, and no type of membrane dominates the market. Fouling has been the major problem with all RO membranes, particularly in wastewater treatment. The most prevalent fouling ingredients include iron precipitates, suspended solids, calcium carbonate, sulfate precipitates, and organics. Physical and chemical pretreatment and membrane-cleaning techniques have been developed by all major manufacturers of RO units to reduce the magnitude of the fouling problem. Although capital, operating, and maintenance costs are quite high, RO is commercially available for wastewater treatment. References 190 to 206 are suggested for detailed information on RO and RO wastewater treatment. Research is continuing to improve the quality of membrane materials, to reduce replacement costs, to increase loading rates, and to reduce operation pressures.

Electrodialysis: In both electrodialysis and a similar process, transport depletion, soluble salts are removed from water by passing an electrical current through an array of ion-permeable membranes and solution compartments (refs. 207 to 210). The electrodialysis membranes are alternately anion selective and cation selective. The major problems in using electrodialysis are

1. Temporary fouling of membranes by colloidal organic materials

2. Permanent fouling of anion-selective membranes by dissolved organic materials

3. Scaling at the anion-selective membranes because of precipitation of pH-sensitive materials

Organic materials can be removed during pretreatment by using activated carbon, but the cost is therefore increased.

In transport-depletion units, the anion-selective membrane is replaced with an inexpensive neutral membrane. If the proper neutral membrane is selected, the cost of treating water is slightly reduced; fouling, however, is significantly reduced (refs. 211 and 212).

Ion exchange: In ion exchange, ions of a given species in solution displace ions of a different species from an insoluble ion-exchange material, or resin. All resins tend to be specific in exchanging ions. This tendency is described as the selectivity coefficient. By choosing the correct resin and ion medium, cations and anions can be removed generally or selected ions can be removed specifically. References on specific nutrient removal were cited in the discussion of specific ion exchange in the section entitled "Tertiary Treatment." More general information on ion exchange is contained in references 168, 207, 208, and 213 to 215.

Distillation: For many years, research on distillation techniques has been performed on both seawater and less saline streams. Many different configurations have been produced that are efficient for the specific removals for which they were designed. However, because of problems in adapting the processes to the impurities present in wastewater, only limited treatment of wastewater has been attempted. These problems include (1) corrosion of heat-exchange surfaces, (2) coating of surfaces with organic materials, (3) scaling, and (4) incomplete odor and color control as a result of volatile organic carryover. These problems have not been overcome sufficiently to warrant full-scale testing. The distillation configurations most applicable for wastewater are multistage flash evaporation, multiple-effect evaporation, and vapor-compression distillation. Selective seeding is potentially useful for reducing distillation problems (ref. 216).

Process evaluation for MIUS.- All dissolved-solids-removal systems are expensive to operate and therefore should be used in the MIUS only if necessary. In these systems, the disposal of the brine stream is difficult at best. Expensive and elaborate drying systems may have to be designed into the small MIUS. Low-grade waste heat is, however, usually available from the MIUS power generation system. Minimal treatment design is always the goal, but the more expensive processes require the most careful scrutiny. In addition, except for RO, most desalination techniques have not been tested extensively in wastewater streams. Unless absolutely required, none of these processes should be considered.

Freeze concentration: Low-cost freeze-concentration systems are possible because of the low operational temperatures and pressures. Although further testing is required to define the limitations of the process with respect to a wastewater stream, freeze concentration has good potential for future use but not in early MIUS applications.

Reverse osmosis: Reverse osmosis has been proved capable of dissolved-solids-removal operations in wastewater treatment; however, the pretreatment must include primary, secondary, and tertiary processes plus pH control. Thus, the expensive RO process provides for dissolved-solids removal only. Brine concentration is limited by carbonate and sulfate scaling. A more useful approach in the MIUS could be the low-pressure-membrane RO (refs. 200 to 204). Use of low-pressure RO reduces removal efficiency and thereby increases flow and reduces membrane clogging. Because only moderate levels of dissolved-solids removal are generally required for MIUS operation, low-pressure RO may have application in the MIUS.

Electrodialysis: The electrodialysis process is similar in function and operation to the RO process, and it has the same advantages and disadvantages. Ease of operation, reliability, and costs should be directly compared before either process is selected. Similarly, low-pressure RO and transport depletion are somewhat parallel techniques, each of which affords some advantages. Transport depletion apparently can reduce scaling problems significantly compared to electrodialysis by separating the precipitating ion pairs that compose the insoluble salt molecule, which can cause membrane fouling (ref. 212). Thus, the transport-depletion process should be carefully tested under MIUS operating conditions.

Ion exchange: The complexity of the removal and regeneration systems within the ion-exchange process reduces its usefulness for small MIUS applications, but complete studies should be made, especially of specific ion removal of ammonia. As with other dissolved-solids processes, a test program for evaluating MIUS applicability of the ion-exchange process is needed.

Distillation: Compared to other dissolved-solids-removal systems, distillation processes afford little or no advantage even with their potential for using waste heat because either the temperature of waste heat generally available in the MIUS is not high enough for use in distillation systems or, for low-temperature systems, the size of the units makes them impractical for use in the MIUS. There are advantages in using units with seeding capabilities, however, because the solids can be concentrated into as little as 3 to 5 percent of the water (ref. 216).[6] Again, testing is required to verify the usefulness of distillation processes.

Disinfection

The specific disinfection processes to be discussed in this report are chlorine, ozone, heat, and ultraviolet (uv) radiation. These are the processes that hold the highest potential for use in an early MIUS because enough data are available to evaluate the processes and because equipment is available to implement the processes.

Process description.- The ultimate goal of using disinfection processes is the total destruction of disease-causing micro-organisms. Although this goal is seldom reached in practice, the destruction is generally sufficient to prevent disease transference to the population. The two general types of disinfectants that have been used for wastewater treatment are chemical agents and physical means. Chemical agents that have been used or evaluated are (1) alcohols, (2) halides (bromine, chlorine, and iodine), (3) heavy metals, (4) ozone, (5) soaps and detergents, (6) peroxides, (7) acids, and (8) alkalies. Physical means used are (1) heat, (2) uv radiation, (3) radioisotope radiation, (4) biological attack, and (5) sedimentation (plain and chemically enhanced).

The characteristics for a good disinfectant are (1) to have broad-spectrum toxicity to micro-organisms, (2) to be soluble or dispersable in water, (3) to be capable of onsite generation or stability, (4) to be nontoxic to higher life forms, (5) to be capable of penetrating toxic mechanisms, and (6) to be widely available at reasonable cost. The more efficient the disinfectant is in each of these categories, the more useful it becomes as a potential process. Factors that are critical to a disinfectant are (1) interference by competing chemicals, (2) concentration or magnitude of chemical agent or intensity of physical means, (3) temperature, (4) number of organisms to be removed, (5) type of organism, (6) nature of surrounding medium, and (7) control time.

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[6] Private communication from Resource Conservation Corporation, October 1972.

Chlorine: The most widely used disinfectant in the United States is chlorine. Detailed discussions on the use of chlorine can be found in references 2 to 4 and 217 to 222. Whether the chlorine is available as free chlorine or as calcium or sodium hypochlorite, the reaction with water forms hypochlorous acid after which the oxidation or disinfection action takes place. Because chlorine reacts with ammonia at a very rapid rate, chlorine can be used to reduce the nutrient nitrogen in the water and to disinfect simultaneously. The method used in ammonia reduction is called breakpoint chlorination; if properly performed, it is a useful, safe process. A chlorine to ammonia-nitrogen ratio as high as approximately 9 to 1 has been reported (ref. 221) as being required in wastewater. If breakpoint chlorination is not practical, or if ammonia is not removed before chlorination, chloramines, which are highly toxic to aquatic life, are formed (refs. 223 and 224). Chlorination with light catalyzation has also been attempted (ref. 225). The chlorine residual required for potable water has been found to be ineffective for preventing regrowth of coliforms in wastewater (refs. 226 and 227). It must be noted that chlorine is an adequate but not optimal disinfectant.

Ozone: Ozone has been used in Europe for decades, and research in the United States has indicated that ozone is a viable choice for the disinfection of wastewater. The ozone process has several advantages in wastewater treatment: (1) simultaneous removal of odors, colors, and tastes; (2) oxidation of organic compounds such as phenolics and amines; (3) oxidation of inorganic compounds such as chromous and ferrous ions; (4) freedom from storage and handling problems; (5) generally better germicidal action than chlorine; and (6) absence of residual chemicals in water. Many recent articles have been published describing the use and effects of ozone (refs. 228 to 234).[7] Because chlorine is much cheaper than ozone, improvements in the efficiency of present ozone-generation systems is required to accomplish major increases in the application of ozone.

Heat: Thermal disinfection has not been practical in large-scale wastewater treatment because heat is not generally available. In the MIUS, however, if enough 394-K (250° F) heat is available from the final design, this form of disinfection becomes a viable alternative to other forms of disinfection.

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[7] Louis Coin, Claude Hannoun, and Cyril Gomelia, An Inactivation of the Poliomyelitis Virus Present in Water by Use of Ozone, research by the Society for Treatment and Utilization of Water for the City of Paris.

Ultraviolet radiation: Ultraviolet radiation is an effective germicidal agent in clear water, but any turbidity or coloration greatly reduces its capability. Very little work has been done on a detailed evaluation of uv for disinfection of wastewater (ref. 227), and more research should be done if uv radiation alone is to be considered for use in an MIUS.

Process evaluation for MIUS.- Although disinfection has been practiced for many years and its effects on most micro-organisms are well known, the effect of disinfectants on viruses is not well defined. In addition, the masking of micro-organisms by other impurities in wastewater is a problem that is best overcome by greatly increased dosages, which, in turn, increase the cost of the process. Each previously discussed disinfectant has advantages and disadvantages, and the general conclusion is that each could be used in some manner in the MIUS. The following specific comments apply to chlorine, ozone, heat, and uv radiation.

Chlorine: The advantages of chlorine as a disinfectant are (1) that the technology is well understood and developed, (2) that measuring equipment for application is available, (3) that equipment is comparably inexpensive, and (4) that ammonia removal is possible. The disadvantages of chlorine as a disinfectant are (1) that residual chlorine is detrimental to aquatic life, (2) that chloramines formed in the disinfection process are extremely toxic to aquatic life, (3) that increased system cost and complexity would result from a decision by water authorities to require dechlorination before disposal of effluent water, and (4) that some forms of chlorine require storage as a dangerous chemical.

Ozone: The advantages of ozone as a disinfectant are (1) that ozone is a more efficient disinfectant than chlorine, (2) that ozone improves odor, taste, and color of wastewater, (3) that ozone oxidizes many chemicals, (4) that ozone adds no chemicals to the water, (5) that oxygen is the only ozone residual and is beneficial to the wastewater, and (6) that ozone is not stored. The disadvantages of ozone as a disinfectant are (1) that high capital cost for equipment results from the use of ozone, (2) that high electrical input is required for ozone disinfection, and (3) that toxic ozone gas must not be vented to the atmosphere.

Heat: The advantages of heat disinfection are (1) that heat disinfection is a simple process, (2) that complete sterilization is possible, (3) that no chemicals are added to the wastewater, and (4) that waste heat is used. If ample heat is available, the only major disadvantage of thermal disinfection is the high capital and maintenance costs associated with the heat exchangers required for proper disinfection.

Ultraviolet radiation: The advantages of uv radiation are (1) that uv radiation disinfection is a simple process and (2) that no chemicals are added to the wastewater. The disadvantages of uv radiation as a disinfectant are (1) that in comparison to ozone, heat, or chlorine, the germicidal spectrum of uv radiation is less well defined; (2) that uv radiation disinfection is more easily masked by turbidity and particulate encapsulation of micro-organisms than the other three processes; and (3) that dosage of uv radiation cannot be directly measured.

Conclusions.- On the basis of the previously mentioned advantages and disadvantages, the preferred disinfection process is heat if waste heat is available. Tests are underway to define the parameters that are required for proper process operation. If heat is not used, both chlorine and ozone are acceptable on the basis of current evaluations.

Sludge Handling

Sludge-handling processes discussed are sludge concentration, digestion, conditioning, dewatering, drying, thermal disposal, and ultimate disposal.

Process availability.- Potential processes for sludge handling are varied because the requirements are wide ranging and because no single process has obvious advantages over the others. Sludge-handling problems increase as the population density increases, particularly for the MIUS because the wastewater-treatment and sludge-handling facilities are centered in a small, highly populated area. More efficient wastewater-treatment processes are usually accompanied by greater sludge-handling problems because the sludge is either more difficult to dehydrate or includes large amounts of chemical sludge or both. Extreme care must be used in process selection to prevent health hazards or nuisance problems such as odors and flies. In processing sludge, chemical, physical, or biological treatment can be used. In the end, however, the greatest problem is the ultimate disposal of the residue. Table XIV indicates the processes that have been evaluated for this paper.

Because a thorough evaluation of sludge-handling and sludge-disposal practices complete with 451 references (ref. 235) and an excellent design manual for sludge treatment and disposal (ref. 236) are available, the sludge-handling processes described in table XIV are not discussed herein.

For additional information on the various aspects of sludge handling, see references 126 and 237 to 259 of this report.[8]

Process evaluation for MIUS.- The processes for sludge handling were evaluated with particular attention given to useful products, minimum nuisance potential, tested processes, and small land use. Newer processes with potential application in MIUS are recommended for further testing.

Sludge concentration: Both the gravity-thickening and flotation methods of sludge concentration require relatively large tanks; therefore, they are undesirable and should be avoided. However, the Lamella thickener, a rapid-settling system for wastewater, has a vibration tank that is very effective for sludge thickening. The small-settling-profile/sludge-thickening combination appears to be a viable process unit for the MIUS.

Digestion: Generally, the reduction of solids is greater when aerobic digestion is used than when anaerobic digestion is used for the same detention time. However, some high-rate anaerobic, thermally enhanced digesters compare favorably with aerobic digesters. A 40- to 60-percent reduction in volatile suspended solids can be expected when domestic sludge is treated. The best probable choices for sludge digestion in MIUS are a high-rate thermophilic anaerobic digester and a progressive staged aerobic digester.

1. One choice is a high-rate thermophilic anaerobic digester operating at temperatures between 322 and 333 K (120° and 140° F) but maximized for the production of methane gas. If heat is required for the process, it can be obtained from the powerplant low-grade waste heat. The gas produced can be used in the MIUS as a source of fuel.

2. A second choice, a progressive staged aerobic digester, is described in the section entitled "Separate Systems." This system is to be tested on a small scale by the author to verify the claim of 100-percent volatile-solids reduction within a reasonable time.

Other aerobic digesters with solids reductions not much greater than those of the high-rate anaerobic digester offer few advantages and no useful gas product.

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[8] Private communication on land disposal systems from Lockwood Corporation of Gering, Nebraska, 1974.

Conditioning: The development of freezing and heat-treating processes is insufficient for inclusion in a small treatment system; therefore, these conditioning processes are not considered in early MIUS configurations. Chemical addition, especially lime stabilization to pH levels of 11.0 to 11.5, is proven technology and will be applied as necessary in any MIUS. Elutriation appears profitable when the sludge characteristics are vastly improved by its use. The profitable aspects of this process must be determined for each wastewater stream.

Dewatering: The use of vibrating screens tends to allow more fine particles to remain in the supernatant fluid; therefore, settling rates are reduced when the fluid is recycled to the wastewater stream. This undesirable activity reduces the usefulness of the vibrating screen. The remaining dewatering methods, vacuum filtration, centrifugation, pressure filtration, and rotating drum gravity filtration, all provide good dewatering capabilities. The pressure filter produces the driest sludge, which is advantageous, but its difficult operating characteristics are less than desirable. The simplicity and low power input of the rotating drum gravity filtration system are desirable, but pilot-scale testing should be performed before commitment. Pilot-scale testing should also be performed for vacuum filtration because sludge age or chemical type greatly affects the usefulness of the process. Filter media selection for particular sludges is also required.

The quality of solids capture can range from very good when vacuum filtration and pressure filtration are used, to fair when centrifugation is used, to poor when rotation systems are used, and to very poor when vibrating screens are used. These factors must be evaluated together with maintenance and automatic operation. No one process has a definite advantage over another in this area.

Drying: Because of the large land area required for drying beds, this form of sludge drying is not considered acceptable for the MIUS. Heat drying at high temperatures is not considered useful from an energy use standpoint because all systems require high-grade heat for flash or rapid drying. A low-temperature dryer operating at a temperature of 394 K (250° F) or lower would be useful for an MIUS. Odors could be controlled with ozone or activated-carbon filters. This area of development could be advantageous for later MIUS application. In any drying process, stabilization of the sludge to destroy the pathogenic bacteria and odors would be required as a preparatory step.

Thermal sludge volume reduction: Incineration, wet oxidation, and pyrolysis appear to be useful for thermal reduction of sludge volume in the MIUS. Should incineration be used, it would be in conjunction with the solid-waste disposal system. For pyrolysis, two useful options are available. Thermal destruction of all solid waste is feasible, and a small, separate system pyrolyzing only sludge to form activated carbon for use in the wastewater-treatment processes is also feasible. Pyrolysis is discussed in the section entitled "Separate Systems." In wet oxidation, the supernatant fluid appears to be a viable substitute for methanol for use in the biological denitrification process. Thus, to arrive at the proper thermal sludge volume reduction system, the entire series of processes must be integrated.

Ultimate disposal: Lagooning, ocean dumping, and composting normally are not probable choices for ultimate disposal of MIUS sludge. If the sludge can be sterilized and conditioned, it could be at least partly used as a fertilizer and soil conditioner around the MIUS complex. Landfill is the method for the ultimate disposal of ash if thermal sludge volume reduction is used. Thermal reduction and ash landfill probably will be the mode of operation for early MIUS units.

Separate Systems

In addition to the processes previously discussed, several processes or systems have been developed that may be advantageous compared to standard technology or as packaged, preengineered systems. Some of the current nonstandard technology or preengineered package systems that appear to aid in the production of very high quality water, which is essentially equal to tertiary treated water or to that produced by sludge-handling processes, are described in this section. None of these nonstandard systems should be used without a thorough investigation of its applicability to a specific MIUS system.

Nonstandard technology.- Nonstandard technology includes several techniques that present alternatives to the customary systems.

Petmar progressive digester: The Petmar progressive digester is a multistage digester that provides food supply for more homogeneous micro-organism groups in each of five stages. Additional information on the Petmar progressive digester is available from Petmar Corporation, 515 South Paula Drive, Dunedin, Florida 33528. Removal of essentially all volatile solids from wastewater has been reported for this patented process.

Sludge pyrolysis/activated-carbon treatment system: The sludge pyrolysis/activated-carbon treatment system, which was developed at the NASA Jet Propulsion Laboratory, Pasadena, California, uses the organic solids contained in wastewater to purify the wastewater.[3] This process is accomplished by pyrolyzing the sewage sludge, which contains the organic solids, to produce a powdered activated carbon. The activated carbon, which is introduced at a secondary stage in the process, flows in a water slurry countercurrent to the sewage flow and removes dissolved and suspended organic matter. The carbon slurry then is transferred from the adsorption-contactor and recycled to the primary sedimentation basin. Here, the recycled sludge settles together with the influent wastewater solids. These steps result in the removal of suspended organic solids, the reduction of turbidity, and the removal of odors. Settled sludge is withdrawn from the coagulator-settler and is passed through either a filtration or a centrifugation process to separate the solids from the liquid. The filter cake is fed to a pyrolysis furnace to regenerate the exhausted carbon continuously. The activated carbon then is slurried and recycled back into the process stream. The major advantages of the process include (1) the elimination of the problem of biologically active organic-waste disposal, (2) the lack of sensitivity of the process to toxic materials, and (3) the potential reduction in the physical size of the treatment plant because aeration and sludge digestion may be completely eliminated.

Ulta-Ion process: In the Ulta-Ion process, screened, comminuted sewage is mixed with a patented mixture of five or more selected ingredients formulated for the specific wastewater flow. After settling, the water is filtered and disinfected with uv radiation. Results published by the manufacturer indicate very low BOD, COD, and nutrient levels in the effluent. The process should be evaluated further for potential MIUS applications because the unit is compact and relatively automatic in operation. Additional information on the Ulta-Ion process is available from Ultradynamics, 2 Wait Street, Paterson, New Jersey 07524.

Chem Pure system: Primary settled wastewater is treated with sulfuric acid, contacted with iron, neutralized, settled, air stripped, filtered, and contacted

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[3] Private communication from Yukio Nakamura, NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 1973.

with carbon in the Chem Pure process. Rapid, heavy flocculation is produced. Published results indicate reductions of 98 percent in BOD, 95 percent in COD, 98 percent in suspended solids, 84 percent in phosphorus, and 50 percent in ammonia. Coliforms in the effluent are less than 1 most probable number (MPN)/100 ml. Additional information on the Chem Pure system is available from Sterling Engineering, 3460 Hollenberg Drive, Bridgeton, Missouri 63044.

Lin-Pro system: Comminuted wastewater is contacted with sulfur dioxide and iron, neutralized, settled, and sand filtered in the Lin-Pro process. Preliminary tests have shown 98-percent reductions in BOD, COD, suspended solids, ammonia Kjeldahl nitrogen, and phosphate; a 90-percent reduction in sodium, potassium, and chlorides; and a coliform count of less than 2 MPN/100 ml. Additional information on the Lin-Pro system is available from Associated Piping and Engineering Corp., 1707 West Compton Boulevard, Compton, California 90224.

Preengineered treatment plants.- With the addition of nitrogen nutrient removal, the following preengineered treatment plants would operate within the limits acceptable to an early MIUS operation.

1. AWT Systems Incorporated, 910 Market Street, Wilmington, Delaware 19899

2. Met-Pro Systems Division, 5th and Mitchell, Lansdale, Pennsylvania 19446

3. Neptune Microfloc Incorporated, P.O. Box 612, 1965 Airport Road, Corvallis, Oregon 97330

TREATMENT EFFICIENCIES

In the review of the published data on contaminant-removal efficiency of the various processes discussed in this document, the fact became clear that general tables would not significantly aid the reader in the determination of useful processes. As an example, typical published data present variations in processing efficiencies for BOD removal such as: (1) lime clarification, 55 to 83 percent; (2) filtration, 40 to 72 percent; and (3) carbon adsorption, 50 to 90 percent. With these processes arranged in series, using these ranges and starting with an influent BOD concentration of 200 mg/liter, the concentrations of effluent indicated in the following table would result.

Effluent	Concentration, mg/liter	
	Min.	Max.
Clarifier	90	34
Filtration	54	9.5
Carbon adsorption	27	.95

In an attempt to be more specific, the USPO estimated the removal efficiencies of the various processes in normal operation and as they would be used in the MIUS; these estimates are given in table XV. In areas that are left blank or in processes that are not listed, the removal is considered too small to be significant in the overall system.

SYSTEMS FOR MIUS

A system design is a compilation of some of the previously described processes in a number and manner that produces the desired effluent quality from the influent. There are, of course, an endless variety of combinations that could be used to perform the desired treatment. However, to achieve optimum performance at minimum or near minimum cost and complexity is the job of the engineer.

In this report, the following wastewater processes and equipment have been reviewed.

1. Preparatory
    a. Racks and screens
    b. Grit chambers
    c. Skimmers
    d. Comminutors
    e. Equalization basins
    f. Preaerators
    g. Raw/intermediate wastewater pumping
2. Primary

    - a. Sedimentation
        - (1) Standard
        - (2) Tube
        - (3) Lamella
    - b. Flotation
        - (1) Dissolved air
        - (2) Vacuum
        - (3) Chemical addition
        - (4) Straining
- 3. Secondary
    - a. Activated sludge
    - b. Trickling filter
    - c. Rotating biological disk
- 4. Tertiary
    - a. Physical filtration
        - (1) Sand/single medium
        - (2) Multimedia
        - (3) Microscreen
    - b. Flotation
        - (1) Land application
        - (2) Air stripping
        - (3) Gas-phase separation
    - c. Chemical
        - (1) Chemical clarification
            - (a) Lime
            - (b) Iron

      - (c) Alum
      - (d) Polyelectrolyte
    - (2) Carbon
      - (a) Granular
      - (b) Powdered
    - (3) Electrochemical
    - (4) Nutrient oxidation
    - (5) Specific ion exchange
  - d. Biological
    - (1) Algae uptake
    - (2) Biological digestion
    - (3) Nitrification
    - (4) Denitrification
- 5. Dissolved salts
  - a. Freeze concentration
  - b. Reverse osmosis
  - c. Electrodialysis
  - d. Transport depletion
  - e. Ion exchange
  - f. Distillation
- 6. Disinfectants
  - a. Chlorine
  - b. Ozone
  - c. Heat
  - d. Ultraviolet radiation

The following sludge-handling processes and equipment have been reviewed in this report.

1. Sludge concentration
    a. Gravity thickening
    b. Dissolved-air flotation
    c. Vibration
    d. Sludge pumping
2. Digestion
    a. Aerobic
    b. Anaerobic
    c. Sludge lagoons
    d. Imhoff tanks
3. Conditioning
    a. Freezing
    b. Chemical addition
    c. Heat treatment
    d. Elutriation
4. Dewatering
    a. Vacuum filtration
    b. Centrifugation
    c. Pressure filtration
    d. Vibration
    e. Rotation
5. Drying
    a. Beds
    b. Heat
6. Thermal sludge volume reduction
    a. Incineration

   - b. Recalcining
   - c. Wet oxidation
   - d. Pyrolysis

7. Ultimate disposal
   - a. Composting
   - b. Fertilizing and soil conditioning
   - c. Lagooning
   - d. Landfill disposal
   - e. Ocean disposal
   - f. Land use

After evaluation, the list of reviewed wastewater and sludge-handling processes and equipment was reduced to a list of processes and equipment that could be used in an MIUS, as follows.

1. Preparatory
   - a. Skimmers
   - b. Comminutors
   - c. Equalization basins
   - d. Preaerators
   - e. Raw/intermediate wastewater pumping
2. Primary
   - a. Sedimentation
     - (1) Tube
     - (2) Lamella
   - b. Chemical addition
   - c. Straining
3. Secondary - rotating biological disk
4. Tertiary

- a. Physical
    - (1) Single-medium filtration
    - (2) Multimedia filtration
- b. Chemical
    - (1) Chemical clarification
        - (a) Lime
        - (b) Alum
        - (c) Iron salts
        - (d) Polyelectrolytes
    - (2) Carbon
        - (a) Granular
        - (b) Powdered
    - (3) Nutrient oxidation
    - (4) Ion exchange
- c. Biological
    - (1) Nitrification
    - (2) Denitrification
- d. Dissolved salts - not applicable (NA)
- e. Disinfectants
    - (1) Chlorine
    - (2) Ozone
    - (3) Ultraviolet radiation

The following list is composed of the suggested probable MIUS sludge-handling processes.

1. Sludge concentration
    - a. Gravity thickening
    - b. Vibration

    - c. Sludge pumping
2. Digestion
    - a. Aerobic
    - b. Anaerobic
3. Conditioning
    - a. Chemical addition
    - b. Heat treatment
4. Dewatering
    - a. Vacuum filtration
    - b. Centrifugation
    - c. Rotation
5. Drying - heat
6. Thermal sludge volume reduction
    - a. Incineration
    - b. Recalcination
    - c. Wet oxidation
    - d. Pyrolysis
7. Ultimate disposal
    - a. Fertilizing and soil conditioning
    - b. Landfill disposal

Although most of the suggested processes are independent, some are dependent. An example is the incineration of sludge in which the ultimate disposal of the ash, which is normally landfill, is required. Thus, landfill could relate to the disposal of the sludge ash rather than the disposal of the sludge itself.

The following list is one possible combination of wastewater processes that could be used for an MIUS. Figure 12 is a system schematic of the selected processes.

1. Preparatory

    - a. Equalization basin processing
    - b. Preaeration
    - c. Raw/intermediate pumping

2. Primary - straining
3. Secondary - rotating biological disk processing
4. Tertiary
    - a. Multimedia filtration
    - b. Alum chemical clarification
    - c. Granular-carbon filtration
    - d. Biological nitrification
    - e. Biological denitrification
5. Dissolved salt - NA
6. Disinfection - chlorine
7. Sludge concentration
    - a. Gravity thickening
    - b. Sludge pumping
8. Digestion - NA
9. Conditioning - NA
10. Dewatering - vacuum filtration
11. Drying - NA
12. Thermal sludge volume reduction - incineration

ECONOMICS

The current technology in water and wastewater equipment and process cost estimating has been reviewed. The review was conducted by researching data from the Environmental Protection Agency, other governmental agencies, professional agencies, and the commercial/industrial community. The documentation collected during the review came from conferences, seminars, library reviews, manufacturers, and personal contacts. The information is presented graphically as cost compared to daily flow. The review showed that any cost information presented had limitations for further use. One of these limitations was that the cost information was highly site specific; that is, the information was dependent on the exact type of process and on the number of duplicate processes and the amount of duplicate equipment in the total system. Because published information was practically nonexistent for flows of less than 1893 m^3/day (0.5×10^6 gal/day), extrapolations were performed by USPO in certain instances. The economy of scale for the processes is apparent in the curves presented for capital cost, operating cost, and maintenance cost (figs. 13 to 31). The information for the curves was obtained from references 140 and 260 to 281.[9-15]

Capital Cost

Curves for capital cost compared to daily flow were developed individually for different types of primary treatment, secondary treatment, site preparation, sludge-handling, physical-chemical treatment, process, and package plants. The curves for the different components and processes are presented in figures 13 to 20.

Operation and Maintenance Cost

Curves for operation and maintenance cost compared to daily flow were developed individually for different types of primary treatment, secondary treatment, site preparation, sludge-handling, and physical-chemical treatment processes.

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[9] Private communication from Walter F. McMichael, National Environmental Research Center, Cincinnati, Ohio, September 1972.

[10] Private communication from George Noges, Smith and Loveless Corporation, February 1973.

[11] Unpublished data from H. Mueler, Neptune Microfloc Incorporated, February and March 1973.

[12] Private communication from J. S. Neulight, Met-Pro Corp., February 1973.

[13] Monthly Technical Report, Economic Evaluation of Total Energy, Decision Sciences Corp., March and April 1973.

[14] Private communication from Berry Godbeer, Siemag Corp., May 1973.

[15] Private communication from Bart Tuffly, Rocketdyne Division of Rockwell International, 1973.

The separate components of the operating and maintenance cost (labor, power, chemical, fuel, and miscellaneous cost) are presented in figures 21 to 31. Although the figures contain line costs for each of the elements defined, it must be clearly understood that these are averaged numbers and could be represented by wide bands instead. These bands range normally from 0.3 to 3.00 of the average for the upper limit ratios, respectively (ref. 261). Finally, all costs are defined as of January 1972.

CONCLUSIONS

The following conclusions appear to be justified on the basis of research required for preparing this document.

1. Wastewater flows and composition can be defined to a degree of accuracy that is useful in the detailed design sizing of an MIUS wastewater-treatment system.

2. All basic techniques of wastewater collection and of gravity, pressure, and vacuum sewers appear to be applicable to the MIUS.

3. Most processes used in conventional wastewater-treatment systems are applicable to the MIUS. However, because of the constraints of sizing and of proximity to densely populated areas in an MIUS application, some processes have significant advantages and should receive first consideration. Use of this technique reduces the number of processes from which an MIUS design is chosen.

4. New processes developed for separate treatment systems that cannot be categorized with standard processes offer the possibility of improved treatment and reduced cost. However, these processes must be tested and evaluated further before they are considered for use in an MIUS.

5. Judicious application of treatment processes, integration of the wastewater-treatment system with the other utilities, and sharing of the operational personnel among the various utilities should make the cost of MIUS onsite treatment of wastewater competitive with that of interceptor service to a regional plant and will provide cooling and irrigation water for the MIUS facility.

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National Aeronautics and Space Administration
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TABLE I.- WATER USE BY FUNCTION

[From ref. 15]

Function	Volume, m³/day (gal/day)	Percent of total
Lavatory	0.045 (12)	7
Toilet	.265 (70)	39
Kitchen	.030 (8)	4
Cleaning	.015 (4)	2
Shower	.212 (56)	31
Laundry	.114 (30)	17

TABLE II.- HOUSEHOLD WATER USES

[From ref. 8]

Type of use	Quantity of water used, percent
Toilet flushing	45
Bathing	30
Kitchen	6
Drinking	5
Laundry	4
Cleaning	3
Sprinkling	3
Carwashing	1
Miscellaneous	3

TABLE III.- ESTIMATED POTABLE WATER USE

[From ref. 8]

Use	Per capita quantity used, m^3/day (gal/day)
Drinking, cooking	0.004 to 0.008 (1 to 2)
Dishwashing	.004 to .015 (1 to 4)
Garbage disposal unit	0 to .015 (0 to 4)
Laundering, cleaning	.011 to .026 (3 to 7)
Bathing	.038 to .095 (10 to 25)
Total	.057 to .159 (15 to 42)

TABLE IV.- ESTIMATED DISTRIBUTION OF SEWAGE

[From ref. 20]

Waste	Per capita volume of waste, m^3/day (gal/day), for total per capita flow, m^3 (gal), of -				
	0.114 (30)	0.151 (40)	0.189 (50)	0.284 (75)	0.379 (100)
Kitchen	0 (0)	0.026 (7)	0.038 (10)	0.038 (10)	0.057 (15)
Toilet	0.057 (15)	.057 (15)	.076 (20)	.095 (25)	.114 (30)
Showers, washbasins	.057 (15)	.068 (18)	.076 (20)	.095 (25)	.132 (35)
Laundry	0 (0)	0 (0)	0 (0)	.057 (15)	.076 (20)

TABLE V.- WATER USE FOR A FAMILY OF FOUR

[From ref. 9]

Use	Volume, m^3/day (gal/day)	
	Family	Per capita
Drinking and cooking	0.030 (8)	0.008 (2.0)
Dishwashing	.057 (15)	.014 (3.75)
Toilet flushing	.363 (96)	.091 (24.0)
Bathing	.303 (80)	.076 (20.0)
Laundering	.129 (34)	.032 (8.5)
Carwashing	.038 (10)	.009 (2.5)
Lawn watering	.379 (100)	.095 (25.0)
Garbage disposal operation	.011 (3)	.003 (.75)
Total	1.310 (346)	.328 (86.5)
All uses except toilet and lawn watering	.568 (150)	.142 (37.5)

TABLE VI.- HOUSE AND PER CAPITA FLOW

Function	Quantity, m^3 (gal)	
Laundry	0.132	(35)
Kitchen	.061 + .011P[1]	(16 + 3P)
Bath	.004 + .087P	(1 + 23P)
Toilet	.091P	(24P)

[1] P = the number of people per household.

TABLE VII.- WASTEWATER LOADINGS

Characteristics	Av loading, mg/liter	Av per capita loading, kg/day (lbm/day)	Max. percent of av	Min. percent of av
Biological oxygen demand (BOD)	222	0.0476 (0.105)	134	74
Chemical oxygen demand (COD)	393	.0885 (.195)	156	66
Total solids	[1]958	.2091 (.461)	114	88
Total suspended solids (TSS)	184	.0404 (.089)	160	59
Total dissolved solids (TDS)	675	.1483 (.327)	116	80
Kjeldahl nitrogen	30	.0073 (.016)	113	87
Ammonia nitrogen	12	.0027 (.006)	101	77
Total phosphate	51	113 (.025)	117	82

[1] As a composite of test data, the sum of TDS and TSS does not equal the value for total solids.

TABLE VIII.- PREPARATORY TREATMENT PROCESSES OR OPERATIONS

Process or equipment	Function
Racks and screens	Interception of coarse or floating solids
Grit chambers	Removal of grit, sand, and gravel
Skimmers	Removal of grease, oil, soap, cork, etc.
Comminutors	Grinding of solids
Equalization storage	Improvement of hydraulic and contaminant distribution
Preaeration	Replenishment of oxygen
Raw wastewater pumping	Provision of water pressure through treatment sequence

TABLE IX.- PRIMARY TREATMENT PROCESSES OR OPERATIONS

Process	Function
Sedimentation	Remove suspended solids by quiescent settling
Flotation	Remove suspended solids by gas bubble attachment
Chemical addition	Enhance settling and flotation
Straining	Remove suspended solids by fine screen straining

TABLE X.- DETENTION TIMES FOR VARIOUS SURFACE-LOADING RATES AND TANK DEPTHS

[From ref. 1]

Surface-loading rate, $m^3/day/m^2$ ($gal/day/ft^2$)	Detention time, hr, for tank depth, m (ft), of -			
	2.1 (7)	2.4 (8)	3.0 (10)	3.6 (12)
16 (400)	3.2	3.6	4.5	5.4
24 (600)	2.1	2.4	3.0	3.6
33 (800)	1.6	1.8	2.25	2.7
41 (1000)	1.25	1.4	1.8	2.2

TABLE XI.- ACTIVATED-SLUDGE PROCESSES

Process	Removal efficiency, percent	Approximate detention time, hr
Conventional	85 to 95	4 to 8
Tapered aeration	85 to 95	4 to 8
Complete mix	85 to 95	3 to 5
Step aeration	85 to 95	3 to 5
Contact stabilization[1]	80 to 90	.5 to 1 2 to 4
Extended aeration	75 to 95	18 to 36
Oxygen aeration	85 to 95	1 to 3
Modified aeration	75 to 90	1.5 to 3
Two-stage aeration		
First stage	80 to 90	.7 to 3
Second stage	92 to 95	.7 to 3

---

[1] Two stages.

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TABLE XII.- TRICKLING FILTER DESIGN OPTIONS

Medium	Height, m (ft)	Filtration rate	Number of filters	Clarifier	Recirculation
Rock (various types)[1]	1.8 to 12.2 (6 to 40)	Low	1	Single	None
Plastics (various types, various shapes)	--	High	2 (in series)	Dual	Before clarifier
Wood	--	Super high	--	--	After clarifier

[1] Slag, metal, clay brick, and coal are options.

TABLE XIII.- TERTIARY TREATMENT PROCESSES

Process	Removal[1]
Physical	
Filtration	S-O
Flotation	S-O
Land application	S-O-N-P
Air stripping	N
Sorption	N-P
Chemical	
Chemical clarification	S-O-P
Carbon adsorption	S-O
Electrochemical	S-O-P
Oxidation	O-N
Specific ion exchange	N-P
Biological	
Algae	N-P
Activated sludge	N-P
Nitrification	N
Denitrification	N

[1] S refers to suspended-solids removal; O refers to organic removal, particularly organic carbon; N refers to nitrogen removal in ammonia or nitrate/nitrite; and P refers to phosphorus removal.

TABLE XIV.- SLUDGE-HANDLING OPERATIONS AND PROCESSES

Operation	Process
Sludge concentration	Gravity thickening Dissolved-air flotation Vibration
Digestion	Aerobic Anaerobic Sludge lagoons Imhoff tanks
Conditioning	Freezing Chemical addition Heat treatment Elutriation
Dewatering	Vacuum filtration Centrifugation Pressure filtration Vibration Rotating drum gravity filtration
Drying	Drying beds Heat drying
Thermal disposal	Incineration Recalcining Wet oxidation
Ultimate disposal	Composting Fertilizing/soil conditioning Lagooning Landfill disposal Ocean disposal Land use

TABLE XV.- REMOVAL EFFICIENCY OF VARIOUS PROCESSES

Process	Removal efficiency, percent, of -							
	BOD	COD	Coliform	Ammonia nitrogen	Nitrate nitrogen	Phosphorus	TSS	TDS
Primary								
Sedimentation	35	30	35	20	--	10	60	--
Chemical addition	65	60	60	--	--	70	80	--
Straining	30	25	30	15	--	10	50	--
Secondary								
Rotating biological disk	90	85	95	90	--	20	90	--
Tertiary								
Filtration	40	30	95+	--	--	25	65	--
Chemical clarification	85	60	80+	15	--	90	60	15
Carbon adsorption	70	60	--	20	--	25	70	--
Oxidation	80	70	99+	--	--	--	--	--
Specific ion exchange	--	--	--	90	90	90	--	90
Nitrification	--	--	--	90	--	--	--	--
Denitrification	--	--	--	--	85	--	--	--
Disinfection								
Chlorine	--	--	99+	--	--	--	--	--
Ozone	--	--	99+	--	--	--	--	--
Heat	--	--	99+	--	--	--	--	--

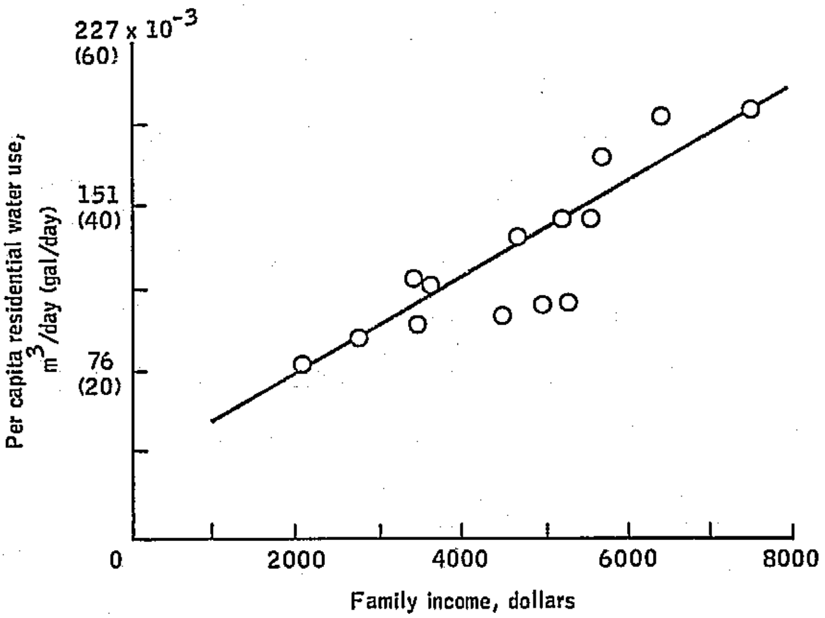

Figure 1.- Per capita residential water use as a function of family income (ref. 14).

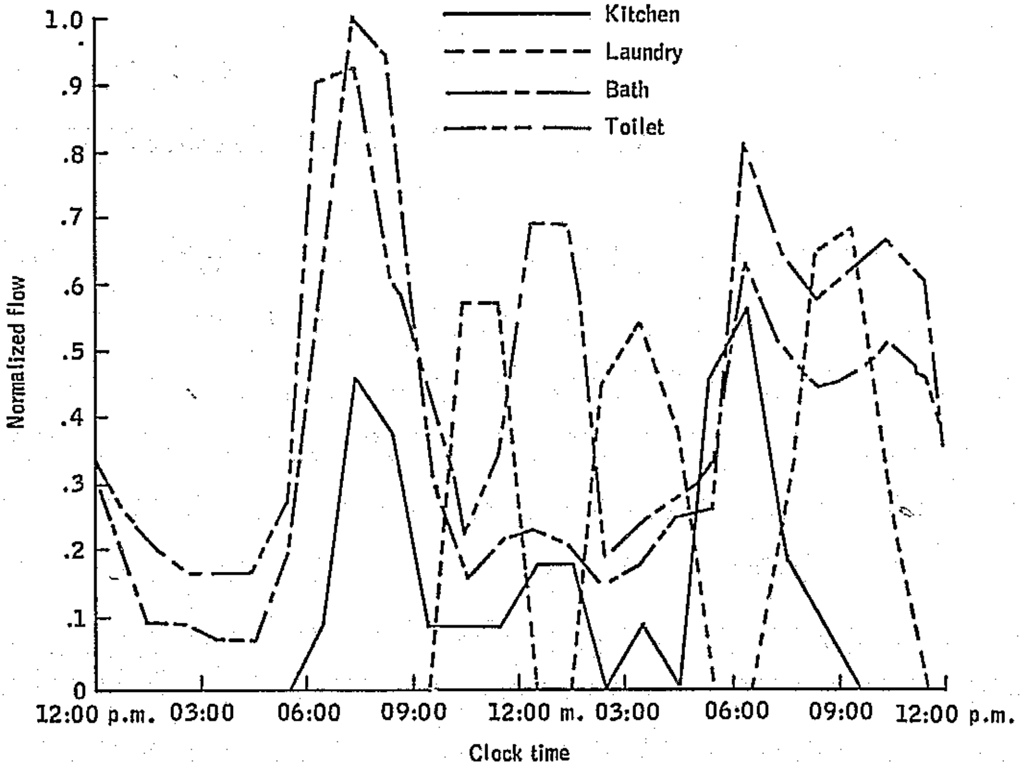

Figure 2.- Functional water use during an average day.

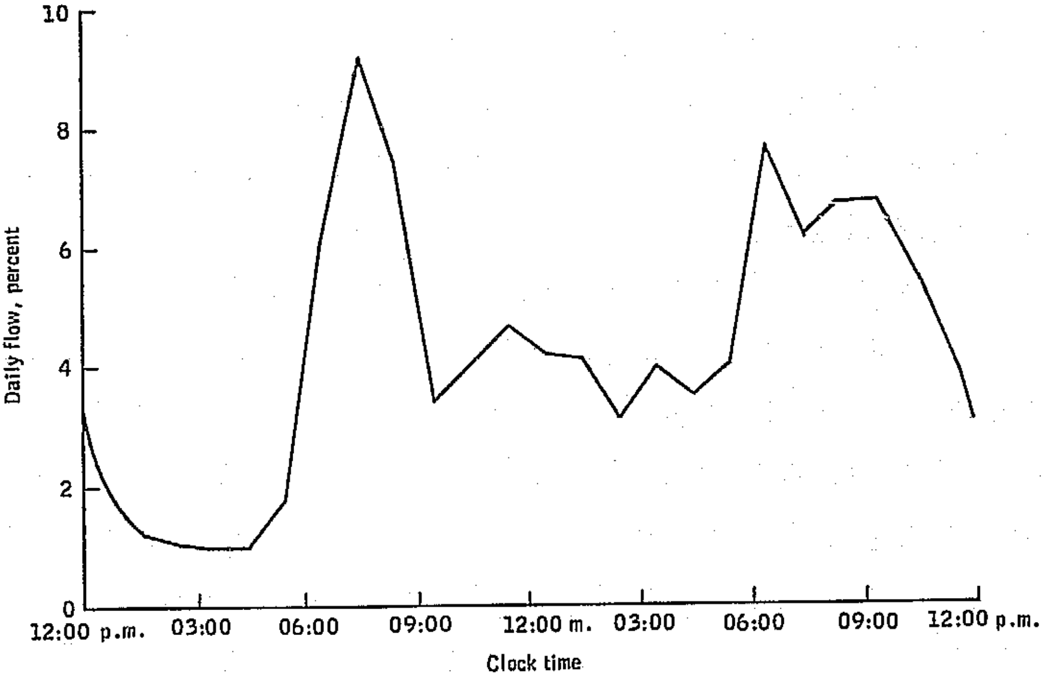

Figure 3.- Composite hourly hydrograph (baseline).

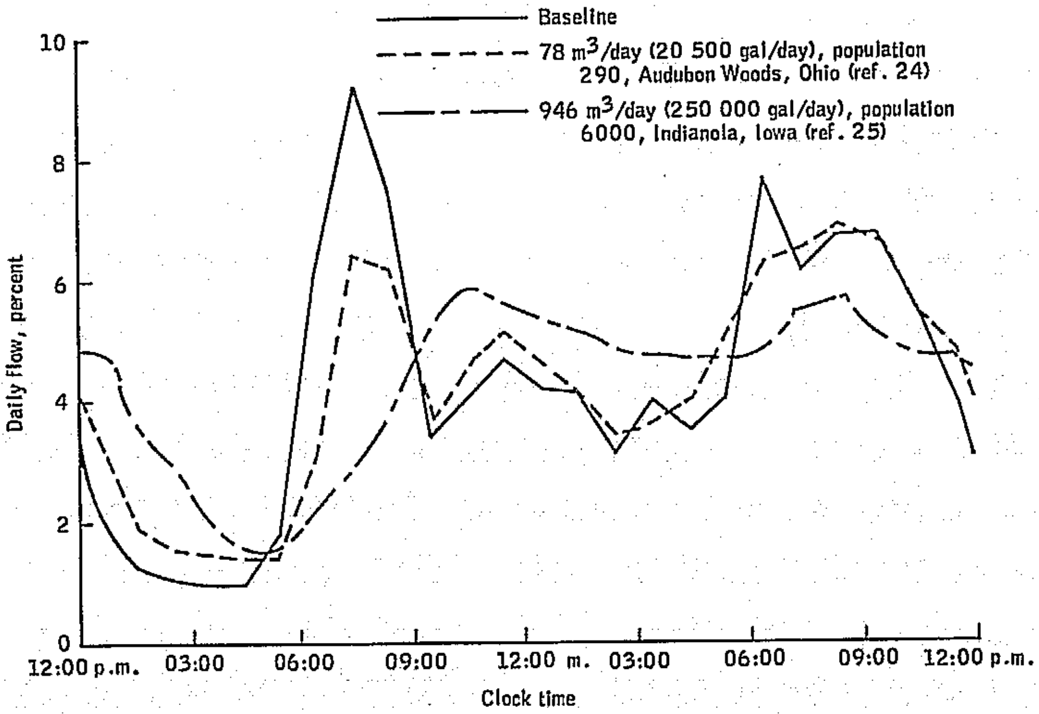

Figure 4.- Comparison of the water demand for two populations to the baseline.

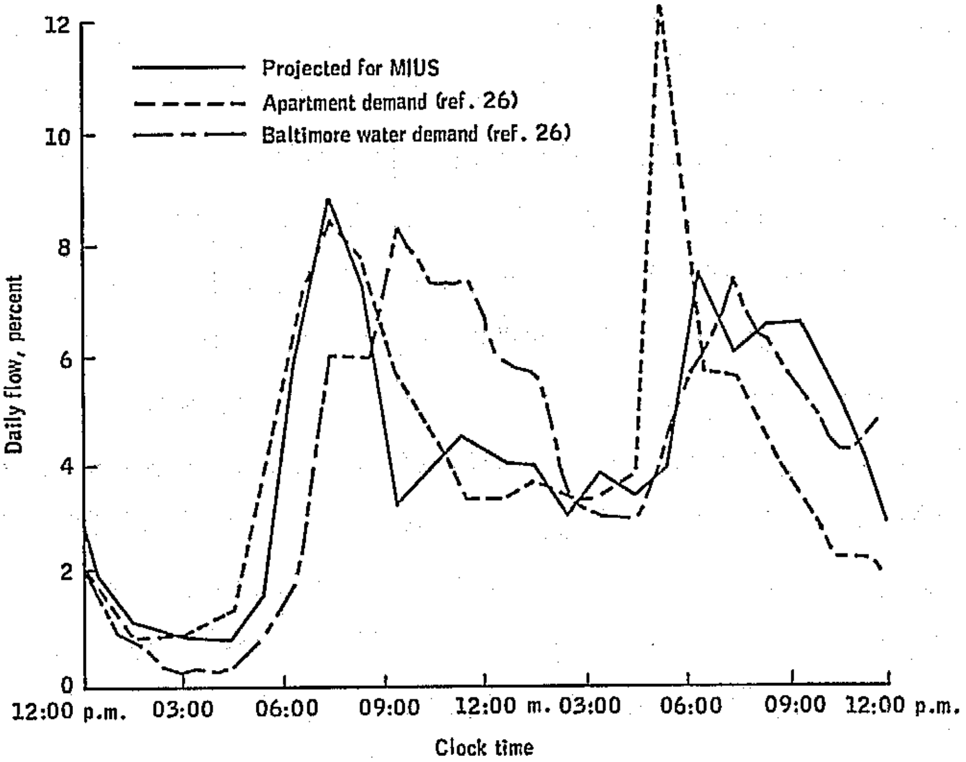

Figure 5.- Comparison of the projected water demand of an MIUS to actual water demand.

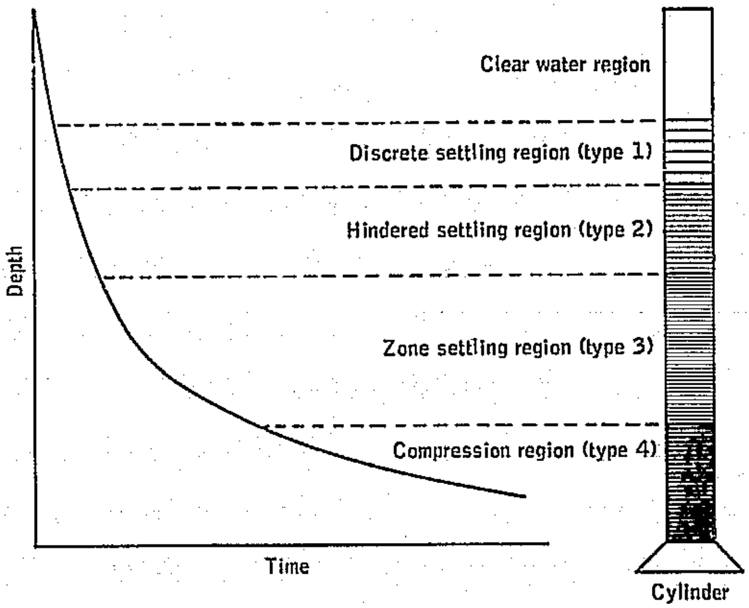

Figure 6.- Schematic diagram of flocculent settling regions (ref. 1).

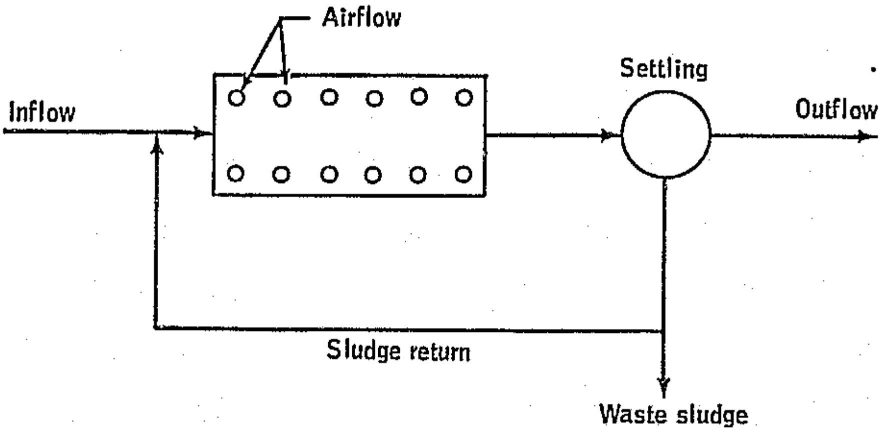

Figure 7.- Conventional, modified, and extended aeration schematic.

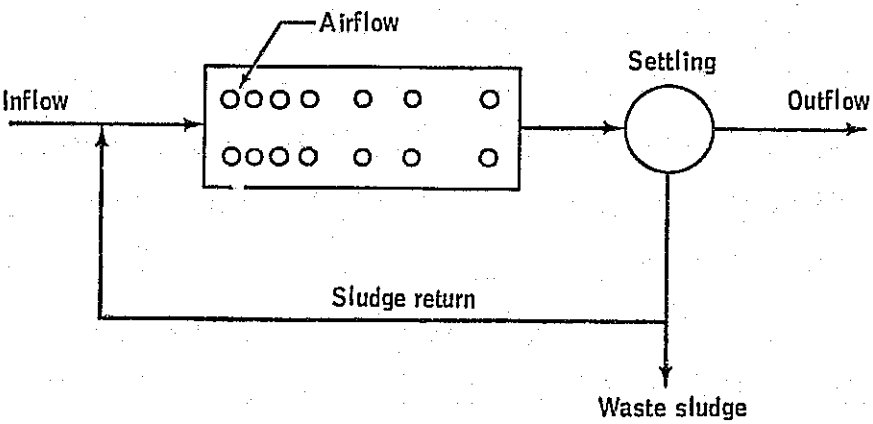

Figure 8.- Tapered aeration schematic.

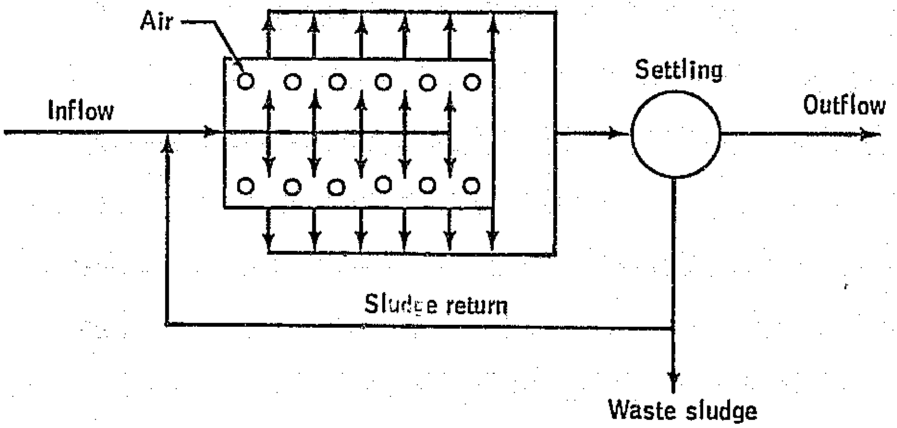

Figure 9.- Complete mix aeration schematic.

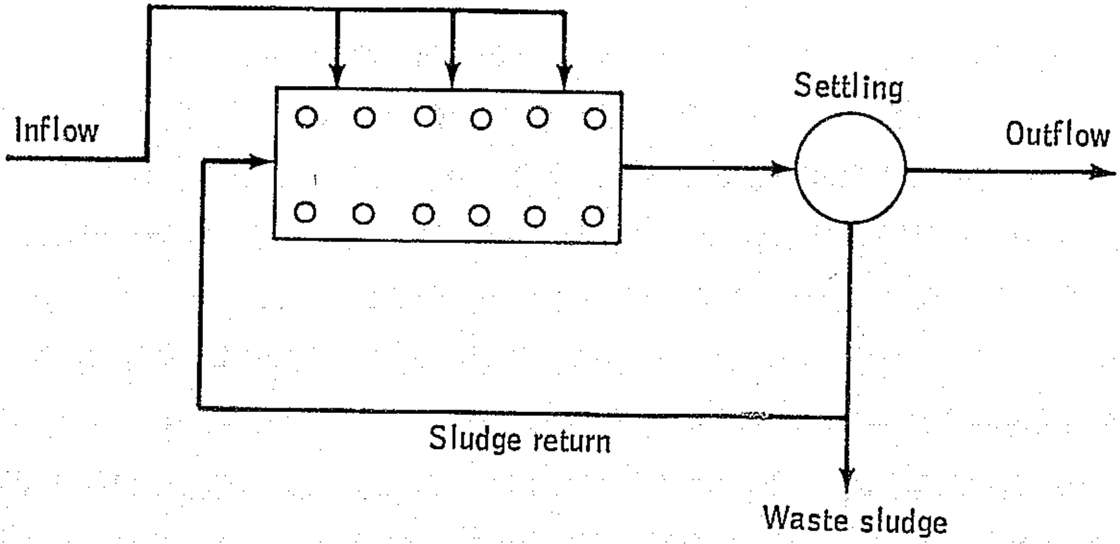

Figure 10.- Step aeration schematic.

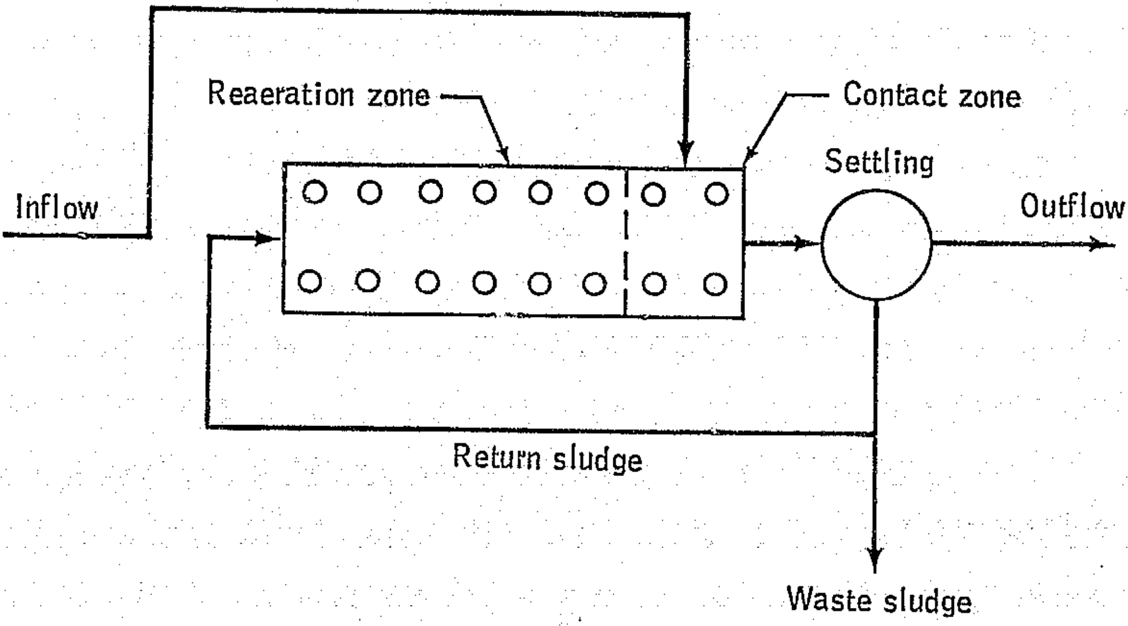

Figure 11.- Contact stabilization schematic.

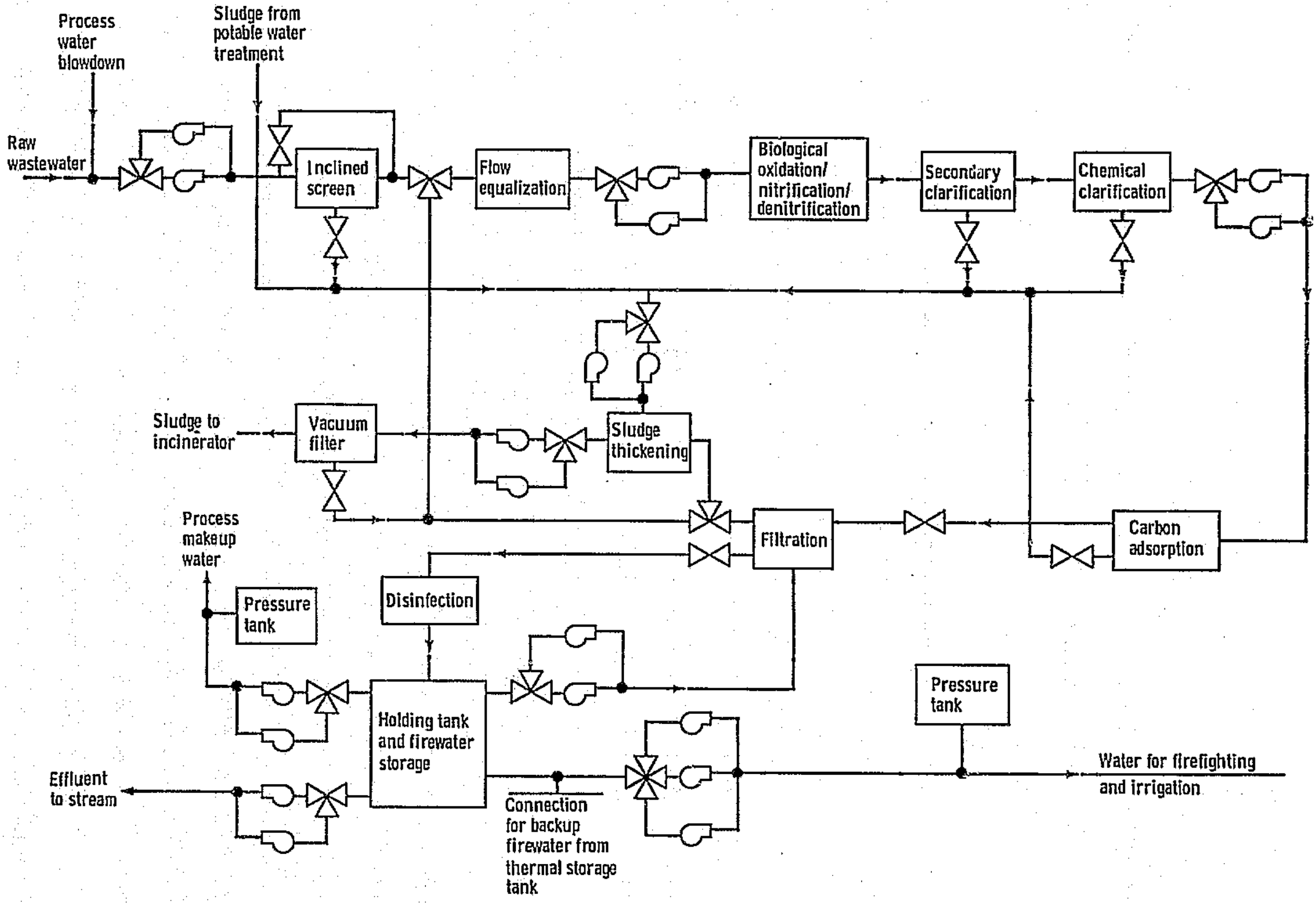

Figure 12.- System schematic of a potential combination of processes for an MIUS wastewater system.

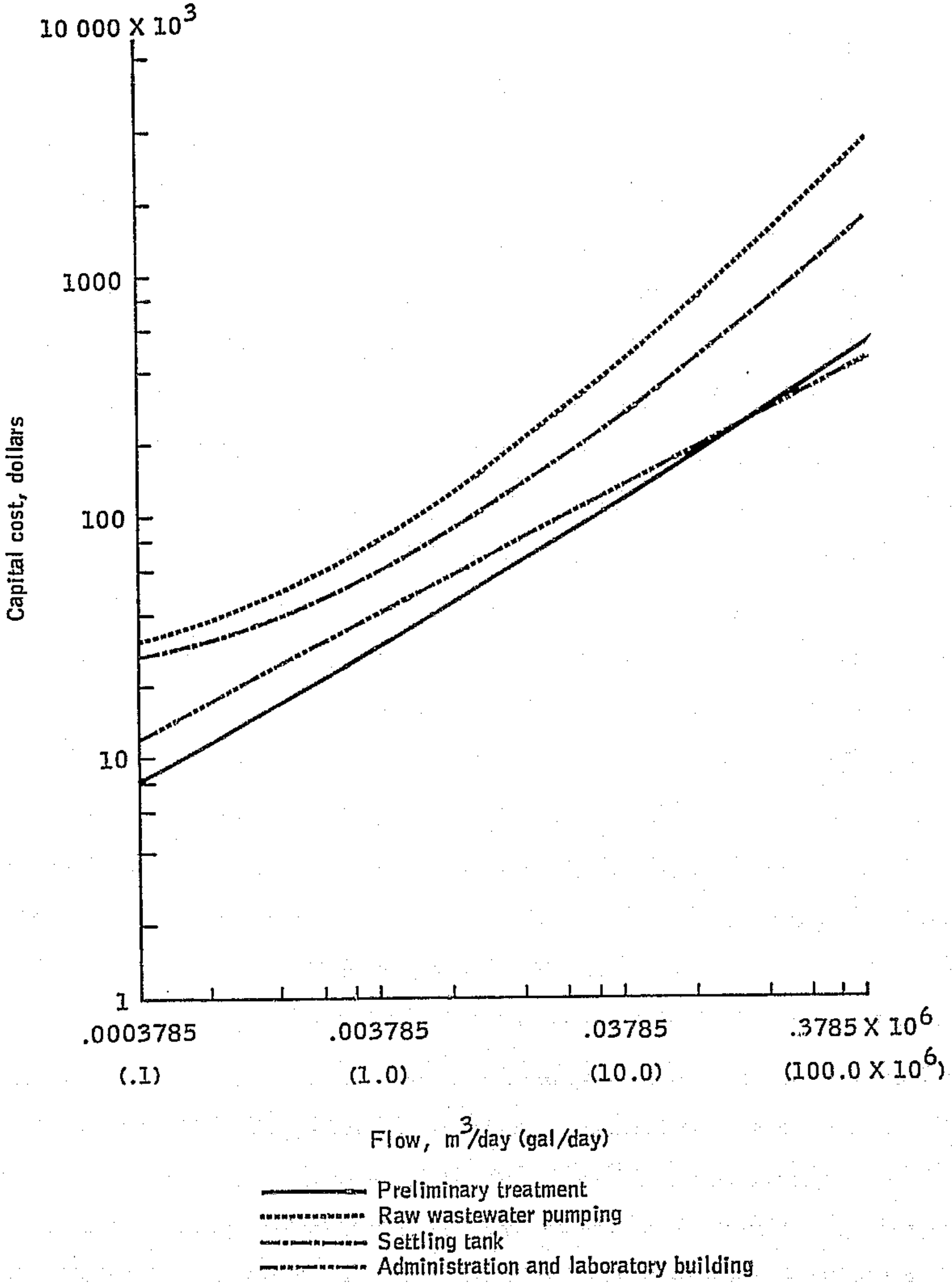

Figure 13.- The relationship between basic capital cost components and daily flow during preliminary treatment.

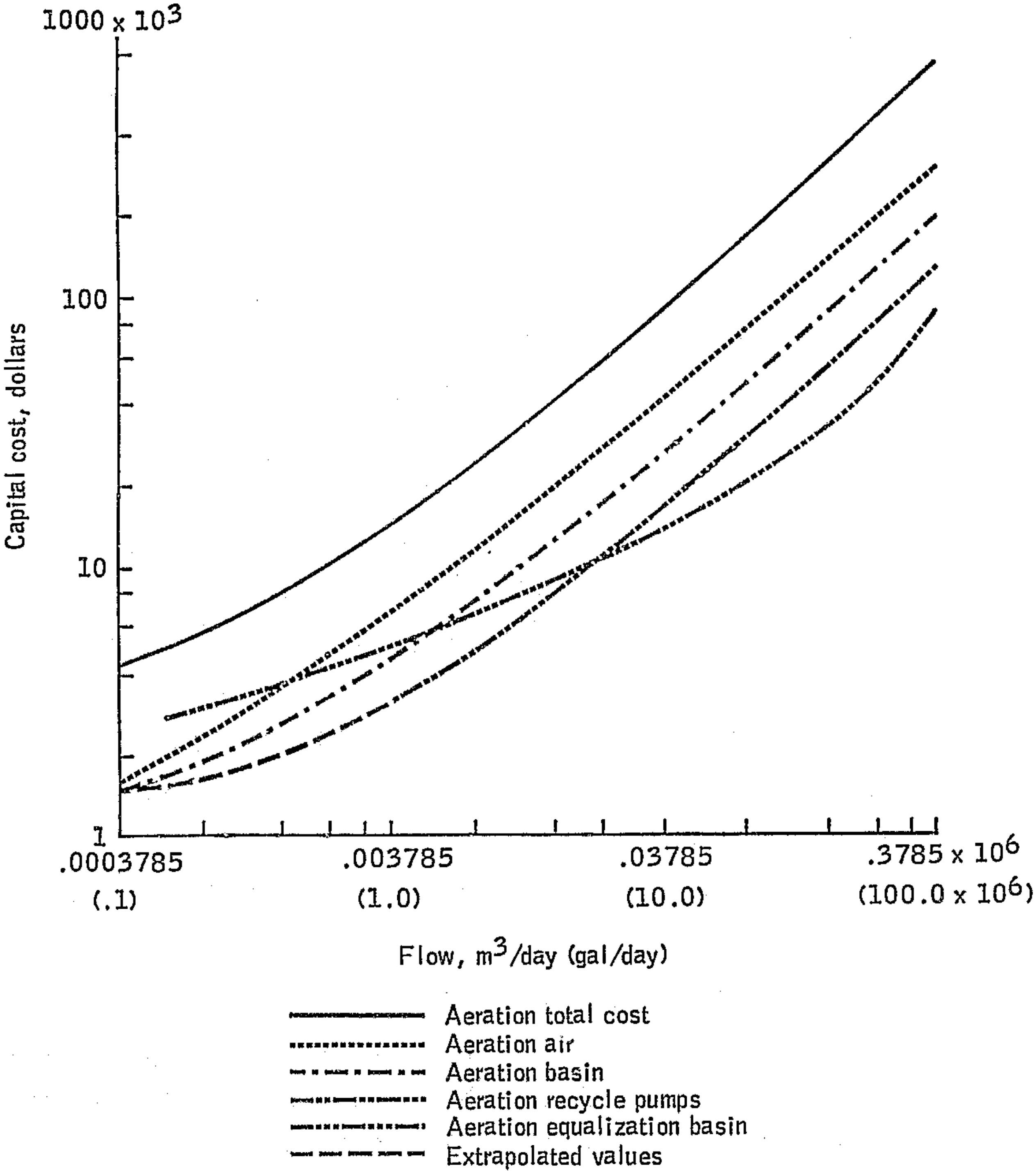

Figure 14.- Estimated cost for single-stage aeration process. (For two-stage, BOD, and nitrification, the values should be doubled.)

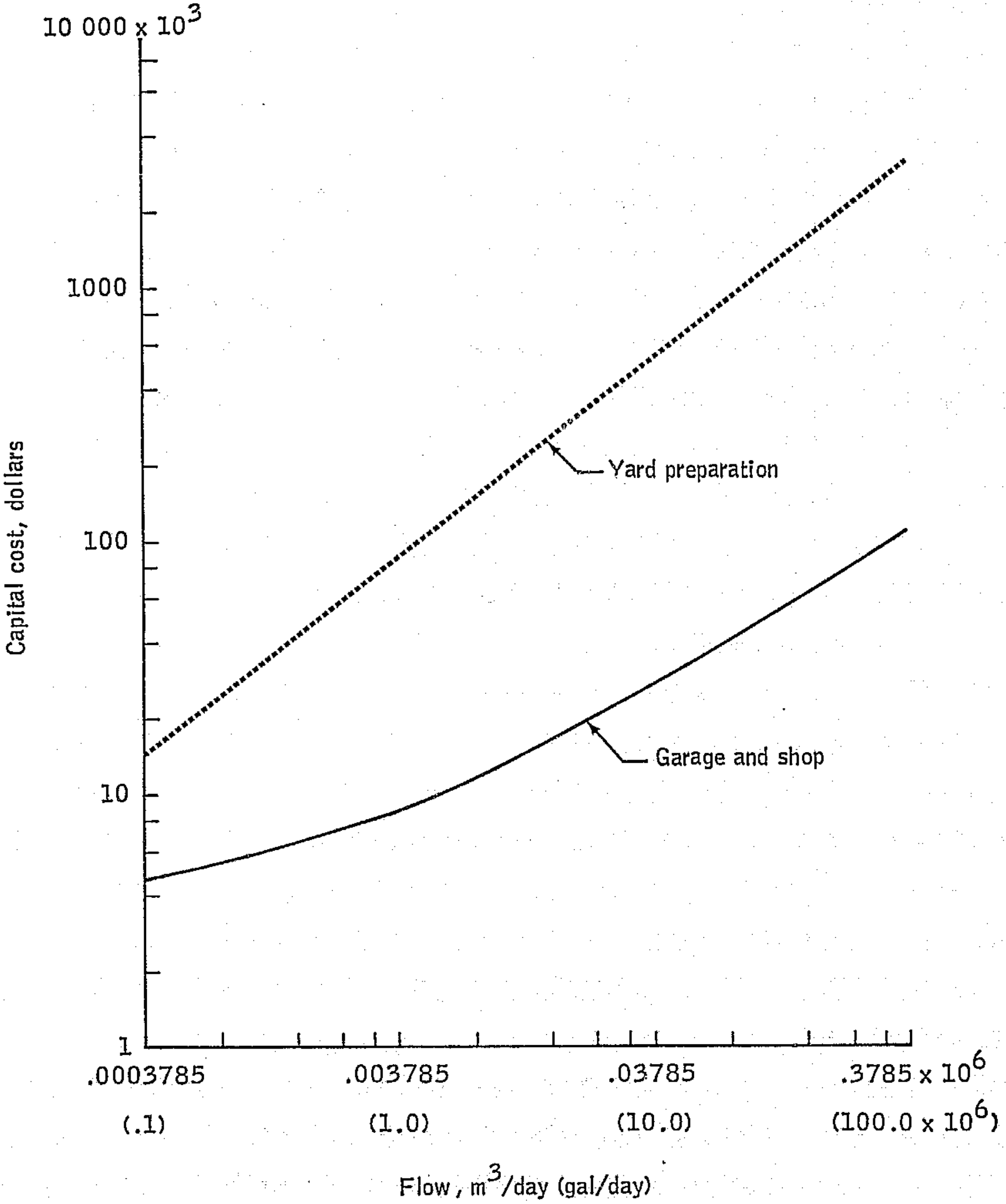

Figure 15.- Estimated costs for yard preparation and garage facilities.

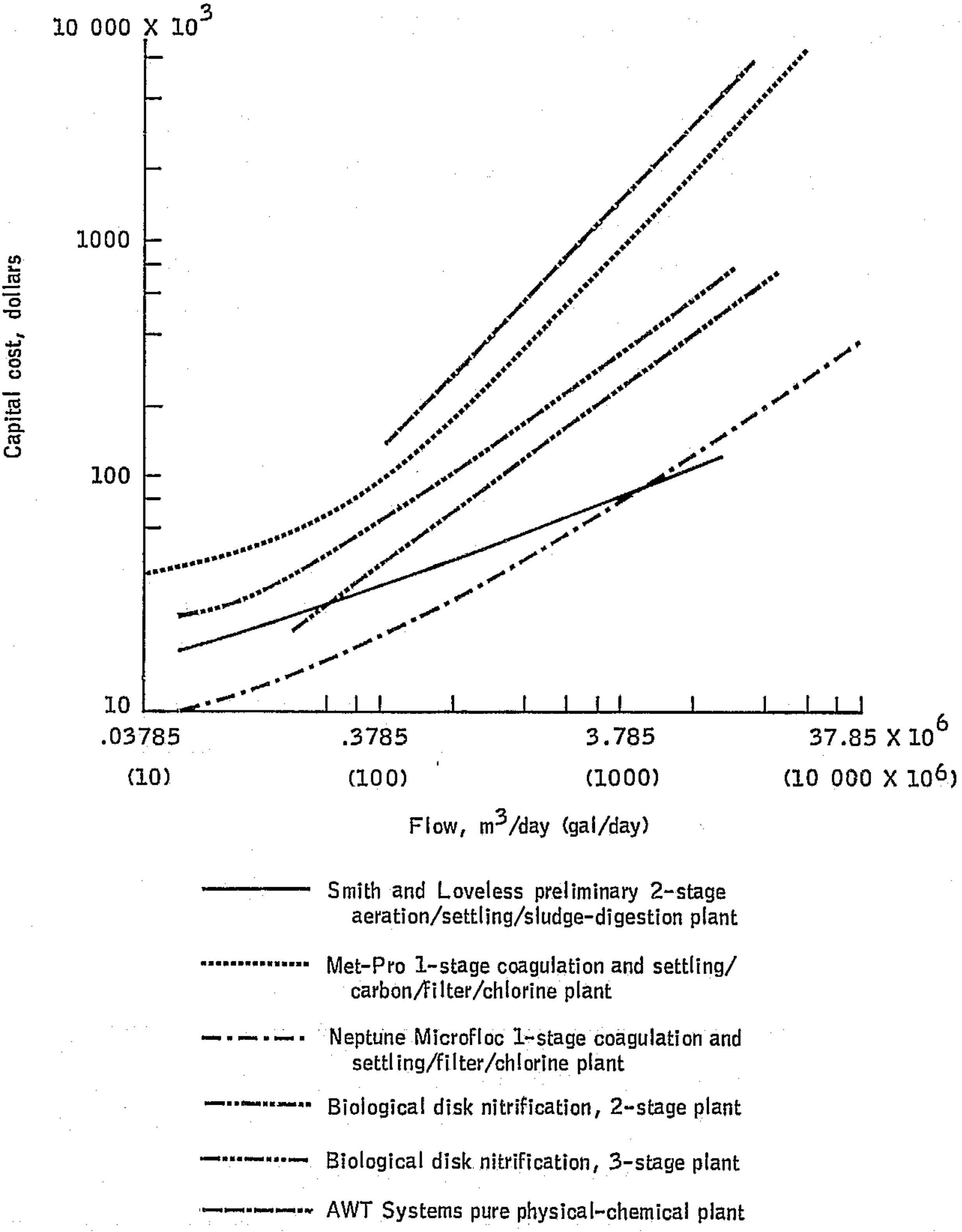

Figure 16.- Estimated costs of package plants.

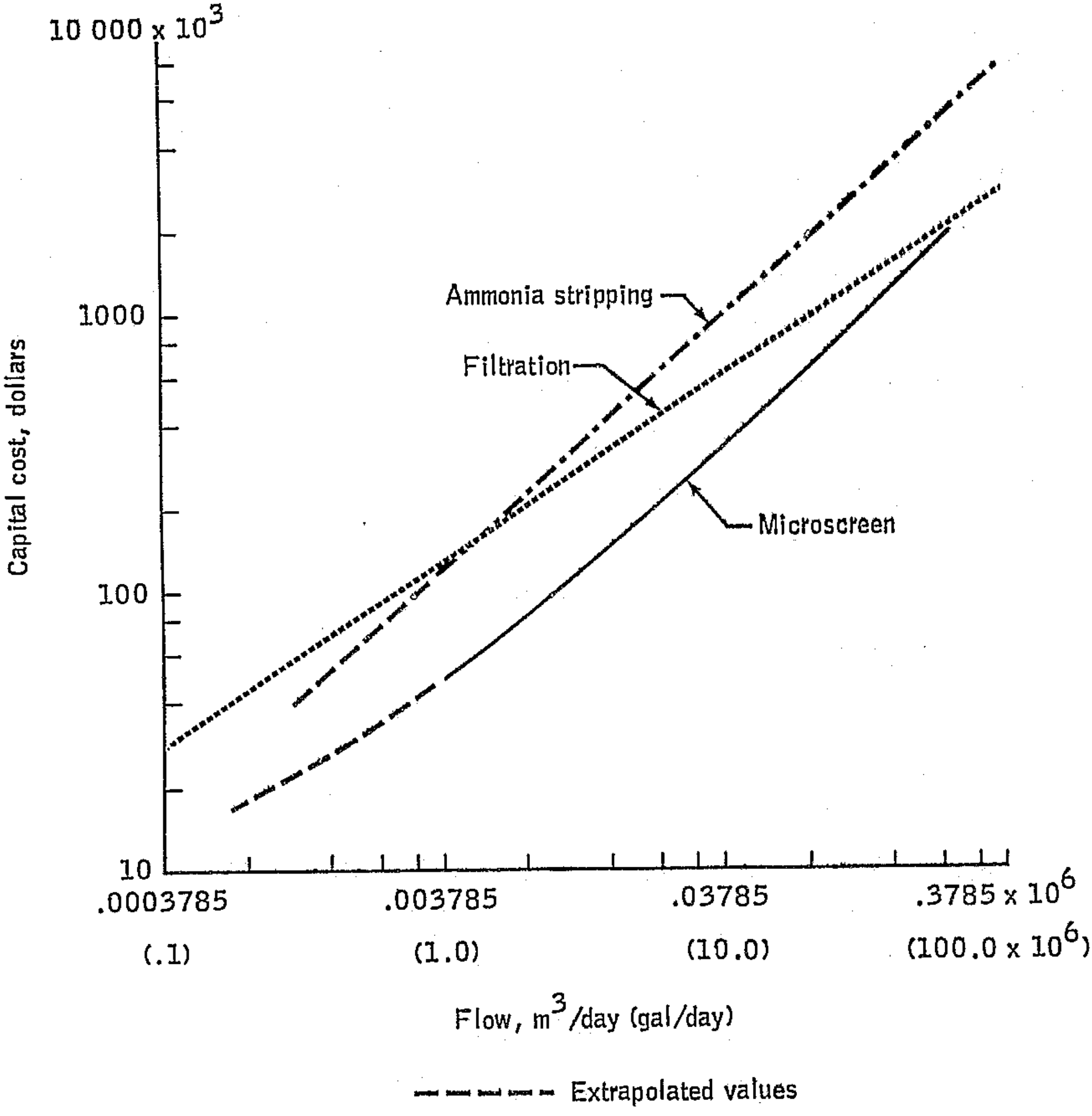

Figure 17.- Estimated costs of physical-chemical processes.

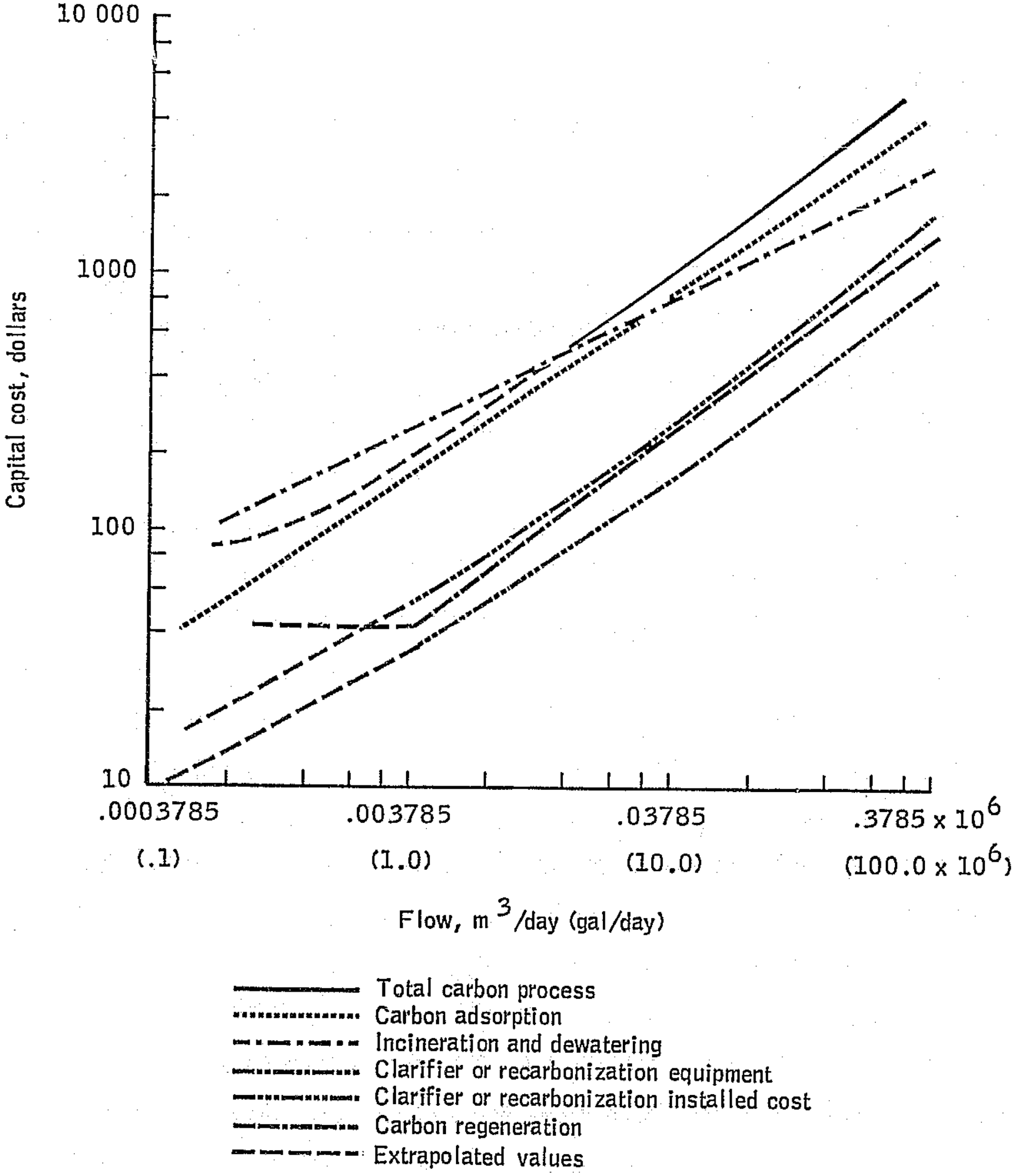

Figure 18.- Estimated costs of physical-chemical processes using carbon.

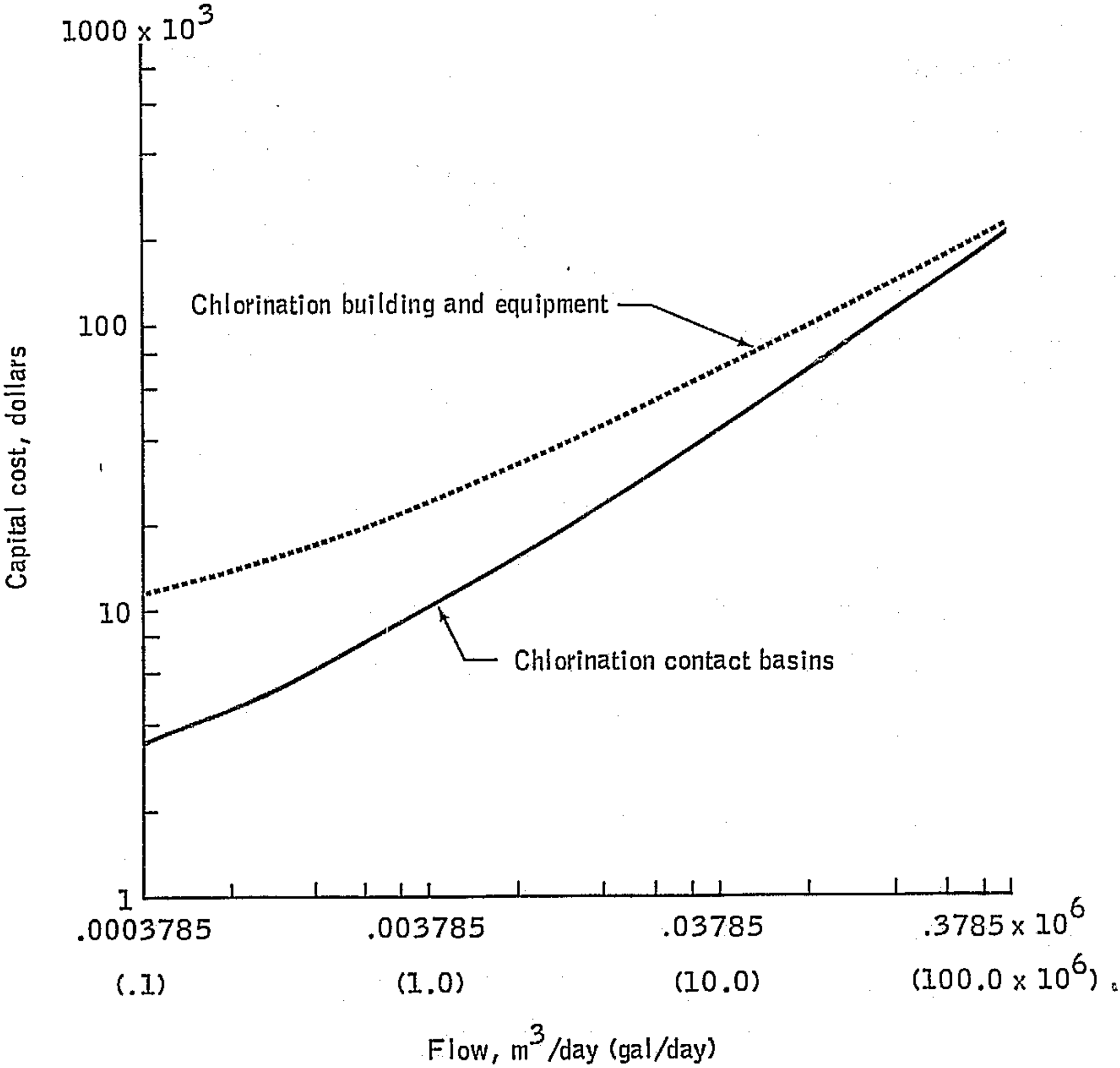

Figure 19.- Estimated costs of chlorination processes.

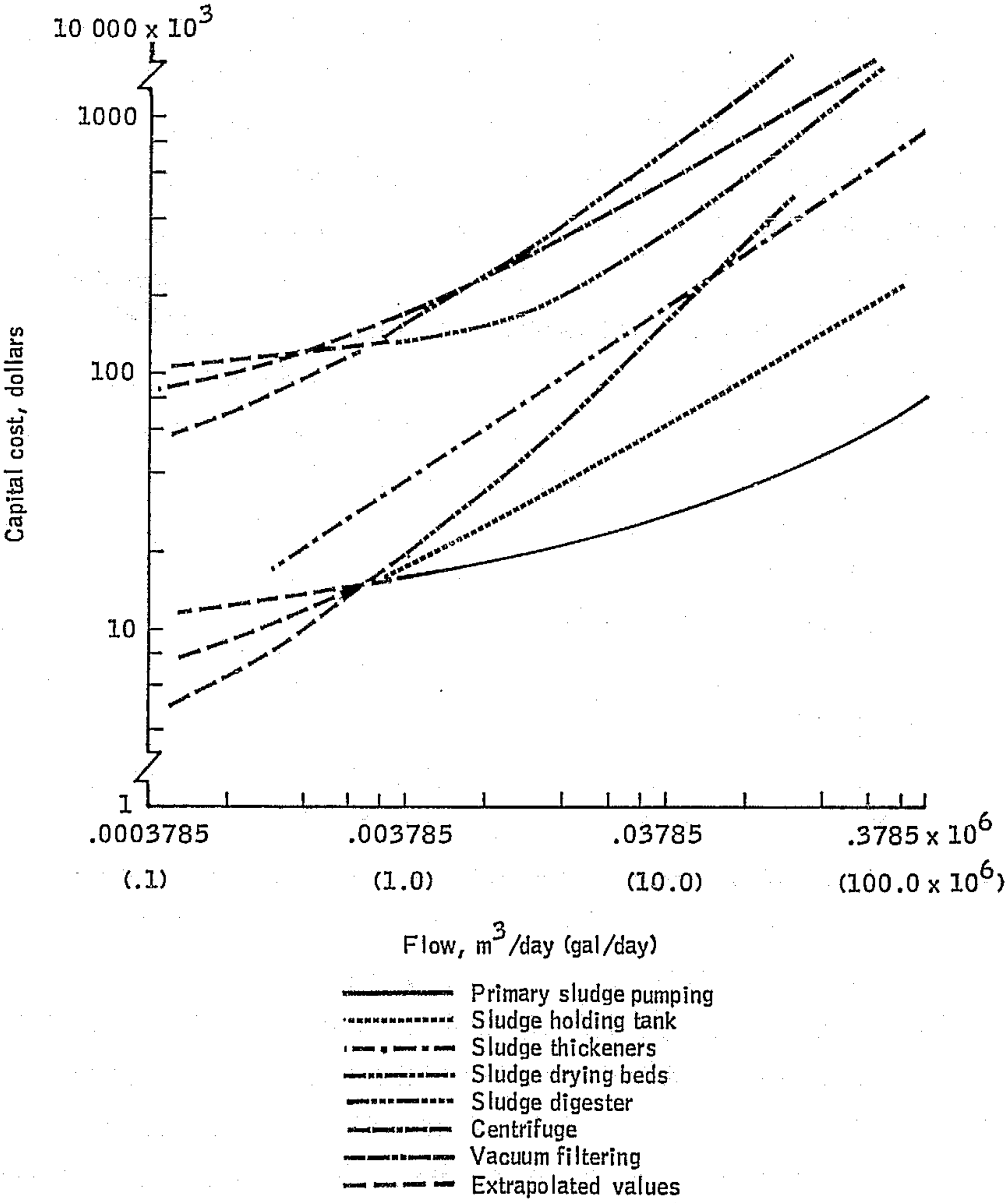

Figure 20.- Estimated costs of sludge-handling processes.

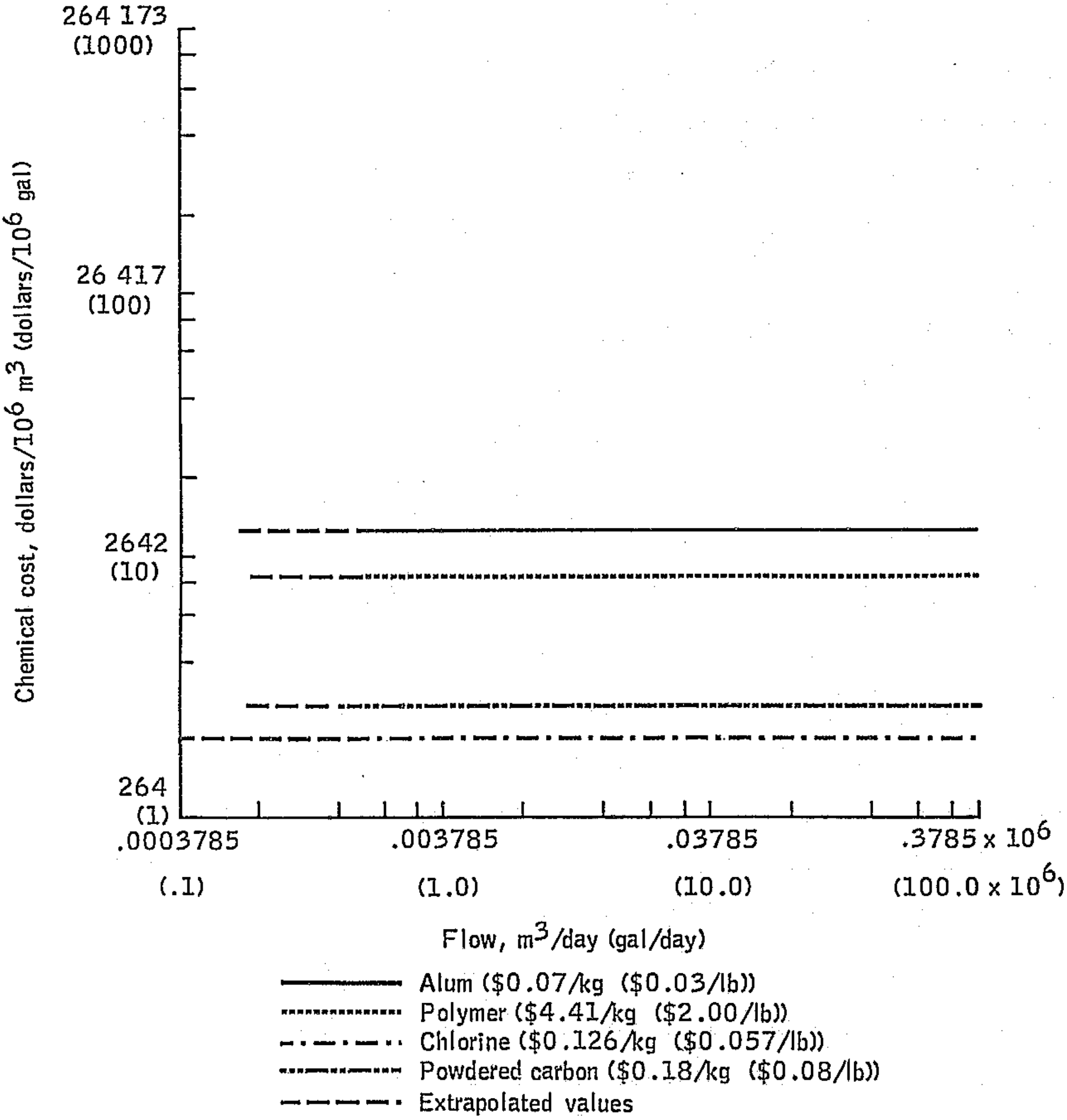

Figure 21.- Chemical component costs of potable water.

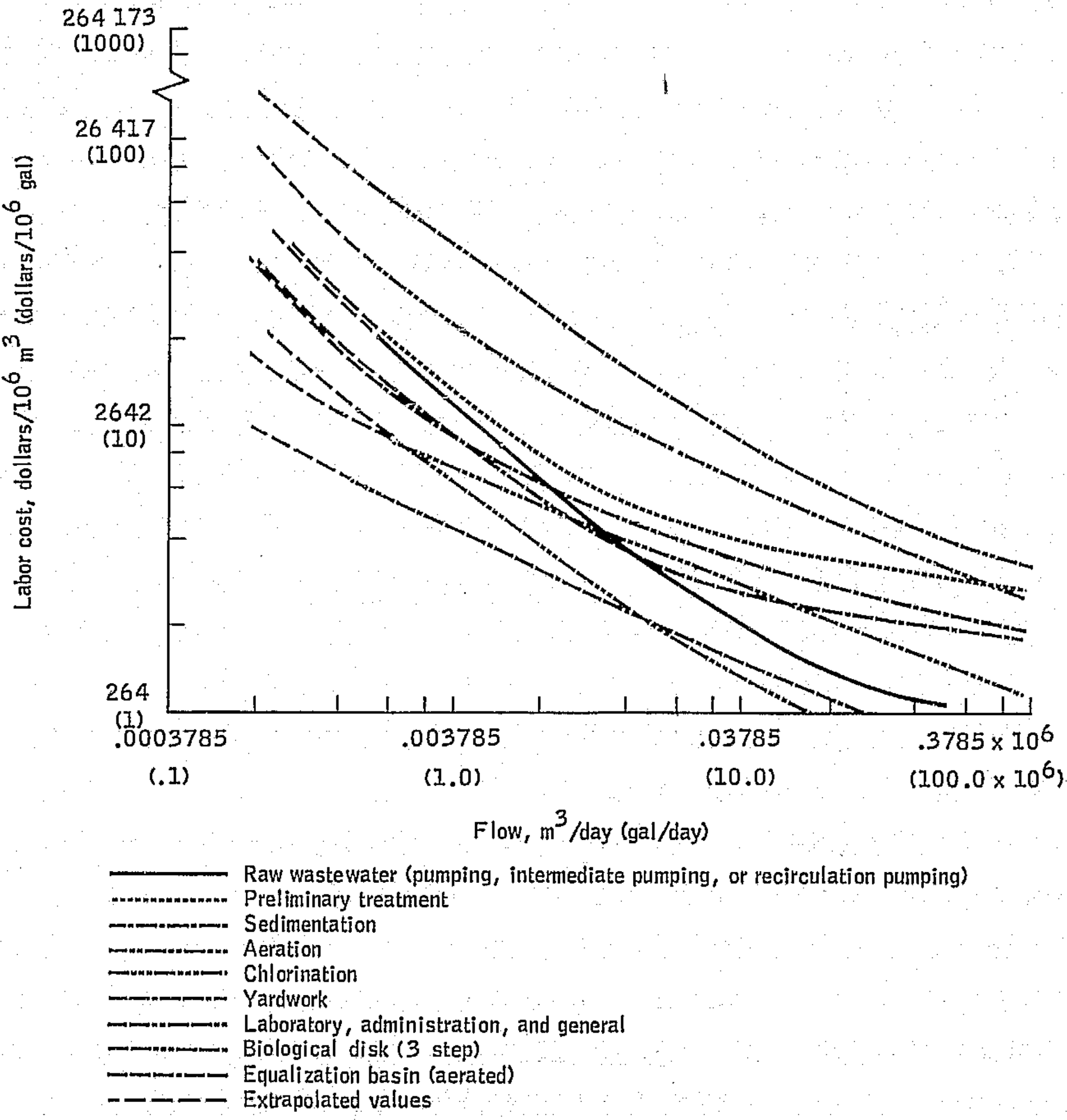

Figure 22.- Biological and basic component labor costs of potable water.

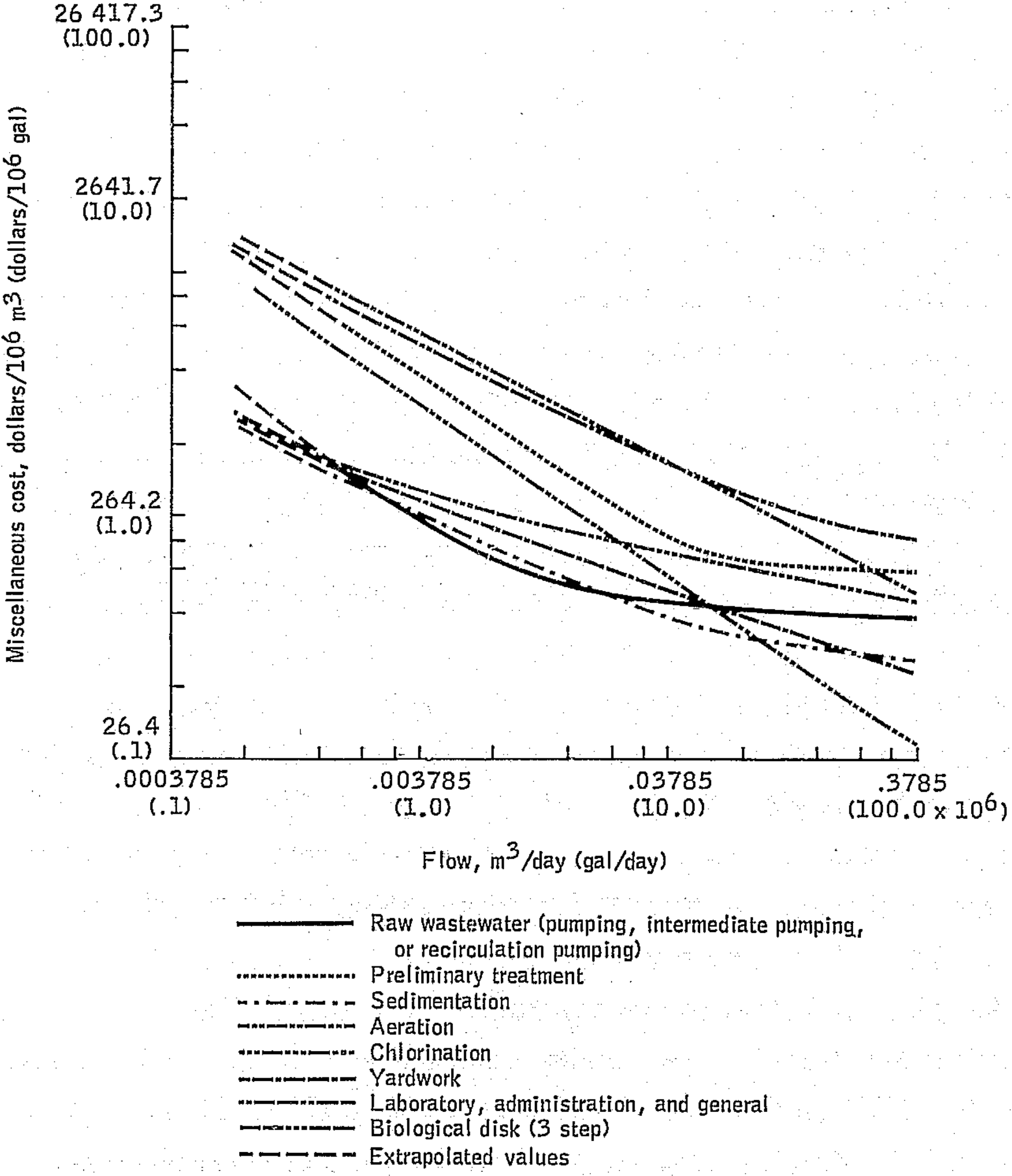

Figure 23.- Biological and basic miscellaneous component costs of potable water.

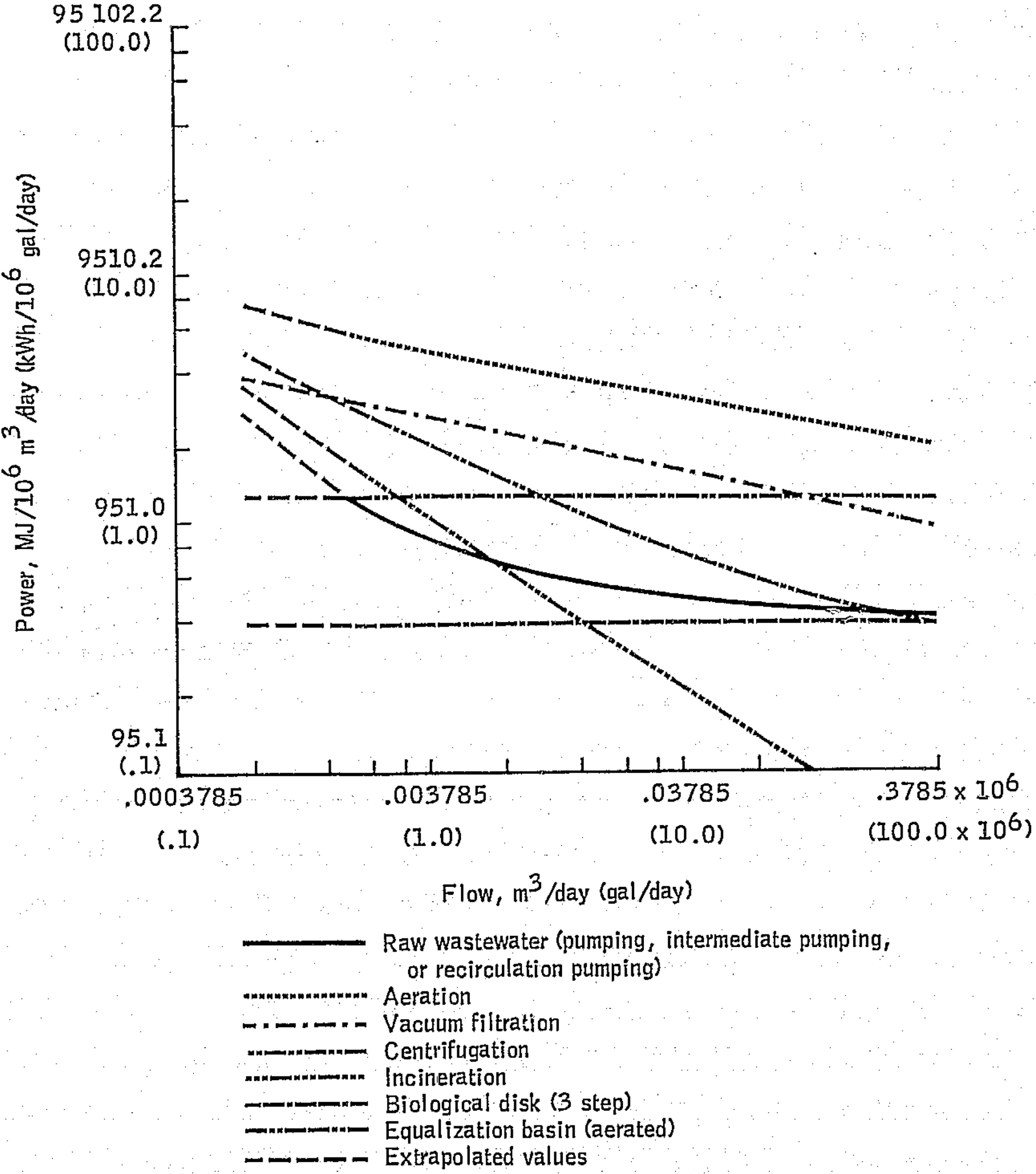

Figure 24.- Biological component power requirements.

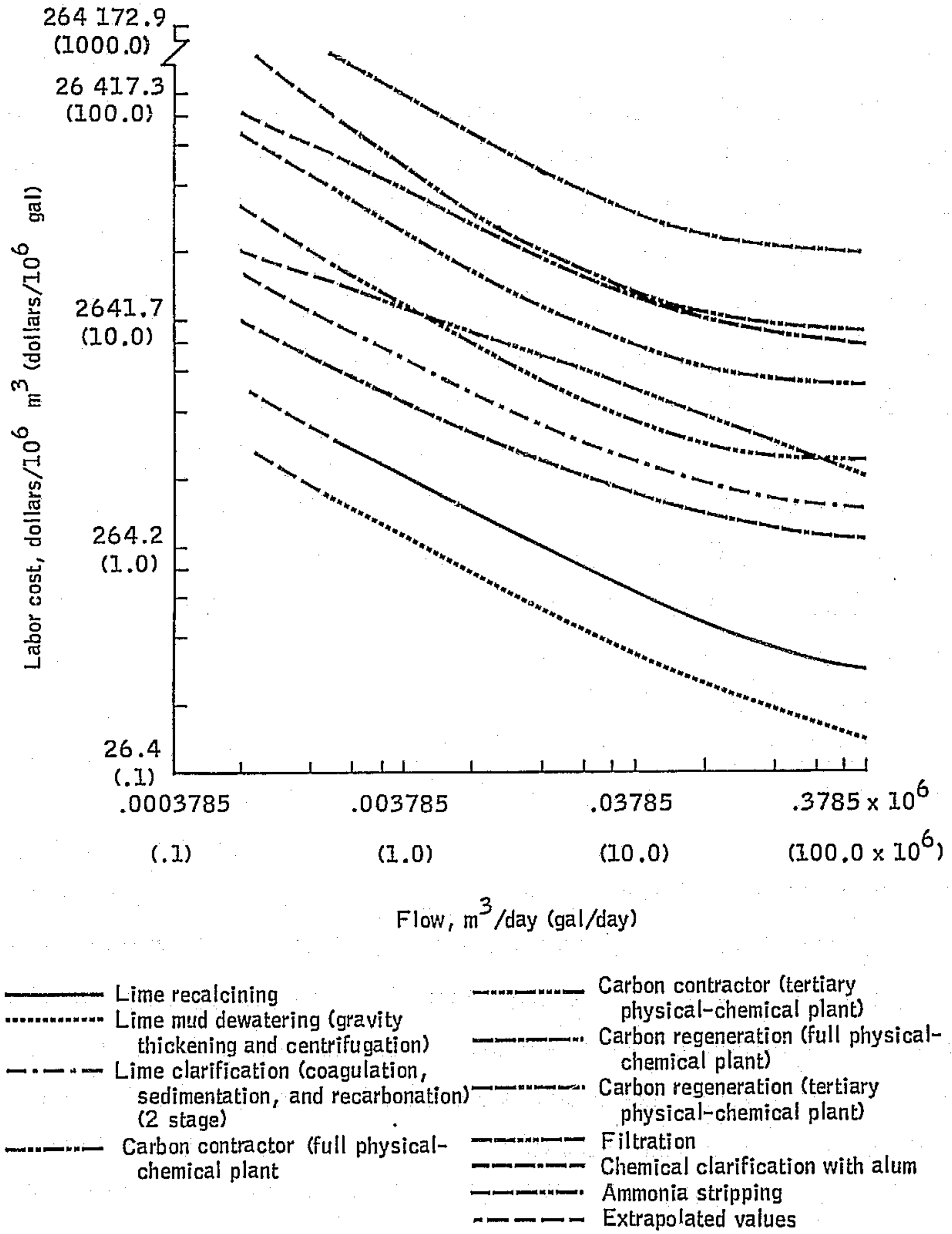

Figure 25.- Component labor costs for physical-chemical processes.

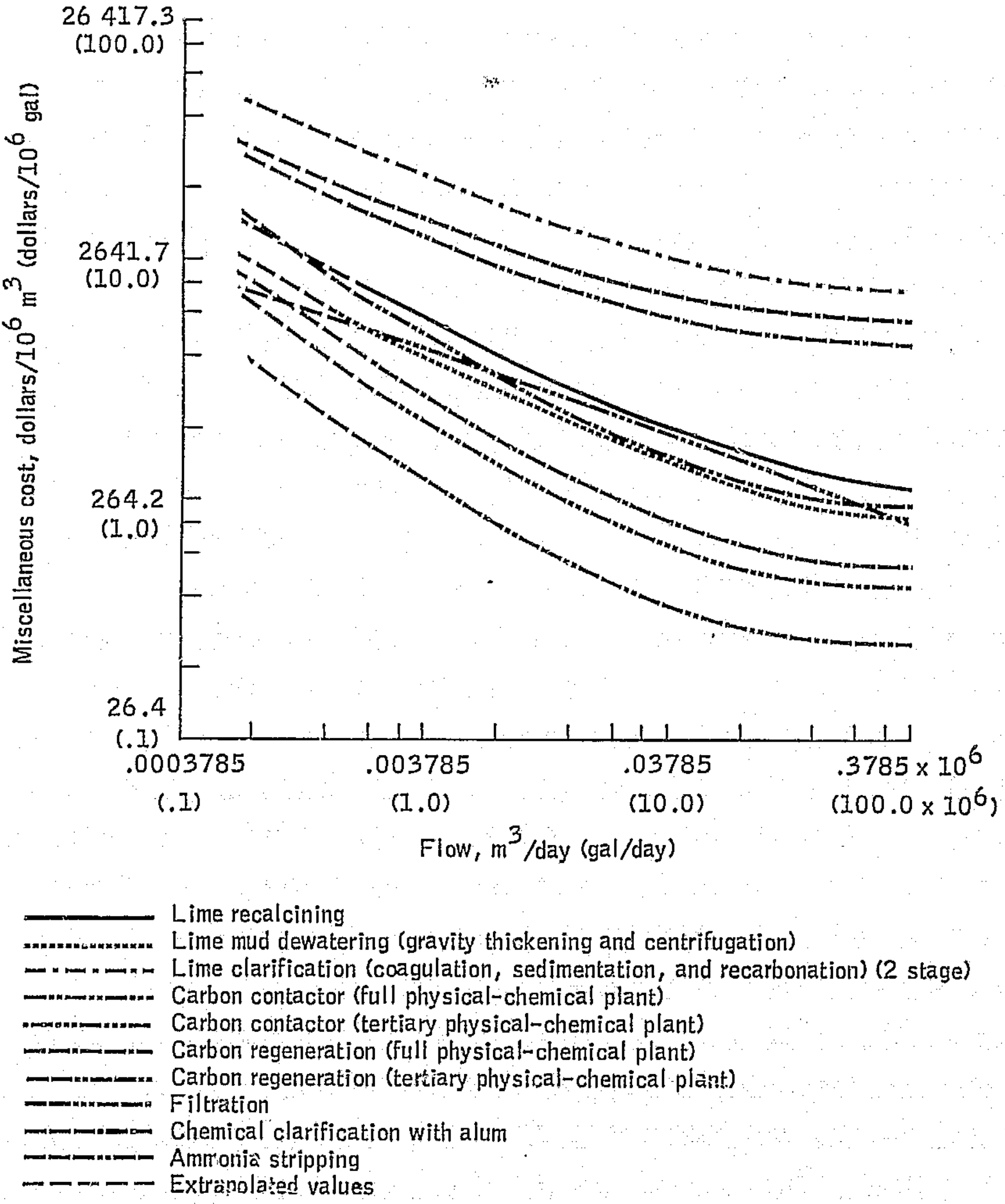

Figure 26.- Miscellaneous component costs for physical-chemical processes.

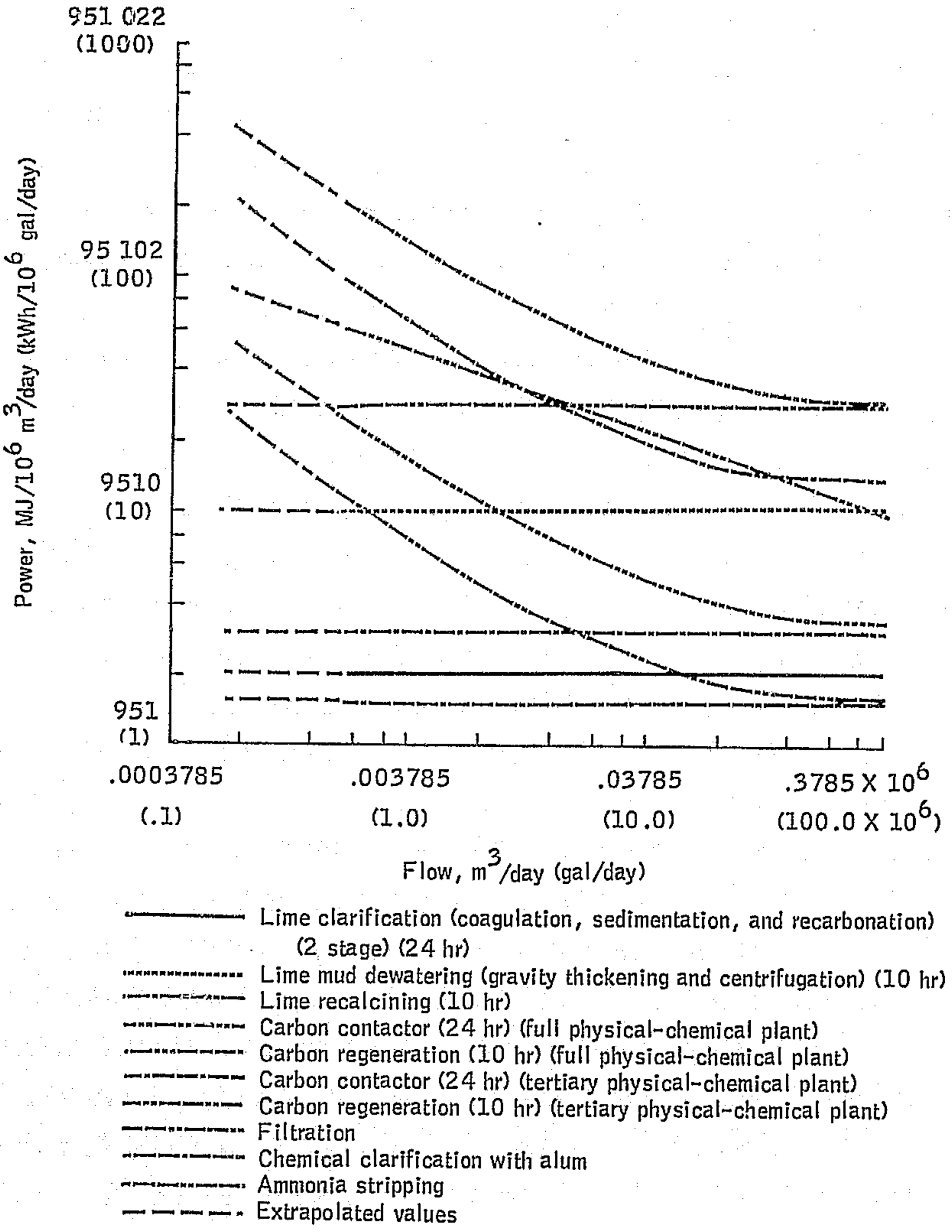

Figure 27.- Component power requirements for physical-chemical processing plants.

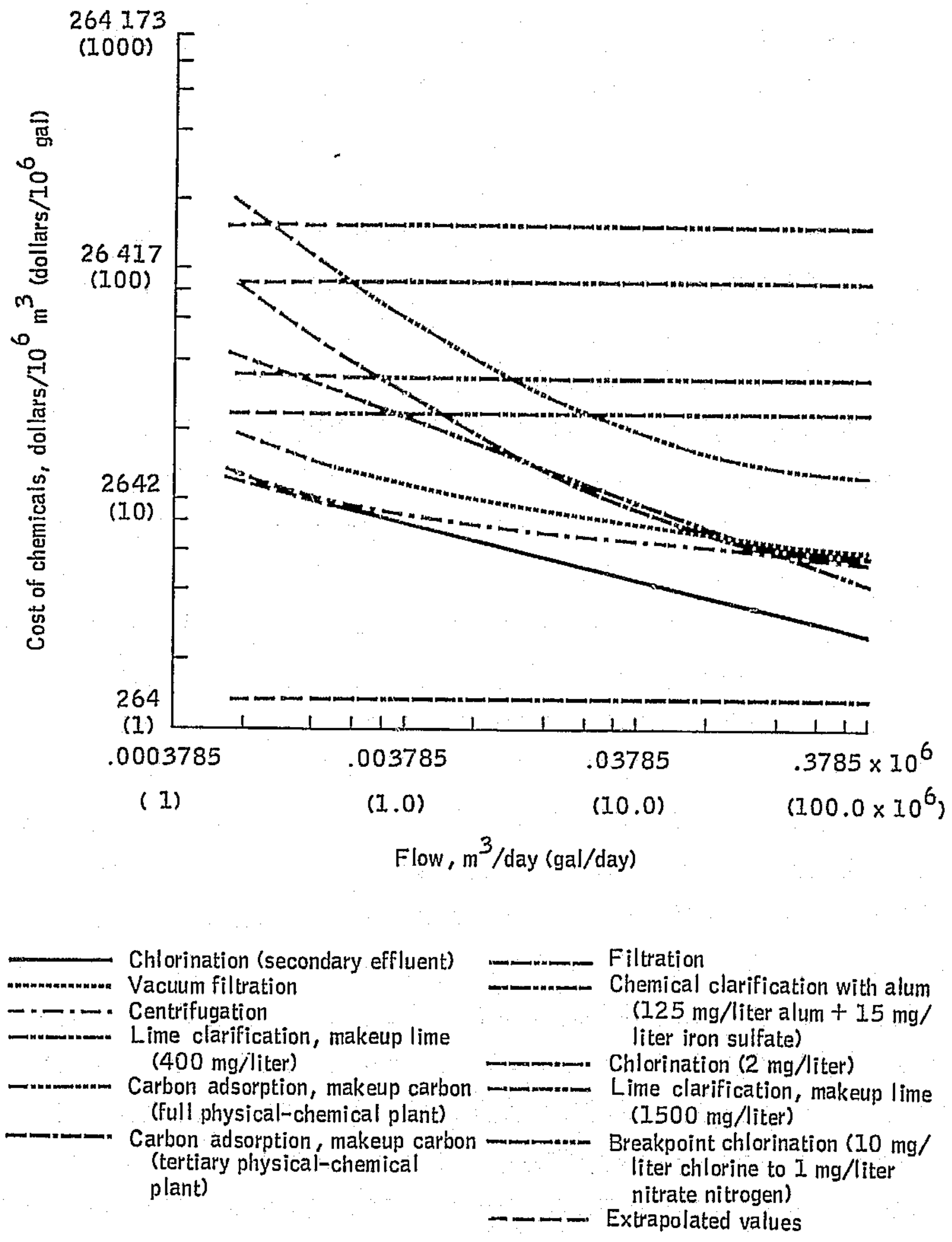

Figure 28.- Chemical component costs for physical-chemical processes.

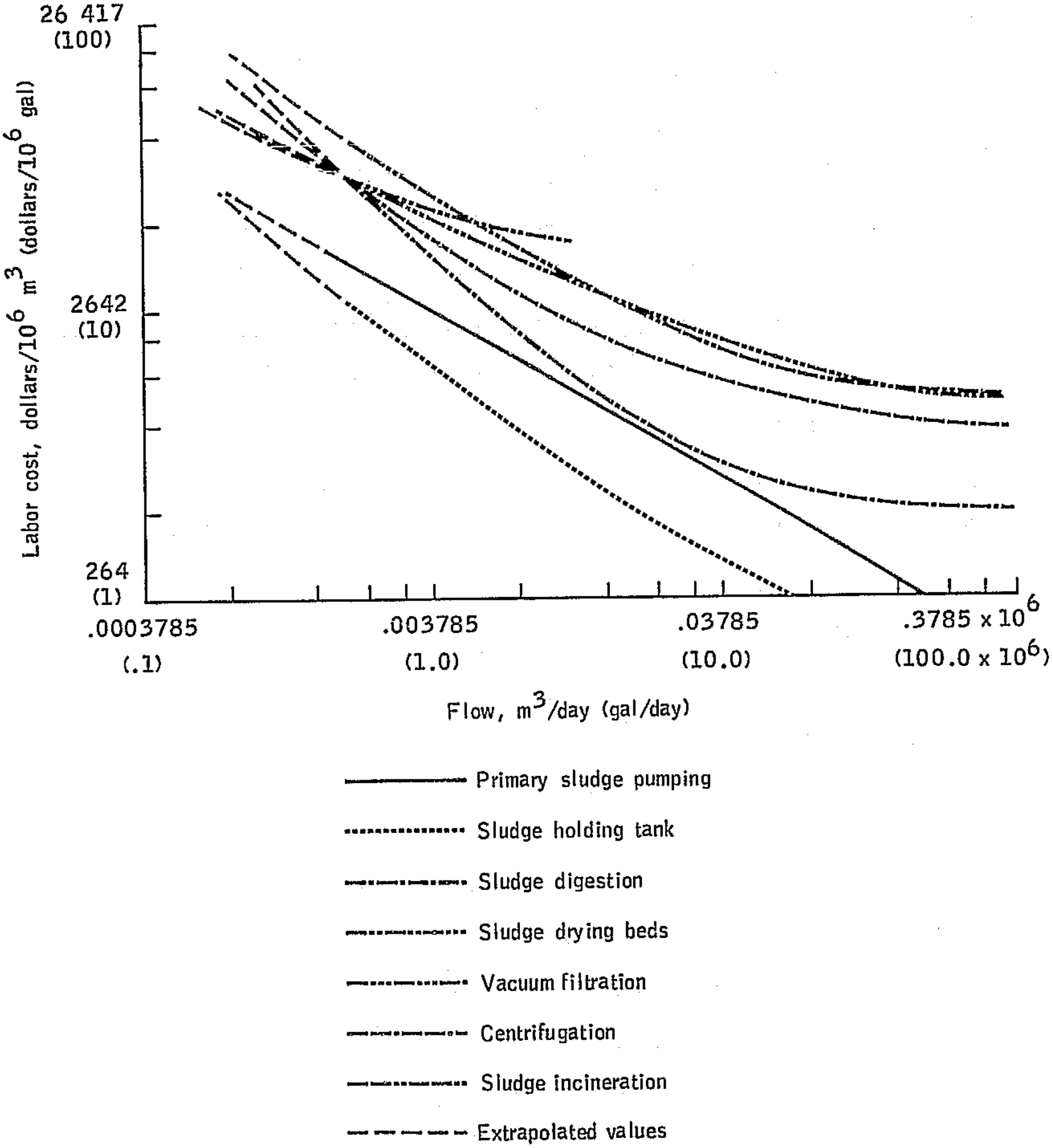

Figure 29.- Component labor costs for sludge handling.

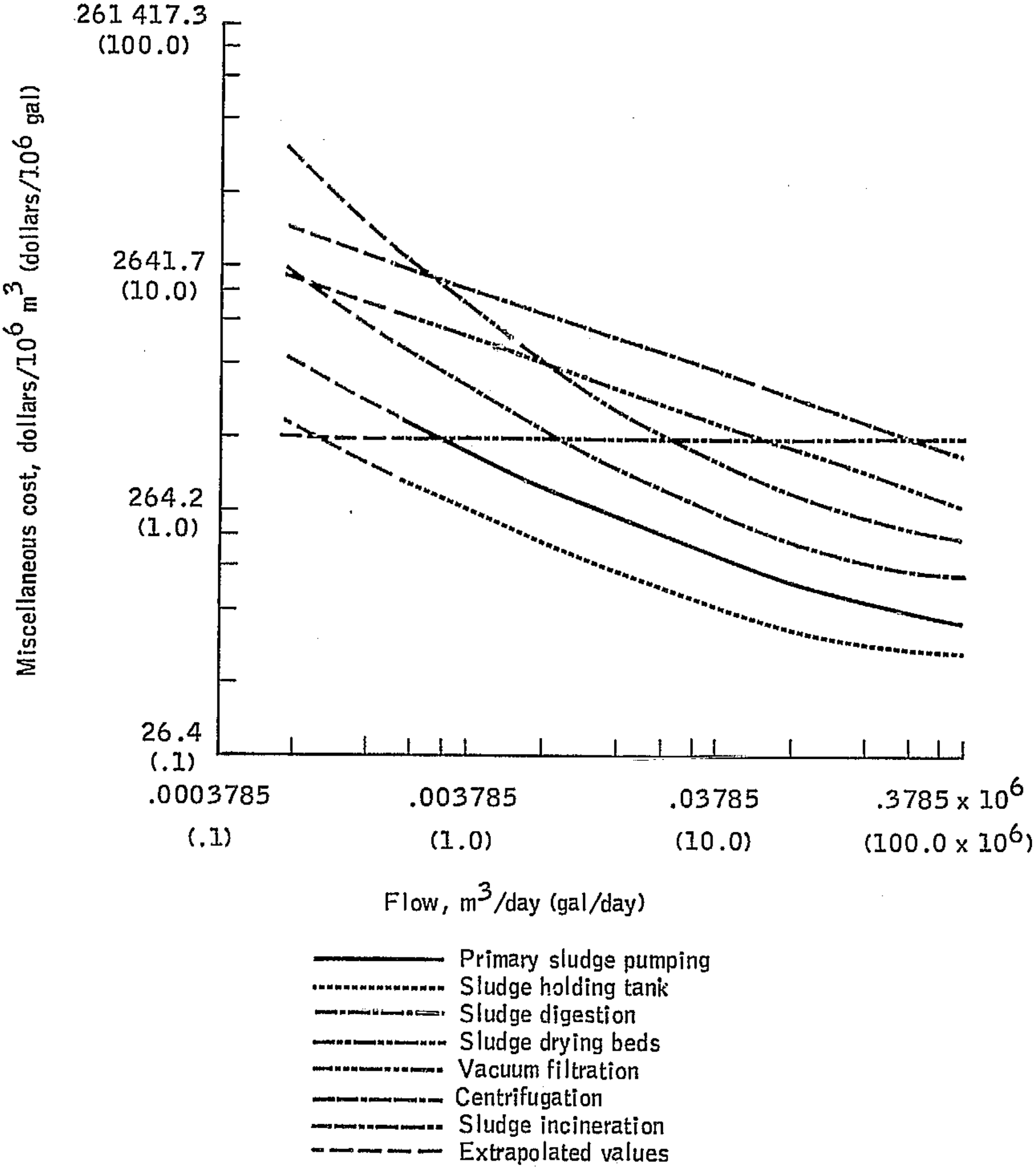

Figure 30.- Miscellaneous component costs for sludge handling.

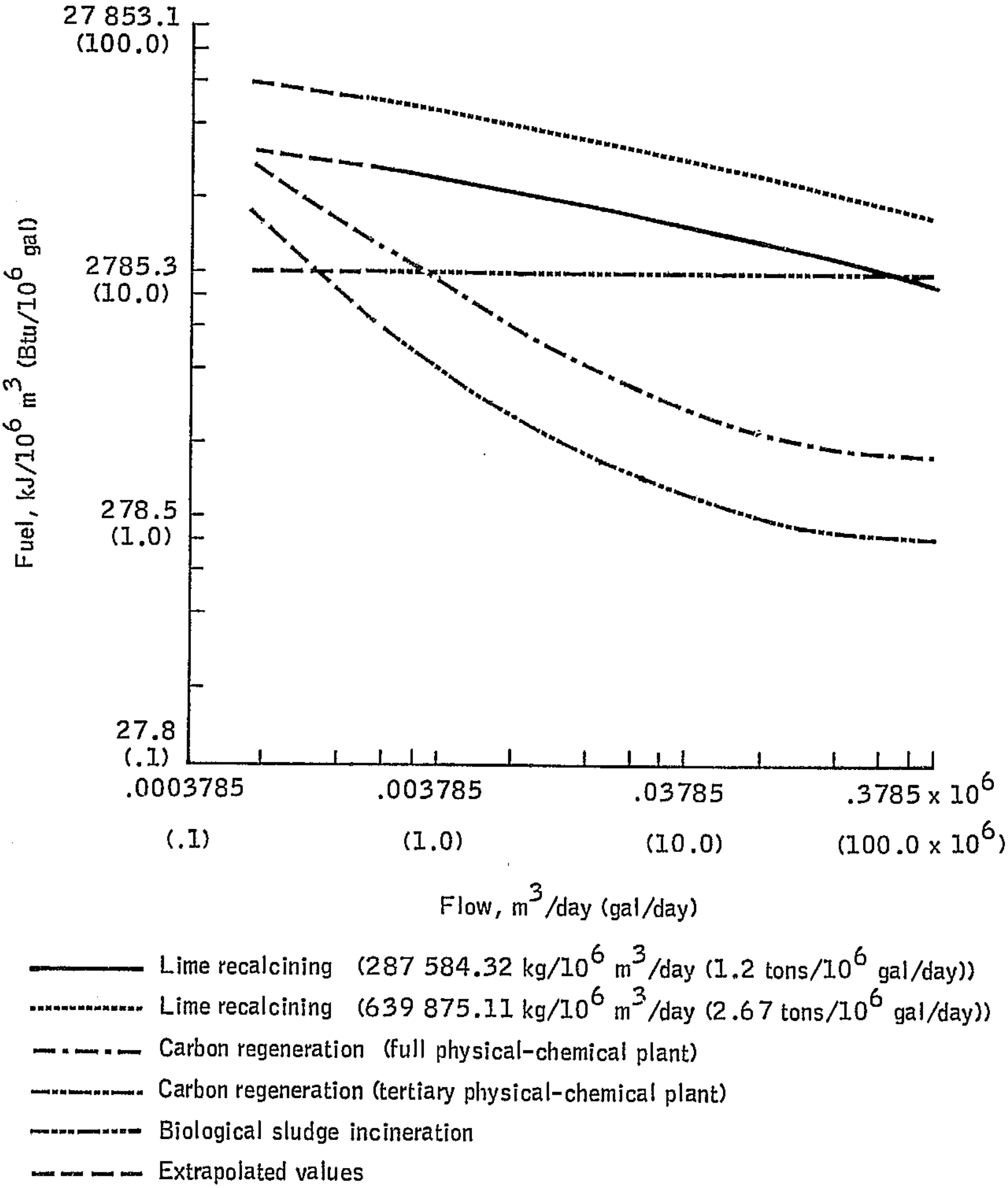

Figure 31.- Component fuel requirements for physical-chemical processes.