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APPRAISAL OF POWDERED ACTIVATED CARBON PROCESSES FOR MUNICIPAL WASTEWATER TREATMENT

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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APPRAISAL OF POWDERED ACTIVATED CARBON PROCESSES FOR MUNICIPAL WASTEWATER TREATMENT

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The information herein deals with an evaluation of the use of powdered activated carbon as a means of treating municipal wastewater. It serves to explore the strengths and weaknesses of this new technology and identify those areas where improvements would be of greatest value. As such, it fulfills the need for continuing technology assessment in emerging areas.

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ABSTRACT

Powdered activated carbon has been the subject of several developmental efforts directed towards producing improved methods for treating municipal wastewaters. Granular activated carbon has proven itself as an effective means of reducing dissolved organic contaminant levels, but is plagued with specific operational problems which can be avoided with powdered carbon. The work reported herein was aimed at putting powdered activated carbon (PAC) treatment in proper perspective relative to competing technology. All work with PAC and PAC regeneration was reviewed and representative process approaches selected for comparison with activated sludge, activated sludge with nitrification, and granular activated carbon. While no one PAC approach is clearly superior from a performance standpoint, biophysical processes are attractive because they can be incorporated into existing biological plants. Comparison of capital and operating costs were made for plants with throughput rates of 1, 5, 10, 25, and 50 MGD. Cost relations were generated in curvilinear relations to allow interpolation. Based on these estimates, it was determined that independent physical-chemical PAC systems are not economically competitive with other modes of treatment. PAC may offer advantages for specific cases where highly variant flows are experienced such as plant receiving flows of a seasonal nature or areas with combined storm sewer systems. A sensitivity analysis was also conducted to determine where improvements could be made to make PAC competitive. Lower carbon doses and/or inexpensive throwaway carbon would be needed to successfully challenge the other systems evaluated.

This report was submitted in fulfillment of Contract No. 68-03-2211 by Battelle-Northwest under the sponsorship of the U.S. Environmental Protection Agency. Work was subcontracted to Clean Water Consultants. This report covers a period from June 1975 to July 1976.

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SECTION 1

INTRODUCTION

Over the past 15 years, a great deal of effort and resources have been invested in wastewater treatment process research and development. This has been the result of recognition of the need for more highly polished effluents from wastewater treatment facilities in order to meet higher receiving water quality requirements and in some instances for reuse purposes. Treatment process research and development has focused both on improvement of the effectiveness and reliability of existing wastewater treatment schemes and on development of entirely new treatment processes.

Sorption on activated carbon has emerged as an integral part of many of the new process developments. In fact, activated carbon sorption is the most efficient process yet known for the reduction of dissolved organic substances in wastewater to very low levels.

Activated carbon can be employed either in a granular or powdered state to effect complete or tertiary treatment of wastewaters. Granular carbon applications are by far the more common and, of the two, are the only systems presently utilized in any full-scale municipal wastewater treatment facilities. Development of powdered carbon technology has lagged behind largely as a result of a lack of efficient regeneration systems. Interest in powdered carbon has remained high, however, because of potential advantages over granular carbon systems including:

- the cost of powdered carbon on a per pound basis is substantially less than that of granular carbon;
- powdered carbon will equilibrate with soluble wastewater organics in a fraction of the time required by granular carbon;
- powdered carbon is easily slurried and transported, and can be supplied on demand by metering pumps;
- powdered carbon dosage can be rapidly changed to meet varying feed organic strength;
- a powdered carbon system requires a fraction of the carbon inventory required by granular carbon systems;

- a powdered carbon adsorption system has considerably less headloss than a granular carbon system; and

- hydrogen sulfide formation problems associated with many granular carbon systems can be easily avoided in powdered carbon systems.

With continued interest in upgrading wastewater treatment systems through conversion to or addition of physical chemical modules, these potential advantages over granular carbon have led to several process development and modification activities focused on powdered activated carbon. These efforts have been further encouraged by the successful pilot-scale demonstration of regeneration and reuse of powdered carbon employed to treat municipal wastewater and the full-scale regeneration of spent industrial powdered carbon routinely carried out by two commercial concerns.

In order to assess the technical and economic viability of powdered activated carbon technology in the municipal treatment field, the Environmental Protection Agency (EPA) commissioned Battelle-Northwest (BNW) and Clean Water Consultants (CWC) to undertake the current study. The objective of the program was to perform a detailed evaluation of the body of data generated in the aforementioned process development activities. The literature was reviewed and a series of personal interviews with workers in the field was conducted. Information thus collected was evaluated and three base case treatment processes were selected for further study. Each of these selected processes was subject to a detailed economic analysis for treatment plant sizes of 1, 5, 10, 25, and 50 MGD. Economic comparisons were developed for several activated sludge alternatives and for a granular activated carbon system in the same size range of plants. In each of the base case systems, the sludge handling and regeneration processes examined were those utilized in the original development work for the particular process. One additional regeneration scheme (multiple hearth furnace) was subsequently selected and examined for all of the powdered carbon treatment processes in all size ranges.

Due to the fact that the various powdered carbon treatment processes are still in the developmental stage, a number of assumptions were inherent in the analysis. Thus, a sensitivity analysis was performed for certain of the key assumptions to evaluate their potential impact on the relative economics. Although this analysis is based upon limited data in some cases and assumptions have been necessary, it is believed that a valid picture of the relative feasibility of powdered activated carbon treatment process technology in the municipal area has emerged.

It should be noted that, although laboratory and bench scale studies were included in the literature review, only processes which had been developed on the pilot plant scale were considered for inclusion in the economic analysis.

In the following sections of this report, powdered activated carbon process development activities in the area of municipal waste treatment are described, selection of the base case systems is discussed, and the technical and economic analysis is presented.

SECTION 2

SUMMARY AND CONCLUSIONS

PERFORMANCE

- Independent physical chemical systems utilizing powdered activated carbon are unaffected by toxic substances in the influent stream.
- Powdered activated carbon in bio-physical processes reduces the sensitivity of the system to toxic substances and seems to stimulate quicker recovery of some systems after a toxic material has passed through the system.
- In general, powdered activated carbon systems can be utilized over a broader range of influent BOD conditions, while producing high quality effluents than more conventional systems.
- Powdered activated carbon systems are less subject to upset from changes in influent composition than are more conventional systems.
- From a process performance point of view, none of the developmental powdered activated carbon municipal treatment systems was found to be clearly superior to the others.
- Developmental work on the various powdered activated carbon treatment processes has been carried out under widely different conditions which makes direct comparison difficult.
- All of the pilot studies reported in the literature indicate that each of the processes is capable of producing a high quality effluent.
- Bio-physical processes are attractive in that they offer the possibility of implementation at existing activated sludge plants with no modification of existing facilities other than the addition of powdered carbon handling and feeding systems and a regeneration system.
- Laboratory scale studies of a combined contact stabilization-powdered activated carbon process indicate good potential for this approach.

- A full scale plant employing the duPont PACT process for treatment of industrial waste is currently under construction. Another full-scale bio-physical plant utilizing the Zimpro approach is planned for a municipal system in Medina, Ohio. These projects should commercialize the approach and should provide valuable full-scale operational experience.

- Publicly available data did not lead to a clear choice of a powdered carbon regeneration system based upon technical considerations.

- Two regeneration systems, the AST system and the transport system, have been operated routinely in regeneration of powdered activated carbon used in corn syrup refining. No such experience exists for carbon used in municipal waste treatment.

- Wet oxidation appears attractive since this approach does not require dewatering prior to regeneration or collection of dry powdered activated carbon after regeneration.

- Two powdered activated carbon regeneration approaches, the multiple hearth furnace and wet oxidation, will be implemented in the full-scale applications in the foreseeable future. Both will regenerate powdered carbon used in bio-physical waste treatment processes.

ECONOMICS

The following summary table presents the costs for the several alternative processes evaluated in this study. The conclusions of the economic study are:

- Independent physical-chemical (IPC) systems (using either granular or powdered carbon) are not cost competitive with conventional activated sludge for removal of BOD in normal municipal applications.

- The granular carbon IPC system is comparable in costs to conventional activated sludge followed by coagulation and filtration at a carbon dosage of 1,500 lb/MG. At a carbon dosage of 750 lb/MG, the granular carbon system would be slightly lower in cost than activated sludge followed by coagulation and filtration.

- The IPC powdered carbon systems with the specified design criteria are not competitive in cost with the granular carbon system.

- The Battelle process approach (single clarifier - combined sludge handling) would offer savings in costs over the granular carbon system if a carbon dosage of 200 mg/l and an alum dosage of 125 mg/l provides a satisfactory degree of treatment.

- The two-stage Eimco process cost is comparable to the granular carbon system (1,500 lb/MG) cost at a powdered carbon dosage of 100 mg/l. The cost would also be comparable at the specific dosage of 300 mg/l if a cheap, throwaway carbon were available at a cost of 1¢/lb, an unlikely circumstance. A single-stage Eimco system with 100 mg/l powdered carbon would be comparable in cost to a granular carbon system operating at a dosage of 750 lb/MG.

- A reduction in powdered carbon price from that used in this report (32.5¢/lb) to 16¢/lb would have an insignificant effect on the competitive position of the IPC powdered carbon systems.

- The cost of the bio-physical approach where powdered carbon is added to the aeration basin of the activated sludge process is intermediate in cost between single-stage nitrification and two-stage nitrification. If the approach provides a comparable degree of reliability of nitrification, it would offer an economic advantage over two-stage activated sludge. A proposed version of the bio-physical process where the design criteria are modified so as to provide only BOD removal appears comparable in cost to conventional activated sludge.

- The IPC powdered carbon system regeneration costs are based on fluidized bed furnace loading rates recommended independently by two manufacturers. These rates (5-7 $lb/ft^2/hr$) are higher than those originally determined (3 $lb/ft^2/hr$) by Battelle-Northwest. Should the lower loading rate be necessary, a significantly adverse cost impact would result.

- Multiple hearth regeneration of powdered carbon resulted in slightly higher capital costs (including costs of pressure filtration for carbon dewatering), substantially higher fuel requirements in the larger capacity plants, and substantially lower power requirements for all capacity plants. Effects of labor and maintenance materials were not significant. The net cost effect of using multiple hearth regeneration in conjunction with pressure filtration was not significant (i.e., within the probable limits of accuracy of these preliminary estimates) for the Eimco and Battelle processes but the addition of a carbon dewatering process in the bio-physical process resulted in a cost increase.

- The areas offering the potential for the most favorable economic results are: 1) determining the minimum carbon dosages compatible with satisfactory performance of the Battelle process for a variety of wastewater characteristics, 2) maximizing the loading rates on the FBF regeneration process. Power, fuel, and labor costs compose such a small portion of the overall IPC process costs that there is little potential gain from reductions in the assumptions used for these variables.

SUMMARY TABLE

	Costs/1,000 gallons (Dollars)				
	1 mgd	5 mgd	10 mgd	25 mgd	50 mgd
Activated Sludge					
Conventional	1.02	0.49	0.38	0.29	0.24
Single Stage Nitrification	1.10	0.51	0.41	0.31	0.26
Two Stage Nitrification	1.21	0.59	0.46	0.35	0.29
Conventional With Coagulation & Filtration*	1.49	0.71	0.55	0.44	0.37
Granular Carbon System*					
1,500 lbs carbon/mg	1.84	0.73	0.58	0.46	0.40
750 lbs carbon/mg	1.75	0.66	0.52	0.40	0.35
200 lbs carbon/mg	1.72	0.64	0.48	0.36	0.31
Powdered Carbon Systems					
Eimco*					
Basic Process	2.08	0.94	0.77	0.62	0.56
Single Stage	1.96	0.89	0.73	0.60	0.54
Two Stage With 100 mg/l Carbon	1.89	0.72	0.57	0.42	0.37
Two Stage With 300 mg/l Throwaway (5¢/lb) Carbon	1.68	0.81	0.68	0.53	0.48
Battelle*					
Basic Process	1.70	0.97	0.87	0.78	0.71
200 mg/l Carbon, 125 mg/l alum	1.18	0.55	0.46	0.39	0.35
200 mg/l Carbon Without Filtration	0.96	0.48	0.41	0.36	0.33
Bio-Physical					
Basic Process	1.46	0.55	0.43	0.33	0.29
Carbonaceous Criteria	1.43	0.52	0.39	0.30	0.26
Effect of 50% Reduction in Carbon Price on Basic Process					
Eimco	2.02	0.88	0.71	0.56	0.50
Battelle	1.58	0.85	0.75	0.66	0.59
Bio-Physical	1.44	0.53	0.41	0.31	0.27
Effect of Multiple Hearth Regeneration on Basic Process					
Eimco	2.21	1.00	0.81	0.65	0.60
Battelle	1.66	0.91	0.78	0.72	0.67
Bio-Physical	1.66	0.63	0.50	0.38	0.33
Filtration	0.22	0.07	0.05	0.034	0.024

*These processes include effluent filtration

SECTION 3

RECOMMENDATIONS

It appears that processes involving powdered activated carbon addition to the activated sludge process are being commercialized by the private sector. Two firms are independently engaged in projects which will lead to full-scale plants using this basic approach but with different regeneration techniques.

An IPC system, that being developed by JPL, will be operated on the 1 mgd scale in the near future. This project should provide the basis for commercialization or abandonment of the approach dependent upon the results of the demonstration program.

The economic analysis conducted in this study indicate that the Eimco approach is not cost competitive with granular carbon systems unless a very cheap throwaway carbon becomes available or unless the carbon dosage requirements were much lower than the 300 mg/l assumed here. The Battelle-Northwest process also requires a drastic reduction in carbon dosage below the assumed value of 600 mg/l for economic viability. However, the required reduction would result in a carbon dosage comparable to that assumed in the Eimco process.

Laboratory studies of contact stabilization-powdered activated carbon systems indicate good potential for development of a high performance, low residence time process. Such a process would offer the potential of significant cost savings.

None of the classic tests such as iodine, methylene blue, phenol, erythrosin, molasses, or BET can be used to accurately predict the performance of activated carbon in any of the wastewater treatment processes studied. This makes comparison of different regeneration systems operated at different locations extremely difficult.

In view of the above considerations, the following recommendations are made:

1. The Battelle-Northwest process should be reexamined to determine if the carbon and alum dosage can be reduced to make the process economically competitive while maintaining good process performance. In addition, consideration should

be given to substitution of a cheaper coagulant such as lime with no coagulant recovery or abandonment of alum recovery in the basic process. Stukenberg[43] reported that such modifications in the basic Battelle process appeared feasible.

2. Developmental efforts on the contact stabilization-powdered activated carbon process should be undertaken on the pilot scale.

3. A standard test by which to measure the activity of virgin and regenerated powdered activated carbon should be developed, if possible.

4. Consideration should be given to parallel operation of several pilot powdered activated carbon regeneration systems operating in concert with one or more treatment systems in order to obtain comparable regeneration data.

SECTION 4

POWDERED CARBON TREATMENT SYSTEMS

Process development activities for application of powdered activated carbon to municipal waste treatment have been directed toward both independent physical-chemical (IPC) systems and combined biological-carbon (CBC) systems. In addition, some work has been conducted on the use of powdered activated carbon in a tertiary treatment mode.

Much of the developmental work with powdered activated carbon systems has been with industrial wastes. Although this work cannot be directly translated to municipal use, the body of data generated for industrial applications has been drawn upon to assist in the current evaluation.

INDEPENDENT PHYSICAL-CHEMICAL (IPC) SYSTEMS

There have been four recent major investigations of the use of powdered activated carbon for the treatment of raw municipal wastewaters and one major study on the treatment of secondary effluent. The various developmental programs are described below.

Battelle-Northwest Study[1,2]

The Battelle-Northwest study developed the process shown schematically in Figure 1. The process involves contacting raw sewage with powdered activated carbon to effect removal of dissolved organic matter. An inorganic coagulant, alum, is then used to aid in subsequent clarification. Addition of polyelectrolyte is followed by a short flocculation period. Solids are separated from the liquid stream by gravity settling, and the effluent is then disinfected and discharged or can be filtered prior to disinfection. Carbon sludge from the treatment process is thermally regenerated by a fluidized bed process. Alum is recovered by acidifying the regenerated carbon-aluminum oxide mixture to pH 2 with sulfuric acid. This reclaimed alum is then reused in the treatment process. A pH adjustment, accomplished with a lime slurry, is required to raise the pH to 6.5-7.0 for aluminum hydroxide precipitation when reclaimed alum is recycled.

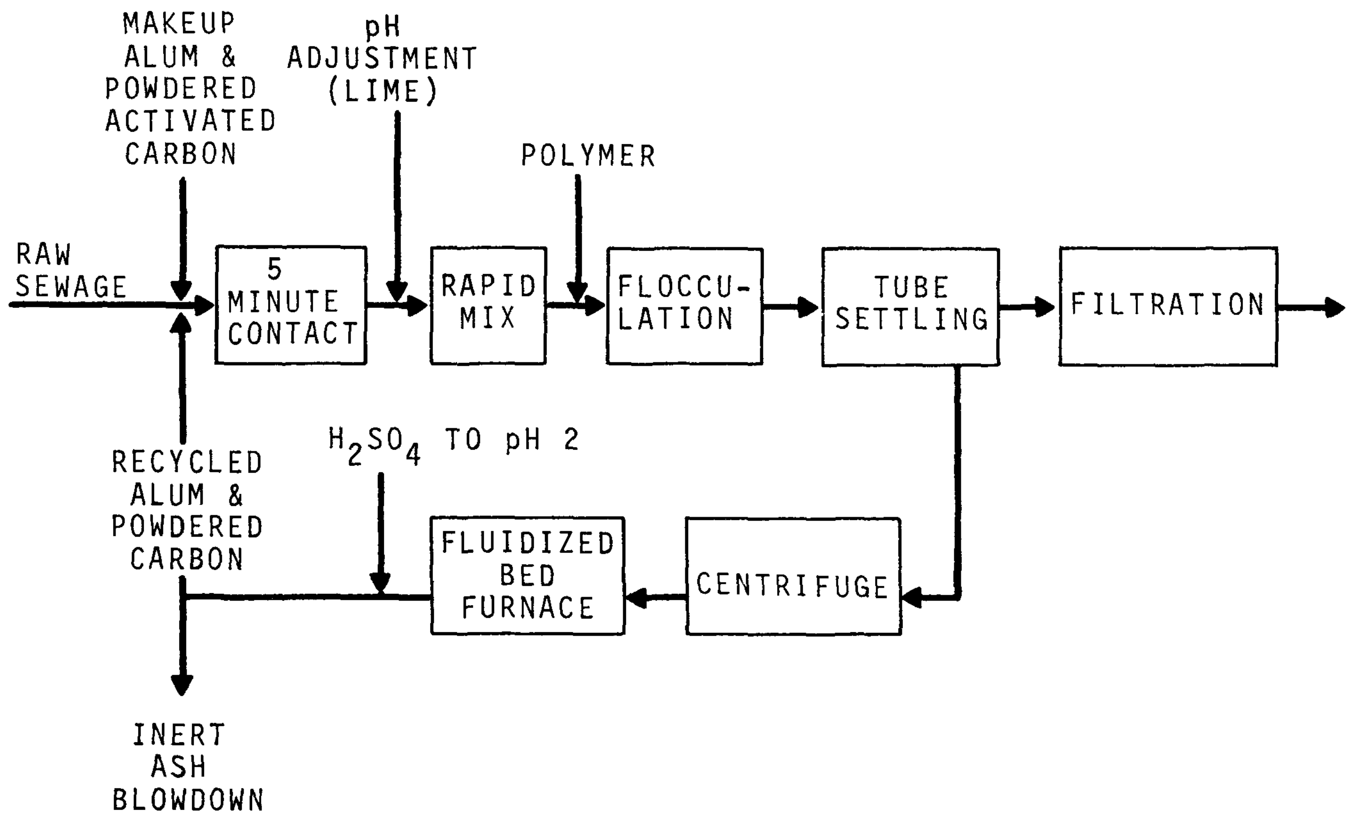


FIGURE 1. PROCESS FLOW SHEET, BATTELLE-NORTHWEST POWDERED ACTIVATED CARBON TREATMENT SYSTEM

The process was first evaluated in a nine-month laboratory study. Aqua Nuchar A (product of Westvaco) was selected for use after screening 15 different commercial carbons.

Based upon the favorable results of the laboratory study, a 100,000 gpd mobile treatment plant was constructed (see Figure 2). This pilot plant was operated in Albany, New York, from June to October, 1971, and April to June, 1972. The pilot plant was composed of two major systems: a liquid treatment system was contained, almost entirely, in a forty-foot mobile trailer van. It was designed for a nominal capacity of 100,000 gpd. Carbon, alum, and polyelectrolyte were added in a pipe reactor, providing rapid mixing of the chemicals, preceding flocculation and separation in a tube settler. Clarified effluent was chlorinated and released with the option of routing through a gravity filter prior to chlorination. Sludge was dewatered in a centrifuge.

Carbon was regenerated in a fluidized inert sand bed unit (the development of which is discussed later in this report) which was 36 inch ID, refractory lined, and self supported. As illustrated in Figure 3, this unit consisted of three main sections: a firebox housing the burner, 30 inches ID by 20 inches high; a bed section containing inert sand, 27 inches ID bottom, 36 inches ID top by 60 inches high; and a freeboard 36 inches ID by 72 inches high. A schematic diagram of the carbon regeneration system is shown in Figure 4. The pilot furnace used in the Battelle study was built by Nichols Research and Engineering Corporation.

The pilot study confirmed that proper control of pH within the system was critical. A pH of 4 or less in the first few minutes of carbon contact was found necessary to prevent excessive carryover of carbon particles from the downstream clarifier. The pH was adjusted to near neutral with lime prior to flocculation. The tube clarifier was found to perform well (effluent turbidity <2 JTU) at overflow rates as high as 2880 gpd/ft^2. Filter runs averaged 10 hours at a loading rate of 4.4 gpm/ft^2. No polymer filter aid was normally used.

Three different high molecular weight anionic polyelectrolytes were used in the pilot study: Atlasep 2A2 (product of ICI America, Inc.), Decolyte 930 (product of Diamond Shamrock Chemical Company), and Purifloc A-23 (product of Dow Chemical Company). All of these polymers were observed to produce large, rapidly settling floc particles. Each of these polyelectrolytes performed satisfactorily at a dosage of 2 mg/l.

The carbon sludge was found to readily dewater in a six inch solid bowl centrifuge. The dewatered sludge ranged from 20-35 percent solids at 70 percent recovery with no conditioning polymer. Use of polymers increased the solids recovery to 95 percent.

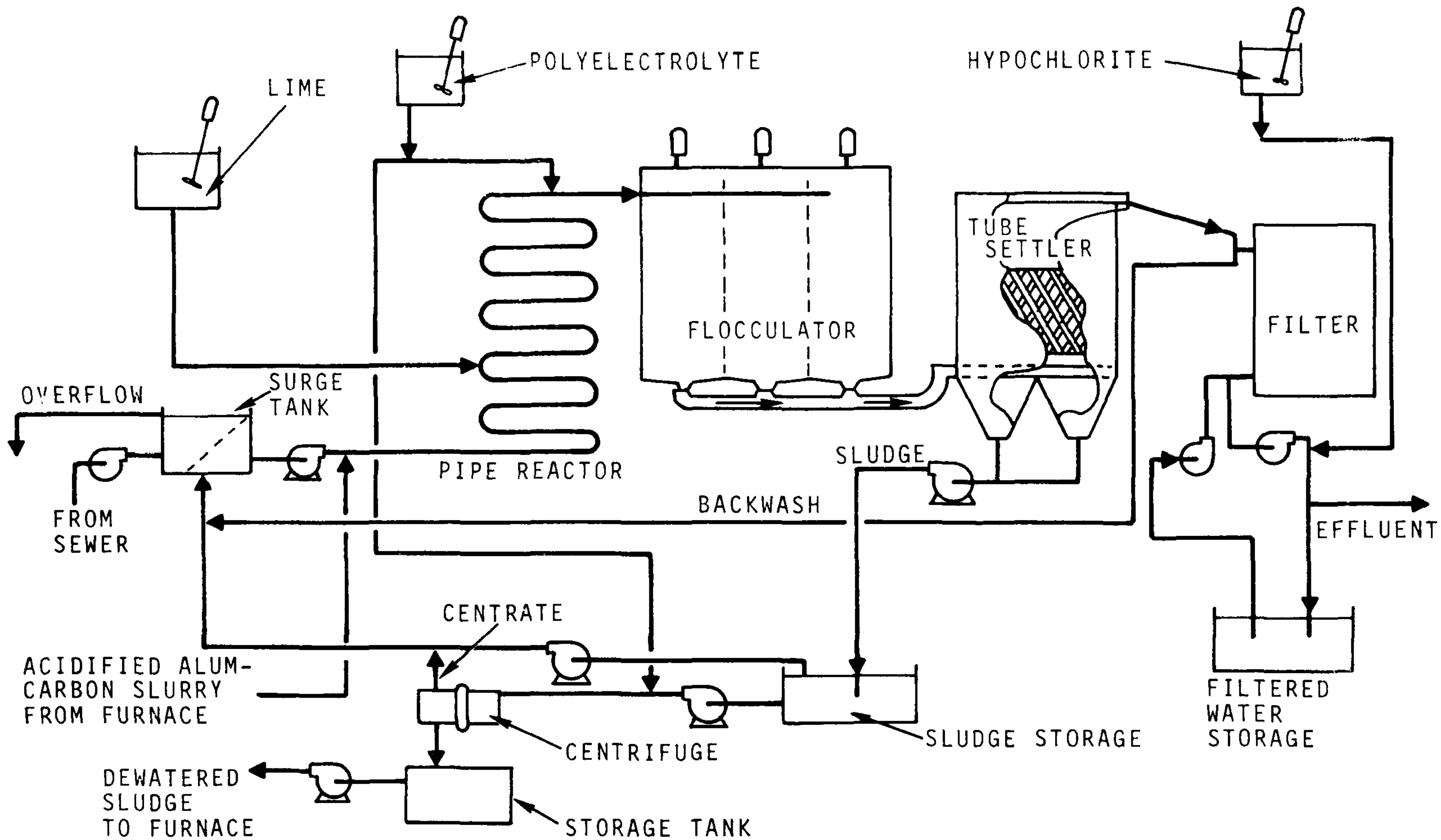


FIGURE 2. SCHEMATIC FLOWSHEET OF MOBILE PILOT PLANT, BATTELLE-NORTHWEST POWDERED ACTIVATED CARBON TREATMENT SYSTEM

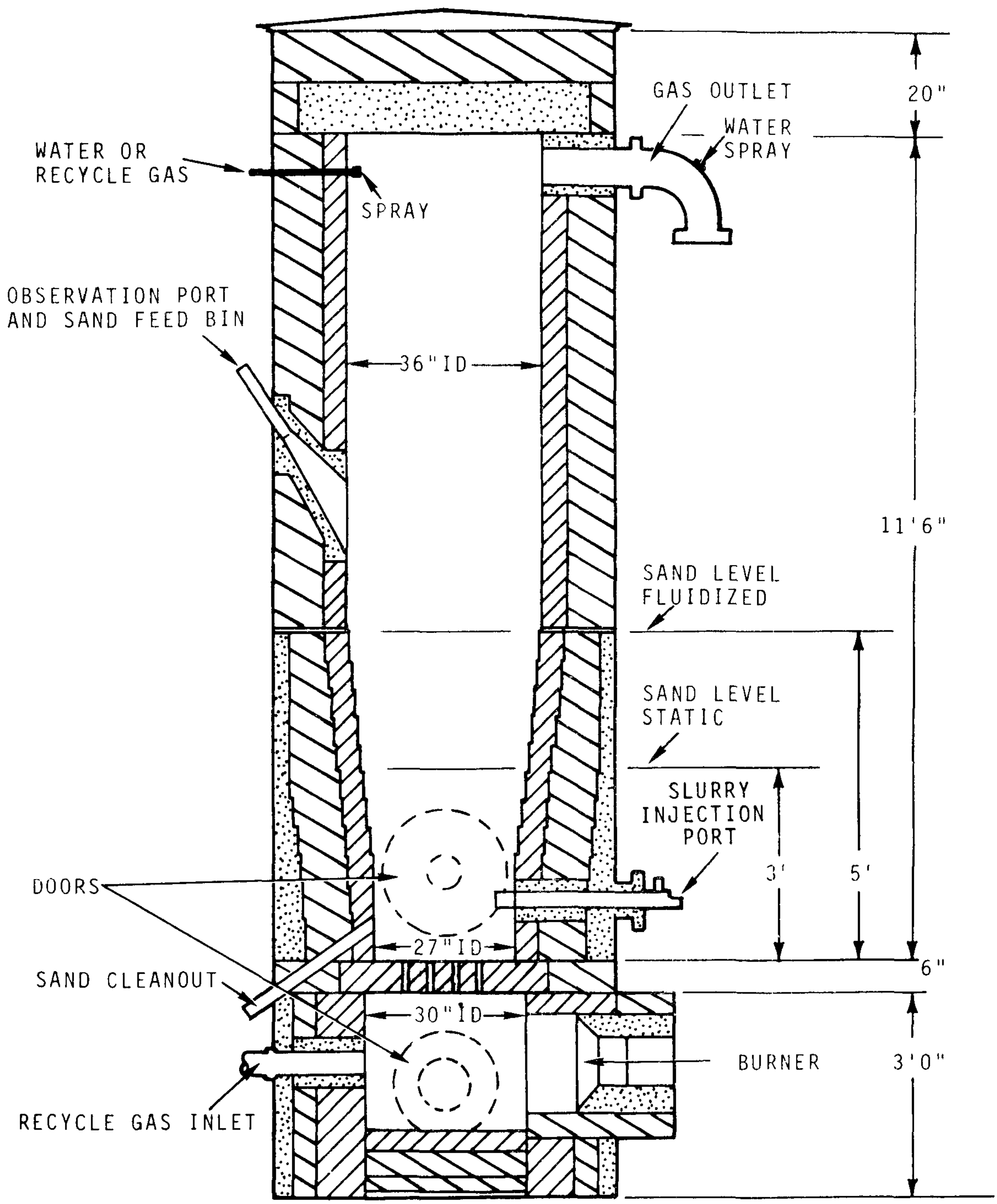


FIGURE 3. FLUIDIZED BED REGENERATION UNIT FOR POWDERED ACTIVATED CARBON

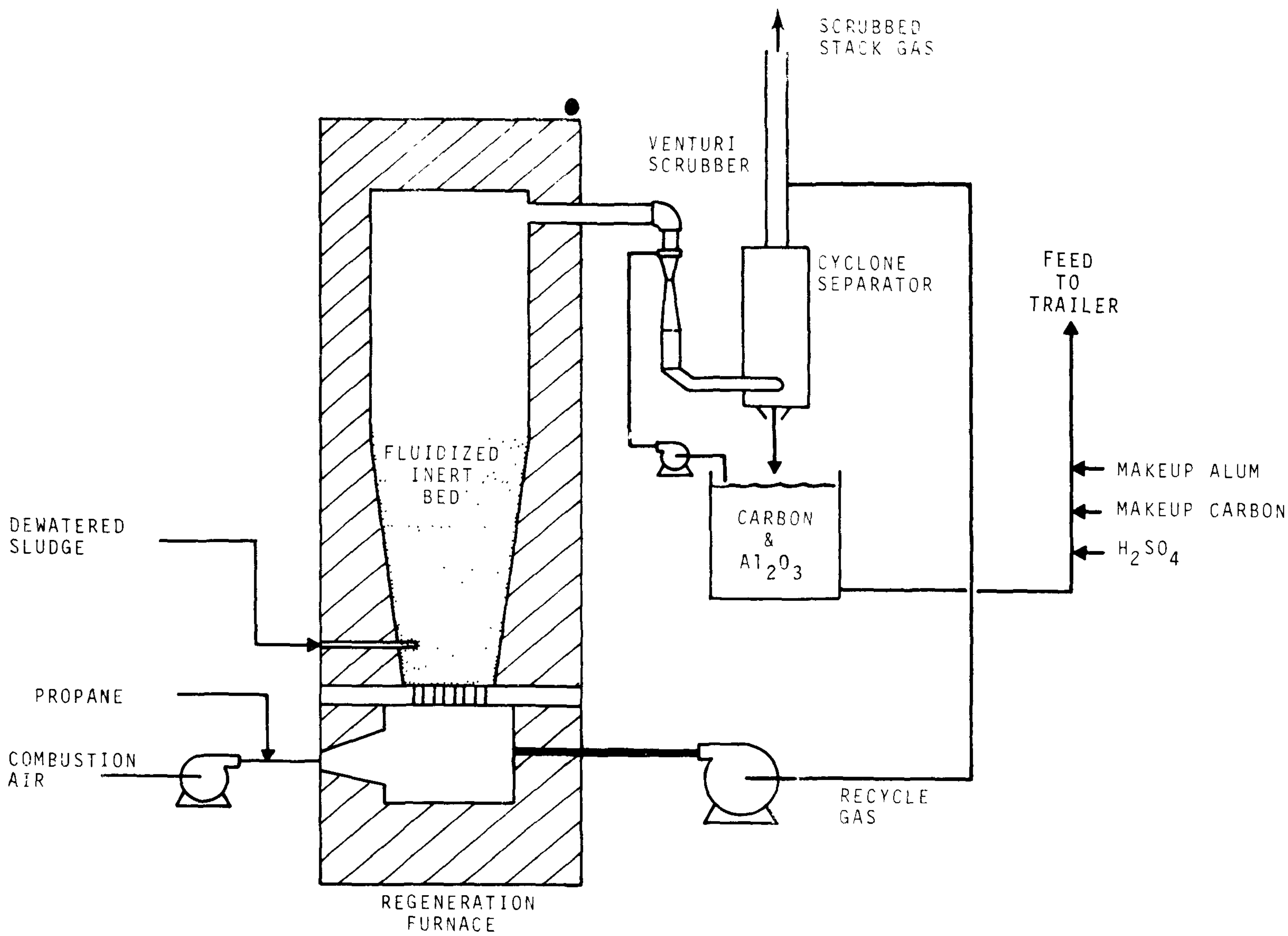


FIGURE 4. REGENERATION SYSTEM SCHEMATIC FLOWSHEET, BATTELLE-NORTHWEST POWDERED ACTIVATED CARBON PILOT PLANT

The pilot system was operated on both storm flows from a combined sewer and on dry weather, municipal wastewater flows. Excellent degrees of wastewater purification were achieved in both cases. During the dry weather conditions, average plant effluent BOD, COD, and suspended solids concentrations for the 1971 studies were 17.8, 35, and 7.7 mg/l, respectively. This represents removals of 82.3 percent BOD, 87.3 percent COD, and 94 percent suspended solids.

Plant operational data for the 1972 studies were comparable to those observed in the 1971 portion of the program. During the 1972 operations, the average effluent turbidity, suspended solids, COD, and BOD concentrations were 0.67 JTU, 3.1 mg/l, 39 mg/l, and 17 mg/l, respectively. This represents average removals of 98.1 percent suspended solids, 82.6 percent COD and 81.3 percent BOD.

The results described above were achieved at total plant detention times which averaged slightly less than 90 minutes. Recovery of 91 percent of the powdered carbon was achieved. The operation of the carbon regeneration facility is described in a subsequent section.

Eimco Study[3-6]

Eimco Corporation constructed a 100 gpm pilot plant in Salt Lake City, Utah, for evaluation of powdered activated carbon treatment of raw sewage. The pilot plant is shown schematically in Figure 5. It was operated for 16 months to evaluate lime, alum, and ferric iron coagulation and single and two-stage counter-current carbon treatment. Aqua Nuchar A was the carbon selected for use in this work. A second follow-on study of 15 months duration was subsequently conducted.

Screened and comminuted raw wastewater was obtained from the main Salt Lake City pump station discharge line. The desired flow was pumped to the chemical treatment unit, a 12 ft diameter solids-contact clarifier provided with a surface skimmer. Chemicals were added to achieve coagulation-precipitation and aid flocculation and clarification. The settled solids were removed and collected for gravity thickening and vacuum dewatering tests.

The chemically treated effluent then flowed by gravity to the carbon contactors which could be operated either single-stage (parallel) or two-stage counter-current (series). The carbon contactors were 10 ft diameter solids-contact units. Powdered activated carbon was fed and maintained as a concentrated slurry. Spent carbon was periodically withdrawn to control slurry concentration. The spent carbon removed was gravity thickened in a 5 ft diameter unit and then dewatered on a 3 ft by 3 ft vacuum filter.

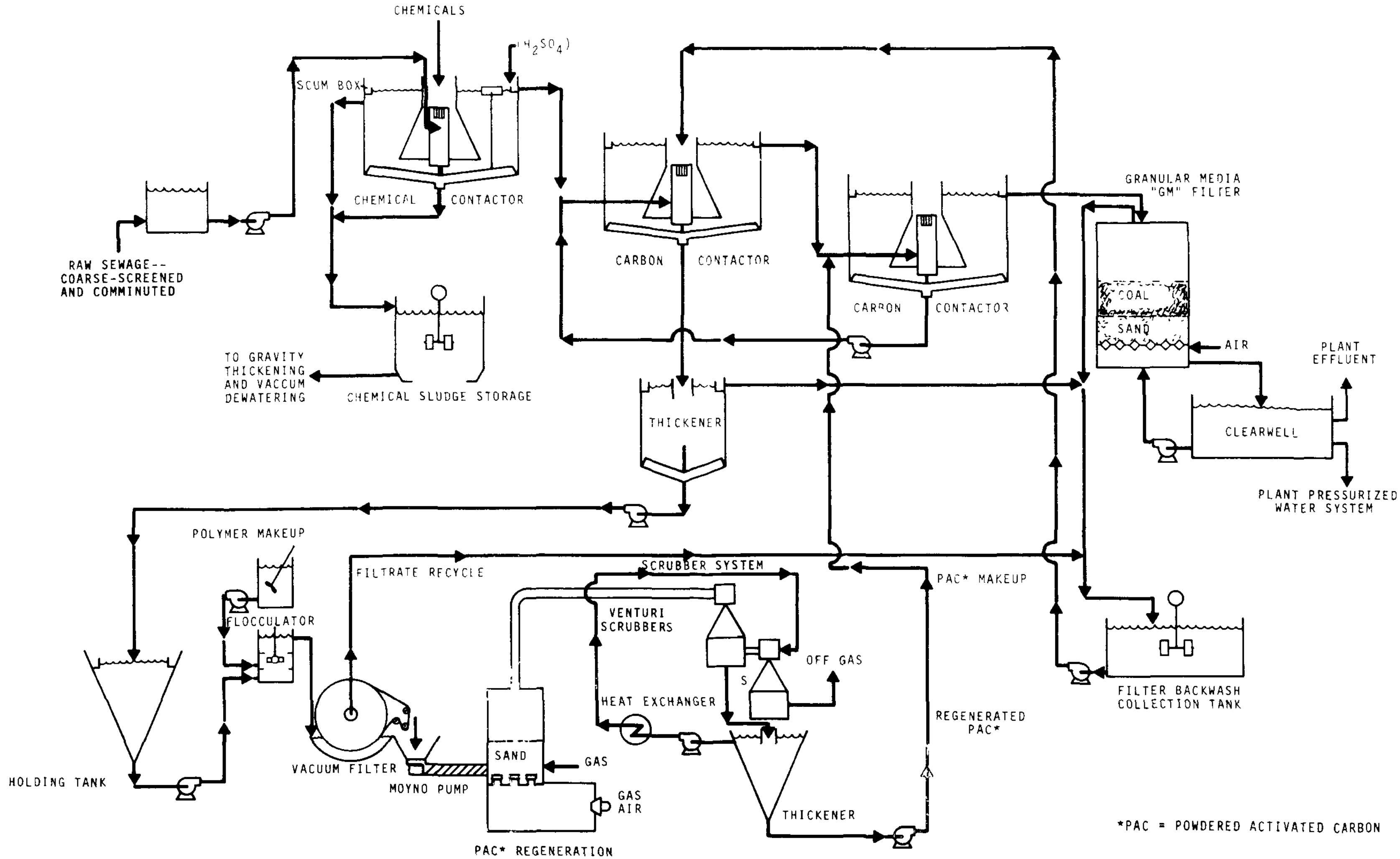


FIGURE 5. PROCESS FLOW DIAGRAM FOR EIMCO PILOT PLANT

The effluent from carbon treatment was filtered through a 3.5 ft diameter granular media filter. The filter bed consisted of 1.5 ft of 1 to 1.5 mm coal over 1.0 ft of 0.6 to 0.8 mm sand. The backwash water, containing spent carbon, was collected and recycled back to the carbon contactors. The final effluent was collected in a clear well and used for backwashing the filter and as plant water.

It was found that single stage carbon contact in a slurry contactor actually provided the equivalent of 2-4 contacts due to the biological action occurring in the slurry contactor. Hydrogen sulfide problems developed but could be controlled by maintaining the solids detention time in the clarifier to three days or less. However, the process developers concluded that two-stage countercurrent carbon contacting required less carbon than single-stage carbon contacting to produce a given effluent quality in terms of soluble COD and thus recommended the latter approach. Although this appeared to be the case, the pilot plant results were not precise enough to define the difference between the two types of contacting modes with a significant level of statistical confidence.

A clear choice of chemical for the chemical pretreatment step did not emerge from the study. Lime was identified as the chemical of choice for wastewaters low in alkalinity and high in phosphorus. For a high alkalinity-low phosphorus wastewater either alum or ferric chloride were deemed acceptable. It was noted that lime had no consistent effect on soluble COD removal while both alum and ferric chloride reduced the soluble COD by 40 to 50 percent. Although the lime sludge produced in the primary was found to thicken and dewater more easily than the other chemical-primary sludges, five to six times as much sludge was produced by lime treatment than by alum or ferric chloride treatment. For the Salt Lake City case, alum appeared to be the chemical of choice. Effluent phosphorous concentrations of as low as 0.4 mg/l were achieved at an Al^{+3} dosage of 13 mg/l.

A carbon dosage of 75-300 mg/l was employed throughout this work and was found to produce an effluent soluble COD of 15-30 mg/l. During the period June to September 1973, the pilot plant operating on a weak influent at a carbon dosage of approximately 100 mg/l was able to produce an effluent which averaged 3 mg/l soluble COD.

Anaerobic biological action in the carbon contactors was believed to contribute significantly to the removal of soluble COD in the treatment system.

Thickening and dewatering of spent carbon were effectively accomplished. The spent carbon concentration of 25 to 50 g/l in the carbon contactor blowdown was increased to 70 to 100 g/l in a gravity thickener with a solids loading averaging 10/lb/ft^2/day.

The thickened material then was readily dewatered to 78 percent moisture in a vacuum filter at rates of 6 to 9 $lb/ft^2/hr$. About 0.2 percent cationic polyelectrolyte by weight was required for conditioning to obtain about 90 percent solids recovery across the vacuum filter and produce a readily dischargeable filter cake.

The Eimco pilot plant carbon furnace was of the same basic design as used in the Battelle pilot plant, but was constructed by BSP Division of Envirotech.

Infilco Studies[7,8,44]

The Infilco Company conducted evaluations of the powdered carbon treatment of secondary effluents and raw sewage. The first investigation, high rate solids-contact treatment units embodying internal slurry recirculation were operated singly and in series as powdered activated carbon sorption systems. Secondary (activated sludge) sewage treatment plant effluent was treated in a 30,000 gpd pilot plant using a slurry of activated carbon and a cationic polyelectrolyte flocculation agent.

A two-stage counter-current system was used. Application of the process involved series operation of two solid-contact clarifiers of a type used widely for water treatment. Carbon was fed to the second unit and a first-stage slurry was developed from carbon advanced from the second contact-clarifier. Spent carbon was withdrawn from the system by blowdown from the first unit. To protect the receiving stream from carbon lost during process disruption, post filtration was provided.

Preliminary laboratory study of three powdered activated carbons resulted in selection of Atlas Chemical Industries' Darco S-51 for the pilot plant program and it was found that polyelectrolyte flocculation was required to produce floc which settled well. A study of 26 compounds disclosed that Dow Chemical Company's Purifloc C-32 was the most effective and it was used throughout the pilot plant work. A polyelectrolyte dosage of 6-7 mg/l was required for effective flocculation at carbon feed rates up to 140 mg/l while a dosage of 10 mg/l of C-32 was required at carbon feed rates of 266 mg/l.

Slurry settling rates far exceeded requirements at the pilot plant which was operated at hydraulic loads from 0.4 to 1.6 gpm/ft^2 of clarification area. In spite of this, it was necessary to reduce the pilot plant throughput when influent suspended solids were high because of an inability to remove solids as rapidly as they were accumulated within the system during these periods.

The volume of system blowdown ranged from 0.05-0.1 percent of the throughput. Its solids content of 13-22 percent by weight should enable economical recovery of carbon for reuse by reactivation without further concentration.

Pilot plant influent filtered COD averaged 27.2 mg/l and ranged from 23-34 mg/l during the study. Two-stage counter-current treatment with 67, 146, and 266 mg/l of carbon achieved respective reductions of 60, 72, and 84 percent, and residual COD concentrations were 10.8, 7.4, and 4.4 mg/l.

A COD reduction of 65 percent and an effluent COD of 9.7 mg/l was obtained in a one unit contactor system with a carbon dosage of 140 mg/l.

Carbon loadings for the two-stage systems ranged from 9-24 mg of BOD per 100 mg of carbon and a loading of 13.1 percent by weight was obtained during single unit treatment.

In later work with screened and degritted raw sewage, Infilco again utilized a two stage counter-current system composed of solids contact clarifier units. This was essentially the same 30,000 gpd system utilized in the prior work with secondary effluents.

Laboratory studies preceeded the pilot plant investigation in order to facilitate selection of a powdered activated carbon and a coagulant for use in the pilot studies. As a result of the laboratory studies, Aqua Nuchar A was selected for use in the major portion of the study, primarily on the basis of the price differential between Aqua Nuchar A and Darco S-51.

None of the polymers studied in the laboratory were found to be consistent in reducing supernatant turbidity to 10 JTU except at very high dosages. Four polyelectrolytes were judged to be superior to the others tested: Purifloc C-31, Purifloc C-32, Primafloc C-7, and CAT-FLOC. Based upon price and handling considerations, C-31 was selected as the primary flocculating agent. Later pilot plant operations incorporated alum as an auxiliary flocculant in some instances.

During the pilot plant operations, each of the contactors was operated at throughput rates of 0.5-1.5 gpm/ft^2 which corresponded to carbon contact times of 35-12 minutes. Carbon (Aqua Nuchar A) dosage was varied from 100-250 mg/l, polymer dosage was varied from 2 mg/l-20 mg/l, and alum dosage was varied from 0-50 mg/l, with high alum dosage corresponding to low polymer dosage.

Mean values of the influent COD to the pilot plant for the various operating periods ranged from 82.4 percent at a carbon dosage of 100 mg/l to a high of 92.2 percent at a carbon dosage of 200 mg/l. It was noted that the final effluent had a perceptible and distinctive sour odor (not hydrogen sulfide) which was quite disagreeable. In one comparative run using Darco S-51 carbon, no substantial difference in effluent quality was evident.

No attempt to regenerate spent carbon was made in the course of this investigation.

Jet Propulsion Laboratory (JPL) Study[9,10]

The JPL process is a two-stage counter-current adsorption system using powdered activated carbon. A block flow diagram is shown in Figure 6. Fresh activated carbon is mixed with wastewater in the second mixing basin, settled and the entire mixture of settled sewage solids and activated carbon is transferred to the primary mixing basin. Settled solids and carbon are removed from the primary settling basin, dewatered and transferred to a pyrolysis reactor. The reactor produces activated carbon and a burnable gas. The activated carbon is then recycled to the secondary mixing basin.

Activated carbon is intended to serve two functions: 1) adsorption of organics and other pollutants, and 2) settling aid in both the primary and secondary sedimentation basins. It is also believed that the carbon acts as a filtration aid and prevents compression of sewage solids during dewatering.

A trailer mounted pilot plant was constructed by JPL in Pasadena and operated at Orange County Sanitation District Plant No. 1 in Fountain Valley, California beginning February 1974. Typical operating conditions for the pilot study are shown in Table 1.

Results reported in the paper by Humphrey et al.,[9] are summarized in Table 2. These results were achieved with carbon from the pyrolysis reactor at dosages from 300 to 600 mg/l.

The staff of the Orange County Sanitation District analyzed seven runs in July-August 1974. The results of the test data are summarized in Table 3. The secondary effluent shown in the table is unfiltered and it is believed by the Sanitation District staff that secondary effluent standards (BOD = 30 mg/l, suspended solids = 30 mg/l) could be achieved by chemical treatment with ferric chloride and polymers or filtration; or by removal of fine carbon in the feed.

A sample of activated carbon was dry screened into the following size fractions:

Above 100 mesh
100 - 200 mesh
200 - 300 mesh
Below 325 mesh

Samples of degritted raw wastewater were treated with 600 mg/l of carbon from these four size fractions and analyzed for COD at various times from 0 to 30 minutes after addition of the carbon. The results of this test showed that, in the size ranges studied,

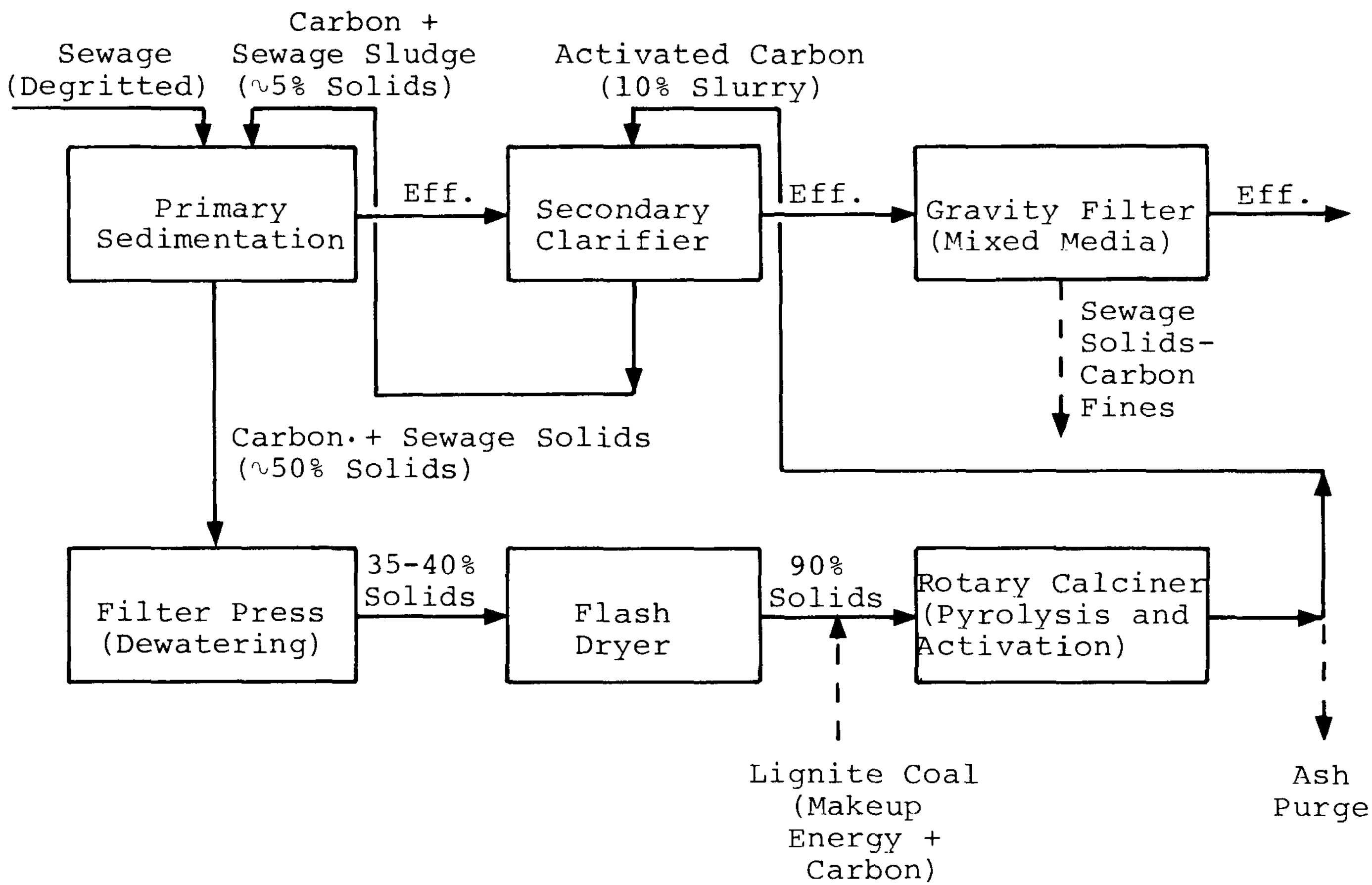


FIGURE 6. JPL-ACTS PROCESS FOR OCSD

TABLE 1

JPL PILOT PLANT OPERATED AT ORANGE COUNTY SANITATION DISTRICT PLANT NO. 1

Capacity:	7 gpm
Primary mixing:	0.25 hp mixer @ 1725 rpm detention time = 28 minutes
Primary settling:	overflow rate = 335 gpd/ft^2 detention time = 86 minutes
Secondary mixing:	0.33 hp mixer @ 1725 rpm detention time = 28 minutes
Secondary settling:	equipped with 1 Microfloc settling tube module, 8 ft long overflow rate = 385 gpd/ft^2 detention time = 86 minutes
Solids handling system:	No equipment for continuous sludge removal; therefore, system shut down for batch removal of sludge from primary and secondary settling basins
Dewatering:	(1) Rotary vacuum filter, or (2) Netzsh plate filter: 11 plates, 14 x 14 in. total filter area = 32.7 ft^2
Pyrolysis reactor:	8 in. ID stainless steel tube equipped with an external gas fired jacket bed temperature = 1800°F

TABLE 2

JPL PILOT PLANT RESULTS[9]

Parameter	Influent	Concentration, mg/l		Percent Removal
		Secondary Effluent	Secondary Effluent (Filtered)	
Total Suspended Solids	404	117	1	99
Volatile Suspended Solids	298	101	0	100
Grease	44	7	2	95
Biochemical Oxygen Demand	182	14	6	97
Cadmium	0.30		0.026	84
Chromium	0.94		0.36	40
Copper	0.74		0.017	97
Lead	0.21		0.05	73
Nickel	0.32		0.13	63
Silver	0.016		0.002	88
Zinc	1.01		0.07	93

TABLE 3

JPL PILOT PLANT RESULTS
(Operation by Sanitation District Staff)

Date 1974	Waste-Water Flow gpm	Primary Carbon Dose mg/l	Secondary Carbon Dose mg/l	COD Inf mg/l	COD Pri Eff mg/l	COD Sec Eff mg/l	SS Inf mg/l	SS Pri Eff mg/l	SS Sec Eff mg/l	BOD Inf mg/l	BOD Pri Eff mg/l	BOD Sec Eff mg/l
July 8	5	Sec Sl* 512	Nuchar 455	999	167	109	402	166	98	203	101	70
July 9	5	Sec Sl 135	Reactor 645	475	140	124	406	126	142	267	209	142
July 16	7	Sec Sl 701	Nuchar 605	618	122	76	476	206	100	200	81	55
July 23	7	Sec Sl 592	Reactor 636	218	109	109	424	238	180	162	41	8
Tube settler installed in Secondary												
Aug. 6	7	Darco 620	Darco & Nuchar 394	574	303	139	396	110	50	226	97	57
Aug. 19	7	Sec Sl Nuchar 569	Darco 341	591	92	35	394	184	88	226	64	51
Aug. 26	10	Darco 492	Darco & Nuchar 415	767	132	86	552	144	98	174	97	52

*Sec Sl - Settled sewage solids and carbon from secondary settling basin.

COD removal was not related to particle size. It was concluded that carbon sizes which are difficult to settle are not necessary for adsorption in the treatment process.

Metals removals recorded in the pilot work by JPL were clouded by the fact that the sedimentation tanks had been previously used for a plating solution. The following test data are results which were achieved by the Sanitation District when leaching from the settling tanks had been eliminated:

	Influent Range mg/l	Effluent Range mg/l
Cadmium	0.12 - 0.25	0.02 - 0.04
Chromium	0.36 - 1.48	0.10 - 0.22
Copper	0.78 - 1.80	0.05 - 0.3
Lead	0.20 - 0.46	0.02 - 0.16
Nickel	0.11 - 0.52	0.08 - 0.11
Silver	0.02 - 0.04	0.002 - 0.008
Zinc	0.33 - 1.36	0.12 - 0.36

A material balance on solids in the liquid treatment system was difficult to perform because of the method of withdrawing sludges and good results were not obtained. Material balances on the pyrolysis reactor were not attempted because of its small size and intermittent mode of operation.

A summary of carbon loading rates and COD removal in the secondary sedimentation basin is shown in Table 4. These data indicate very low COD removal efficiency for carbon produced in the reactor. Subsequent tests have shown that carbon can be produced which is equal to commercial carbon.

About 1.25 pounds of carbon can be produced per pound of carbon added to the secondary mixing basin. However, at this yield (1.25:1) a poor carbon is produced. It is necessary to reduce this ratio to 1:1 or less to produce a suitably active carbon.

A 1.0 MGD treatment plant utilizing the JPL process has been designed by Carollo Engineers for the Sanitation District. Construction of this plant is taking place with funds from an Environmental Protection Agency Step I Grant.

COMBINED BIOLOGICAL-CARBON (CBC) SYSTEMS

Another method of gaining benefits from the use of powdered activated carbon is the addition of carbon directly to the mixed liquor in an activated sludge plant aeration basin. Three companies, DuPont, ICI United States, and Zimpro, have performed

TABLE 4

CARBON LOADING AND COD REMOVAL

Date 1974	Type Primary Carbon	lb Carbon / lb Solids into Pri	lb Carbon / lb COD into Pri	Type Secondary Carbon	lb COD Removed / lb Carbon in Secondary
July 8	Sec Sl* from Nuchar	1.27	0.513	Nuchar	0.127
July 9	Sec Sl from Nuchar	0.33	0.284	Reactor Product	0.025
July 16	Sec Sl from Nuchar	1.47	1.134	Nuchar	0.076
July 23	Sec Sl from Nuchar	1.40	2.715	Reactor Product	0
Aug. 6	Darco	1.57	1.080	Darco & Nuchar	0.416
Aug. 19	Sec Sl from Nuchar & Reactor Plant	1.44	0.963	Darco	0.167
Aug. 23	Darco & Sec Sl from Nuchar	1.57	0.641	Darco	0.111

*Sec Sl - Settled sewage solids and carbon from secondary settling basin.

major studies in the area. In addition, some laboratory bench scale work on powdered carbon-contact stabilization systems have been carried out by Battelle-Northwest and by the University of Washington. The benefits which are attributed to this approach are:

- Improved BOD and COD removal by sorption and improved settling even at lower than optimum temperatures, lower MLVSS (mixed liquor volatile suspended solids) and/or at higher than design flow rates.
- Sorption of color and toxic agents that cannot be removed by merely expanding a plant.
- Reduction of aerator and effluent foam by sorption of detergents.
- More uniform plant operation and plant effluent quality during periods of widely varying organic and hydraulic loads.
- Improved solids settling (lower sludge-volume index, increased sludge solids, and lower effluent solids).
- Increased aerobic digester capacity through foam reduction.

The mechanisms which account for these benefits are postulated to be as follows:

- Sorption on the extensive surface area of the carbon.
- Biological sorption and degradation. The carbon settles in the sludge with pollutants sorbed, and the pollutants thus remain in the system rather than escaping in the effluent. The longer the sludge ages, the greater the chance for bio-oxidation of slowly oxidized organics.
- Continuous regeneration of the carbon by biological action. While the carbon and bio-organisms are sorbing organic pollutants, the bio-organisms continuously degrade the pollutants, thereby freeing carbon surface areas again for sorption of more pollutants.
- Improved solids settling. Improved settling in the secondary clarifier leads to lower suspended solids and BOD in the effluent. The settling rate of some powdered carbons plus biosolids is greater than that for biosolids alone.

DuPont PACT Process[11-14]

DuPont conducted several bench scale studies in the middle 60's to study the biological treatability of the waste stream at their Chambers Works in Deepwater, New Jersey. The treatability was questionable, the sludge settled poorly, and toxic substances inhibited the treatment process. In 1967, DuPont began adding powdered activated carbon to their bench scale activated sludge units. The BOD removal dramatically improved, the Sludge Volume Index (SVI) dropped substantially, and the toxicity of the treated effluent was lower. These bench scale tests were expanded to include municipal and other industrial wastewaters to determine the effect of such things as metals, sludge age, and temperature on the system.

Pilot plant studies were run between October 1971 and December 1972 comparing the PACT Process with 1) completely mixed activated sludge; 2) adsorption in granular carbon columns; 3) granular columns followed by activated sludge; and 4) activated sludge followed by granular carbon columns. The flow rate of the system was 50 gpm. A schematic of the pilot plant is shown in Figure 7.

The wastewater used in the study was from the DuPont Chambers Works Plant. The plant manufactures fluorinated hydrocarbons, petroleum additives, dyes, and various aromatic intermediates. Its waste is extremely complex and variable and the organic constituents range from highly biodegradable methanol to stable compounds and polymer by-products. Most of the 4,150 processes are batch operations. Pretreatment consisted of equalization, neutralization by lime addition, and clarification.

Twenty-four hour composite samples were withdrawn daily from critical locations within the system and analyzed for BOD, COD, TOC, SS, VSS, and nutrients. In addition, samples were obtained and used in tests for sludge settleability, sludge dewatering and handling, and carbon regeneration.

The PACT system, the carbon + bio system, and the bio + carbon system were run concurrently between October 1971 and December 1972. Table 5 compares the average performance of three systems, including data from the biological stage of the bio + carbon system and the carbon stage of the carbon + bio. The biological stage of the systems were operated so that nutrients were not limiting.

The main variables affecting effluent quality of the PAC system were found to be powdered carbon dosage, aeration basin temperature, and sludge age (or F/M). Traditional kinetic theory was postulated to explain the sludge growth and substrate removal kinetics.

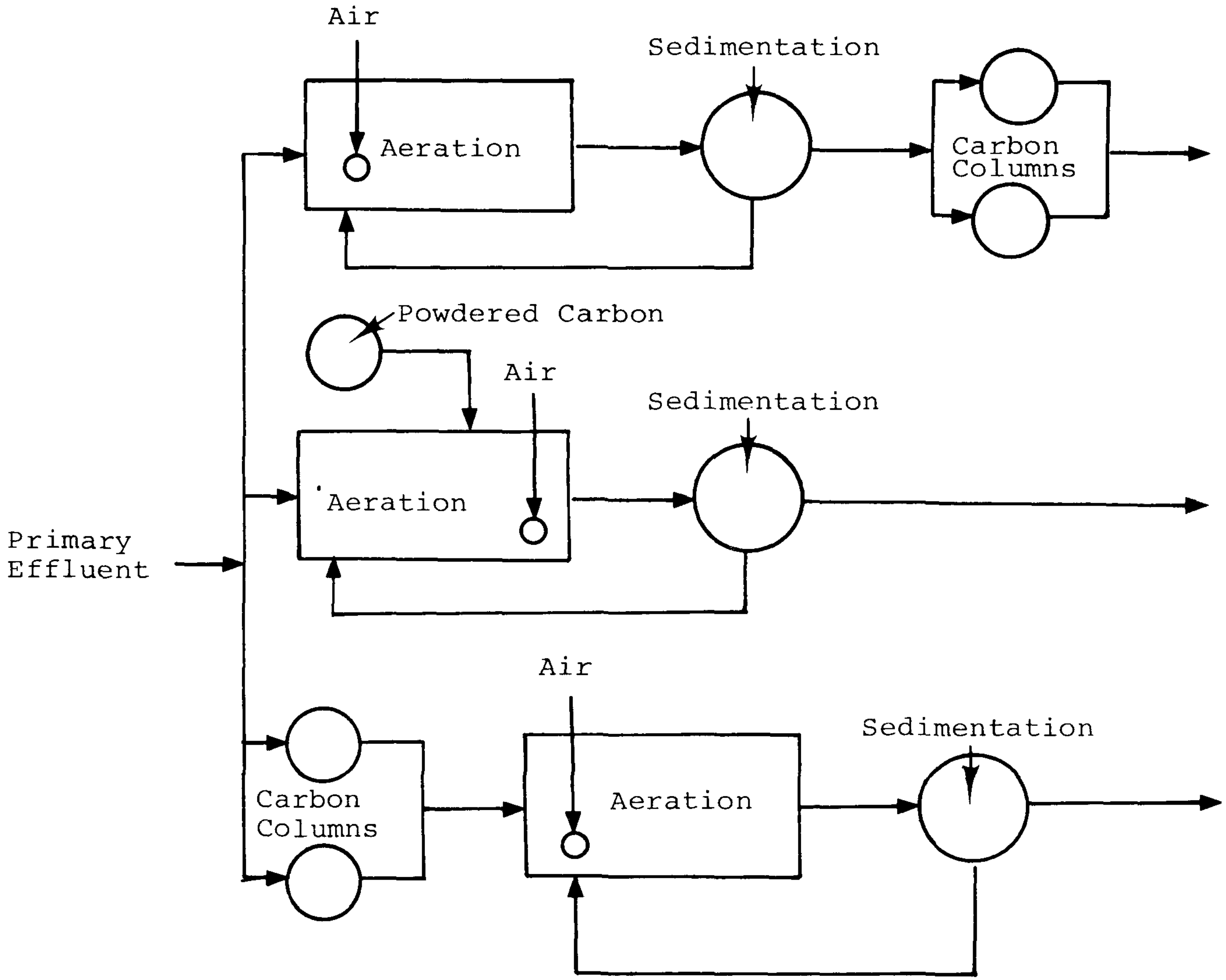


FIGURE 7. PILOT PLANT SCHEMATIC

TABLE 5

AVERAGE PILOT PLANT PERFORMANCE

Parameter	Pilot Plant Inf.*	PACT**	Bio + Carbon	Carbon + Bio	Carbon	Bio	Assumed Criteria
Total BOD_5, mg/l	171	15	10	13	99	17	-
Soluble BOD_5, mg/l	154	10	8	8	88	11	30
Total COD, mg/l	389	89	65	120	191	206	-
Soluble COD, mg/l	324	74	49	57	190	116	200
Soluble TC, mg/l	93	30	24	25	55	43	45
Color, APHA Units	970	390	97	160	130	910	-

*After primary treatment.
**Carbon dose ranged from 60 to 320 mg/l.

ICI United States Studies[15-19]

ICI United States has conducted a series of studies in which powdered activated carbon has been added to the mixed liquor of activated sludge systems treating a variety of industrial wastes. These studies are summarized below.

Polyols and Derivatives Waste Treatment Facility

The waste from this facility is equalized prior to the activated sludge process. The design flow is 150,000 gpd but the plant operates at about two-thirds capacity. The waste is characterized by a high average BOD and COD of 1700 mg/l and 3200 mg/l, respectively. Mixed liquor volatile suspended solids (MLVSS) average 2500 mg/l. Powdered carbon (Hydrodarco C) was added at a rate sufficient to maintain a level of 1000 mg/l in the system. Figures 8 and 9 present the frequency distribution of percent BOD and COD removals for the month before carbon was added and for the two-month test period. Average BOD and COD removals improved 20 percent and 25 percent, respectively, with powdered carbon present. In addition, the test period occured during the cold weather months of December and January.

Combined Waste Treatment Facility

In this case a municipal plant received 70 percent of its flow from a textile dyeing and finishing mill. Subsequent to primary clarification and roughing filter treatment, the flow passes to a contact stabilization process designed for 1 MGD flow. During the previous two years, the daily average flows have ranged between 0.75 and 1.8 MGD, at times peaking over 2 MGD. Influent BOD changes between 90 and 350 mg/l, averaging 150 mg/l. Powdered activated carbon was added to the contact zone at a rate of 20-25 mg/l based on influent flow. An equilibrium aerator level of 900 mg/l was achieved. Figure 10 shows that the BOD removal increased from 70 to 90 percent and the variability in effluent quality was decreased. As soon as carbon addition was discountinued, BOD removal dropped dramatically.

Solids Settling - Extended Aeration

Following neutralization, an acid dye and fine chemical waste is lime neutralized and treated in a conventional extended aeration process. Flow is about one-half of the 0.22 MGD design. Influent BOD averages 600 mg/l and COD 1200 mg/l. Prior to carbon addition, the average effluent suspended solids was 78 mg/l. After carbon addition, effluent suspended solids was reduced to 25 mg/l. F/M ratios varied from as low as 0.09 to as high as 1.43 through the test period -- conditions that would be expected to cause effluent solids problems.

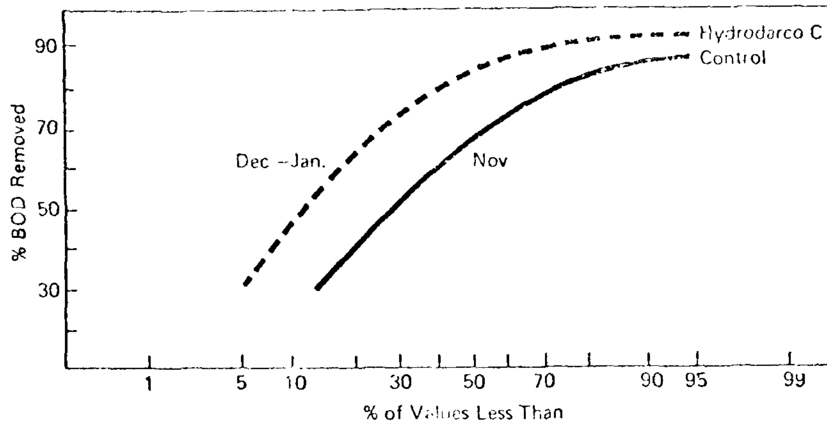


FIGURE 8. EFFECT OF POWDERED CARBON ON BOD REMOVALS

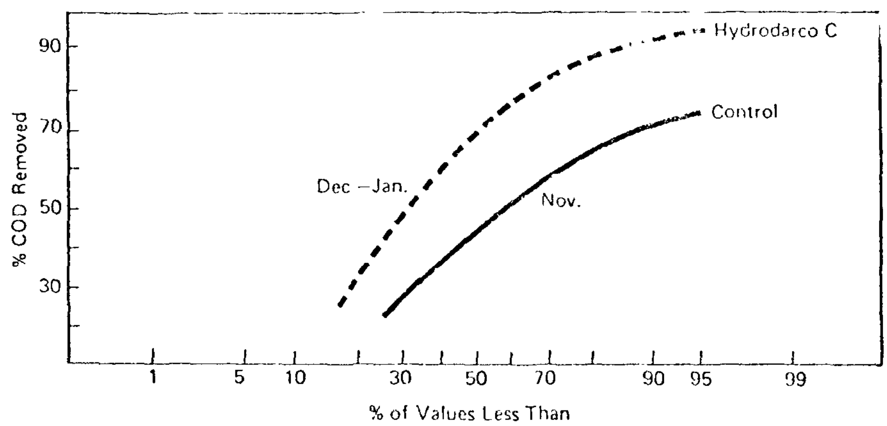


FIGURE 9. EFFECT OF POWDERED CARBON ON COD REMOVALS

Norfolk, Nebraska, Water Pollution Control Plant

This test involved a completely mixed activated sludge plant designed to treat 3.7 MGD with a BOD load of 13,700 lb/day. During the carbon test, flow averaged 2.1 MGD (57 percent of design) and the BOD averaged 7759 lb/day (also 57 percent of design). Industrial waste constitutes greater than 50 percent of the load. These industrial wastes are from two packing houses, two milk processors, one food processing plant and the surreptitious dumping of heavy metals by an electronics firm. A schematic of the plant is shown in Figure 11.

Powdered activated carbon addition began on April 5, 1973, and continued until May 4. The recommended carbon evaluation program was to add carbon at successively higher influent dosages of 9, 18, and 30 mg/l, each for a period of 10 days. The equilibrium aerator levels for these influent dosages were calculated to be 95, 245, and 470 mg/l, respectively. All other operating parameters were maintained at pre-carbon conditions.

All analyses were run by plant personnel for process control. Data averages for the pretest and test period are shown in Tables 6 and 7. All pre-carbon data were taken during the month immediately preceeding the test period.

The average effluent suspended solids dropped from 58 to 19 mg/l, and the Sludge Volume Index (SVI) dropped from 145 to 97. The range of F/M increased and the average F/M increased from 0.21 to 0.31. Influent BOD loading increased 12 percent. However, effluent BOD's were maintained at slightly below the pre-test level. The amount of thickened sludge increased 62 percent from a weekly average of 5.29 tons/day to 8.55 tons/day.

Zimpro Studies[20-22]

Zimpro, Inc., currently markets a proprietary wet air oxidation system which has been applied to the regeneration of powdered activated carbon used in wastewater treatment. In early work, Zimpro studied a two-stage counter-current sorption system. Primary effluent from the Rothschild, Wisconsin, sewage treatment plant was influent to the system. The spent carbon accumulated every 24 hours was removed, regenerated by partial wet air oxidation, and reused in the treatment process.

The liquid treating phase reduced the COD from an average of 233 mg/l to 34 mg/l with an average carbon loading of 0.394 g COD/g carbon. The carbon was used through 23 cycles.

Following their initial work, Zimpro abandoned the IPC system and adopted a CBC approach. The system shown in Figure 12 was employed to treat the entire 0.8 mgd flow at the Rothschild, Wisconsin, sewage treatment plant. This demonstration involved

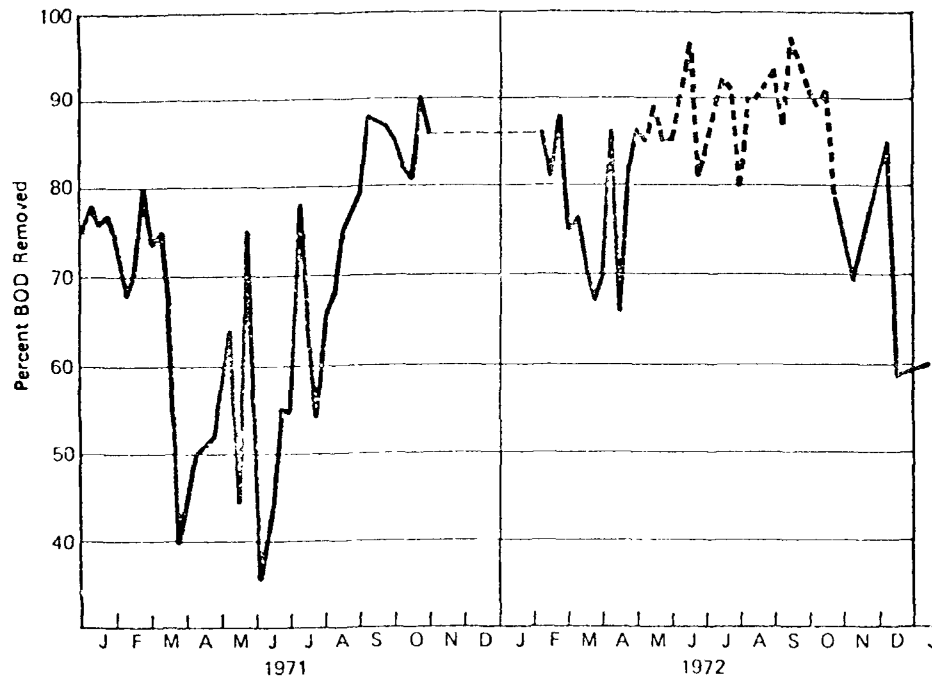


FIGURE 10. EFFECT OF POWDERED CARBON ON BOD REMOVAL

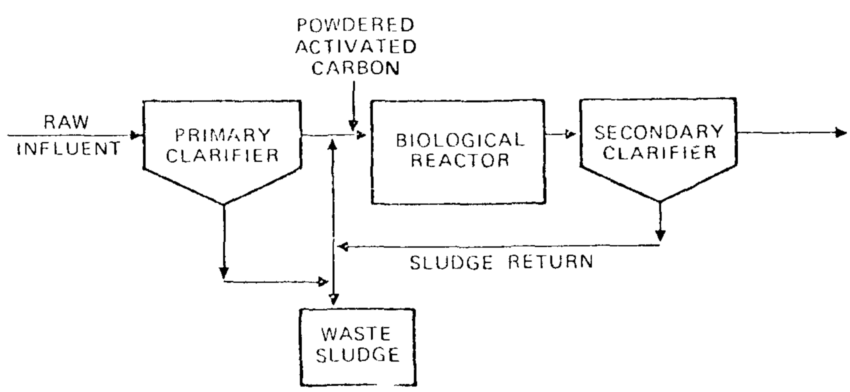


FIGURE 11. ACTIVATED SLUDGE PROCESS

TABLE 6

SUMMARY OF RESULTS

	Control	Carbon	% Change
Flow, MGD (cu m/day)	2.08 (7873)	2.03 (7684)	- 2.4
Influent BOD, ppm	165	190	+15
Organic Load/lb/day (kg/day)	2862 (6296)	3217 (7077)	+12
MLSS, ppm	2689	2211	-18
biosolids, ppm	2689	2000	-25
carbon, ppm	0	200	-
SVI	145	97	-33
Effluent solids, ppm	58	19	-67
Effluent BOD, ppm	4.6	4.0	-13

TABLE 7

SLUDGE HANDLING SUMMARY

	Control	Carbon	% Change
Sludge Waste Rate, gpd (cu m/day)	24,386 (92)	23,750 (90)	- 3
Wet tons filtered/day (kg/day)	5.29 (23,276)	8.55 (37.620)	+62
Pounds filtered/day (d.b.) (kg/day)	11,178 (24,592)	17,038 (37,484)	_52
Filter yield lb/ft ^{2}/hr (kg/m ^{2}/hr)	4.2 (99.5)	7.0 (165.8)	+67
Pounds polymer/ton (d.b.) (g/kg)	5.02 (0.52)	3.82 (0.39)	-24
Cake Solids, %	18	16	

treating sewage using the existing activated sludge system with a few modifications. Liquid alum was added in the 5,000 gallon aerated grit chamber ahead of the sewage lift pumps and powdered activated carbon was added to the 156,000 gallon aeration contact tank in the secondary system. Spent carbon was continuously regenerated using the Zimpro wet air oxidation system. The two clarifiers were each 35 ft in diameter by 10 ft deep. A side stream from the clarifier went to a 2 ft^2 dual media gravity filter.

Spent carbon was withdrawn from the recycle sludge line, thickened, and was then recovered in the WAO unit.

The results of 51 days of steady state operation are summarized in Table 8.

Zimpro observed that it was possible to maintain a mixed liquor suspended solids concentration much higher than that of conventional activated sludge systems. In addition, the solids loadings on the clarifier was substantially higher than for a conventional activated sludge system. Both of these observations are attributed to the presence of a high concentration of powdered activated carbon.

Typical operating parameters include a MLSS concentration of 13,000 mg/l, MLVSS of 4000 mg/l, ML carbon concentration of 8000 mg/l, sludge residence time of 10-15 days, and a carbon dose of 120 mg/l.

A high degree of nitrification was observed as well as partial denitrification in the sedimentation basins.

The Zimpro system has been selected for installation on a full-scale basis at the Liverpool regional treatment plant in Ohio's Medina County near Cleveland.

Contact Stabilization-Carbon Systems[23,24]

In a study carried out at Battelle-Northwest, Olesen[23] studied a form of contact stabilization integrated with powdered carbon addition and chemical coagulation with alum. His system consisted of a 1 gpm bench scale unit which was operated to study system response to diurnal variations in the influent wastewater composition. The results of this study are summarized below.

Carbon Dosage mg/l	Influent TOC mg/l		Effluent TOC mg/l	
	Average	Range	Average	Range
600	57	26-164	1.5	0 -20
400	50	34-105	4.5	2.5-9
200	50	34-92	3	1 -6.5
100	53	30-80	9.5	3 -20
0	50	15-88	9.5	2 -28

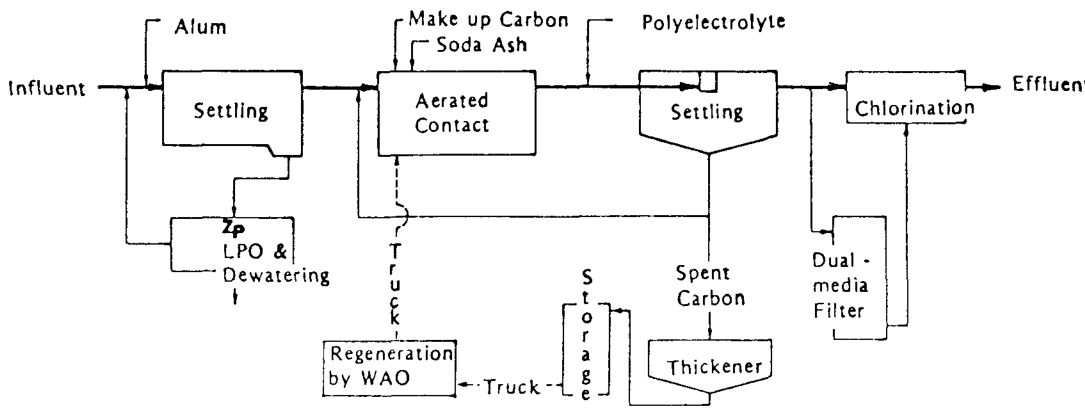


FIGURE 12. FULL-SCALE POWDERED CARBON TREATMENT AT ROTHSCHILD, WISCONSIN S.T.P.

TABLE 8

FULL-SCALE POWDERED CARBON TREATMENT AT ROTHSCHILD, WISCONSIN S.T.P.

	Average Values - mg/l			
	Raw Sewage	Primary Effluent	Clarifier Effluent	Filter Effluent
BOD	159	98	5.8	1.7
COD	319	208	55.8	17.5
SS	277	130	31.2	3.6
TKN	24.9	22.1	3.5	2.9
NH_3-N	17.6	17.9	1.7	1.7
P	8.8	7.4	2.2	1.7
NO_3-N	-	-	-	12.6

It was reported that the process was capable of producing an effluent with a COD of approximately 10 mg/l and a turbidity of less than 2 JTU with a very short system detention time.

More recent studies on powdered carbon addition contact stabilization systems have been carried out at the University of Washington on the laboratory scale.[24] It was concluded that the combined carbon contact stabilization system is capable of producing secondary effluent quality in a short detention time configuration. Hydrodarco H was the powdered activated carbon utilized in this study. It was estimated that at a Hydrodarco H dose of 150 mg/l and a contact time of 30 minutes the following effluent quality could be achieved:

Soluble COD	30 mg/l
Soluble BOD_5	10 mg/l
Suspended Solids	30 mg/l
Total COD	80 mg/l
Total BOD	26 mg/l

Larger scale studies of this process are planned in conjunction with a pilot study being carried on at Seattle METRO's West Point Plant.

SECTION 5

POWDERED CARBON REGENERATION

Several types of regeneration systems have been proposed for the regeneration of powdered activated carbon. Two methods, those employing the atomized suspension technique and the transport reactor, have been utilized on a full scale basis but not for regeneration of carbon used in wastewater treatment. These various regeneration schemes are discussed below.

ATOMIZED SUSPENDED TECHNIQUE (AST)[25-27]

The AST system has been commercialized by CPC International. A 4000 pound per day unit has been in operation at a CPC International corn syrup refining plant in Corpus Christi, Texas for several years. That firm now plans to install two 10,000 pound per day units in its plant in Argo, Illinois and is now licensing the technology for manufacture.

Very little publicly available information exists on the application of the AST system to regeneration of powdered activated carbon. A forerunner of the CPC system is described in a recent article by Prohacs and Barclay[25] and the CPC system itself in two U. S. patents.[26,27] Some of the information in this study was provided by CPC International representatives.

The AST system is shown schematically in Figure 13. Spent carbon is pumped in slurry form to a spray nozzle positioned at one end of a radiantly heated reaction vessel 1 to 3 feet in diameter and 10 to 50 feet high. The aqueous carbon suspension is atomized with steam provided from a steam supply line in the spray nozzle. The carbon is quickly heated to 1200°F in an oxygen free atmosphere of superheated steam. As the carbon particles drop in the chamber they are further heated, to as high as 1900°F, which destroys the organic contaminants on the carbon and causes them to volatilize. A convection tube is provided within the upper one tenth to one third of the reactor vessel to provide a more efficient heat exchange between the reactor vessel walls and the carbon slurry. The convection tube is open at both ends and is a shell of similar cross sectional geometry as the reactor vessel but provides a space between the reactor vessel wall and itself.

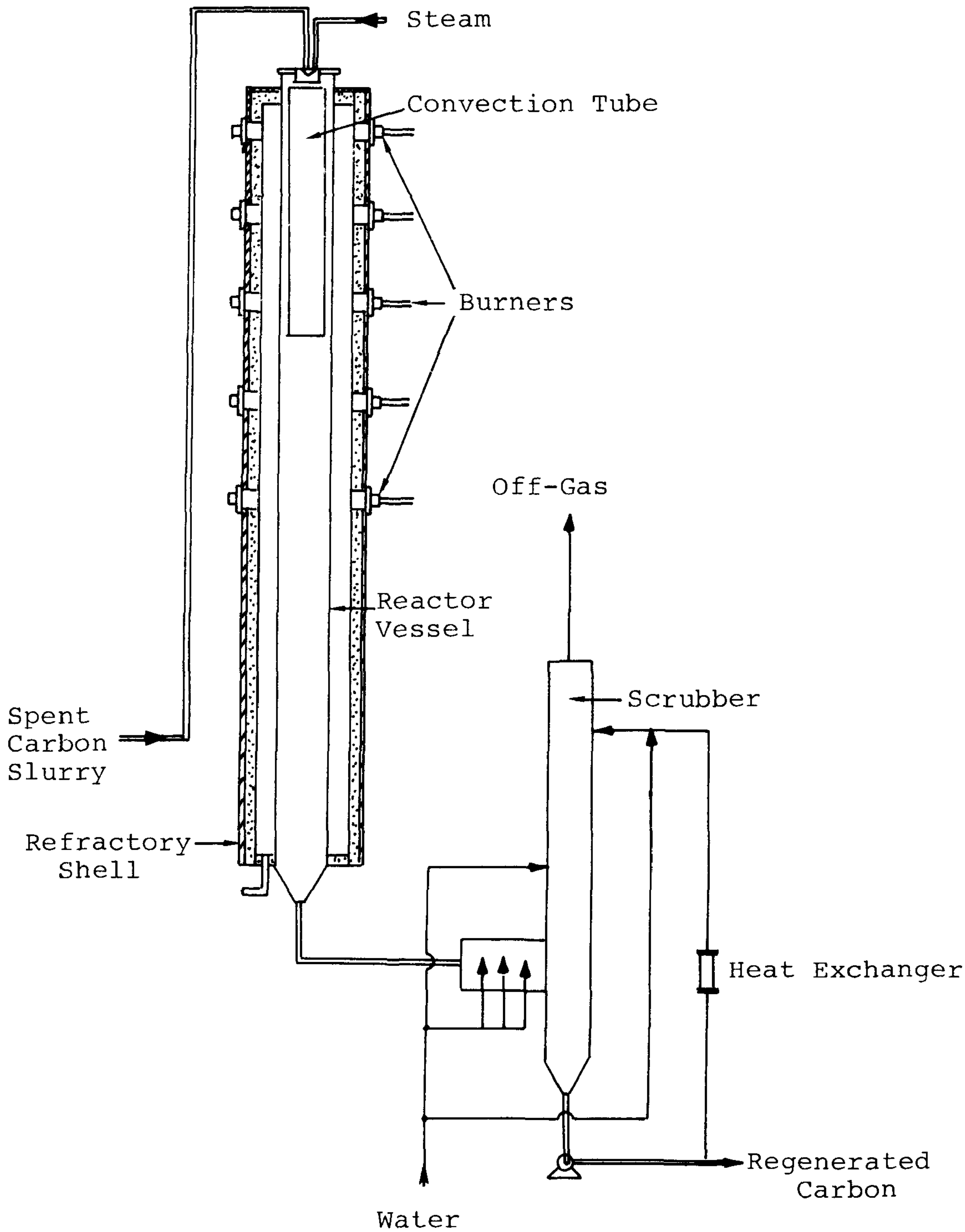


FIGURE 13. AST REGENERATION SYSTEM

As the stream of carbon particles suspended in superheated steam exit the convection tube, a major portion of the stream is recycled upward between the convection tube wall and the reactor vessel wall. Thus, by passing in close proximity to the reactor vessel wall, the temperature of this recycle stream approaches the reactor vessel wall temperature. Upon reaching the upper portion of the reactor, this stream is mixed with the incoming carbon suspension providing additional heating efficiency.

The residence time in the reactor is less than 30 seconds. It is suggested that pyrolysis gases from the process can be recovered and reused as fuel gas. Carbon losses of less than ten percent are reported.

BIOLOGICAL REGENERATION[28-31]

Fram Corporation of Providence, Rhode Island, has reported the development of a biological regeneration process for activated carbon. Although most of the effort in this area has been with granular activated carbon, some work with powdered activated carbon was performed. Subsequent to the original work, a completely separate company, Facet Enterprises of Warwick, Rhode Island, was established to market the patented biological carbon regeneration process. Representatives of Facet Enterprises indicated that work has been accomplished with powdered activated carbon but were unwilling to release any data for this study. Thus, this alternative could not be examined in any detail.

FLUID BED FURNACE[1,5,6,32,33]

The Fluidized Bed Furnace (FBF) is the regeneration system used by both Battelle-Northwest and Eimco in the powdered carbon systems previously described (see Figure 3). Early developmental work on this concept was carried out at the Columbus, Ohio laboratory of Battelle Memorial Institute.

The results obtained during the Battelle development study showed that efficient regeneration and recovery of spent powdered carbon could be achieved in a fluidized-bed system. Under proper operating conditions, the spent carbon could be regenerated to an active form as effective as virgin activated carbon in its ability to sorb organic components from a typical secondary sewage effluent. Recovery of the regenerated carbon was about 85 percent per regeneration cycle.

The following major conclusions were drawn from the development studies:

- A system utilizing an inert bed of fluidized solids through which the fine carbon is passed or a system employing pulsation of the fine carbon solids are equally effective from a technical standpoint.

- A temperature between 1000°F and 1500°F and a gas atmosphere containing nitrogen, oxygen, carbon dioxide, and water vapor are most effective for efficient regeneration of the spent carbon.

- Temperature is a primary variable; raising the temperature increases both the sorptive capacity and the weight losses of carbon during processing.

- Oxygen content is also a primary variable and should be held to a minimum to reduce carbon losses through combustion.

- From a practical standpoint, the fluidized inert bed system is the most feasible because of higher unit capacity when processing a relatively wet spent carbon feed.

- After 3.6 cycles of sorption and regeneration, the regenerated carbon is almost as effective as virgin carbon in removing total organic materials from secondary sewage effluent.

- Average carbon losses per regeneration cycle can be expected to be less than 15 percent in a continuously operated system.

- The overall physical performance of the fluidized-bed regeneration unit was excellent.

The Battelle-Northwest pilot plant in Albany, New York, provided a field evaluation of the FBF regeneration technique. The conclusion from several months of operation of the regeneration facility (see Figures 3 and 4) were:

- Powdered activated carbon can be successfully regenerated in a fluidized-bed furnace.

- Satisfactory regeneration can be achieved at a temperature of 1250°F with a stack gas oxygen concentration of less than 0.5 percent.

- After 6.7 regenerations, the regenerated carbon was as effective as virgin carbon in removing organic matter from raw sewage.

- Average carbon losses per regeneration cycle were 9.7 percent.

- Hearth plugging problems during pilot plant operations resulted from corrosion of the recycle gas system. Such corrosion problems can be precluded easily in design of a full scale system.

- Inert material buildup averaged 2.9 percent per cycle during the pilot plant operations. Sand carryover from the fluidized-bed furnace was believed to represent the most significant fraction of this buildup.

- Stack gases from the regeneration furnace should not present significant air pollution problems.

A FBF was extensively evaluated on a pilot scale by researchers at the Eimco Corporation.[5,6] A sketch of the pilot furnace is shown in Figure 14. The carbon cake was pumped directly into the fluidized sand bed which was maintained at an operating temperature of 1500 to 1700°F. The sand bed was maintained in a fluidized condition by the flow of hot gases from the firebox.

To prevent structural failure, the temperature in the firebox was maintained at less than 2100°F by using 150 percent excess air. The excess oxygen was then scavenged by combustion of fuel gas injected directly into the bed. A seven foot freeboard provided about seven seconds carbon detention time.

The hot gases and regenerated carbon were cooled from about 1600°F to 200°F by the addition of water (about 25 gpm) sprayed directly into the exit duct. After cooling, the gases and regenerated carbon were passed through two venturi scrubbers. Scrubber water flow was about 30 and 15 gpm, respectively. Although no data was collected on particulate emissions from the furnace stack, no visual evidence of carbon or particulate losses were observed. The scrubber water was collected in a carbon recovery and scrubber water recycle tank. The recycled scrubber water was passed through a heat exchanger, to prevent temperature buildup.

After regeneration, settled carbon was pumped to the inventory tank for volume and concentration data collection. It was then pumped to the carbon makeup tank for reuse.

Burner air and injection and burner gas flows were manually adjusted to provide the desired fluidization velocity and exit oxygen concentration. Carbon cake was automatically fed to the furnace at a rate necessary to maintain a preset bed temperature. Performance of the furnace was judged on the basis of carbon losses (total suspended solids) and regenerated carbon characteristics.

High carbon losses were experienced in the first series of runs and were attributed largely to various operational difficulties. However, it was concluded that certain furnace modifications would improve performance. Several modifications were made but high carbon losses persisted. Subsequently, it was concluded that the bed injection (BIG) principle was not workable. Therefore, the Eimco FBF was modified to incorporate the off gas

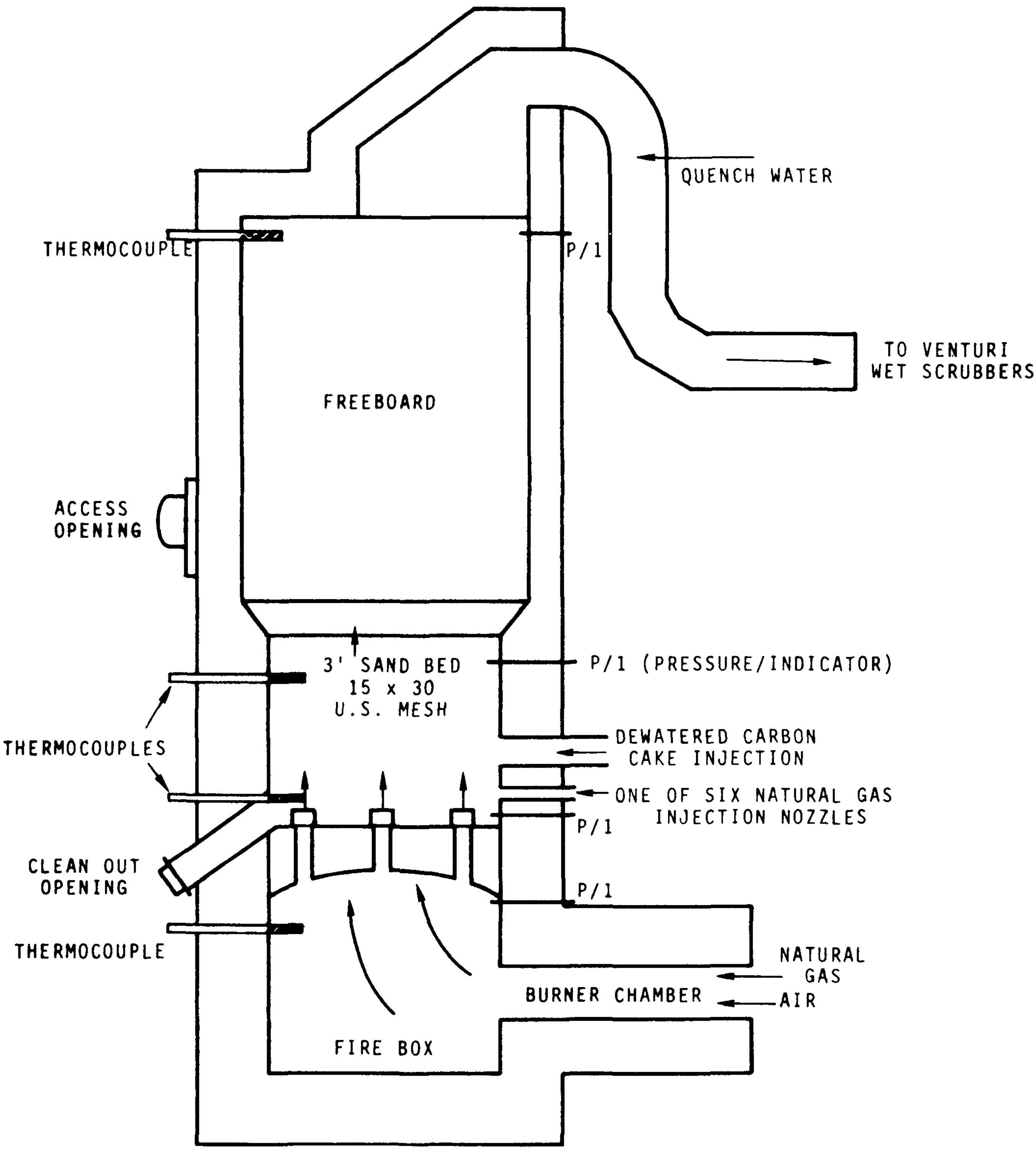


FIGURE 14. FLUIDIZED-BED REGENERATION FURNACE, EIMCO PILOT STUDY

recycle (OGR) principle utilized in the Battelle-Northwest study. The modified Eimco furnace is depicted in Figure 15. Table 9 shows furnace operating conditions and resulting losses for several runs with the modified furnace.

Upon completion of the runs with the modified furnace, it was concluded that the FBF regeneration system using the OGR principal of operation efficiently regenerated carbon. As indicated in Table 9, fixed carbon recoveries of 76 to 100 percent were experienced with an overall average in excess of 90 percent. Some loss of carbon adsorptive properties was experienced. The limited time during which efficient recoveries were experienced precluded being able to identify operating conditions which would maximize recovery of adsorptive properties for the system studied.

JPL PYROLYSIS[9-10]

The Jet Propulsion Laboratory's work on pyrolysis has been previously touched upon. As shown in Figure 6, settled carbon-sewage sludge from the primary clarifier is dewatered through a filter press to 35-40 percent solids and flash dried to 90 percent solids before entering an indirect-fired rotary calciner for pyrolysis and activation of the carbon-sewage solids to activated carbon and ash. Activated carbon is fed back to the secondary clarifier to complete the carbon recycle. A portion of the carbon-ash is purged from the carbon recycle to accommodate removal of the sand, clay, metals and other inorganic compounds present in the incoming sewage. The accompanying loss of activated carbon with the purge ash depends on the ash concentration established in the carbon recycle stream as well as on the level of ash (inorganic materials) in the incoming sewage. The energy value of the purged carbon can be recovered in a separate furnace by steam injection to make producer gas or by other means. Separation of ash and carbon derived from sewage processing by air or hydraulic classification including chemical assisted flotation has been unsuccessful to date. Acid washing at best removes 20 percent of the ash at considerable expense. Carbon losses with the ash purge constitute the largest single loss. Additional losses of carbon are found in the pyrolysis and activation of carbon. Conversion of sewage to activated carbon compensates to some extent for the losses, but it appears that activated carbon makeup is necessary from commercial sources, or by conversion of fuel or waste additions to activated carbon. Commercial activated carbon is expensive and cannot be justified as makeup in significant amounts (>5-10 percent). Refuse when pyrolyzed and activated results in significant ash concentrations in the product carbon (>70 percent). Lignite coal was selected for use in the process since it represents a source of low ash carbon with activation comparable to commercial activated carbons and also provides at low cost the necessary makeup energy to the system for operation of the calciner and flash dryer.

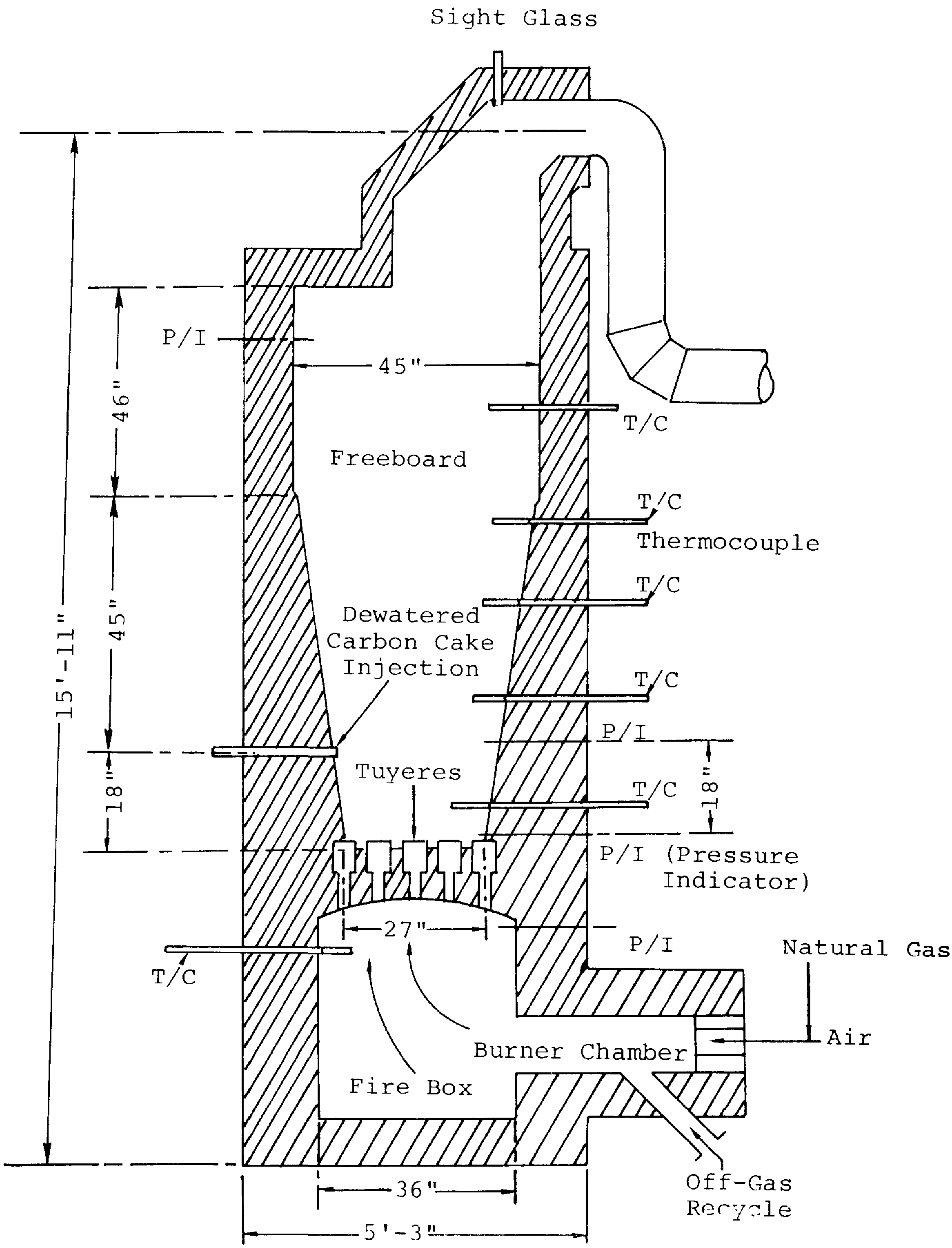


FIGURE 15. MODIFIED EIMCO FLUIDIZED-BED

TABLE 9

FLUIDIZED-BED FURNACE RESULTS
EIMCO PILOT STUDY

Run Number	6	7	8	9	11
Run Date, (1973)	June 17-18,	July 18-20,	Sept 11-13,	Oct 8-10,	Nov 2-3,
Pretreatment Chemical	Alum	$FeCl_3$	$FeCl_3$	$FeCl_3$	Alum
Operation Principal	OGR[a]	OGR	OGR	OGR	OGR
Feed Point (from Bed Floor), inc.	18	18	18	18	18
Sand Bed Depth, in:					
Static	32	32	36	-	-
Fluidized	-	44+	48+	-	-
Sand Size, US Mesh	16x30	16x30	16x30	16x30	16x30
Gas Flow, SCFM:					
Burner Air	80	90	85	90	93
Burner Gas	8	9	9.2	10	10
Off Gas Recycle	70	60	75	80	90
Gas Velocity, ft/sec:					
Bottom of Bed	2.0	2.2	2.2	2.7	2.9
Freeboard[b]	0.8	1.0	1.0[c]	1.1	1.1
Run Length, hr	30.7	28.3	21.5	51.7	46.0
Feed Rate, dry lb/hr	21	27	37	16	13
Moisture in Feed, % by weight	76	76	76[a]	73	72
Average Temperature, °F:					
Freeboard	1130	1330	1170	1470	1470
Sand Bed	1250	1400	1250	1550	1550
Firebox	1900	1970	1960	2000	2000
Average Pressure, in. of H_2O:					
Freeboard	-4	-3	-3	-1	0
Firebox	57	64	72	70	68
Average O_2 Content of Stack Gas, % by Volume	0.3	0.3	0.3	0.0	0.1
Fixed Carbon Recovery, %	100	78	93	100	76

a - off gas recycle
b - includes water vapor
c - estimated

The inclusion of a flash dryer is considered extremely important for achieving high thermal efficiencies (~70 percent) for carbon-sewage sludge drying, pyrolysis and activation with an indirect-fired rotary calciner. JPL concluded that although direct-fired furnaces such as rotary kilns and multiple-hearths provide high thermal efficiencies independent of a flash dryer, they are subject to high powdered carbon losses in the stack gases as well as high carbon oxidation losses from air leaks and/or oxidation flames. In addition, they felt that the multiple-hearth units are expensive relative to rotary calciners. Preliminary cost evaluations suggested a factor of 2 to 3 difference in installed equipment costs. Other cost factors such as equipment life and maintenance charges alter the impact of initial equipment cost differences on the overall process economics.

Pyrolysis and activation tests were conducted in pilot test equipment including direct fired rotary kiln, indirect-fired rotary calciners and multiple-hearth reactor, Table 10. Initial testing was conducted at Versa-Tech, Louisville, Kentucky, in a 6 1/2 inch I.D. by 7-foot long by 3-foot electrically heated rotary calciner. Feed rates were at 5.7 to 9.7 lb/hr of wet (31-48 percent moisture) carbon-sewage with a retention time of 9 to 14 minutes at wall temperatures of 650-760°C. Steam activation was low because of operational problems with the amount and temperature of steam injected. However, despite the mechanical problems of operation, carbon-sewage sludge was pyrolyzed and activated. Activation was low. Iodine absorption was measured at 288 to 367 mg/gram carbon. The low activation was accompanied by a corresponding high yield of carbon, 98 to 127 percent based on the activated carbon feed.

Later tests were conducted at the Combustion Engineering test facility at Springfield, Ohio. An uninterrupted 50 hour test was conducted on a 6 1/2 inch I.D. by 11-foot long, 6-foot natural gas fired rotary calciner. Feed rates were 8 to 10 lb/hr with a very wet (73 percent moisture) carbon-sewage. Temperatures were varied from 600 to 900°C, solids retention time from 10 to 20 minutes and steam rates from 0 to 1.3 lb/hr. The resulting carbon activation had an iodine adsorption of 330-590 mg/gram carbon. Yields were from 65 to 125 percent based on activated carbon feed. Hourly samples were taken of product carbon and analyzed for iodine adsorption and ash content. Product discharge was segregated and weighed on an hourly basis. Very close monitoring of the operation was achieved. Initial operation was at 600°C and then increased by 100°C increments. It was readily evident that temperatures below 800°C were inadequate for pyrolysis and activation. The product carbon especially at the lower temperatures of 600 and 700°C retained some of the sewage odor and showed very low activation. Test results in the region of 800 to 900°C were very promising for obtaining good pyrolysis and activation. At 15-minutes retention time and 830-850°C, there appeared to be a threshold condition for carbon activation.

TABLE 10

PYROLYSIS AND ACTIVATION OF CARBON-SEWAGE IN PILOT TEST EQUIPMENT

Equipment	Carbon-Sewage Reactor Feed	Conditions	Resultant Carbon: Activity Iodine (mg/g)	Resultant Carbon: Yield[2] %
6 1/2 in. I.D. x 7 ft long, 3 ft Electrically Heated Rotary Calciner, Versa Tech, Louisville, KY	Carbon[1]/Sewage, 1.2, 1.3 Moisture - 31, 48% 5.7 - 9.7 lb/hr	5 Runs, 1-3 hr/Run Solids Retention, 9-14 min Wall Temp. - 800, 860°C Gas Temp. - 650, 760°C Steam, 0-0.4 lb/hr Nitrogen, 1-4 ft^3/hr	288-367	98-127
6 1/2 in. I.D. x 11 ft long 6 ft Natural Gas Heated Rotary Calciner, Combustion Engineering, Springfield OH	Carbon[1]/Sewage, 0.6-1.8 Moisture - 73% 8-10 lb/hr	50 hr Operation Solids Retention, 10-20 min Solids Temp. - 600-900°C Steam, 0-1.3 lb/hr Nitrogen, 1-10 ft^3/hr	330-590	65-125
15 in. I.D. x 12 ft long Natural Gas-Fired Rotary Kiln, Combustion Engineering Springfield, OH	Carbon[1]/Sewage, ∿1.0 Moisture - 73% 30 lb/hr	2 hr Operation Solids Retnetion ∿10 min Temp. - 850°C	Negative Results From Air Leaks and Large Vent Losses	
36 in. I.D. x 6 Hearth Furnace with 2 1/2 Hearths in Place, Direct Natural Gas Fired. Nichols Eng. & Res. Co., Belle Mead, NJ	Carbon[1]/Sewage 0.5-2.0 Moisture, 58-72% 75 lb/hr, 5000 lb/total	66 hr Operation Solids Retention ∿30 min Gas Temp. - 840-950°C Steam - 0 lb/hr	350-600	70-126

1-Darco G-60 (Iodine AbS. = 464 mg/gram)
2-% Yield = (Carbon Out/ Carbon in) x 100

A temperature of 850°C indicated significantly higher activation and lower yields than operation at 830°C. Increased retention time (20 minutes) at 830°C was found to increase the extent of activation but not as greatly as a temperature increase from 830 to 850°C.

A short duration test was attempted in a 15-inch diameter by 12-foot long natural gas, direct-fired rotary kiln. Feed was 30 lb/hr for a 10 minute retention time at 850°C. This test was unsuccessful but it did emphasize some negative aspects of the direct-fired rotary kiln for carbon-sewage pyrolysis and activation.

Approximately 5000 pounds of wet carbon-sewage sludge (58-72 percent moisture) was used for 66 hours of operation of a multiple-hearth reactor at Nichols Engineering and Research Company, Belle Mead, New Jersey. Tests were conducted in a 36-inch I.D. by 6 hearth reactor with the top 3 1/2 hearths removed. This change allowed operation at a feed rate of 75 lb/hr. A dry cyclone on the exhaust gases provided for capture of powdered carbon leaving the multiple hearth with the exhaust gases. This was followed by a water scrubber and afterburner. Operation of the multiple hearth was carried out with the after-burner both "on" and "off." Approximately 5 to 20 percent of the product carbon was recovered in the dry cyclone and wet scrubber as carry-over from the multiple hearth by the exhaust gases.

Initial operation of the multiple-hearth was conducted at a combustion gas temperature of 950°C with the bed temperature 100°C lower. Under these conditions, activation of the carbon was high, iodine adsorption was greater than 1000 mg/gram carbon, but yields were low (70 percent or less, yield based on activated carbon feed). To improve carbon yield, gas temperatures were reduced to 840°C. Carbon activation was accordingly reduced, iodine adsorption was reduced to 350 mg/gram carbon, and yields increased up to 126 percent (activated carbon feed). The combination of feed rate and rabble arm rotation at 1 RPM provided approximately 30 minutes solids retention in the multiple hearth. Care was exercised to maintain the multiple hearth at a slightly positive pressure to eliminate air leaks. Burners were kept slightly fuel rich (up to 10 percent excess fuel) to maintain a reducing flame. With these provisions, the test results of carbon activation and yield from the multiple-hearth reactor corresponded to that obtained in the rotary calciner. Since the combustion gases firing the multiple hearth contained approximately 20 percent moisture, no need was found for separate steam injection. Achieving carbon activation was not a problem with proper activation temperatures.

Gas samples of off-gas were obtained from the gas holder at Versa-Tech in the operation of the electrically heated rotary calciner and also from the off-gas line of the gas-fired rotary calciner at Combustion Engineer's test facility. The gas analyses are presented on a dry and nitrogen free basis in Table 11. The energy value of this gas was approximately 300 Btu/ft^3.

MULTIPLE-HEARTH FURNACE

Multiple-hearth furnaces of the type illustrated in Figure 16 have been used extensively for the regeneration of granular activated carbon. Although it is known that Nichols Engineering and Research have carried out some studies on regeneration of spent powdered activated carbon used in municipal wastewater treatment, no published information could be discovered on the use of this system to regenerate powdered activated carbon. However, a multiple-hearth furnace is under construction at DuPont's Chambers Works Plant for regeneration of spent carbon from the PACT process. DuPont selected this method after detailed study of several alternative regeneration techniques.

TRANSPORT SYSTEM[34-36]

Westvaco Corporation has developed and commercialized a patented method for powdered carbon regeneration (U. S. Patent 3,647,716). A 20,000 lb per day unit was placed in operation at Covington, Virginia, in early 1971 to regenerate spent carbon from corn syrup refineries. A schematic of the system is shown in Figure 17.

Spent carbon feed at Covington is a sticky solid of approximately 50 percent moisture exhibiting extremely poor flow properties. To assure reliable feeding, a bin activator is utilized to withdraw spent carbon from a 24 hour storage tank. The bin activator serves a weigh belt feeder which in turn discharges the metered feed through a rotary air lock and into a pneumatic mixing tube.

The carbon is dispersed and suspended by a metered oxidizing air stream and pneumaticaly conveyed to the top of a vertical venturi-type section inside the furnace. Steam may also be utilized as the oxidizing stream on carbons with low organic loading. High velocity, high-temperature flue gas enters just below the venturi section and intensively mixes with the carbon-water-air stream above the venturi, resulting in instantaneous heat transfer and optimum gas/solid contacting.

The reactor process steps are drying, volatilization of organics, burning of volatiles, and steam activation of residual carbon. These steps occur almost simultaneously in the reactor above the venturi section in the space of a few seconds. The steam selectively activates any carbon residue left in the carbon micropore structure. Overall reactor temperature for these steps is 1,750 to 1,850°F, depending on spent carbon loading.

TABLE 11

GAS CHROMATOGRAPH ANALYSIS OF CARBON-SEWAGE PYROLYSIS AND ACTIVATION OFF-GAS

Off-Gases* (Vol %)	Test Date** 1-1/20/75	2-1/20/75	3-1/21/75	4-1/22/75	5-1/23/75	4/29/75
CO_2	-	17.5	19.1	17.0	18.2	21.1
H_2	11.9	30.9	34.6	41.6	38.7	44.2
O_2	0.2	0.2	0.2	0.2	0.4	1.1
CH_4	13.05	16.7	13.2	11.4	11.0	10.3
CO	13.8	20.7	18.2	19.7	17.1	17.4
C_2H_6	-	0.2	-	0.2	0.2	-
C_2H_4	-	-	-	3.4	-	3.3
C_3H_6	-	-	-	-	-	0.7
Total Accounting	38.9	87.0	86.3	93.5	85.6	98.1

*Corrected for Nitrogen, Water
**1/20-23/75, Versa-Tech Results: 4/29/75, Combustion, Engineering Test Results.

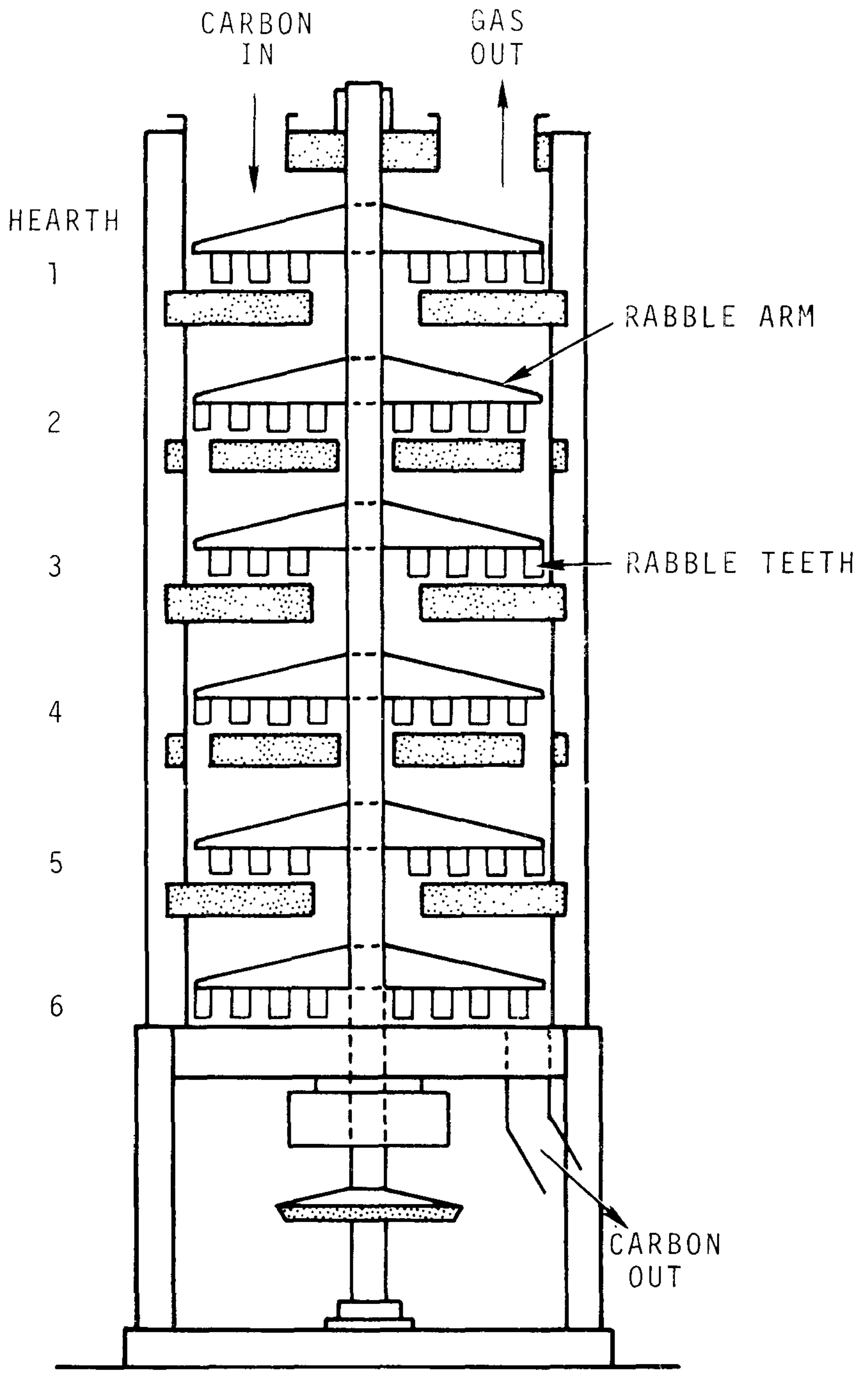


FIGURE 16. CROSS-SECTIONAL VIEW OF MULTIPLE HEARTH FURNACE

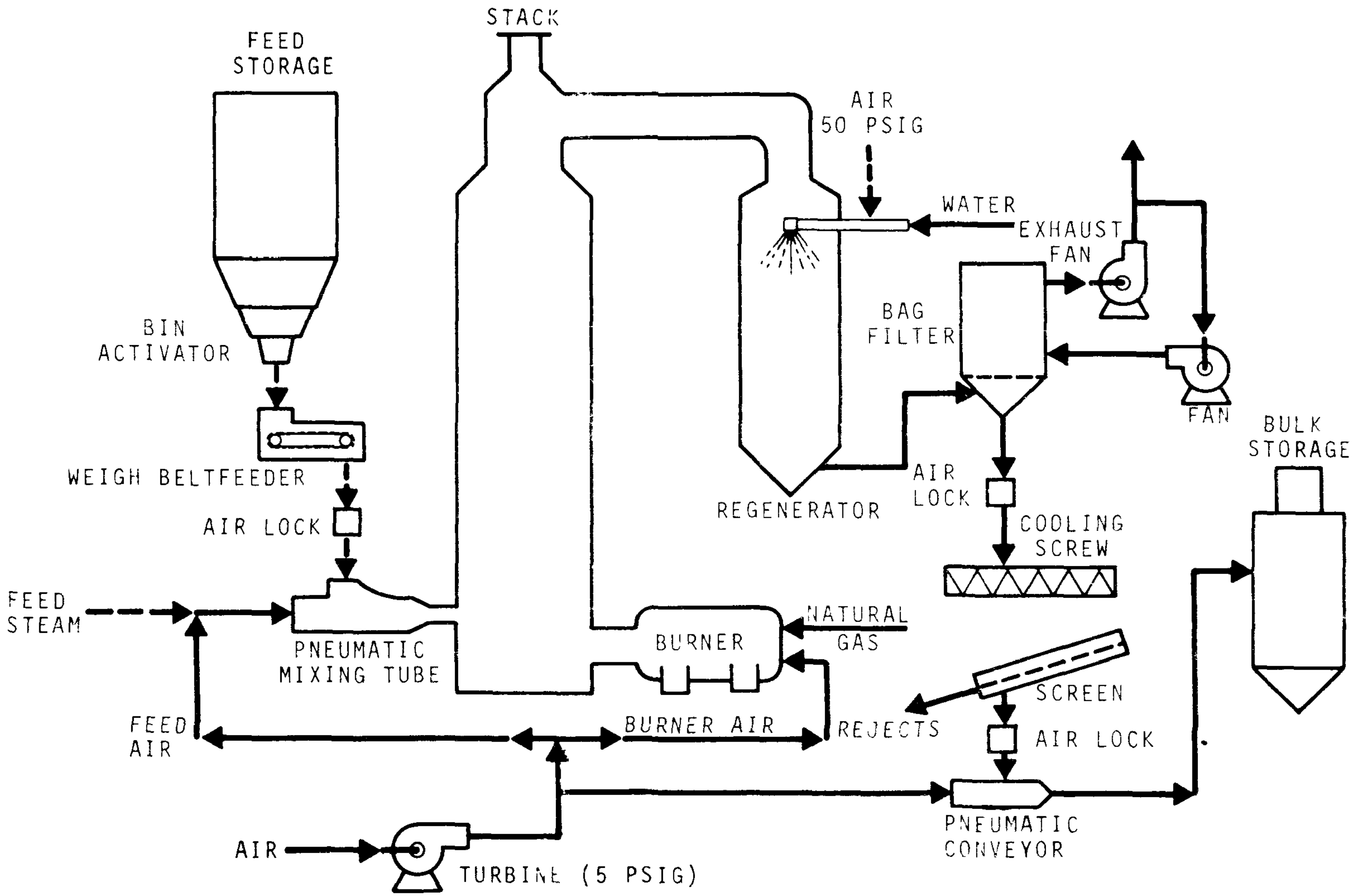


FIGURE 17. SCHEMATIC OF THE WESTVACO POWDERED CARBON REGENERATION SYSTEM

In the 10-ton per day unit at Covington, no more than 1 lb of carbon is suspended in the furnace at any instant, allowing almost immediate response to control changes.

Good control of the sorptive activity of the regenerated carbon is maintained by careful attention to temperature, feed rate, and the air-to-feed ratio in the reactor. Once the proper conditions of feed rate, temperature and firing rate have been set, the process is reported to be extremely steady, and only minute trimming adjustments are necessary to hold the activity and yields in the desired range. Loadings of organic impurities in the range of 10-50 percent of the weight of the original carbon can be burned off with very little loss. It is generally possible to keep yields in the range of 75-95 percent, with lower loadings favoring higher carbon yields. For corn syrup spent-carbon, a yield relative to the amount of original carbon used in the process is about 80-90 percent.

Suspended particles at 1,800°F exit the reactor via a horizontal refractory-lined duct to a downflow evaporative cooler in which the gas stream is cooled to 450°F with a three-compartment glass-cloth bag filter. The carbon is continuously discharged by air locks, conveyed by a water-cooled screw conveyor, and screened for any foreign material. A pneumatic conveyor then delivers the regenerated carbon to bulk storage tanks.

Due to the high steam volume, all interior surfaces in the bag filter must be kept above the gas dewpoint. Dry collection was selected at Covington because the product is shipped to users by rail. Wet scrubber collection is considered practical and should result in capital savings if carbon is used onsite and stored in slurry form.

By July 1973, the Covington operation was treating 12.5 tons per day of carbon from two corn syrup refineries with plans to serve as many as seven refineries in the near future. The operation of the regeneration furnace is now considered routine and is considered to be a part of the production capacity at Covington. The major problem, now overcome, arose during the initial operation and was related to slagging. Some of the slag was resulting from silica filter aids used in the corn industry. This problem was resolved by shutting down the furnace once per week and removing the slag (about 100 lb per week) from the bottom of the furnace as a routine function. The other initial source of slag was found to be caused by leaching of nickel from the stainless-steel shell. This has been solved by installing refractories within the shell.

The Westvaco transport system for powdered carbon regeneration was piloted in conjunction with a pilot study of the DuPont PACT process. In this application, a mixture (approximately

50-50) of waste activated sludge and powdered carbon were supplied to the furnace. No data on the pilot study were made available for use in this study.

WET AIR OXIDATION[20-22,37]

Zimpro, Inc., has investigated the feasibility of applying their Wet Air Oxidation process to regeneration of powdered activated carbon used in wastewater treatment. The regeneration process developed by Zimpro is shown in Figure 18.

The flow scheme for carbon regeneration is similar to that used by Zimpro in the wet air oxidation of sewage sludge and industrial wastes. Spent carbon is withdrawn from the wastewater contact system and concentrated by gravity thickening.

Thickened spent carbon slurry at approximately 6-8 percent solids is pressurized to system pressure, mixed with compressed air and heated to a reaction temperature in the heat exchangers. Heated air and spent carbon slurry are conveyed to a reactor where selective oxidation and a consequent temperature rise occurs. Hot spent gases and regenerated slurry continuously pass out of the reactor through the heat exchangers where they are cooled while heating the incoming slurry and air. Cooled gases and regenerated carbon slurry are released directly back into the wastewater flow stream via a pressure control valve. The regeneration system is designed to be thermally self sustaining so steam injection from an auxiliary boiler is required only during start-up.

The system temperature is maintained in the 390-470°F range at a pressure of 700-750 psi. Temperature can be controlled by bypassing the heat exchanger or by multiple point air addition. Turbulence created by air addition is thought to prevent and breakdown scale in the system, thus providing a self cleaning feature. It also improves the heat transfer.

Zimpro has reported on several pilot and full scale projects which have involved the use of wet air oxidation for carbon regeneration. In one of these the wastewater treatment involved a CBC process that utilized powdered activated carbon and bacteria indigenous to sewage in a conventional activated sludge type flow scheme. The raw waste was a domestic sewage with a variety of industrial contributions. Spent carbon, consisting of about three parts of activated carbon solids to one part biomass was regenerated in a continuous wet air oxidation unit.

During an in-process study, several regeneration conditions were applied, the one of maximum severity resulting in a fixed carbon loss of less than nine percent. Solids were isolated from the regenerated carbon slurries, dried and examined for response to four selected chemical tests. Table 12 shows the results.

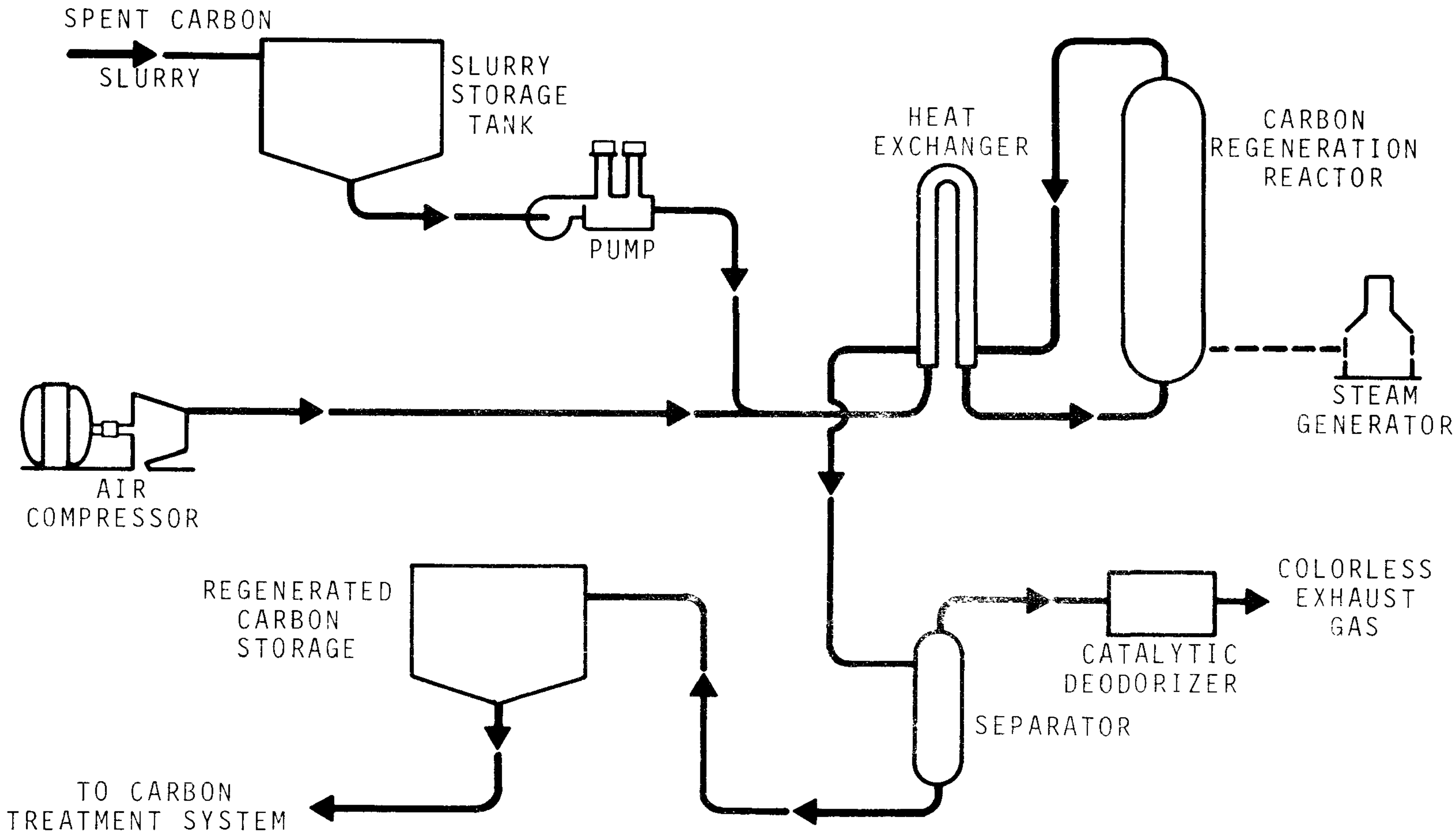


FIGURE 18. ZIMPRO CARBON REGENERATION FLOW DIAGRAM

The progressive increases in all relative efficiencies shows that the activated carbon, although loaded with impurities and mixed with biomass, can be processed by a continuous wet air oxidation reactor to give regenerated solids responding well to classical activated carbon tests. Relative efficiencies for methylene blue, erythrosin, and molasses color are restored to a greater extent than that of iodine.

The ash content change was from 6.0 percent to about 11.0 percent in each case.

In the second study, a full-scale chemical-CBC treatment was conducted by slightly modifying the conventional primary-activated sludge plant. The wastewater was a domestic sewage heavily loaded with a paper mill waste containing clays, titanium dioxide, and polymer latex. Treatment with alum and soda ash to neutralize the alum was accomplished prior to the CBC process.

The spent carbon slurry was regenerated by a continuous, full-scale wet air oxidation unit under three conditions with fixed carbon recoveries of 97, 97, and 91 percent. Table 13 shows the results of the four chemical adsorptions and BET total specific surface determination.

TABLE 12

PROPERTIES OF REGENERATED CARBON
FROM A BIO-PHYSICAL PROCESS

Condition	A	B	C	D	E
Adsorbate Relative Efficiencies, %					
Iodine	24.0	29.2	30.4	52.9	56.3
Methylene Blue	24.2	24.2	31.2	63.3	65.3
Erythrosin	38.8	35.6	50.6	82.0	129.0
Molasses Color	65.7	74.2	83.5	94.7	95.7
Percent Ash in* 100% Dry Solid	11.1	11.1	10.8	11.0	11.4

*Parent Carbon percent ash, 100 percent dry solid basis = 6.0%

TABLE 13

PROPERTIES OF CARBON REGENERATED FROM A
CHEMICAL BIO-PHYSICAL PROCESS

Condition	A	B	C
Adsorbate Relative Efficiencies, %			
Iodine	32.8	48.9	57.6
Methylene Blue	68.5	95.7	119.6
Erythrosin	46.5	91.0	95.4
Molasses Color	85.6	90.8	93.9
Recovery of BET Surface, %	58.6	52.8	74.8
% Ash, 100% Dry Solid Basis	68.0	68.2	75.3

SECTION 6

BASE CASE SELECTION

At the beginning of the program, available published literature on powdered activated carbon wastewater treatment and regeneration technology was reviewed and pertinent data extracted. Following review of the data, personal contacts were made with firms and researchers responsible for original development studies on powdered activated carbon treatment and regeneration systems. These personal contacts involved both telephone interviews and site visits. Organizations contacted during the course of the program are as follows:

CPC International

EI DuPont de Nemours & Company

Envirotech Corporation

Facet Enterprises, Inc.

ICI United States

Infilco

Jet Propulsion Laboratory

Neptune Microfloc

Nichols Research and Engineering

Orange County Sanitation District

University of Washington

Westvaco Corporation

Zimpro Incorporated

The activities of these organizations as related to powdered activated carbon technology have been previously discussed. Interviews with individuals active in the field provided additional insight into the intricacies of the various technologies.

Prior to commencing the study, it had been hoped that a single base case could be selected for the economic analysis. This selection was to be based on technical evaluations of the merits of the various technologies. It soon became obvious, however, that selection of a single base case, while possible, would not provide the comprehensive analysis desired. No one process scheme clearly exceeded all others in performance. In fact, most of the processes reportedly were capable of producing high quality effluents. Moreover, the characteristics of the various processes are vastly different and the development efforts have proceeded along distinctly different lines at different locations. Therefore, it was decided to perform the economic analysis for at least one IPC system and one CBC system. After more detailed evaluation, two IPC systems and one CBC system were finally selected as discussed below.

A similar problem exists with regard to evaluating the quality of carbons regenerated by different techniques. Although data exist on losses and recoveries of quantities of carbon in different regeneration systems and under different operating conditions, no standard test exists by which the effectiveness of regenerated carbons in wastewater treatment can be measured. None of the classic tests such as iodine, phenol, methylene blue, erythrosin, molassess color, or BET can be used to accurately predict the performance of activated carbon in any of the wastewater treatment processes studied. Therefore, the evaluation of various carbon regeneration studies carried out at different locations under different circumstances is extremely difficult.

IPC SYSTEMS

Two stage countercurrent contacting theoretically provides for the most efficient use of powdered activated carbon. Both Infilco, in their work and Eimco, in their work on chemically clarified raw sewage, employed this approach as did studies on secondary effluent treatment conducted by the EPA at Lebanon, Ohio.[38] Thus, it was considered important to include a two stage countercurrent system in the economic analysis. Of the development efforts incorporating this approach, the Eimco study represented the largest scale pilot operation, generated the largest body of data, operated for the longest period of time, and was the only program in which carbon regeneration was carried out on a large scale. It also represented a system in which phosphorous removal was accomplished. Therefore, one of the base case systems was patterned after the Eimco flowsheet.

The Battelle-Northwest process was also selected as a base case system because it represented a widely different approach which had been successfully piloted on a large scale. This process being a single stage, short detention time type system represented a low capital cost approach. In addition, a large body of data existed for use in this study.

The JPL system was not chosen as one of the base cases for several reasons. Only a limited quantity of data was available to this study. In addition, a larger scale demonstration program will be underway in the near future. This program should generate much better information on design and operating parameters, and process performance than is presently available. Thus, it was concluded that detailed analysis of the JPL system should be delayed until completion of the demonstration program.

CBC SYSTEMS

Only a limited quantity of data, much of it unpublished and most of it on the bench scale, is available at this time on the contact stabilization-powdered activated carbon system. Based on work to date, this approach appears to be very promising but was not considered to be at a stage of development for consideration in this analysis.

DuPon't PACT process, Zimpro's bio-physical process, and ICI's several studies have many similarities. The liquid treatment scheme is the same basic concept in all cases. However, most of duPont's work has been with industrial wastes. Zimpro, on the other hand, has generated much data on municipal waste. Therefore, the base case selected for the economic analysis was patterened most closely after Zimpro's bio-physical system. It should be recognized, however, that the main difference is in the regeneration systems and thus the economic analysis of the liquid treatment system should provide insight into the PACT process economics and activated sludge-powdered carbon systems in general.

REGENERATION SYSTEMS

For each of the base systems, the regeneration system utilized in the original developmental work was maintained for the economic analysis. This provided a system for which actual field data existed for a regeneration system working in concert with a treatment system. Thus, a FBF was selected for the Battelle and Eimco systems, and a wet oxidation system in the case of the CBC system.

Although pilot data was generated for the transport system, working in conjunction with the DuPont PACT process, it was not made available for use in this study.

Nichols Research and Engineering provided information which enabled an economic analysis to be performed for the multiple hearth furnace for all of the base case processes. CPC International did the same for the AST system. It should be noted, however, that actual pilot plant experience for these two systems working in conjunction with the various wastewater treatment systems does not exist and that there is a greater degree of uncertainty in the economic analyses in these latter cases. For the multiple hearth furnace full scale operational experience will soon be forthcoming at duPont's Chambers Works.

In summary, three thermal regeneration processes and the wet oxidation process are included in the analysis.

SECTION 7

PROCESSES EVALUATED

In order to determine the economic competitiveness of powdered activated carbon processes in the municipal wastewater treatment field, the costs of the following processes were evaluated for plant capacities of 1, 5, 10, 25, and 50 MGD.

- Activated sludge, conventional.
- Activated sludge, single stage for nitrification.
- Activated sludge, conventional followed by chemical coagulation, sedimentation, and filtration.
- Granular carbon treatment of chemically coagulated, settled, and filtered raw wastewater.
- Powdered carbon treatment of raw wastewater in a two-stage system as developed by Eimco.
- Powdered carbon treatment of raw wastewater in a single-stage system as developed by Battelle-Northwest.
- Powdered carbon addition to the aeration basin of the activated sludge process in a bio-physical process.

The assumed raw wastewater composition is shown in Table 14. Table 15 presents estimated effluent quality parameters for primary treatment and for the other processes evaluated. This table should be used with caution since the values given are only estimates. A higher degree of uncertainty exists in the case of the powdered carbon systems since the estimates were derived on the basis of extrapolations of data generated in developmental studies.

Process flowsheets and design parameters are given in the next section with the corresponding economic data.

TABLE 14

ASSUMED COMPOSITION OF RAW WASTEWATER
(VALUES IN mg/l UNLESS INDICATED)

	Raw Sewage
Solids, Total	700
Dissolved Solids, Total	500
Fixed	300
Volatile	200
Suspended Solids, Total	200
Fixed	50
Volatile	150
Settleable Solids ml/l	10
BOD_5-20°C	200
TOC	200
COD	500
Total N	40
Organic N	15
Free Ammonia	25
Nitrites	0
Nitrates	0
Total P	10
Organic P	3
Inorganic P	7

TABLE 15

ESTIMATED PROCESS EFFLUENT QUALITY CHARACTERISTICS

	Primary Treatment	Activated Sludge	Activated Sludge Nitrification	Activated Sludge and Coagulation and Filtration	Granular Carbon System	Eimco Process	Battelle Process	Bio-Physical Process
BOD (mg/l	140	25	15	15	20	20	20	20
Suspended Solids (mg/l)	70	25	15	0.5	7	10	10	20
Total P (mg/l)	9.8	6.7	6.7	0.1	0.1	0.3	6.7	6.7
Total N (mg/l)	32	25	25	25	25	25	25	28
NH_3-N (mg/l)	25	23	1	23	23	23	23	3
NO_3-N (mg/l)	-	-	23	-	-	-	-	18

SECTION 8

PROCESS ECONOMICS

BASIS FOR COST ESTIMATES

The Appendix contains the cost curves used as the basis for cost estimates in this report. Some of these curves were developed for EPA by CWC under Task Order 3 of EPA Contract 68-03-2186. Many other curves were developed specifically for this evaluation. The cost curves are based on fourth quarter 1975 cost levels.

The capital cost curves for each unit process do include an allowance (25 percent) for contractors overhead and profit and a 15 percent contingency allowance. In addition, each includes an allowance for a proportional share of overall plant electrical system costs. Experience indicates that a 15 percent allowance for electrical system costs is reasonable. Blanket application of this allowance to each unit process may result in some inequities in electrical system cost allocation among the unit processes but when the treatment system cost components are added together, any such inequities will be balanced. Also, each unit process includes a 15 percent allowance for miscellaneous items to account for items associated with a unit process that would be defined in a unit takeoff from construction drawings for the entire plant but which cannot otherwise be accurately defined. Construction labor was estimated from the Richardson Estimating and Engineering Standards. In some cases, the labor required to install manufactured equipment was estimated by the manufacturer. Where such estimates were not available, the cost of labor for equipment installation was estimated as 35 percent of the equipment costs. The capital cost curves presented do not include an allowance for costs of engineering, legal, fiscal, administrative, financing during construction, or yardwork related to interconnecting the various unit processes. These factors are added to the subtotals determined from the curves.

The following sections present the detailed cost estimates for each of the processes evaluated. The report then concludes with a section which analyzes the relative economics of the various processes. Because the powdered carbon processes have not been widely applied and experience is largely on the pilot scale, the potential effects of changes in the assumed critical design or operating parameters and costs are also discussed.

Some assumptions are common to all of the processes. It was assumed for the comparative, base cases that all sludges would be incinerated for all alternative processes. The potential impact of other methods of waste sludge disposal on the relative economics is discussed in the last section of the report. General administrative O&M costs (management, clerical, laboratory analysis, yardwork, etc.) were not included in any of the alternatives. The differences in these costs between alternatives would be small (or non-existant in many cases) and would have no significant effect on the relative economics of the processes. Land costs are not included in the base cases but the last section discusses the impact that relative space requirements of the various alternatives could have on the relative economics based on varying land values.

ACTIVATED SLUDGE, CONVENTIONAL

Design Basis

The activated sludge system schematic is shown in Figure 19. The major unit processes are primary sedimentation, activated sludge aeration and secondary sedimentation, chlorination, gravity thickening of primary sludge, dissolved air flotation thickening of waste activated sludge, vacuum filtration of the two thickened sludges, and incineration of the dewatered sludges. Effluent filtration and ultimate sludge ash disposal were not included in this analysis. Provisions for standby units were not included.

The design conditions for raw wastewater characteristics and the primary sedimentation tank design with expected primary effluent quality are shown in Table 16.

Using these primary effluent data and McKinney's model,[39] the activated sludge system design criteria were developed. The aeration system design was limited to a maximum oxygen uptake rate of 70 mg/l/hr. A mean cell residence time of five days was used. The return activated sludge pumps were sized for a one percent sludge concentration and completing a system solids balance. The secondary sedimentation basins were sized based on hydraulic overflow rate of 600 gal/ft^2/day at average flow. The resultant design parameters are shown in Table 17. The chlorine contact basins are sized for a 30 minute detention time at peak dry weather flow (PDWF, 1.5 times design flow). A dosage rate of 10 mg/l was applied to the PDWF for sizing feed equipment.

The gravity thickener sizing is based on a solids loading of 20 lb/ft^2/day. Solids concentrations of five percent (influent) and ten percent (underflow) were assumed.

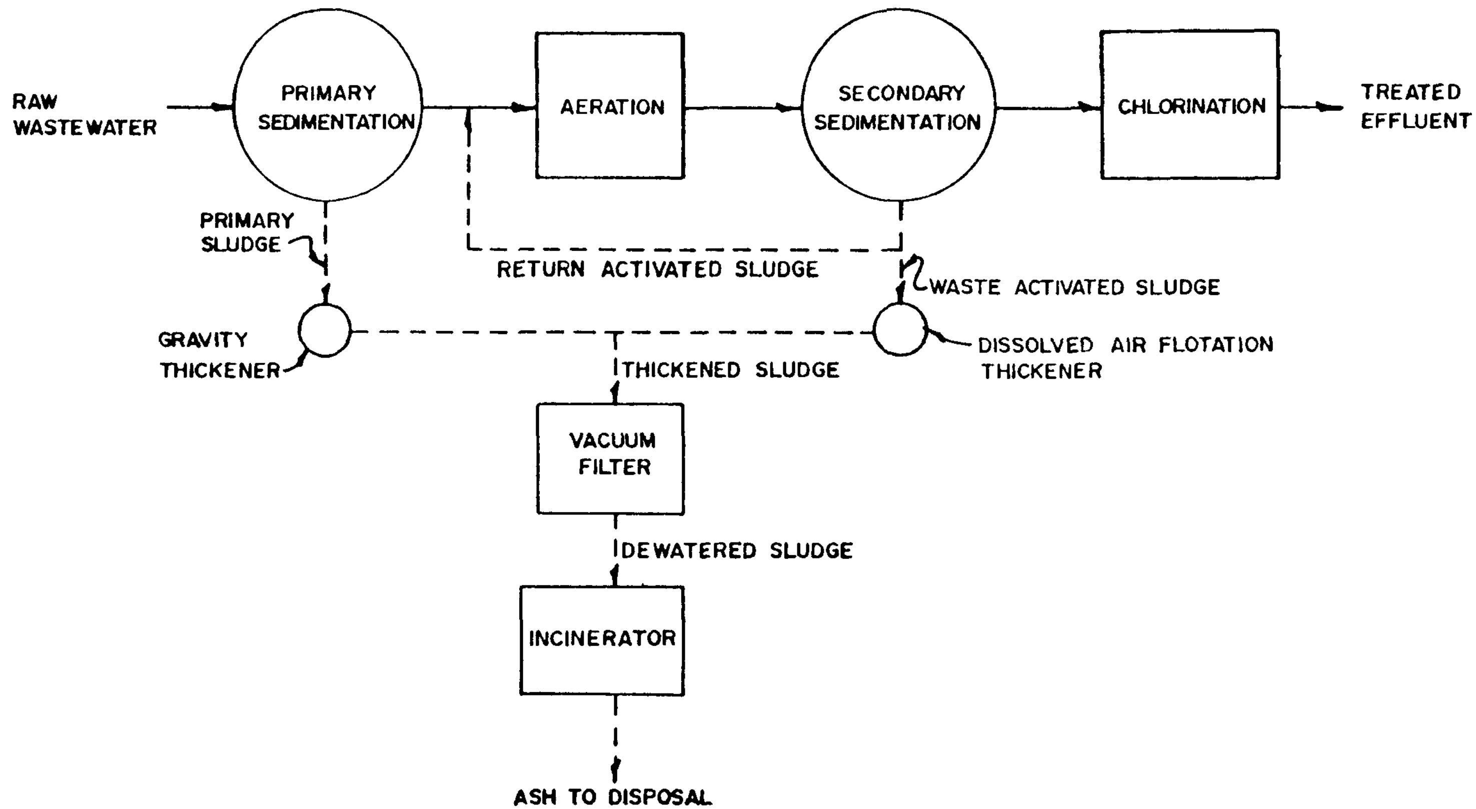


FIGURE 19. ACTIVATED SLUDGE PROCESS SCHEMATIC

TABLE 16

DESIGN CONDITIONS FOR ACTIVATED SLUDGE
PRIMARY SEDIMENTATION UNIT

Raw Wastewater:	
Suspended Solids	200 mg/l
Volatile Content	75 percent
BOD_5	200 mg/l
Temperature	20°C
Peaking Factor (Dry Weather)	1.5
Primary Sedimentation Design Parameters:	
Surface Loading @ Average Flow	800 gpd/ft^2
Suspended Solids Removal	65 percent
Sludge Concentration	5 percent
BOD_5 Removal	30 percent
Effluent BOD_5	140 mg/l

TABLE 17

ACTIVATED SLUDGE SYSTEM DESIGN PARAMETERS

Design Parameters	
Activated Sludge	
Aeration Basins	
F/M, lb BOD_5/lb MLVSS	0.355
MLVSS, mg/l	3,150
Hydraulic detention time, hr	4
Mean Cell Residence Time (MCRT) days	5
Sedimentation Basins	
Surface loading, gpd/ft^2 @ ADWF	600
Solids loading, lb/ft^2/day @ PDWF	<35
Return activated sludge, percent of influent flow	46
Return activated sludge concentration, percent	1
Chlorination	
Detention time @ PDWF, minutes	30
Dosage, mg/l	10
Gravity Thickener (Primary Sludge)	
Solids load, lb/ft^2/day	20
Solids concentration in, percent	5.0
Solids concentration out, percent	10.0
Dissolved Air Flotation Thickener (Waste Activated Sludge)	
Solids loading, lb/ft^2/day	20
Solids concentration in, percent	1
Solids concentration out, percent	3
Vacuum Filtration	
Solids loading lb/ft^2/hr hr	3
Polymer dosage lb/ton	18
Solids concentration out, percent	16
Run time, hr/day	20
Multiple Hearth Incineration	
Loading, lb/ft^2/hr	6
Downtime, percent	30

The dissolved air flotation thickener sizing is also based on a 20 lb/ft^2/day solids loading. This solids loading was chosen so as to avoid the need for chemical thickening aids. Solids concentration of one percent (influent) and three percent (float) are assumed.

The vacuum filter sizing is based on a 3 lb/ft^2/day solids loading and a 20 hr/day runtime. The polymer feed systems for the vacuum filters were sized based on 18 lb of polymer/ton of dry solids.

Using a dewatered sludge concentration of 16 percent, the multiple hearth incinerators were sized for a 6 lb/ft^2/hr loading (wet) solids basis) and a 70 percent operation runtime.

Unit process component sizes are summarized in Table 18. The only exceptions to the above criteria are the solids thickening and dewatering equipment for the 1 MGD design. The thickeners sized for the 1 MGD plant were smaller than available equipment so both primary and waste activated sludges are combined and thickened by gravity.

Costs

The capital and operation costs for the unit processes shown are developed through a review of the costs of actual plant construction and operation, equipment cost data from manufacturers, and published cost data. These generalized cost curves should not be used for estimating a given plant cost but are readily usable for comparing alternative processes as in this report. Individual plant costs must be developed based on the specific wastewater treatment plant design, local labor and material costs, and local climatic and site conditions.

Some of the limitations, in addition to the general local conditions discussed above, include no standby provisions, no specific modular sizing other than minimum available sizes, and no adjustments for local regulatory agency design restrictions.

Capital Costs

Sedimentation. The source of the construction cost curve for sedimentation was the report to EPA, "Costs of Chemical Clarification of Wastewater," January 1976.[40] These cost data were developed from quantity takeoffs and equipment manufacturer's estimates. The cost curve in the Appendix shows construction cost as a function of clarifier surface area.

TABLE 18

UNIT PROCESS SIZES, ACTIVATED SLUDGE

Unit Process or Component	Capacity, MGD 1	5	10	25	50
Primary Sedimentation Tanks surface area, ft^2	1,250	6,250	12,500	31,250	62,500
Aeration Tanks, volume, ft^3	23,300	111,500	223,000	557,500	1,115,000
Aerators, hp	40	200	400	1,000	2,000
Secondary Sedimentation Tanks surface area, ft^2	1,667	8,335	16,670	41,675	83,350
RAS pumps, MGD	.46/.69 (1)	2.30/3.45	4.60/6.90	11.5/17.8	23.0/34.5
WAS pumps, gpm	45	225	450	1,125	2,250
Sludge Pumps, gpm	15	75	150	375	750
Chlorination, volume, ft^3 contact tank, ft^3	4,180	20,900	41,800	104,500	209,000
Feed equipment, tons/year average/peak	15.2/22.8 (1)	76/114	152/228	380/570	760/1,140
Gravity thickener surface area, ft^2	98 (2)	271	542	1,355	2,710
Dissolved Air Flotation thickener, surface area, ft^2	-	219	438	1,095	2,190
Vacuum filter area, ft^2	113 (3)	163	326	815	1,630
Polymer feed, lb/hr	2.55 (3)	4.41	8.82	22	44
Incineration, ft^2	121	605	1,210	3,020	6,040

(1) Average/Peak - Average flow is used to determine the power requirement and maintenance materials cost. Peak capacity is used to determine construction cost and labor requirement.

(2) Both primary and waste activated sludges thickened by gravity thickener in 1 MGD example.

(3) Smallest unit used is a 6 x 6 which has a surface area of 113 ft^2. Operation time will be 48.5 hr/week or 2,522 hr/year. Polymer feed system is adjusted accordingly.

Aeration Basins. Historical aeration basin cost data has been updated with results of other detailed cost studies by CWC and recent costs obtained by Black & Veatch and CH2M-Hill. All data have been adjusted to the last quarter of 1975, Bureau of Labor Standards (BLS) wholesale price index for concrete products. Construction cost as a function of aeration basin volume is shown in the Appendix.

Mechanical Aeration Equipment. Cost data for installed mechanical equipment have been derived from experienced cost data and equipment costs supplied by manufacturers.

Return Activated Sludge Pumping Station. The cost relationships for recycle pumping developed by Black & Veatch[40] were adjusted and used as a basis for estimating the cost of the return activated sludge pumping stations in this study. The costs shown by Black & Veatch have approximately doubled due to inflation, stricter OSHA requirements, and regulatory agency reliability standards.

The pumping stations are assumed to employ vertical diffusion vane pumping units with attendent valves, piping, and control facilities. The pump is suspended in the wet well and motors and motor control centers are housed in a superstructure.

Waste Sludge Pumping Stations. Waste sludge pumping equipment costs are based on the use of intermittent sludge pumping with positive displacement pumps. The cost data presented in the Black & Veatch cost curves were updated for this study.

Included in the pump station cost is an underground structure which houses the pumps and piping and is constructed adjacent to and in conjunction with the sedimentation basin. Also included is a superstructure which houses electrical control equipment. This curve is applicable to both primary and waste activated sludge pumping.

Chlorination. The chlorine contact basin cost curve is based on the same construction used for the aeration basin cost curve. The chlorine feed equipment cost curve is based on chlorine gas feed and is taken from the draft report by CWC for the EPA "Estimating Initial Investment Costs and Operating and Maintenance Requirements of Stormwater Treatment Processes."

Gravity Thickening. These costs were developed using the same approach used in the earlier CWC work.[40]

Dissolved Air Flotation Thickening. The flotation thickener cost curve was taken from the CWC report.[40] Steel fabricated units are available with surface areas up to 450 square feet. The concrete basin costs include the tank, flotation cell equipment, air compressor, and controls.

Vacuum Filtration Costs. Vacuum filtration costs were obtained from equipment manufacturers and include the basic filter, associated vacuum and filtrate pumps, internal piping, and other appurtenant equipment and controls. The costs for polymer feed and storage equipment associated with the vacuum filter were taken from the CWC report.[40]

Operation and Maintenance Costs

The operation and maintenance costs consist of labor, power and maintenance materials. The individual cost curves were developed through a variety of resources including recent CWC work for the EPA and the Black & Veatch study.[41] In some instances, operating plants were consulted for information on labor requirements.

Sedimentation Basins. O&M requirements are based on the Black & Veatch report.[41]

Mechanical Aeration. Operation and maintenance requirements of the aeration system are expressed in terms of the installed aerator horsepower. Labor requirements are based on the Black & Veatch report.[41] The power requirements were calculated on the basis of an assumed oxygen transfer of 2 lb O_2/hp-hr or 3.0 lb O_2/kWh. Maintenance material costs are based on the Black & Veatch report.[41]

Return Activated Sludge Pumping Station. The return activated sludge pumping station labor requirements are based on the Black & Veatch report.[41] The power requirements were developed using a head of ten feet and the pumping efficiencies shown in the Appendix. The maintenance material cost curve is an update of the Black & Veatch curve.[41]

Waste Sludge Pumping Station. Labor requirements for the waste sludge pumping stations are based on the Black & Veatch report. The power requirements were based on a pumping head of 25 feet and a pumping efficiency of 40 percent (progressing cavity pumps). Maintenance material costs were updated from the Black & Veatch report.[41]

Chlorination. Labor requirements and maintenance material costs for chlorination are based on the Black & Veatch report. The chlorine costs are based on recent suppliers quotes for one ton cylinders and tank car lots.

Gravity Thickening. Gravity thickener labor requirements are based on data presented in the EPA Technology Transfer manual on sludge treatment and disposal,[42] assuming a loading of 20 lb/ft^2/day. The maintenance material costs were based on the sedimentation basin data.

Flotation Thickening. O&M cost curves for flotation do not include chemical feed. The thickeners for this project were sized so as to require no chemical additives.

All three cost curves (labor, power, and maintenance materials) were taken from recent CWC work.[40]

Vacuum Filtration. The O&M cost curves were based on recent CWC work[40] but adjusted for 20 hr/day operation. These curves were developed with information obtained from Metropolitan Denver Sewage Disposal District experience, manufacturer's data, and the Black & Veatch report.[41]

Polymer Feeding. The O&M cost curves for polymer feeding and mixing were based on recent CWC work.[40] Labor requirements were based on actual plant experience at Metro Denver. Power requirements were based on the use of plunger metering pumps and 6.4 hp-hr for mixing 100 pounds of polymer. Annual maintenance material costs were assumed to be three percent of the equipment cost.

Multiple-Hearth Incineration. Labor requirements for multiple-hearth incineration were taken from recent CWC work[40] and adjusted for 70 percent operation runtime (6,132 hr/year). The fuel requirements were provided by equipment manufacturers for combined raw primary and waste activated sludges, vacuum filtered to 16 percent solids. Power requirements were developed in the same manner.

The Black & Veatch incineration maintenance material cost curve[41] was converted to a square foot of hearth basis by assuming a loading rate of 6 lb/ft^2/hr (wet), updated, adjusted to 70 percent operation runtime.

Tables 19-29 present the cost estimates which are then summarized in Table 30.

TABLE 19

CAPITAL COSTS, ACTIVATED SLUDGE

	MGD				
	1	5	10	25	50
Primary Sedimentation Tanks	70,000	260,000	440,000	940,000	1,600,000
Aeration Basins	140,000	360,000	530,000	900,000	1,400,000
Aeration Equipment	67,000	230,000	390,000	800,000	1,200,000
Secondary Sedimentation Tanks	90,000	330,000	590,000	1,200,000	2,050,000
Return Activated Sludge Pumping Station	70,000	160,000	230,000	390,000	540,000
Waste Activated Sludge Pumping Station	75,000	170,000	220,000	360,000	490,000
Primary Sludge Pumping Station	44,000	93,000	140,000	200,000	290,000
Chlorine Contact Basins	51,000	140,000	200,000	340,000	530,000
Chlorination Equipment	12,000	37,000	60,000	110,000	180,000

TABLE 19 (Cont'd.)

	MGD				
	1	5	10	25	50
Gravity Thickener	66,000	72,000	90,000	130,000	160,000
Dissolved Air Flotation Thickener	N/A	180,000	190,000	280,000	360,000
Vacuum Filter	205,000	250,000	370,000	640,000	1,000,000
Polymer Feed and Storage	37,000	50,000	90,000	200,000	390,000
Incineration	1,100,000	1,900,000	2,600,000	4,100,000	6,000,000
Subtotal	2,027,000	4,232,000	6,140,000	10,590,000	16,190,000
Yardwork	248,000	592,000	860,000	1,482,000	2,267,000
TOTAL CONSTRUCTION COST	2,311,000	4,824,000	7,000,000	12,072,000	18,457,000
Engineering, Fiscal, Legal	277,000	579,000	840,000	1,449,000	2,215,000
Interest During Construction	231,000	482,000	700,000	1,207,000	1,846,000
TOTAL CAPITAL COSTS	2,819,000	5,885,000	8,540,000	14,728,000	22,518,000

TABLE 20

ACTIVATED SLUDGE, 1 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	570	3,300	-	440
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	1,400	220,000	-	3,100
Secondary Sedimentation	620	3,300	-	580
Return Activated Sludge Pumping	720	10,000	-	460
Waste Activated Sludge Pumping	105	900	-	1,300
Primary Sludge Pumping	63	300	-	610
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	500	N/A	-	1,500
Gravity Thickener	400	1,000	-	130
Dissolved Air Flotation Thickener	N/A	N/A	-	N/A
Vacuum Filter	692	34,600	-	4,850
Polymer Feed and Storage	300	692	-	35
Incineration	1,600	36,000	3.8×10^6	3,500
TOTAL	6,970	310,092	3.8×10^6	16,505

TABLE 21

ACTIVATED SLUDGE, 5 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	1,200	3,300	-	1,600
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	2,700	1,100,000	-	6,400
Secondary Sedimentation	1,400	3,300	-	2,000
Return Activated Sludge Pumping	930	42,000	-	840
Waste Activated Sludge Pumping	210	4,500	-	4,000
Primary Sludge Pumping	130	1,500	-	1,900
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	1,150	N/A	-	2,500
Gravity Thickener	400	1,500	-	130
Dissolved Air Flotation Thickener	760	190,000	-	120
Vacuum Filter	2,500	120,000	-	17,000
Polymer Feed and Storage	310	2,050	-	49
Incineration	4,900	190,000	24×10^6	6,800
TOTAL	16,590	1,658,150	24×10^6	43,339

TABLE 22

ACTIVATED SLUDGE, 10 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	1,800	6,600	-	2,700
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	3,800	2,050,000	-	8,700
Secondary Sedimentation	2,100	6,600	-	3,600
Return Activated Sludge Pumping	1,100	78,000	-	1,300
Waste Activated Sludge Pumping	270	9,000	-	6,300
Primary Sludge Pumping	170	3,000	-	3,000
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	1,800		-	3,000
Gravity Thickener	410	2,800	-	230
Dissolved Air Flotation Thickener	1,400	350,000	-	160
Vacuum Filter	4,000	250,000	-	28,000
Polymer Feed and Storage	320	2,200	-	78
Incineration	7,000	370,000	50×10^6	9,200
TOTAL	24,170	3,128,200	50×10^6	57,068

TABLE 23

ACTIVATED SLUDGE, 25 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	3,100	9,900	-	5,600
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	7,100	5,100,000	-	14,000
Secondary Sedimentation	3,800	9,900	-	7,000
Return Activated Sludge Pumping	1,500	170,000	-	2,600
Waste Activated Sludge Pumping	410	22,500	-	12,000
Primary Sludge Pumping	250	7,500	-	5,600
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	3,300		-	4,000
Gravity Thickener	470	6,000	-	470
Dissolved Air Flotation Thickener	3,400	800,000	-	300
Vacuum Filter	7,300	570,000	-	52,000
Polymer Feed and Storage	330	2,400	-	140
Incineration	13,000	900,000	140×10^6	17,000
TOTAL	43,960	7,598,200	140×10^6	120,710

TABLE 24

ACTIVATED SLUDGE, 50 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	4,900	20,000	-	9,500
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	13,000	10,200,000	-	18,000
Secondary Sedimentation	5,900	20,000	-	13,000
Return Activated Sludge Pumping	2,000	340,000	-	5,000
Waste Activated Sludge Pumping	540	45,000	-	19,000
Primary Sludge Pumping	340	15,000	-	9,000
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	5,400		-	5,000
Gravity Thickener	590	12,000	-	760
Dissolved Air Flotation Thickener	6,500	1,400,000	-	500
Vacuum Filter	11,000	1,000,000	-	80,000
Polymer Feed and Storage	340	2,800	-	220
Incineration	20,000	1,800,000	300×10^6	30,000
TOTAL	70,510	14,854,800	300×10^6	189,980

TABLE 25

ACTIVATED SLUDGE, 1 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 2,819,000 x 0.09439	$266,000
Labor 6,970 Hours @ $9/Hour	62,730
Power 310,092 kWh @ $0.02/kWh	6,200
Fuel 3.8×10^6 SCF @ $1.50/TCF	5,700
Maintenance Materials	16,500
Chemicals Chlorine 15.2 Tons @ $220/Ton	3,340
Polymer 6430 lb @ $2/lb	12,860
TOTAL	$373,330

Cost/MG @ Capacity = $\frac{\$373,330}{365 \times 1}$ = $1,023/MG

TABLE 26

ACTIVATED SLUDGE, 5 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 5,885,000 x 0.09439	$555,000
Labor 16,590 Hours @ $9/Hour	149,310
Power 1,658,150 kWh @ $0.02/kWh	33,160
Fuel 24 x 10^6 SCF @ $1.50/TCF	36,000
Maintenance Materials	43,340
Chemicals Chlorine 76 Tons @ $220/Ton	16,720
Polymer 32,193 lb @ $2/lb	64,380
TOTAL	$897,910

$$\text{Cost/MG @ Capacity} = \frac{\$897,910}{365 \times 5} = \$492/\text{MG}$$

TABLE 27

ACTIVATED SLUDGE, 10 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 8,540,040 x 0.09439	$806,000
Labor 24,170 Hours @ $9/Hour	217,530
Power 3,128,200 kWh @ $0.02/kWh	62,565
Fuel 50 x 10^6 SCF @ $1.50/TCF	75,000
Maintenance Materials	57,070
Chemicals Chlorine 152 Tons @ $220/Ton	33,440
Polymer 64,386 lb @ $2/lb 50	128,770
TOTAL	$1,380,375

Cost/MG @ Capacity = $\frac{\$1,380,375}{365 \times 10}$ = $378/MG

TABLE 28

ACTIVATED SLUDGE, 25 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 14,728,000 x 0.09439	$1,390,000
Labor 43,960 Hours @ $9/Hour	$ 395,640
Power 7,598,200 kWh @ $0.02/kWh	$ 151,965
Fuel 140×10^6 SCF @ $1.50/TCF	$ 210,000
Maintenance Materials	$ 120,710
Chemicals Chlorine 380 Tons @ $100/Ton	$ 38,000
Polymer 160,600 lb @ $2/lb	$ 321,200
TOTAL	$2,627,515

Costs/MG @ Capacity = $\frac{\$2,627,515}{365 \times 25}$ = $288/MG

TABLE 29

ACTIVATED SLUDGE, 50 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 22,518,000 x 0.09439	$2,125,000
Labor 70,510 Hours @ $9/Hour	$ 634,590
Power 14,854,000 kWh @ $0.02/kWh	$ 297,090
Fuel 300×10^6 SCF @ $1.50/TCF	$ 450,000
Maintenance Materials	$ 189,980
Chemicals	
Chlorine 760 Tons @ $100/Ton /Ton	$ 76,000
Polymer 321,200 lb @ $2/lb 2/lb	$ 642,400
TOTAL	$4,415,060

$$\text{Cost/MG @ Capacity} = \frac{\$4,415,060}{365 \times 50} = \$242/\text{MG}$$

TABLE 30

ACTIVATED SLUDGE ANNUAL COST SUMMARY

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	266	555	806	1,390	2,125
Labor	63	149	218	396	635
Power	6	33	62	152	297
Fuel	6	36	75	210	450
Maintenance Materials	16	43	57	121	190
Chemicals					
Chlorine	3	17	33	38	76
Polymer	13	64	129	321	642
TOTAL	373	898	1,380	2,628	4,415
Costs/1,000 Gals (Operating @ Capacity)	$1.02	$0.49	$0.38	$0.29	$0.24

ACTIVATED SLUDGE, SINGLE STAGE FOR NITRIFICATION

The design of this system is based on a mean cell residence time of ten days to achieve nitrification in a single stage activated sludge system. Table 31 presents the design parameters for the nitrification system. Table 32 presents the resulting unit process sizes. Capital and O&M costs are based on the same sources described in the preceding section for the conventional activated sludge system. Tables 33-44 present the results of the cost calculations.

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION

This system consists of the activated sludge design previously described with downstream chemical coagulation and filtration. The chemical coagulation and filtration designs are the same as used for the granular carbon system described in detail later in this report. The process schematic is shown in Figure 20 and the design criteria are summarized in Table 45.

Unit process sizes are shown in Table 46. Table 47 presents the capital costs. Costs for the chemical clarification, sludge handling, chlorination, and filtration portions of the system were obtained from work conducted by CWC under EPA Contract 68-03-2186. Appropriate cost curves are presented in the Appendix.

O&M costs are summarized in Tables 48-52. These costs were taken from component costs determined previously in the study. Tables 53-57 summarize total annual costs for each capacity and Table 58 is an overall summary.

GRANULAR CARBON TREATMENT OF CHEMICALLY COAGULATED, SETTLED, AND FILTERED RAW WASTEWATER

The process schematic is shown in Figure 21. The design criteria are shown in Table 59. Gravity filters were used at all capacities. Pressure filters may be more economical in capacities of five mgd or less, but for comparative purposes, gravity filters were used in all cases. Filter costs were obtained from the earlier CWC report.[40] A minimum of four filters were provided to insure reliability. The other criteria are self-explanatory.

Unit process sizes are shown in Table 60. Table 61 presents the capital costs. Costs for the chemical clarification, sludge handling, chlorination, and filtration portions of the system were obtained from work conducted by CWC under EPA Contract 68-03-2186.[40] Capital costs for the carbon influent pumping and the carbon contacting system were obtained by updating the curves from the EPA Technology Transfer Manual, "Process Design Manual

TABLE 31

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION SYSTEM DESIGN PARAMETERS

Design Parameters	
Activated Sludge	
Aeration Basins	
F/M, lb BOD_5/lb MLVSS	0.20
MLSS, mg/l	3,270
Hydraulic Detention Time, hr	7
Mean Cell Residence Time (MCRT), Days	10
Sedimentation Basins	
Surface Loading, gpd/ft^2 @ ADWF	600
Solids Loading, lb/ft^2/day @ PDWF	35
Return Activated Sludge, Percent of Influent Flow	69
Return Activated Sludge Concentration, Percent	0.8
Chlorination	
Detention Time @ PDWF, Minutes	30
Dosage, mg/l	10
Gravity Thickener (Primary Sludge)	
Solids Load, lb/ft^2/day	20
Solids Concentration in, Percent	5.0
Solids Concentration out, Percent	10.0
Dissolved Air Flotation Thickener (Waste Activated Sludge)	
Solids Loading, lb/ft^2/day	20
Solids Concentration in, Percent	1
Solids Concentration out, Percent	3
Vacuum Filtration	
Solids Loading lb/ft^2/hr	3
Polymer Dosage lb/ton	18
Solids Concentration out, Percent	16
Run Time, hr/day	20
Multiple Hearth Incineration	
Loading, lb/ft^2/hr (Wet Solids)	6
Downtime, Percent	30

TABLE 32

UNIT PROCESS SIZES, SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION

Unit Process or Component	1	5	10	25	50
Primary Sedimentation Tanks Surface Area, ft^2	1,250	6,250	12,500	31,250	62,500
Aeration Tanks, Volume, ft^3	39,000	195,000	300,000	975,000	1,950,000
Aerators, hp	70	350	70	1,750	3,500
Secondary Sedimentation Tanks Surface Area, ft^2	1,667	8,335	16,670	41,675	83,350
RAS Pumps, MGD	.69/1.03(1)	3.45/5.18	6.90/10.3	17.2/25.9	34.5/51.8
WAS Pumps, gpm	36	180	360	900	1,800
Sludge Pumps, gpm	15	75	150	375	750
Chlorination, Volume of Contact Tank, ft^3	4,180	20,900	41,800	104,500	209,000
Feed Equipment, Tons/Year Average/Peak	15.2/22.8	76/114	152/228	380/570	760/1,140
Gravity Thickener Surface Area, ft^2	89(2)	271	542	1,355	2,710
Dissolved Air Flotation Thickener, Surface Area, ft^2		175	350	875	1,750
Vacuum Filter Area, ft^2	113(3)	148	297	742	148
Polymer Feed, lb/hr	2 55(3)	4.01	8.03	20	40
Incineration, ft^2	110	550	1,101	2,750	5,500

(1) Average/Peak - Average flow is used to determine the power requirements and maintenance materials cost. Peak capacity is used to determine construction cost and labor requirements.
(2) Both primary and waste activated sludges thickened by gravity thickener in 1 MGD.
(3) Smallest unit used is a 6 x 6 which has a surface area of 113 ft^2. Operation time will be 44.1 hr/week or 2,295 hr/year. Polymer feed system is adjusted accordingly.

TABLE 33

CAPITAL COSTS, SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION

	MGD				
	1	5	10	25	50
Primary Sedimentation Tanks	70,000	260,000	440,000	940,000	1,600,000
Aeration Basins	220,000	570,000	850,000	1,400,000	2,100,000
Aeration Equipment	130,000	450,000	800,00	1,500,000	2,200,000
Secondary Sedimentation Tanks	90,000	330,000	590,000	1,200,000	2,050,000
Return Activated Sludge Pumping Station	86,000	200,000	300,000	450,000	660,000
Waste Activated Sludge Pumping Station	90,000	190,000	270,000	430,000	600,000
Primary Sludge Pumping Station	44,000	93,000	140,000	200,000	290,000
Chlorine Contact Basins	51,000	140,000	200,000	340,000	530,000
Chlorination Equipment	12,000	37,000	60,000	110,000	180,000
Gravity Thickener	65,000	72,000	90,000	130,000	160,000

TABLE 33 (Cont'd.)

Dissolved Air Flotation Thickener	N/A	160,000	180,000	250,000	330,000
Vacuum Filter	205,000	230,000	340,000	600,000	940,000
Polymer Feed and Storage	37,000	52,000	100,000	250,000	500,000
Incineration	1,100,000	1,700,000	2,400,000	3,900,000	5,800,000
Subtotal	2,200,000	4,484,000	6,760,000	11,700,000	17,940,000
Yardwork	308,000	628,000	946,000	1,638,000	2,512,000
TOTAL CONSTRUCTION COST	2,508,000	5,112,000	7,706,000	13,338,000	20,452,000
Engineering, Fiscal, Legal	301,000	613,000	925,000	1,600,000	2,454,000
Interest During Construction	251,000	511,000	771,000	1,334,000	2,045,000
TOTAL CAPITAL COSTS	3,060,000	6,236,000	9,402,000	16,212,000	24,951,000

TABLE 34

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 1 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	570	3,300	-	440
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	1,700	370,000	-	4,000
Secondary Sedimentation	620	3,300	-	580
Return Activated Sludge Pumping	760	14,000	-	500
Waste Activated Sludge Pumping	99	700	-	1,200
Primary Sludge Pumping	63	300	-	610
Chlorine Contact Basins				
Chlorination Equipment	500	N/A	-	1,500
Gravity Thickener	400	1,000	-	130
Dissolved Air Flotation Thickener	N/A	N/A	-	N/A
Vacuum Filter	630	31,500	-	4,410
Polymer Feed and Storage	270	864	-	70
Incineraton	1,600	35,000	3.7×10^6	3,400
TOTAL	7,212	459,964	3.7×10^6	16,840

TABLE 35

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 5 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	1,200	3,300	-	1,600
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	3,600	1,800,000	-	8,100
Secondary Sedimentation	1,400	3,300	-	2,000
Return Activated Sludge Pumping	1,000	60,000	-	1,100
Waste Activated Sludge Pumping	190	3,500	-	3,500
Primary Sludge Pumping	130	1,500	-	1,900
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	1,150	-	-	2,500
Gravity Thickener	400	1,500	-	130
Dissolved Air Flotation Thickener	630	160,000	-	120
Vacuum Filter	2,400	110,000	-	16,000
Polymer Feed and Storage	310	4,000	-	360
Incineraton	4,600	170,000	22×10^6	6,200
Total	17,010	2,317,000	22×10^6	43,510

TABLE 36

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 10 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	1,800	6,600	-	2,700
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	5,600	3,600,000	-	11,000
Secondary Sedimentation	2,100	6,600	-	3,600
Return Activated Sludge Pumping	1,300	120,000	-	1,700
Waste Activated Sludge Pumping	250	7,000	-	5,400
Primary Sludge Pumping	170	3,000	-	3,000
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	1,800	-	-	3,000
Gravity Thickener	410	2,800	-	230
Dissolved Air Flotation Thickener	1,100	300,000	-	140
Vacuum Filter	3,800	220,000	-	26,000
Polymer Filter and Storage	320	6,200	-	560
Incineration	7,000	340,000	46×10^6	9,000
Total	25,650	4,612,200	46×10^6	66,330

TABLE 37

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 25 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	3,100	9,900	-	5,600
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	11,000	8,600,000	-	17,000
Secondary Sedimentation	3,800	9,900	-	7,000
Return Activated Sludge Pumping	1,700	260,000	-	3,800
Waste Activated Sludge Pumping	370	17,500	-	9,900
Primary Sludge Pumping	250	7,500	-	5,600
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	3,300	-	-	4,000
Gravity Thickener	470	6,000	-	470
Dissolved Air Flotation Thickener	2,600	640,000	-	250
Vacuum Filter	6,900	550,000	-	50,000
Polymer Feed and Storage	400	13,000	-	1,000
Incineration	13,000	800,000	130×10^6	16,000
Total	46,890	10,913,800	130×10^6	120,620

TABLE 38

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 50 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	4,900	20,000	-	9,500
Aeration Basins	N/A	N/A	-	N/A
Aeration Equipment	21,000	17,000,000	-	23,000
Secondary Sedimentation	5,900	20,000	-	13,000
Return Activated Sludge Pumping	2,300	490,000	-	8,200
Waste Activated Sludge Pumping	500	35,000	-	16,000
Primary Sludge Pumping	340	15,000	-	9,000
Chlorine Contact Basins	N/A	N/A	-	N/A
Chlorination Equipment	5,400	-	-	5,000
Gravity Thickener	590	12,000	-	760
Dissolved Air Flotation Thickener	5,200	1,100,000	-	400
Vacuum Filter	10,500	980,000	-	70,000
Polymer Feed and Storage	860	21,000	-	1,600
Incineration	20,000	1,600,000	280×10^6	24,000
Total	77,490	21,293,000	280×10^6	180,460

TABLE 39

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 1 MGD

TATAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 3,060,000 x 0.09439	$288,833
Labor 7,212 Hours @ $9/Hour	$ 64,908
Power 459,964 kWh @ $0.02/kWh	$ 9,199
Fuel 3.7 x 10^6 SCF @ $1.50/TCF	$ 5,550
Maintenance Materials	$ 16,840
Chemicals	
Chlorine 15.2 Tons @ $220/Ton	$ 3,340
Polymer 5,851 lb @ $2/lb	$ 11,702
TOTAL	$400,272

$$\text{Cost/MG @ Capacity} = \frac{\$40,272}{365 \times 1} = \$1,097/\text{MG}$$

TABLE 40

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 5 MGD

TOTAL ANNUAL COSTS

Ammortized Capital @ 7%, 20 Years	
6,236,000 x 0.09439	$588,616
Labor	
17,010 Hours @ $9/Hour	$153,090
Power	
2,317,100 kWh @ $0.02/kWh	$ 46,340
Fuel	
22 x 10^6 SCF @ $1.50/TCF	$ 33,000
Maintenance Materials	$ 43,510
Chemicals	
Chlorine	
76 Tons @ $220/Ton	$ 16,720
Polymer	
29,298 lb @ $2/lb	$ 58,592
TOTAL	$939,868

Cost/MG @ Capacity = $\frac{\$939,868}{365 \times 5}$ = $515/MG

TABLE 41

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 10 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 9,402,000 x .09439	$ 887,455
Labor 25,650 Hours @ $9/Hour	$ 230,850
Power 4,612,200 kWh @ $0.02/kWh	$ 92,244
Fuel 46 x 10^6 SCF @ $1.50/TCF	$ 69,000
Maintenance Materials	$ 66,330
Chemicals	
Chlorine 152 Tons @ $220/Ton	$ 33,440
Polymer 58,591 lb @ $2/lb	$ 117,182
TOTAL	$1,496,501

$$\text{Cost/MG @ Capacity} = \frac{\$1,496,501}{365 \times 10} = \$410/\text{MG}$$

TABLE 42

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 25 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 16,272,000 x .09439	$1,535,914
Labor 46,890 Hours @ $9/Hour	$ 422,010
Power 10,913,800 kWh @ $0.02/kWh	$ 218,275
Fuel 130 x 10^6 SCF @ $1.50/TCF	$ 195,000
Maintenance Materials	$ 120,620
Chemicals Chlorine 380 Tons @ $100/Ton	$ 38,000
Polymer 146,146 lb @ $2/lb	$ 242,292
TOTAL	$2,822,111

Costs/MG @ Capacity = $\frac{\$2,822,111}{365 \times 25}$ = $309/MG

TABLE 43

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION, 50 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 24,951,000 x .09439	$2,355,125
Labor 77,490 Hours @ $9/Hour	$ 697,410
Power 21,293,000 kWh @ $0.02/kWh	$ 425,860
Fuel 280 x 10^6 SCF @ $1.50/TCF	$ 420,000
Maintenance Materials	$ 180,460
Chemicals Chlorine 760 Tons @ $100/Ton	$ 76,000
Polymer 292,292 lb @ $2/lb	$ 584,584
TOTAL	$4,739,439

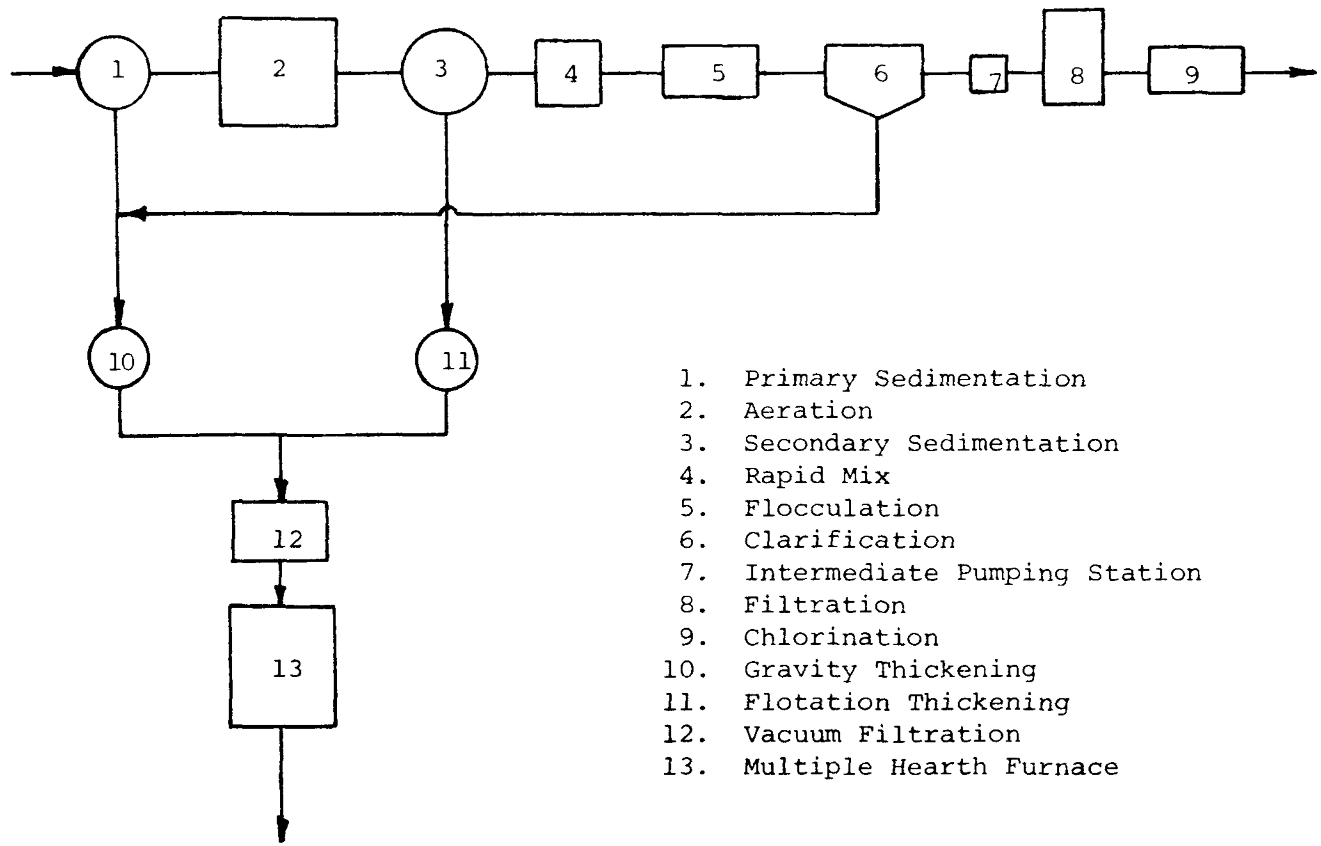
$$\text{Cost/MG @ Capacity} = \frac{\$4,739,439}{365 \times 50} = \$260/\text{MG}$$

TABLE 44

SINGLE STAGE ACTIVATED SLUDGE NITRIFICATION,
ANNUAL COST SUMMARY

Annual Cost ($1,000)

	MGD 1	5	10	25	50
Amortized Capital	289	589	887	1,536	2,355
Labor	65	153	231	422	697
Power	6	46	92	218	425
Fuel	6	33	69	195	420
Maintenance Materials	17	44	66	121	180
Chemicals					
Chlorine	3	17	33	38	76
Polymer	12	59	117	292	584
TOTAL	400	940	1,497	2,822	4,739
Costs/1,000 gals. (Operating at Capacity)	$1.10	$0.51	$0.41	$0.31	$0.26



1. Primary Sedimentation
2. Aeration
3. Secondary Sedimentation
4. Rapid Mix
5. Flocculation
6. Clarification
7. Intermediate Pumping Station
8. Filtration
9. Chlorination
10. Gravity Thickening
11. Flotation Thickening
12. Vacuum Filtration
13. Multiple Hearth Furnace

FIGURE 20. ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION SCHEMATIC

TABLE 45

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, DESIGN PARAMETERS

Primary Sedimentation	
surface loading @ average flow	800 $gpd/ft^2ft.$
sludge concentration	5 percent
suspended solids removal	65 percent
BOD_5 removal	30 percent
Aeration Basins	
F/M	0.355 lb BOD_5/lb MLVSS
MLSS	3150 mg/l
hydraulic detention time	4 hours
mean cell residence time	5 days
Secondary Sedimentation	
surface loading @ average flow	600 $gal/day/ft^2$
solids loading @ peak flow	<35 $lb/ft^2/day$
return activated sludge, percent of inflow	46 percent
return activated sludge concentration	1 percent
Chemical Treatment	
coagulant	alum
coagulant dose	125 mg/l
polymer dose	0.25 mg/l
flash mix time	1 minute
flocculation time (G=70, verticle turbine)	15 minutes
clarifier, hydraulic loading @ peak	0.8 gpm/ft^2
Granular Media Filtration	
type	gravity, tri-media
average hydraulic loading rate	5 gpm/ft^2
number of filters, minimum	4
average backwash recycle, % of filtrate	3 percent

TABLE 45 (Cont'd)

Chlorination	
contact time @ peak flow	30 minutes
dosage, peak	5 mg/l
dosage, average	3 mg/l
Gravity Thickener (primary & chemical sludges)	
solids loading	10 lb/ft^2
solids concentration in	3 percent
solids concentration out	8 percent
Dissolved Air Flotation Thickener (waste activated sludge)	
solids loading	20 $lb/ft^2/day$
solids concentration in	1 percent
solids concentration out	3 percent
Vacuum Filtration	
solids loading	3 $lb/ft^2/hr$
polymer dosage	18 lb/ton
solids concentration out	14 percent
run time	20 hours/day
Multiple Hearth Incineration	
loading (wet basis)	6 $lb/ft^2/hr$
downtime	30 percent

TABLE 46

UNIT PROCESS SIZES

Unit Process or Component	1	5	10	25	50
Primary Sedimentation, ft^2	1,250	6,250	12,500	31,250	62,500
Aeration Basins, ft^3	23,300	111,500	223,000	557,500	1,115,000
Aerators, hp	40	200	400	1,000	2,000
Secondary Sedimentation, ft^2	1,667	8,335	16,670	41,675	83,350
Return Activated Sludge Pumping, MGD	.46/.69 (1)	2.30/3.45	4.60/6.90	11.5/17.8	23.0/34.5
Rapid Mixing, ft^3	93	465	930	2,325	4,650
Flocculation, ft^2	1,395	6,975	13,950	34,875	69,750
Clarifier, ft^2	1,302	6,510	13,020	32,550	65,100
Filtration, ft^2	140	700	1,400	3,500	7,000
Chlorine Contact Basins, ft^3	4,180	20,900	41,800	104,500	209,000
Chlorination Equipment, tons/yr	4.56/11.4 (1)	22.8/57.0	45.6/114	114/285	228/570
Chemical Feeding:					
Alum/lb/hr	45	225	450	1,125	2,250
Polymer, Wastewater, lb/hr	0.09	0.45	0.90	2.25	4.50
Polymer, Sludge, lb/hr	2.55 (2)	4.74	9.48	23.7	47.4
Primary Sludge Pumping, gpm	15	75	150	375	750

TABLE 46 (Cont'd)

Waste Activated Sludge Pumping, gpm	45	225	450	1,125	2,250
Chemical Sludge Pumping, gpm	5	25	50	125	250
Gravity Thickening, ft^2	253[(3)]	825	1,650	4,125	8,250
Flotation Thickening, ft^2	--	219	438	1,095	2,190
Vacuum Filtration, ft^2	113[(2)]	210	420	1,050	2,100
Multiple Hearth Furnace, ft^2	157	785	1,570	3,925	7,850
Intermediate Pumping, MGD	1	5	10	25	50

(1) Average/Peak - Average flow is used to determine the power requirement and maintenance material costs. Peak flow is used to determine construction cost and labor requirement.

(2) Smallest practical vacuum filter is 113 ft^2. Adjust polymer feed accordingly - (113/42) x (0.948) = 2.55 lb/hr.

(3) All sludges are combined and gravity thickened for 1 MGD.

TABLE 47

CAPITAL COSTS, ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION

	MGD				
Process Component	1	5	10	25	50
Primary Sedimentation Tanks	70,000	260,000	440,000	940,000	1,600,000
Aeration Basins	140,000	360,000	530,000	900,000	1,400,000
Aeration Equipment	67,000	230,000	390,000	800,000	1,200,000
Secondary Sedimentation Tanks	90,000	330,000	590,000	1,200,000	2,050,000
Return Activated Sludge Pumping	70,000	160,000	230,000	390,000	540,000
Rapid Mixing	10,000	23,000	37,000	76,000	130,000
Flocculation	13,000	38,000	55,000	100,000	160,000
Clarifier	85,000	230,000	440,000	1,100,000	2,200,000
Filtration	390,000	685,000	1,050,000	1,900,000	2,900,000
Chlorine Contact Basins	51,000	140,000	200,000	340,000	530,000
Chlorination Equipment	7,000	22,000	38,000	69,000	110,000
Chemical Feeding:					
Alum	30,000	45,000	70,000	160,000	300,000
Polymer, Wastewater	10,000	13,000	18,000	32,000	62,000
Polymer, Sludge	36,000	60,000	120,000	300,000	580,000
Primary Sludge Pumping	44,000	93,000	140,000	200,000	290,000
Waste Activated Sludge Pumping	75,000	170,000	220,000	360,000	490,000
Chemical Sludge Pumping	40,000	70,000	100,000	170,000	220,000
Gravity Thickener	70,000	105,000	130,000	180,000	230,000
Dissolved Air Flotation Thickener	N/A	180,000	190,000	280,000	360,000
Vacuum Filter	200,000	280,000	420,000	800,000	1,300,000
Multiple Hearth Furnace	1,100,000	2,100,000	2,900,000	4,900,000	7,000,000
Intermediate Pumping Station	86,000	200,000	280,000	450,000	640,000
SUBTOTAL	2,684,000	5,794,000	8,588,000	15,647,000	24,292,000
Yardwork	376,000	811,000	1,202,000	2,190,000	3,401,000
Total Construction Cost	3,060,000	6,605,000	9,780,000	17,837,000	27,693,000
Envineering, Fiscal, Legal	367,000	793,000	1,175,000	2,140,000	3,323,000
Interest During Construction	306,000	661,000	1,979,000	1,784,000	2,769,000
TOTAL CAPITAL COST	3,733,000	8,059,000	11,944,000	21,761,000	33,785,000

TABLE 48

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 1 MGD

Process Component	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation Tanks	570	3,300	-	440
Aeration Basins	-	-	-	-
Aeration Equipment	1,400	220,000	-	3,100
Secondary Sedimentation Tanks	620	3,300	-	580
Return Activated Sludge Pumping	720	10,000	-	460
Rapid Mixing	480	27,000	-	280
Flocculation	1,100	1,800	-	400
Clarifier	580	3,300	-	450
Filtration	2,900	88,000	-	1,500
Chlorine Contact Basins	-	-	-	-
Chlorination Equipment	390	-	-	300
Chemical Feeding:				
Alum	200	2,400	-	200
Polymer, Wastewater	300	2,100	-	100
Polymer, Sludge	210	1,200	-	100
Primary Sludge Pumping	63	300	-	610
Waste Activated Sludge Pumping	105	900	-	1,300
Chemical Sludge Pumping	60	1,300	-	600
Gravity Thickening	400	1,500	-	140
Flotation Thickening	-	-	-	-
Vacuum Filtration	740	37,000	-	5,000
Multiple Hearth Furnaces	2,000	50,000	5.1×10^6	3,700
Intermediate Pumping Station	740	20,000	-	570
TOTAL	13,578	473,400	5.1×10^6	19,830

TABLE 49

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 5 MGD

Process Component	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation Tanks	1,200	3,300	-	1,600
Aeration Basins	-	-	-	-
Aeration Equipment	2,700	1,100,000	-	6,400
Secondary Sedimentation Tanks	1,400	3,300	-	2,000
Return Activated Sludge Pumping	930	42,000	-	840
Rapid Mixing	580	120,000	-	520
Flocculation	160	8,200	-	800
Clarifier	1,200	3,300	-	1,800
Filtration	3,600	115,000	-	4,200
Chlorine Contact Basins	-	-	-	-
Chlorination Equipment	610	-	-	1,800
Chemical Feeding:				
Alum	400	2,600	-	280
Polymer, Wastewater	400	2,700	-	100
Polymer, Sludge	630	4,500	-	400
Primary Sludge Pumping	130	1,500	-	1,900
Waste Activated Sludge Pumping	210	4,500	-	4,000
Chemical Sludge Pumping	80	6,600	-	900
Gravity Thickening	440	1,500	-	330
Flotation Thickening	760	190,000	-	120
Vacuum Filtration	3,000	160,000	-	21,000
Multiple Hearth Furnaces	5,700	250,000	33×10^6	7,600
Intermediate Pumping Station	1,000	83,000	-	1,400
TOTAL	25,130	2,102,100	33×10^6	57,990

TABLE 50

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 10 MGD

Process Component	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation Tanks	1,800	6,600	-	2,700
Aeration Basins	-	-	-	-
Aeration Equipment	3,800	2,050,000	-	8,700
Secondary Sedimentation Tanks	2,100	6,600	-	3,600
Return Activated Sludge Pumping	1,100	78,000	-	1,300
Rapid Mixing	600	250,000	-	900
Flocculation	190	17,000	-	300
Clarifier	1,800	3,300	-	3,000
Filtration	4,000	140,000	-	6,800
Chlorine Contact Basins	-	-	-	-
Chlorination Equipment	890	-	-	2,200
Chemical Feeding:				
Alum	650	3,000	-	470
Polymer, Wastewater	400	2,900	-	150
Polymer, Sludge	720	7,200	-	620
Primary Sludge Pumping	170	3,000	-	3,000
Waste Activated Sludge Pumping	270	9,000	-	6,300
Chemical Sludge Pumping	120	1,300	-	1,500
Gravity Thickening	490	2,800	-	520
Flotation Thickening	1,400	350,000	-	160
Vacuum Filtration	4,700	300,000	-	35,000
Multiple Hearth Furnaces	8,600	460,000	66×10^6	11,000
Intermediate Pumping Station	1,200	160,000	-	2,300
TOTAL	35,000	3,851,000	66×10^6	90,520

TABLE 51

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 25 MGD

Process Component	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation Tanks	3,100	9,900	-	5,600
Aeration Basins	-	-	-	-
Aeration Equipment	7,100	5,100,000	-	14,000
Secondary Sedimentation Tanks	3,800	9,900	-	7,000
Return Activated Sludge Pumping	1,500	170,000	-	2,600
Rapid Mixing	700	520,000	-	1,800
Flocculation	230	40,000	-	2,300
Clarifier	3,300	6,600	-	5,500
Filtration	5,200	190,000	-	13,000
Chlorine Contact Basins	-	-	-	-
Chlorination Equipment	1,600	7,500	-	2,800
Chemical Feeding:				
Alum	1,200	4,000	-	1,100
Polymer, Wastewater	400	3,500	-	250
Polymer, Sludge	1,100	15,000	-	1,200
Primary Sludge Pumping	250	7,500	-	5,600
Waste Activated Sludge Pumping	410	22,500	-	12,000
Chemical Sludge Pumping	160	33,000	-	2,700
Gravity Thickening	800	6,000	-	1,200
Flotation Thickening	3,400	800,000	-	300
Vacuum Filtration	8,900	700,000	-	65,000
Multiple Hearth Furnaces	16,000	1,200,000	190×10^6	19,000
Intermediate Pumping Station	1,700	470,000	-	5,500
TOTAL	60,850	9,315,800	190×10^6	168,450

TABLE 52

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 50 MGD

Process Component	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation Tanks	4,900	20,000	-	9,500
Aeration Basins	-	-	-	-
Aeration Equipment	13,000	10,200,000	-	18,000
Secondary Sedimentation Tanks	5,900	20,000	-	13,000
Return Activated Sludge Pumping	2,000	340,000	-	5,000
Rapid Mixing	800	1,200,000	-	2,800
Flocculation	350	80,000	-	3,900
Clarifier	5,000	13,200	-	10,000
Filtration	8,000	270,000	-	20,000
Chlorine Contact Basins	-	-	-	-
Chlorination Equipment	2,300	15,000	-	3,500
Chemical Feeding:				
Alum	2,000	6,000	-	2,000
Polymer, Wastewater	420	5,000	-	380
Polymer, Sludge	2,100	24,000	-	1,800
Primary Sludge Pumping	340	15,000	-	9,000
Waste Activated Sludge Pumping	540	45,000	-	19,000
Chemical Sludge Pumping	220	66,000	-	4,000
Gravity Thickening	1,400	12,000	-	1,800
Flotation Thickening	6,500	1,400,000	-	500
Vacuum Filtration	14,000	1,400,000	-	105,000
Multiple Hearth Furnaces	25,000	2,200,000	400×10^6	30,000
Intermediate Pumping Station	2,300	660,000	-	13,000
TOTAL	97,420	17,991,000	400×10^6	272,180

TABLE 53

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 1 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years	
3,733,000 x 0.09439	$352,357
Labor	
13,578 Hours @ $9/Hour	$122,202
Power	
473,400 kWh @ $0.02/kWh	$ 9,470
Fuel	
5.1 x 10^6 CFS @ $1.50/TCF	$ 7,650
Maintenance Materials	$ 19,830
Chemicals	
Alum	
190 Tons @ $70/Ton	$ 13,300
Polymer	
8,329 lb @ $2/lb	$ 16,600
761 lb @ $0.30/lb	$ 230
Chlorine	
4.6 Tons @ $220/Ton	$ 1,012
TOTAL	$544,067

Cost/MG @ Capacity = $\frac{\$544,067}{365 \times 1}$ = $1,490/MG

TABLE 54

ACTIVATED SLUDGE WITH CHEMICAL
COAGULATION AND FILTRATION, 5 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years	
8,059,000 x 0.09439	$ 760,689
Labor	
25,130 Hours @ $9/Hour	$ 226,170
Power	
2,102,100 kWh @ $0.02/kWh	$ 42,040
Fuel	
33 x 10^6 SCF @ $1.50/TCF	$ 49,500
Maintenance Materials	$ 57,990
Chemicals	
Alum	
950 Tons @ $70/Ton	$ 66,500
Polymer	
41,650 lb @ $2/lb	$ 83,300
3,805 lb @ $0.30/lb	$ 1,140
Chlorine	
23 Tons @ $220/Ton	$ 5,060
TOTAL	$1,292,389

$$\text{Cost/MG @ Capacity} = \frac{\$1,292,389}{365 \times 5} = \$708/\text{MG}$$

TABLE 55

ACTIVATED SLUDGE WITH CHEMICAL
COAGULATION AND FILTRATION, 10 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 12,419,000 x 0.09439	$1,127,394
Labor 35,000 Hours @ $9/Hour	$ 315,000
Power 3,851,000 kWh @ $0.02/kWh	$ 77,020
Fuel 66 x 10^6 SCF @ $1.50/TCF	$ 99,000
Maintenance Materials	$ 90,520
Chemicals	
Alum	
1,900 Tons @ $70/Ton	$ 133,000
Polymer	
83,317 lb @ $2/lb	$ 166,600
7,610 lb @ $0.03/lb	$ 2,300
Chlorine	
46 Tons @ $220/Ton	$ 10,120
TOTAL	$2,020,954

Cost/MG @ Capacity = $\frac{\$2,020,954}{365 \times 10}$ = $554/MG

TABLE 56

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 25 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
21,761,000 x 0.09439	$2,054,020
Labor	
60,850 Hours @ $9/Hour	$ 547,650
Power	
9,315,800 kWh @ $0.02/kWh	$ 186,315
Fuel	
190 x 10^6 SCF @ $1.50/TCF	$ 285,000
Maintenance Materials	$ 168,450
Chemicals	
Alum	
4,750 Tons @ $70/Ton	$ 332,500
Polymer	
208,294 lb @ $2/lb	$ 416,600
19,025 lb @ $0.30/lb	$ 5,700
Chlorine	
115 Tons @ $100/Ton	$ 11,500
TOTAL	$4,007,735

$$\text{Cost/Mg @ Capacity} = \frac{\$4,007,735}{365 \times 25} = \$439/\text{MG}$$

TABLE 57

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION, 50 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
33,785,000 x 0.09439	$3,188,966
Labor	
97,420 Hours @ $9/Hour	$ 876,780
Power	
17,991,000 kWh @ $0.02/kWh	$ 359,820
Fuel	
400 x 10^6 SCF @ $1.50/TC	$ 600,000
Maintenance Materials	$ 272,180
Chemicals	
Alum	
9,500 Tons @ $70/Ton	$ 665,000
Polymer	
416,589 lb @ $2/lb	$ 833,200
38,050 lb @ $0.30/lb	$ 11,415
Chlorine	
230 Tonss @ $100/Ton	$ 23,000
TOTAL	$6,830,361

$$\text{Cost/MG @ Capacity} = \frac{\$6,830,361}{365 \times 50} = \$374/\text{MG}$$

TABLE 58

ACTIVATED SLUDGE WITH CHEMICAL COAGULATION AND FILTRATION ANNUAL COST SUMMARY

Annual Cost ($1,000)

	Capacity, MGD				
	1	5	10	25	50
Amortized Capital	352,357	760,689	1,127,394	4,007,735	3,188,966
Labor	122,202	226,170	315,000	547,650	876,780
Power	9,470	42,040	77,020	186,315	359,820
Fuel	7,650	49,500	99,000	285,000	600,000
Maintenance Materials	19,830	57,990	90,520	168,450	272,180
Chemicals:					
Alum	13,300	66,500	133,000	332,500	665,000
Polymer	16,830	84,440	168,900	422,300	844,615
Chlorine	1,012	5,060	10,120	11,500	23,000
TOTAL	$544,067	$1,292,389	$2,020,945	$4,007,735	$6,830,361
Costs/1,000 Gals (Operating @ Capacity)	$1.49	$0.71	$0.55	$0.44	$0.37

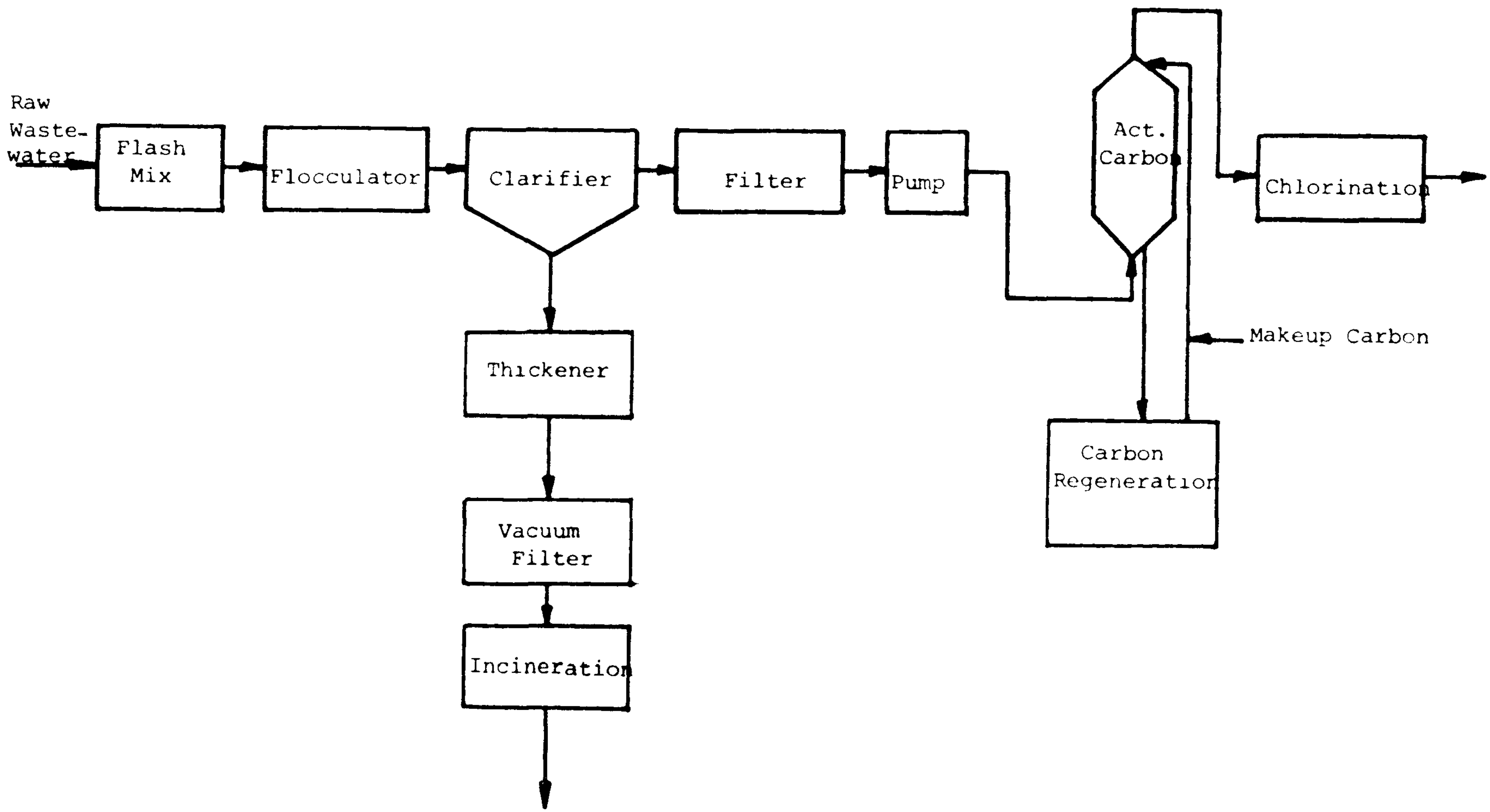


FIGURE 21. GRANULAR CARBON SYSTEM SCHEMATIC

TABLE 59

DESIGN PARAMETERS FOR GRANULAR CARBON SYSTEM

Chemical Treatment	
Coagulant	Alum
Coagulant Dose, mg/l	125
Polyelectrolyte Dose, mg/l	0.25
Flash Mix Time, Min	1
Flocculation Time	15 (G = 70, Vertical Turbine)
Clarifier	
Hydraulic Loading, gpm/ft^2 (peak)	0.8
Gravity Thickener	
Solids Loading, lb/ft^2/day	10
Underflow Solids, %	5
Vacuum Filter (20 hr/day operation)	
Feed Solids, %	5
Yield, lb/ft^2/hr	2.8
Cake Moisture Content, %	75
Lime Dose, % by Weight	40
Multiple Hearth Incinerator	
Loading Rate	7 lb (wet)/hr/ft^2
Downtime, %	30
Granular Media Filter	
Type	Gravity, Tri Media
Average Hydraulic Loading gpm/ft^2	5
Number of Filters, Minimum	4
Average Backwash Recycle, % of Filtrate	3
Carbon Treatment	
Carbon Contactor	Upflow, Countercurrent, Expanded
Average Contact Time	30 Min
Carbon Dose, lb/mg	1,500

TABLE 59 (Cont'd.)

Chlorination	
Contact Time @ PDWF, Min	30
Dosage, mg/l	5 (max) (3 ave)
Carbon Regeneration	
Furnace Type	Multiple Hearth
Downtime, %	30
Loading Rate	40 lb carbon/ft^2/day
Carbon loss	8%/cycle

TABLE 60

GRANULAR CARBON SYSTEMS UNIT PROCESS SIZES

	MGD				
	1	5	10	25	50
Rapid Mix, ft^3	93	465	930	2,325	4,650
Flocculator, ft^3	1,395	6,975	13,950	34,875	69,750
Clarifier, ft^2	1,302	6,510	13,020	32,550	65,100
Filter, ft^2	140	700	1,400	3,500	7,000
Primary Sludge					
Thickener, ft^2	207	1,035	2,070	5,175	10,350
Vacuum Filter, ft^2	37	185	370	925	1,850
Incinerator, ft^2	50	250	500	1,250	2,500
Chemical Feed					
Wastewater					
Alum, lb/hr	45	225	450	1,125	2,250
Poly, lb/hr	0.09	0.45	0.90	2.25	4.50
Primary Sludge					
Lime, lb/hr	35	175	350	875	1,750
Primary Sludge Pumping, gpm	20	100	200	500	1,000
Carbon Influent Pumping, MGD	1.5	7.5	15	37.5	75
Effective Carbon Contactor Vol., ft^3	3,069	15,345	30,690	76,725	153,450
Carbon Regeneration Furnace, ft^2	75(1)	270	540	1,350	2,700
Chlorine Contact, ft^3	4,180	20,900	41,800	104,500	209,000
Chlorine Feed, Tons/yr					
Average	4.56	22.8	45.6	114	228
Peak	11.4	57.0	114	285	570

***Minimum size furnace. Run 50 percent of time.**

TABLE 61

CAPITAL COSTS, GRANULAR CARBON

	MGD				
	1	5	10	25	50
Rapid Mix	10,000	23,000	37,000	76,000	130,000
Flocculator	13,000	38,000	55,000	100,000	160,000
Clarifier	85,000	230,000	440,000	1,100,000	2,200,000
Filter	390,000	685,000	1,050,000	1,900,000	2,900,000
Primary Sludge					
Thickener	70,000	110,000	160,000	200,000	400,000
Vacuum Filter	190,000	270,000	400,000	700,000	1,200,000
Incinerator	1,000,000	1,400,000	1,900,000	2,600,000	3,700,000
Chemical Feed					
Wastewater					
Alum	30,000	45,000	70,000	160,000	300,000
Poly	10,000	13,000	18,000	32,000	62,000
Primary Sludge					
Lime	40,000	100,000	160,000	280,000	400,000
Sludge Pumping					
Primary Sludge	65,000	150,000	200,000	320,000	470,000
Carbon Influent Pumping	45,000	160,000	280,000	560,000	1,000,000
Carbon Contactor System	250,000	1,200,000	2,300,000	5,400,000	10,500,000
Carbon Regeneration System	1,150,000	1,400,000	1,800,000	2,600,000	3,900,000
Chlorine Contact	51,000	140,000	200,000	340,000	530,000
Chlorine Feed	7,000	22,000	38,000	69,000	110,000
SUBTOTAL	3,406,000	5,986,000	9,108,000	16,437,000	27,962,000
Yardwork	477,000	838,000	1,275,000	2,301,000	3,915,000
TOTAL CONSTRUCTION COST	3,883,000	6,824,000	10,383,000	18,738,000	34,877,000
Engineering, Fiscal, Legal	466,000	819,000	1,246,000	2,249,000	3,825,000
Interest During Construction	388,000	682,000	1,038,000	1,874,000	3,188,000
TOTAL CAPITAL COST	4,737,000	8,325,000	12,667,000	22,861,000	38,890,000

for Carbon Adsorption." Analysis of the regeneration costs in the TT Manual indicated that they were low when updated by the EPA STP index. Recent bids indicate that the EPA index does not adequately reflect the inflation of mechanically complex systems such as regeneration furnaces. Thus, data developed by CWC for multiple-hearth furnace systems under EPA Contract 68-03-2186 were used as the basis for capital costs of the carbon regeneration systems.

Tables 62-66 summarize O&M costs. Activated carbon costs were obtained from manufacturers. Labor and maintenance materials for carbon adsorption were obtained from the TT Manual curves. Power requirements for pumping through the carbon system were calculated based on a total head of 50 feet. The TT Manual curves for carbon regeneration labor are in error (i.e., 24,000 manhours/year for 6,000 pounds a day for carbon is obviously far too high). Discussions were held with the authors of that portion of the TT Manual. Based on this, it was decided to use the CWC labor curve for multiple-hearth furnaces. The TT Manual curves were used for regeneration power and maintenance materials. Regeneration fuel requirements are based on the following data furnished by a carbon manufacturer during a recent design project to estimate on-site regeneration energy requirements:

	Btu Per lb Carbon Reactivated
Furnace Gas	3,000
Steam	1,250
Afterburner	2,400
TOTAL	6,650

Tables 67-71 summarize total annual costs for each capacity and Table 72 is an overall summary. It was found cheaper to regenerate carbon even at the one MGD scale rather than use the carbon on a one time basis.

POWDERED CARBON, EIMCO

The process schematic for this process is shown in Figure 22. The design criteria are shown in Table 73. Incineration was assumed as the means of ultimate sludge disposal for the primary sludge in this base case. Most sources of unit process costs have already been described. Unit process costs not previously discussed are covered below.

Powdered Carbon Feed

Costs for powdered carbon feed were developed specifically for this project. Figures 23-25 describe the powdered carbon feed system design. The carbon is stored and fed in a slurry

TABLE 62

GRANULAR CARBON, 1 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	480	27,000	-	280
Flocculator	1,100	1,800	-	400
Clarifier	580	3,300	-	450
Filter	2,900	88,000	-	1,500
Primary Sludge				
Thickener	330	1,000	-	100
Vacuum Filter	1,200	55,000	-	7,000
Incinerator	1,500	80,000	21.5×10^6	4,000
Chemical Feed				
Wastewater				
Alum	200	2,400	-	200
Poly	300	2,100	-	100
Primary Sludge				
Lime Feed	1,200	3,000	-	200
Sludge Pumping				
Primary Sludge	75	5,500	-	800
Chlorination	390	-	-	300
Carbon Adsorption	850	70,000	-	1,500
Carbon Regeneration	950	45,000	10×10^6	2,000
TOTAL	12,055	384,100	31.5×10^6	18,830

TABLE 63

GRANULAR CARBON, 5 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	580	120,000	-	520
Flocculator	160	8,200	-	800
Clarifier	1,200	3,300	-	1,800
Filter	3,600	115,000	-	4,200
Primary Sludge				
Thickener	400	4,800	-	400
Vacuum Filter	3,200	180,000	-	20,000
Incinerator	3,900	250,000	21.5×10^6	7,000
Chemical Feed				
Wastewater				
Alum	400	2,600	-	280
Poly	400	2,700	-	100
Primary Sludge				
Lime Feed	1,900	9,000	-	200
Sludge Pumping				
Primary Sludge	160	27,000	-	2,200
Chlorination	610	-	-	1,800
Carbon Adsorption	1,800	350,000	-	1,800
Carbon Regeneration	4,000	200,000	18.1×10^6	6,400
TOTAL	22,310	1,272,600	39.6×10^6	47,500

TABLE 64

GRANULAR CARBON, 10 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	600	250,000	-	900
Flocculator	190	17,000	-	1,300
Clarifier	1,800	3,300	-	3,000
Filter	4,000	140,000	-	6,800
Primary Sludge				
Thickener	420	9,000	-	650
Vacuum Filter	5,000	340,000	-	35,000
Incinerator	6,000	420,000	32×10^6	10,000
Chemical Feed				
Wastewater				
Alum	650	3,000	-	470
Poly	400	2,900	-	150
Primary Sludge				
Lime Feed	2,000	15,000	-	900
Sludge Pumping				
Primary Sludge	200	50,000	-	3,700
Chlorination	890	-	-	2,200
Carbon Adsorption	2,600	700,000	-	3,200
Carbon Regeneration	6,800	325,000	36.4×10^6	8,300
TOTAL	31,550	2,275,200	68.4×10^6	76,570

TABLE 65

GRANULAR CARBON, 25 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	700	520,000	-	1,800
Flocculator	230	40,000	-	2,300
Clarifier	3,300	6,600	-	5,500
Filter	5,200	190,000	-	13,000
Primary Sludge				
Thickener	600	17,000	-	1,300
Vacuum Filter	9,500	800,000	-	75,000
Incinerator	10,000	900,000	73×10^6	18,000
Chemical Feed				
Wastewater				
Alum	1,200	4,000	-	1,100
Poly	400	3,500	-	250
Primary Sludge				
Lime Feed	2,100	60,000	-	1,800
Sludge Pumping				
Primary Sludge	300	120,000	-	6,800
Chlorination	1,600	7,500	-	2,800
Carbon Adsorption	4,200	1,750,000	-	6,400
Carbon Regeneration	12,000	800,000	91×10^6	12,000
TOTAL	51,330	5,218,600	164×10^6	148,050

TABLE 66

GRANULAR CARBON, 50 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	800	1,200,000	-	2,800
Flocculator	350	80,000	-	3,900
Clarifier	5,000	13,200	-	10,000
Filter	8,000	27,000	-	20,000
Primary Sludge				
Thickener	1,100	26,000	-	2,100
Vacuum Filter	16,000	1,500,000	-	100,000
Incinerator	18,000	1,750,000	130×10^6	30,000
Chemical Feed				
Wastewater				
Alum	2,000	6,000	-	2,000
Poly	420	5,000	-	380
Primary Sludge				
Lime Feed	2,700	52,000	-	2,800
Sludge Pumping				
Primary Sludge	400	230,000	-	10,000
Chlorination	2,300	15,000	-	3,500
Carbon Adsorption	6,000	3,500,000	-	11,520
Carbon Regeneration	19,000	1,600,000	181×10^6	16,000
TOTAL	82,070	10,004,200	311×10^6	215,000

TABLE 67

GRANULAR CARBON, 1 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years 4,737,000 x 0.09439	$447,125
Labor 12,055 Hours @ $9/Hour	$108,495
Power 384,100 kWh @ $0.02/kWh	$ 7,680
Fuel 31.5 x 10^6 SCF @ $1.50/TCF	$ 47,250
Maintenance Materials	$ 18,830
Chemicals	
Makeup Carbon 22 Tons @ $1,000/Ton	$ 22,000
Alum 190 Tons @ $70/Ton	$ 13,300
Polymer - Wastewater 761 lb @ $0.30/lb	$ 230
Lime - Primary Sludge 153 Tons @ $37/Ton	$ 5,660
Chlorine 4.6 Tons @ $220/Ton	$ 1,012
TOTAL	$671,582

$$\text{Cost @ Capacity} = \frac{\$671,582}{365 \times 1} = \$1,839/\text{MG}$$

TABLE 68

GRANULAR CARBON, 5 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years 8,325,000 x 0.09439	$ 785,797
Labor 22,310 Hours @ $9/Hour	$ 200,790
Power 1,272,600 kWh @ $0.02/kWh	$ 25,450
Fuel 39.6 x 10^6 SCF @ $1.50/TCF	$ 59,400
Maintenance Materials	$ 47,500
Chemicals	
Makeup Carbon 109 Tons @ $1,000/Ton	$ 109,000
Alum 950 Tons @ $70/Ton	$ 66,500
Polymer - Wastewater 3,805 lb @ $0.30/lb	$ 1,140
Lime - Primary Sludge 766 Tons @ $37/Ton	$ 28,340
Chlorine 23 Tons @ $220/Ton	$ 5,060
TOTAL	$1,328,977

$$\text{Cost/MG @ Capacity} = \frac{\$1,238,977}{365 \times 5} = \$728/\text{MG}$$

TABLE 69

GRANULAR CARBON, 10 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years 12,667,000 x 0.09439	$1,195,638
Labor 31,550 Hours @ $9/Hour	$ 283,950
Power 2,275,200 kWh @ $0.02/kWh	$ 45,500
Fuel 68.4 x 10^6 SCF @ $1.50/TCF	$ 102,600
Maintenance Materials	$ 76,570
Chemicals	
Makeup Carbon 219 Tons @ $1,000/Ton	$ 219,000
Alum 1,900 Tons @ $70/Ton	$ 133,000
Polymer - Wastewater 7,610 lb @ $0.30/lb	$ 2,300
Lime - Primary Sludge 1,532 Tons @ $37/Ton	$ 56,700
Chlorine 46 Tons @ $220/Ton	$ 10,120
TOTAL	$2,125,378

$$\text{Cost/MG @ Capacity} = \frac{\$2,125,378}{365 \times 10} = \$582/\text{MG}$$

TABLE 70

GRANULAR CARBON, 25 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years 22,861,000 x 0.09439	$2,157,850
Labor 51,330 Hours @ $9/Hour	$ 461,970
Power 5,219,600 kWh @ $0.02/kWh	$ 104,372
Fuel 164 x 10^6 SCF @ $1.50/TCF	$ 246,000
Maintenance Materials	$ 148,050
Chemicals	
Makeup Carbon 547 Tons @ $1,000/Ton	$ 547,000
Alum 4,750 Tons @ $70/Ton	$ 332,500
Polymer - Wastewater 19,025 lb @ $0.30/lb	$ 5,700
Lime - Primary Sludge 3,830 Tons @ $37/Ton	$ 141,700
Chlorine 115 Tons @ $100/Ton	$ 11,500
TOTAL	$4,156,642

$$\text{Cost/MG @ Capacity} = \frac{\$4,156,642}{365 \times 25} = \$456/\text{MG}$$

TABLE 71

GRANULAR CARBON, 50 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
38,840,000 x 0.09439	$3,670,827
Labor	
84,070 Hours @ $9/Hour	$ 738,630
Power	
10,004,200 kWh @ $0.02/kWh	$ 200,100
Fuel	
311 x 10^6 SCF @ $1.50/TCF	$ 466,500
Maintenance Materials	$ 215,000
Chemicals	
Makeup Carbon	
1,096 Tons @ $1,000/Ton	$1,096,000
Alum	
9,500 Tons @ $70/Ton	$ 665,000
Polymer - Wastewater	
38,050 lb @ $0.30/lb	$ 11,415
Lime - Primary Sludge	
7,660 Tons @ $37/Ton	$ 283,420
Chlorine	
230 Tons @ $100/Ton	$ 23,000
TOTAL	$7,369,892

Cost/MG @ Capacity = $\frac{\$7,369,892}{365 \times 50}$ = $404/MG

TABLE 72

GRANULAR CARBON ANNUAL COST SUMMARY

	ANNUAL COST ($1,000)				
	CAPACITY, MGD				
	1	5	10	25	50
Amortized Capital	447	785.6	1,195.6	2,157.8	3,670.8
Labor	108.5	200.8	284.0	462.0	738.6
Power	7.7	25.45	45.5	104.37	200.1
Fuel	47.25	59.4	102.6	246.0	466.5
Maintenance Materials	18.83	47.5	76.6	148.05	215.0
Chemicals					
Makeup Carbon	22.0	109.0	219.0	547.0	1,096.0
Alum	13.3	66.5	133.0	332.5	665.0
Polymer - Wastewater	0.23	1.14	2.3	5.7	11.4
Chlorine	1.0	5.06	10.12	11.50	23.0
Lime - Primary Sludge	5.66	28.34	56.7	141.7	283.42
TOTAL	671.47	1,328.79	2,125.42	4,156.62	7,369.82
Costs/1,000 Gals (Operating at Capacity)	$1.84	$0.73	$0.58	$0.46	$0.40

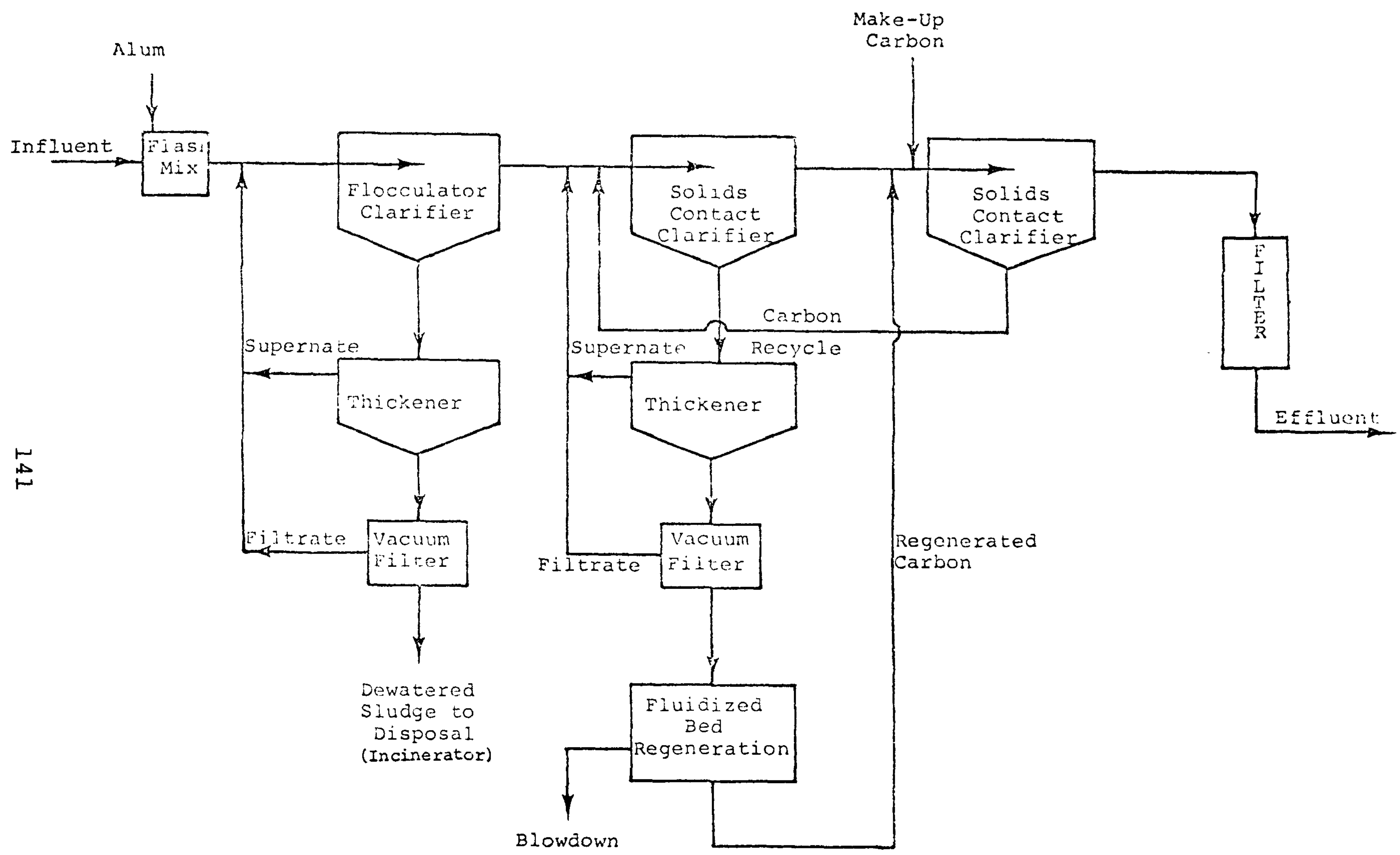


FIGURE 22. EIMCO SYSTEM PROCESS FLOW SHEET

TABLE 73

DESIGN PARAMETERS FOR EIMCO SYSTEM

Chemical Treatment	
Coagulant	Alum
Coagulant Dose, mg/l	125
Polyelectrolyte Dose, mg/l	0.25
Flash Mix Time, Minute	1
Clarifier	
Type	Flocculator-Clarifier
Hydraulic Loading, gpm/ft^2 (Peak)	0.8
Gravity Thickener	
Solids Loading, $lb/day/ft^2$	10
Underflow Solids, %	5
Vacuum Filter	
Feed Solids, %	5
Yield, $lb/hr/ft^2$	2.8
Cake Moisture Content, %	75
Lime Dose, % by Weight	40
Carbon Treatment	
Carbon Contactor	Internal Solids Recycle
Peak Hydraulic Loading, gpm/ft^2	0.8
Carbon Dose, mg/l	300
Carbon Slurry Concentration, g/l	10
Underflow Concentration, %	3
Gravity Thickener	
Solids Loading, $lb/day/ft^2$	20
Underflow Solids, %	12
Vacuum Filter	
Feed Solids, %	12
Polyelectrolyte Dose, lb/Ton Dry Solids	10
Yield, $lb/hr/ft^2$	8
Cake Solids, %	27
Granular Media Filter	
Type	Tri Media
Average Hydraulic Loading gpm/ft^2	5
Average Backwash Recycle, % of Filtrate	3

TABLE 73 (Cont'd.)

Fluidized Bed Furnace	
Solids Loading, $lb/hr/ft^2$	3
Freeboard Velocity, ft/sec	1.2
Firebox Temperature, °F	2000
Operating Temperature, °F	1250
Carbon Recovery, %	90
Blowdown, %	5
Primary Sludge Incineration	
Multiple Hearth, Loading Rate	7 $lb/ft^2/hr$ (Wet Basis)
Chlorination	
Contact Time @ PDWF, Minutes	30
Dosage, mg/l	5 (Max), 3 (Ave)

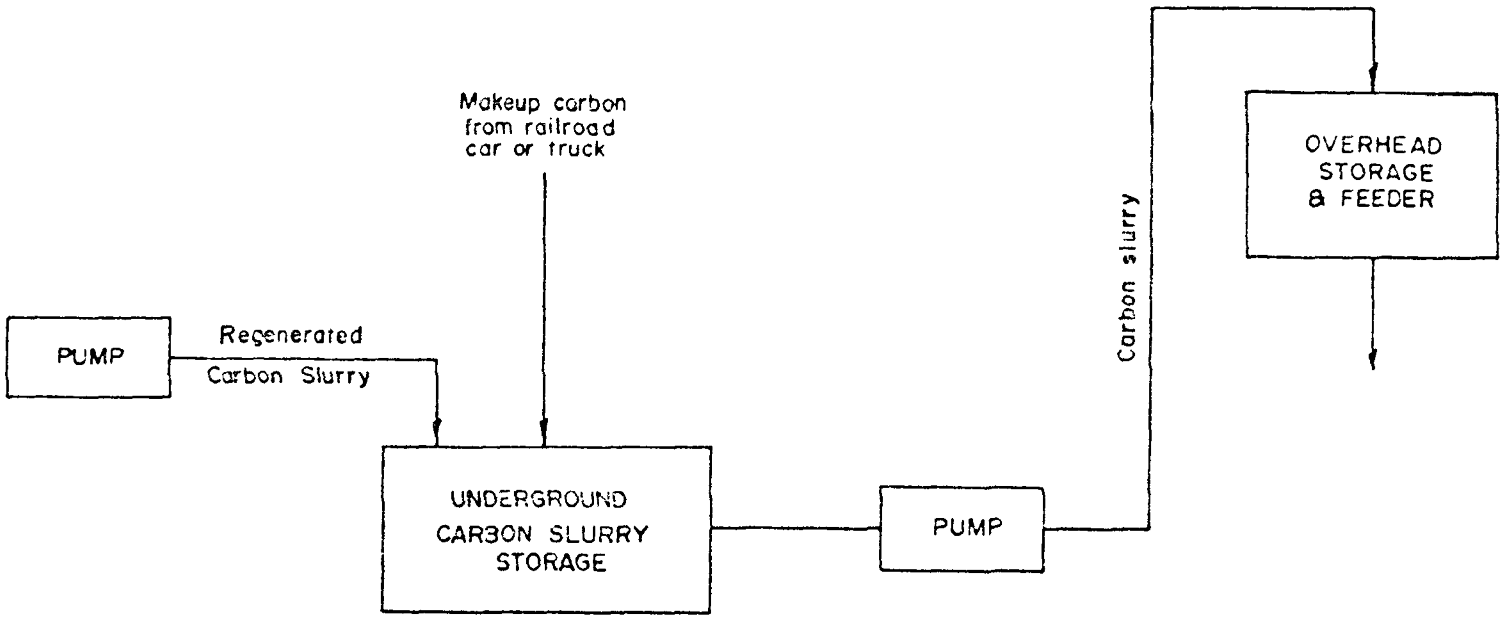


FIGURE 23. POWDERED ACTIVATED CARBON FEED SYSTEM (5-50 mgd)

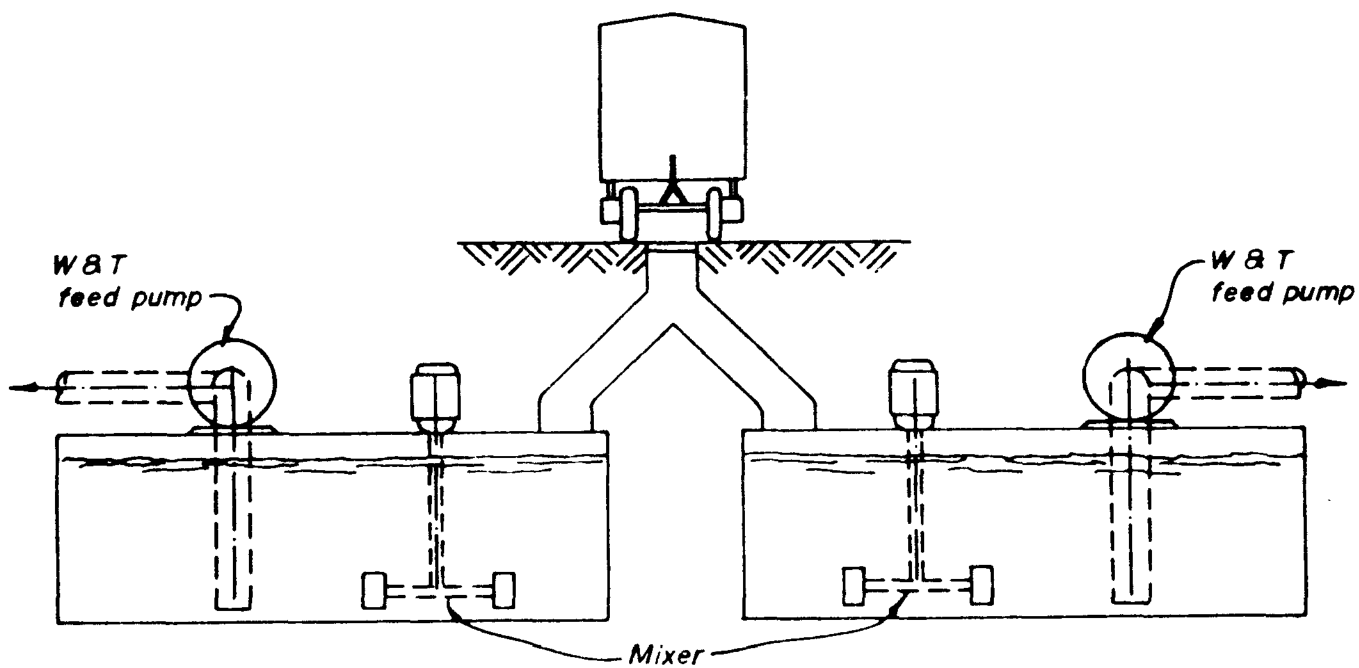


FIGURE 24. POWDERED CARBON STORAGE AND FEEDING (1 mgd)

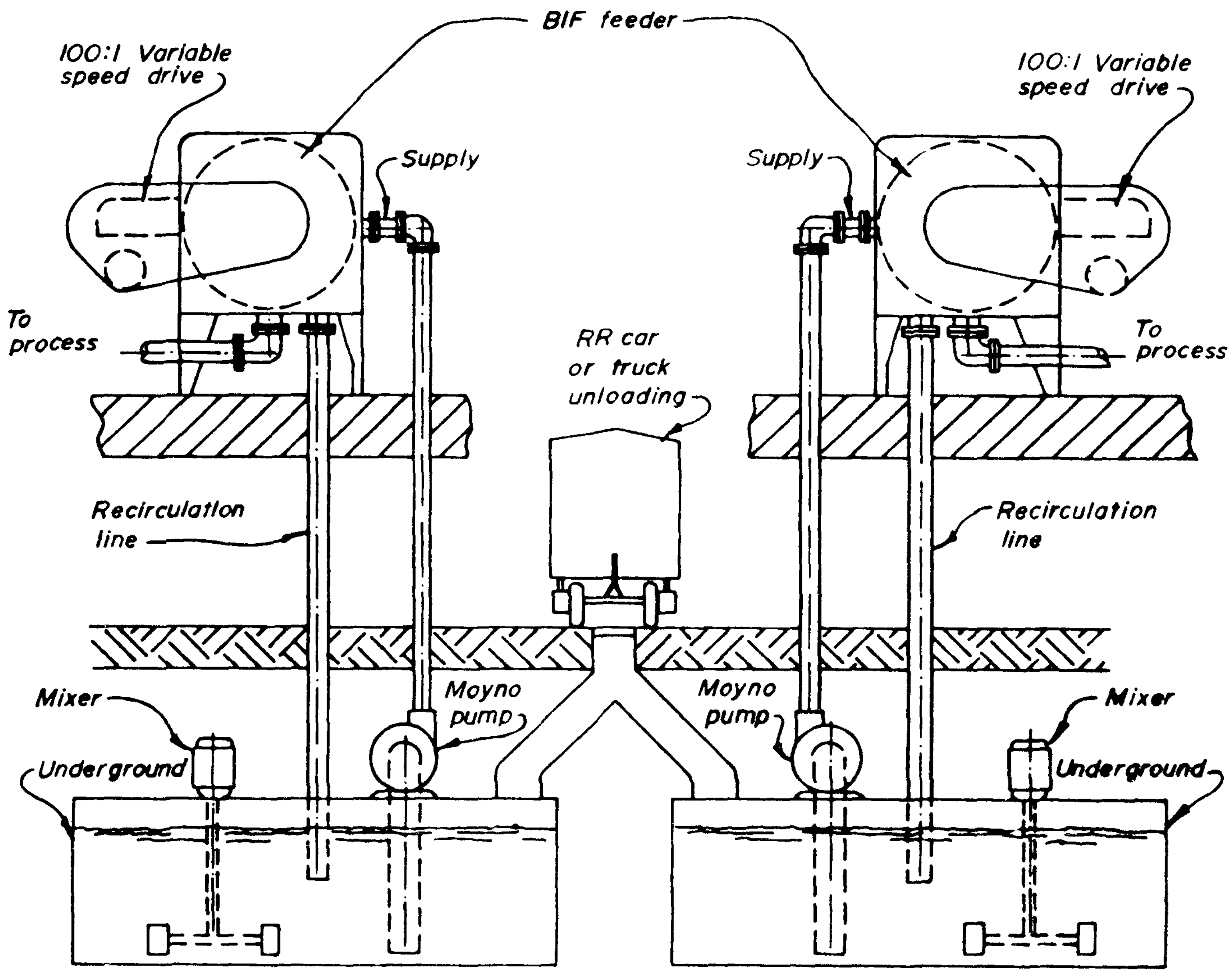


FIGURE 25. POWDERED CARBON STORAGE AND FEEDING (5-50 mgd)

consisting of one pound of carbon per gallon of water. The major elements of the 5 to 50 MGD systems include:

1. Carbon slurry pumping from regeneration furnace to underground storage basin.

2. Underground slurry storage and mixers with bulk unloading facilities.

3. Carbon slurry pumping from underground storage to elevated feeders.

4. Slurry feeders in elevated structure.

The one MGD system includes only carbon slurry storage with mixers and a slurry metering feed pump.

The underground storage volume was varied with plant size with the following minimum storage provided: 1 MGD - 20 days; 5 MGD - 5 days; 10 MGD - 3.5 days; 25 MGD - 3 days; and 50 MGD - 2.5 days.

The previously developed CWC curves[40] for rapid mixing basins (G = 600) were used to estimate the costs of the underground storage basins. Pump and feeder costs were obtained from manufacturers.

<u>Flocculator-Clarifier</u>

Manufacturer supplied equipment cost information coupled with CWC estimates of basin costs provided the basis for the flocculator-clarifier construction cost curve. O&M requirements were based on the previously developed[40] CWC information on flocculation and sedimentation.

<u>Reactor-Clarifiers</u>

These curves were obtained from the earlier CWC report.[40]

<u>Fluidized Bed Regeneration Furnace</u>

Fluidized bed furnace (FBF) regeneration of powdered carbon has been demonstrated only on a pilot scale. Thus, there is a degree of uncertainty about the design criteria and any estimates of costs for full scale systems. Because of this uncertainty, the FBF costs receive added attention in the later analysis of economic sensitivity. Independent estimates of capital and O&M costs for full scale systems were obtained from two manufacturers (Envirotech and Copeland Systems). Both manufacturers rated their FBF systems at higher capacities (from 5 lb/ft^2/hr in the smaller furnaces to 7 lb/ft^2/hr in the larger furnaces) than shown in Table 73. With the exception of power requirements, the data from the two manufacturers were in close agreement. The cost curves in the Appendix are based upon the capacities of the FBF systems as rated by the manufacturers rather than the 3 lb/hr/sq ft. shown in Table 73. Fuel requirements vary with the size of the FBF system and range from 9,000 Btu/pound of carbon at 100 lb/hr to 5,500 Btu/pound at 10,000 lb/hr. The manufacturers agreed closely on fuel requirements. Power requirements as estimated by Envirotech, ranged from 0.82 kWh/pound of carbon at 100 lb/hr to 0.6 kWh/pound of carbon at 3,400 lb/hr. Copeland's estimates were 0.2 kWh/pound of carbon. The power curve is based on Envirotech's estimates with the potential impact of lower power requirements discussed later. Labor and maintenance material requirements were extrapolated from CWC's earlier work on multiple hearth furnaces. The FBF sizing for the plant examples was based on 30 percent downtime. It was found cheaper to regenerate carbon at the one MGD size rather than use the carbon on a one-time basis.

Tables 74-86 present the results.

POWDERED CARBON, BATTELLE

Figure 26 represents a schematic of this process. Table 87 presents the design criteria. The basis of most unit costs has been discussed in previous sections. Costs for centrifuging, sulfuric acid feeding, and tube settling were obtained from the earlier CWC report.[40] The carbon contactor costs were determined using the flocculator cost curve (G = 70). Rapid mixing costs are based on G = 300. It was found to be lower in cost to regenerate carbon in the one MGD plant than to use the carbon on a one-time basis. Thus, regeneration facilities are included for all capacities. Alum feed costs represent only the makeup alum since the recovered alum is recycled with the powdered carbon. Credit of 9,500 Btu/lb of raw sewage solids was taken into consideration in determining the supplemental fuel requirements of the FBF furnace. This heat value essentially balances the heat required to vaporize the added water found in the Battelle process sludge relative to the Eimco process sludge (6.5 lb water/lb carbon vs 2.7 lb water/lb carbon). The heat required to bring the added water vapor up to 1500°F is equivalent to an added 2690 Btu/lb of carbon for the Battelle process sludge relative to the Eimco process sludges. Curve 101 reflects these differences in heat requirements.

POWDERED CARBON, BIO-PHYSICAL

Figure 27 presents a schematic of this process. Table 101 presents the design criteria. Air quantities (mechanical aeration used as basis for cost estimates) are adequate for nitrification. Costs for the wet oxidation system for carbon regeneration were obtained from Zimpro. The regeneration system was sized based upon 30 percent downtime -- consistent with the assumption made for other regeneration techniques. The basic costs provided by

TABLE 74

UNIT PROCESS SIZES, EIMCO PROCESS

	MGD				
	1	5	10	25	50
Rapid Mix, ft^3	93	465	930	2,325	4,650
Floc-Clarifier, ft^2	1,302	6,510	13,020	32,550	65,100
Solids Contact Clarifiers, ft^2 (Each)	1,302	6,510	13,020	32,550	65,100
Filter, ft^2	140	700	1,400	3,500	7,000
Primary Sludge					
Thickener, ft^2	207	1,035	2,070	5,175	10,350
Vacuum Filter, ft^2	37	185	370	925	1,850
Incinerator, ft^2	50	250	500	1,250	2,500
Carbon Sludge					
Thickener, ft^2	195	980	1,960	4,900	9,800
Vacuum Filter, ft^2	16	120	240	600	1,200
FBF, lb/hr (70% Operation)	150	745	1,490	3,725	7,450
FBF, ft^2	30	125	235	500	1,060
Chemical Feed					
Wastewater					
Alum, lb/hr	45	225	450	1,125	2,250
Poly, lb/hr	0.09	0.45	0.90	2.25	4.50
Carbon, lb/hr	104	520	1,040	2,600	5,200
Primary Sludge					
Lime, lb/hr	35	175	350	875	1,750
Carbon Sludge					
Poly, lb/hr	0.5	4.0	8	20	40
Sludge Pumping					
Primary Sludge, gpm	20	100	200	500	1,000
Carbon Sludge, gpm	7	54	108	270	540

TABLE 75

CAPITAL COSTS, EIMCO

	MGD				
	1	5	10	25	50
Rapid Mix	10,000	23,000	37,000	76,000	130,000
Floc-Clarifier	160,000	410,000	700,000	1,400,000	2,800,000
Solids Contact Clarifiers	300,000	1,000,000	1,800,000	2,800,000	5,200,000
Filter	390,000	685,000	1,050,000	1,900,000	2,800,000
Primary Sludge					
Thickener	70,000	110,000	160,000	200,000	400,000
Vacuum Filter	190,000	270,000	400,000	700,000	1,200,000
Incinerator	1,000,000	1,400,000	1,900,000	2,600,000	3,700,000
Carbon Sludge					
Thickener	60,000	110,000	160,000	200,000	400,000
Vacuum Filter	190,000	200,000	300,000	510,000	850,000
FBF	850,000	1,500,000	2,300,000	5,000,000	9,000,000
Chemical Feed					
Wastewater					
Alum	30,000	45,000	70,000	160,000	300,000
Poly	10,000	13,000	18,000	32,000	62,000
Carbon	110,000	190,000	280,000	500,000	840,000
Primary Sludge					
Lime	40,000	100,000	160,000	280,000	400,000
Carbon Sludge					
Poly	13,000	53,000	100,000	220,000	510,000
Sludge Pumping					
Primary Sludge	35,000	52,000	60,000	75,000	90,000
Carbon Sludge	20,000	50,000	52,000	65,000	75,000
Chlorine Contact	51,000	140,000	200,000	340,000	530,000
Chlorine Feed	7,000	22,000	38,000	69,000	110,000
SUBTOTAL	$3,536,000	$6,373,000	$ 9,785,000	$17,125,000	$29,397,000
Yardwork	495,000	892,000	1,370,000	2,398,000	4,116,000
Total Construction Cost	$4,031,000	$7,265,000	$11,155,000	$19,523,000	$33,513,000
Engineering, Fiscal, Legal	$ 484,000	$ 872,000	$ 1,339,000	$ 2,343,000	$ 4,022,000
Interest During Construction	$ 403,000	$ 726,000	$ 1,116,000	$ 1,952,000	$ 3,351,000
TOTAL CAPITAL COST	$4,918,000	$8,863,000	$13,610,000	$23,818,000	$40,886,000

TABLE 76

EIMCO, 1 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	480	27,000	-	200
Flocc-Clarifier	700	7,500	-	800
Solids Contact Clarifiers	2,400	72,000	-	2.400
Filter	2,900	88,000	-	1,500
Primary Sludge				
Thickener	330	1,000	-	100
Vacuum Filter	1,200	55,000	-	7,000
Incinerator	1,500	80,000	12.0×10^6	4,000
Carbon Sludge				
Thickener	330	1,000	-	100
Vacuum Filter	900	40,000	-	5,000
FBF	840	700,000	7×10^6	1,800
Chemical Feed				
Wastewater				
Alum	200	2,400	-	200
Poly	300	2,100	-	100
Carbon	1,700	93,000	-	1,900
Primary Sludge Lime Feed	1,200	3,000	-	200
Carbon Sludge Poly Feed	400	2,600	-	100
Sludge Pumping				
Primary Sludge	75	5,500	-	800
Carbon Sludge	60	3,000	-	500
TOTAL	15,515	1,183,100	19.0×10^6	26,750

TABLE 77

EIMCO, 5 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	580	120,000	-	520
Flocc-Clarifier	1,360	31,000	-	2,800
Solids Contact Clarifiers	3,800	320,000	-	9,000
Filter	3,600	115,000	-	4,200
Primary Sludge				
Thickener	400	4,800	-	400
Vacuum Filter	3,200	180,000	-	20,000
Incinerator	3,900	250,000	21.5×10^6	7,000
Carbon Sludge				
Thickener	400	4,800	-	400
Vacuum Filter	2,300	120,000	-	16,000
FBF	1,700	2,870,000	35×10^6	3,500
Chemical Feed				
Wastewater				
Alum	400	2,600	-	280
Poly	400	2,700	-	100
Carbon	1,800	470,000	-	4,100
Primary Sludge Lime Feed	1,900	9,000	-	200
Carbon Sludge Poly Feed	410	5,000	-	350
Sludge Pumping				
Primary Sludge	160	27,000	-	2,200
Carbon Sludge	120	14,000	-	1,500
TOTAL	26,430	4,455,900	56.5×10^6	72,550

TABLE 78

EIMCO, 10 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	600	250,000	-	900
Flocc-Clarifier	2,100	54,000	-	3,900
Solids Contact Clarifiers	5,600	420,000	-	18,000
Filter	4,000	140,000	-	6,800
Primary Sludge				
Thickener	420	9,000	-	650
Vacuum Filter	5,000	340,000	-	35,000
Incinerator	6,000	420,000	32×10^6	10,000
Carbon Sludge				
Thickener	420	9,000	-	650
Vacuum Filter	3,900	230,000	-	27,000
FBF	2,500	4,900,000	63×10^6	5,000
Chemical Feed				
Wastewater				
Alum	650	3,000	-	470
Poly	400	2,900	-	150
Carbon	2,000	930,000	-	6,100
Primary Sludge Lime Feed	2,000	15,000	-	900
Carbon Sludge Poly Feed	450	7,000	-	550
Sludge Pumping				
Primary Sludge	200	50,000	-	2,700
Carbon Sludge	160	26,000	-	2,200
TOTAL	36,400	7,805,900	95×10^6	121,970

TABLE 79

EIMCO, 25 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	700	520,000	-	1,800
Flocc-Clarifier	3,300	145,000	-	7,600
Solids Contact Clarifiers	9,600	1,000,000	-	42,000
Filter	4,800	160,000	-	10,500
Primary Sludge				
Thickener	600	17,000	-	1,300
Vacuum Filter	9,500	800,000	-	75,000
Incinerator	10,000	900,000	73×10^6	18,000
Carbon Sludge				
Thickener	600	17,000	-	1,300
Vacuum Filter	7,000	500,000	-	50,000
FBF	4,200	12,600,000	154×10^6	7,000
Chemical Feed				
Wastewater				
Alum	1,200	4,000	-	1,100
Poly	400	3,500	-	250
Carbon	2,700	2,300,000	-	11,000
Primary Sludge Lime Feed	2,100	60,000	-	1,800
Carbon Sludge Poly Feed	500	17,000	-	1,000
Sludge Pumping				
Primary Sludge	300	120,000	-	6,900
Carbon Sludge	220	65,000	-	4,300
TOTAL	57,720	19,228,500	227×10^6	240,850

TABLE 80

EIMCO, 50 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Rapid Mix	800	1,200,000	-	2,800
Flocc-Clarifier	5,400	280,000	-	14,000
Solids Contact Clarifiers	14,000	2,000,000	-	84,000
Filter	5,200	190,000	-	13,000
Primary Sludge				
Thickener	1,100	26,000	-	2,100
Vacuum Filter	16,000	1,500,000	-	100,000
Incinerator	18,000	1,750,000	130×10^6	30,000
Carbon Sludge				
Thickener	1,100	26,000	-	2,100
Vacuum Filter	11,000	900,000	-	80,000
FBF	6,000	21,000,000	300×10^6	10,000
Chemical Feed				
Wastewater				
Alum	2,000	6,000	-	2,000
Poly	420	5,000	-	380
Carbon	3,700	4,700,000	-	18,000
Primary Sludge Lime Feed	2,700	52,000	-	2,800
Carbon Sludge Poly Feed	900	30,000	-	1,600
Sludge Pumping				
Primary Sludge	400	230,000	-	10,000
Carbon Sludge	300	130,000	-	7,000
TOTAL	89,020	34,025,000	430×10^6	379,780

TABLE 81

EIMCO, 1 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years 4,918,000 x 0.09439	$464,210
Labor 15,515 Hours @ $9/Hour	$139,635
Power 1,183,100 kWh @ $0.02/kWh	$ 23,662
Fuel 19 x 10^6 SCF @ $1.50/TCF	$ 28,500
Maintenance Materials	$ 26,750
Chemicals	
Powdered Carbon 69 Tons @ $650/Ton	$ 44,850
Alum 190 Tons @ $70/Ton	$ 13,300
Polymer - Wastewater 761 lb @ $0.30/lb	$ 230
Polymer - Carbon Sludge 4,380 lb @ $2.00/lb	$ 9,760
Chlorine 4.6 Tons @ $220/Ton	$ 1,012
Lime - Primary Sludge 153 Tons @ $37/Ton	$ 5,660
TOTAL	$757,569

$$\text{Cost/MG @ Capacity} = \frac{\$757,569}{365 \times 1} = \$2,078/\text{MG}$$

TABLE 82

EIMCO, 5 MGD

TOTAL ANNUAL COSTS

Amortized Capital @ 7%, 20 Years	
8,863,000 x 0.09439	$ 836,579
Labor	
26,430 Hours @ $9/Hour	$ 237,870
Power	
4,455,900 kWh @ $0.02/kWh	$ 89,118
Fuel	
56.5 x 10^6 SCF @ $1.50/TCF	$ 84,750
Maintenance Materials	$ 72,550
Chemicals	
Powdered Carbon - Makeup	
345 Tons @ $650/Ton	$ 224,250
Alum	
950 Tons @ $70/Ton	$ 66,500
Polymer - Wastewater	
3,805 lb @ $0.30/lb	$ 1,140
Polymer - Carbon Sludges	
35,040 lb @ $2.00/lb	$ 70,080
Chlorine	
23 Tons @ $220/Ton	$ 5,060
Lime - Primary Sludges	
766 Tons @ $37/Ton	$ 28,340
TOTAL	$1,716,237

Cost/MG @ Capacity = $\frac{\$1,716,237}{365 \times 5}$ = $940/MG

TABLE 83

EIMCO, 10 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years 13,610,000 x 0.09439	$1,284,648
Labor 36,400 Hours @ $9/Hour	$ 327,600
Power 7,805,900 kWh @ $0.02/kWh	$ 156,118
Fuel 95 x 10^6 SCF @ $1.50/TCF	$ 142,500
Maintenance Materials	$ 121,970
Chemicals	
Powdered Carbon - Makeup 690 Tons @ $650/Ton	$ 448,500
Alum 1,900 Tons @ $70/Ton	$ 133,000
Polymer - Wastewater 7,610 lb @ $0.30/lb	$ 2,300
Polymer - Carbon Sludge 70,080 lb @ $2.00/lb	$ 140,160
Chlorine 46 Tons @ $220/Ton	$ 10,120
Lime - Primary Sludge 1,532 Tons @ $37/Ton	$ 56,700
TOTAL	$2,823,616

$$\text{Cost/MG @ Capacity} = \frac{\$2,823,616}{365 \times 10} = \$774/\text{MG}$$

TABLE 84

EIMCO, 25 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
23,818,000 x 0.09439	$2,248,181
Labor	
57,720 Hours @ $9/Hour	$ 519,480
Power	
19,228,500 kWh @ $0.02/kWh	$ 384,570
Fuel	
227 x 10^6 SCF @ $1.50/TCF	$ 340,500
Maintenance Materials	$ 240,850
Chemicals	
Powdered Carbon	
1,725 Tons @ $650/Ton	$1,121,250
Alum	
4,750 Tons @ $70/Ton	$ 332,500
Polymer - Wastewater	
19,025 lb @ $0.30/lb	$ 5,700
Polymer - Carbon Sludge	
175,200 lb @ $2.00/lb	$ 350,400
Chlorine	
115 Tons @ $100/Ton	$ 11,500
Lime - Primary Sludge	
3,830 Tons @ $37/Ton	$ 141,700
TOTAL	$5,696,631

$$\text{Costs/MG @ Capacity} = \frac{\$5,696,631}{365 \times 25} = \$624/\text{MG}$$

TABLE 85

EIMCO, 50 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
40,886,000 x 0.09439	\$ 3,859,230
Labor	
89,020 Hours @ \$9/Hour	\$ 801,180
Power	
34,025,000 kWh @ \$0.02/kWh	\$ 680,500
Fuel	
430 x 10^6 SCF @ \$1.50/TCF	\$ 645,000
Maintenance Materials	\$ 379,780
Chemicals	
Powdered Carbon	
3,450 Tons @ \$650/Ton	\$ 2,242,500
Alum	
9,500 Tons @ \$70/Ton	\$ 665,000
Polymer - Wastewater	
38,050 lb @ \$0.30/lb	\$ 11,415
Polymer - Carbon Sludge	
351,000 lb @ \$2.00/lb	\$ 702,000
Chlorine	
230 Tons @ \$100/Ton	\$ 23,000
Lime - Primary Sludge	
7,660 Tons @ \$37/Ton	\$ 283,420
TOTAL	\$10,293,025

$$\text{Cost/MG @ Capacity} = \frac{\$10,293,025}{365 \times 50} = \$564/\text{MG}$$

TABLE 86

EIMCO ANNUAL COST SUMMARY

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	464	837	1,285	2,248	3,859
Labor	139	238	328	520	801
Power	24	89	156	384	680
Fuel	28	85	142	340	645
Maintenance Materials	27	73	122	241	380
Chemicals					
Powdered Carbon	45	224	448	1,121	2,242
Alum	13	66	133	332	665
Polymer - Wastewater	0.2	1.14	2.3	5.7	11.4
Polymer - Carbon Sludge	10	70	140	350	702
Chlorine	1	5	10	11.5	23
Lime - Primary Sludge	6	28	57	142	283
TOTAL	757	1,716	2,824	5,697	10,293
Costs/1,000 Gals (Operating @ Capacity)	$2.08	$0.94	$0.77	$0.62	$0.56

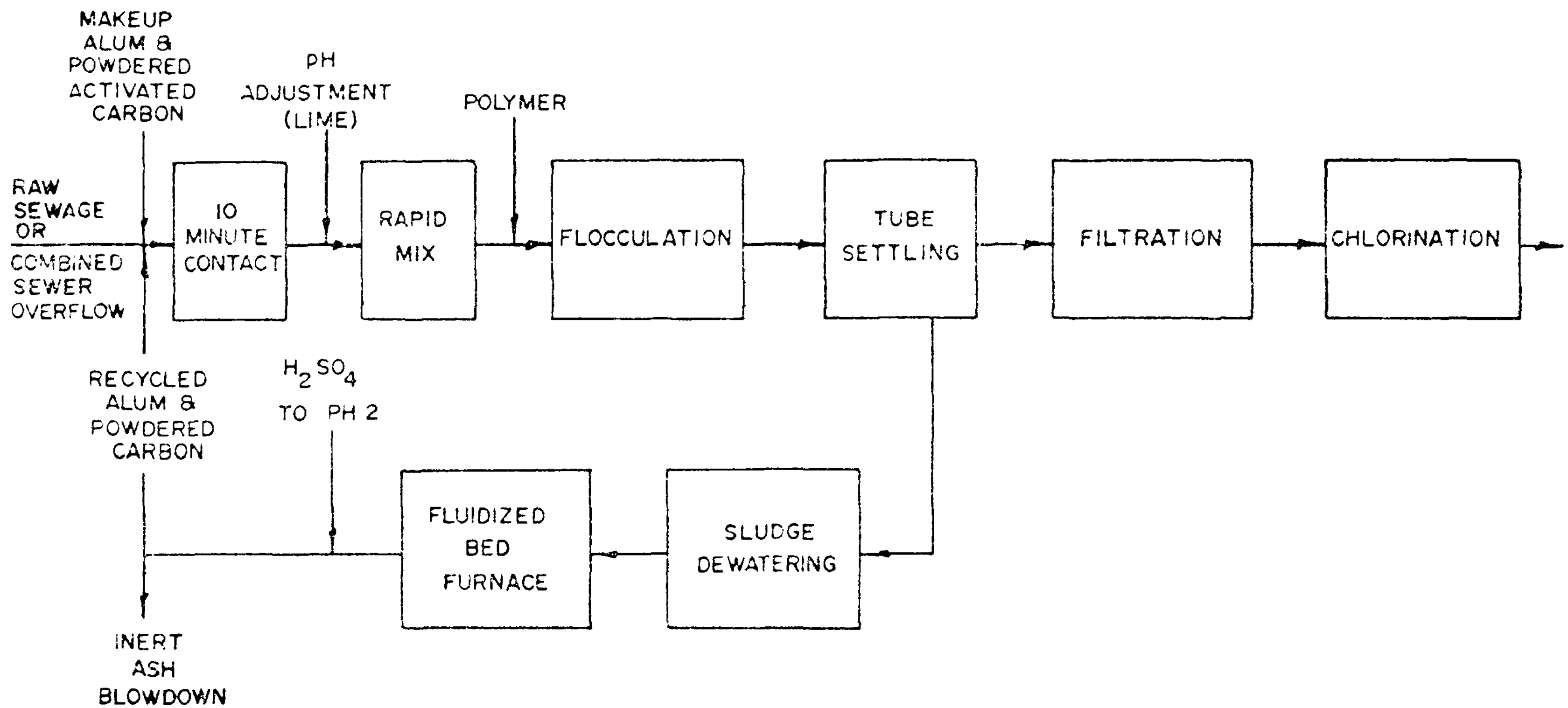


FIGURE 26. BATTELLE PROCESS FLOW SHEET

TABLE 87

BATTELLE PROCESS SYSTEM DESIGN PARAMETERS

Treatment System	
Carbon Contact - Minutes	
Time at pH 4	10
Time at pH 7	5
Flocculation	
Velocity Gradient - fps/ft	70
Time - Minutes	10
Tube Settler Loading Rate - gpd/ft^2	2,880
Filter	
Length of Filter Run - Hours	12
Loading Rate - gpm/ft^2	5
Chlorine Contact Time, Peak Dry Weather Flow - Minutes	30
Chlorine Dose, mg/l	5 (max), 3 (ave)
Chemical Storage Capacity	12
Sludge Storage	
Carbon Dose, mg/l	600
Alum Dose, mg/l	200
Polyelectrolyte Dose, mg/l	2.0
Lime Dose, mg/l	150
Sulfuric Acid, lb/lb Carbon	0.5
Sludge Dewatering Polyelectrolyte Dose, lb/Ton Dry Solids	1
Regeneration System	
Combustion Chamber Temperature, °F	2,000
Bed Temperature, °F	1,500
Fluidizing Gas Velocity, ft/sec	1.3
Maximum Bed Diameter, ft	22
Carbon Recovery, %	91
Alum Recovery, %	91
Blowdown, %	5
Sludge Quantity, lb/MG	7,380
Settler Underflow Concentrations % Solids	4.5
Sludge Carbon Content, % on Dry Basis	57.3
Sludge Inerts Content, % on Dry Basis	17.2
Dewatered Sludge Solids Content, %	22
Dewatered Sludge Flow, lb/hr/MGD (Wet)	1,658
Carbon Feed Rate, lb/hr/MGD	
(100% Operation of FBF)	209
(70% Operation of FBF)	298

TABLE 88

UNIT PROCESS SIZES, BATTELLE PROCESS

	MGD				
	1	5	10	25	50
Chemical Feed					
Makeup Alum, lb/hr	9.7	48.5	97	242.5	485
Carbon, lb/hr	208	1,040	2,080	5,200	10,400
Lime, lb/hr	52.0	260	520	1,300	2,600
Wastewater Polymer, lb/hr	0.69	3.45	6.90	17.25	34.5
Sludge Polymer, lb/hr	0.71	3.55	7.10	17.75	35.5
Sulfuric Acid, lb/hr	104	520	1,040	2,600	5,200
Carbon Contactor, ft^3	928	4,640	9,280	23,200	46,400
Rapid Mix, ft^3	464	2,230	4,640	11,600	23,200
Flocculation, ft^3	928	4,640	9,280	23,200	46,400
Tube Settler, ft^2	347	1,735	3,470	8,675	17,350
Chemical Sludge Pumps, gpm	13.9	69.5	139	348	695
Centrifuge Capacity, gpm	19.8	100	200	500	1,000
Fluidized Bed Furnace, ft^2	55	230	440	1,060	2,130
lb/hr[1]	298	1,490	2,980	7,450	14,900
Chlorination, Tons/Year (Average Peak)[2]	4.65/11.4	22.8/57.0	45.6/114	114/285	228/570
Chlorine Contact Tank, ft^3	4,180	20,900	41,800	104,500	209,000
Filter, ft^2	140	700	1,400	3,500	7,000

[1] Based on 70 percent operation run time, 6,132 hr/yr.

[2] Peak demand for construction cost determination and average demand for O&M requirements.

TABLE 89

CAPITAL COSTS, BATTELLE-NORTHWEST PROCESS

	MGD				
	1	5	10	25	50
Chemical Feed					
Alum	27,000	30,000	34,000	50,000	80,000
Carbon	140,000	280,000	430,000	820,000	1,600,000
Lime	48,000	130,000	200,000	340,000	530,000
Polymer - Wastewater	16,000	47,000	86,000	190,000	380,000
Polymer - Sludge	16,500	47,500	86,500	195,000	385,000
Sulfuric Acid	30,000	40,000	66,000	140,000	270,000
Carbon Contact	12,000	30,000	45,000	75,000	115,000
Rapid Mix	10,000	33,000	52,000	100,000	160,000
Flocculation	12,000	30,000	45,000	75,000	115,000
Sedimentation Tank	60,000	96,000	160,000	320,000	530,000
Tube Settling Modules	12,000	43,000	80,000	170,000	280,000
Chemical Sludge Pumps	50,000	120,000	180,000	270,000	400,000
Centrifuge	130,000	260,000	350,000	580,000	820,000
Fluidized Bed Furnace	1,100,000	2,400,000	4,100,000	9,000,000	17,000,000
Chlorine Contact Tank	51,000	140,000	200,000	240,000	530,000
Chlorination Equipment	7,000	22,000	38,000	69,000	110,000
Filtration	390,000	685,000	1,050,000	1,900,000	2,800,000
SUBTOTAL	$2,111,000	$4,433,500	$ 7,202,500	$14,634,000	$26,095,000
Yardwork	295,000	621,000	1,008,350	2,049,000	3,653,000
Total Construction Cost	$2,406,000	$5,054,000	$ 8,210,850	$16,683,000	$29,748,000
Engineering, Fiscal, Legal	$ 289,000	$ 607,000	$ 985,000	$ 2,002,000	$ 3,570,000
Interest During Construction	$ 241,000	$ 505,000	$ 821,000	$ 1,668,000	$ 2,975,000
TOTAL CAPITAL COST	$2,936,000	$6,166,000	$10,016,850	$20,353,000	$36,293,000

TABLE 90

BATTELLE-NORTHWEST, 1 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Chemical Feed				
Alum[1]	100	2,000	-	200
Carbon	1,700	180,000	-	2,400
Lime[2]	1,600	3,100	-	230
Polymer - Wastewater[3]	520	2,700	-	120
Polymer - Sludge[3]	530	2,700	-	130
Sulfuric Acid	380	1,500	-	170
Carbon Contact	100	1,200	-	390
Rapid Mix	550	18,000	-	500
Flocculation	100	1,200	-	390
Sedimentation	420	-	-	170
Chemical Sludge Pumps	70	3,600	-	600
Centrifuge	2,800	39,000	-	13,000
Fluidized Bed Furnace	1,200	1,330,000	21×10^6	3,600
Chlorination	400	-	-	1,000
Filtration	2,900	88,000	-	1,500
TOTAL	13,370	1,673,000	21×10^6	24,400

[1] Liquid alum
[2] Slaked lime, pumped feeder
[3] Dry polymer

TABLE 91

BATTELLE-NORTHWEST, 5 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Chemical Feed				
Alum[1]	200	2,700	-	200
Carbon	2,000	900,000	-	6,000
Lime[2]	1,800	11,000	-	720
Polymer - Wastewater[3]	700	4,500	-	320
Polymer - Sludge[3]	710	4,600	-	330
Sulfuric Acid	270	1,500	-	270
Carbon Contact	150	5,200	-	650
Rapid Mix	700	100,000	-	1,700
Flocculation	150	5,200	-	650
Sedimentation	610	-	-	560
Chemical Sludge Pumps	140	18,000	-	1,900
Centrifuge	8,700	195,000	-	25,000
Fluidized Bed Furnace	2,520	4,900,000	84×10^6	6,500
Chlorination	610	-	-	1,800
Filtration	3,600	115,000	-	4,200
TOTAL	22,860	6,262,700	84×10^6	49,180

[1] Liquid alum
[2] Slaked lime, pumped feeder
[3] Dry polymer

TABLE 92

BATTELLE-NORTHWEST, 10 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Chemical Feed				
Alum[1]	250	2,700	-	200
Carbon	2,500	1,800,000	-	10,000
Lime[2]	2,800	27,000	-	1,300
Polymer - Wastewater[3]	790	7,000	-	490
Polymer - Sludge[3]	800	7,100	-	500
Sulfuric Acid	500	1,500	-	420
Carbon Contact	170	11,000	-	1,000
Rapid Mix	800	190,000	-	2,800
Flocculation	170	11,000	-	1,000
Sedimentation	860	-	-	1,000
Chemical Sludge Pumps	170	36,000	-	2,800
Centrifuge	15,000	390,000		32,000
Fluidized Bed Furnace	3,500	10,500,000	168×10^6	9,000
Chlorination	890	-	-	2,200
Filtration	4,000	140,000	-	6,800
TOTAL	33,200	13,123,300	168×10^6	71,510

[1] Liquid alum
[2] Quicklime, pumped feeder
[3] Dry polymer

TABLE 93

BATTELLE-NORTHWEST, 25 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Chemical Feed				
Alum[1]	400	2,800	-	270
Carbon	3,700	4,500,000	-	18,000
Lime[2]	3,100	57,000	-	2,200
Polymer - Wastewater[3]	9,100	14,000	-	880
Polymer - Sludge[3]	9,200	15,000	-	890
Sulfuric Acid	1,000	1,500	-	900
Carbon Contact	200	29,000	-	1,800
Rapid Mix	1,000	400,000	-	5,000
Flocculation	200	29,000	-	1,800
Sedimentation	1,400	-	-	2,000
Chemical Sludge Pumps	250	90,000	-	5,000
Centrifuge	31,000	975,000	-	48,000
Fluidized Bed Furnace	5,950	21,000,000	385×10^6	13,000
Chlorination	1,600	7,000	-	2,800
Filtration	4,800	160,000	-	10,500
TOTAL	72,900	27,281,000	385×10^6	113,390

[1]Liquid alum
[2]Quicklime, pumped feeder
[3]Dry polymer

TABLE 94

BATTELLE-NORTHWEST, 50 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Chemical Feed				
Alum[1]	700	3,000	-	450
Carbon	6,100	9,000,000	-	30,000
Lime[2]	4,000	100,000	-	3,500
Polymer - Wastewater[3]	1,800	26,000	-	1,500
Polymer - Sludge[3]	1,900	27,000	-	1,600
Sulfuric Acid	1,800	1,500	-	1,700
Carbon Contact	280	52,000	-	2,500
Rapid Mix	1,200	900,000	-	9,000
Flocculation	280	52,000	-	2,500
Sedimentation	2,000	-	-	3,500
Chemical Sludge Pumps	330	180,000	-	8,500
Centrifuge	54,000	1,950,000	-	61,000
Fluidized Bed Furnace	8,400	35,000,000	630×10^6	17,000
Chlorination	2,300	15,500	-	3,500
Filtration	5,200	190,000	-	13,000
TOTAL	90,290	47,497,000	630×10^6	159,250

[1] Liquid alum
[2] Quicklime, pumped feeder
[3] Dry polymer

TABLE 95

BATTELLE PROCESS, 1 MGD

TOTAL ANNUAL COSTS

Amortized Capital	
2,936,000 x 0.09439	$277,129
Labor	
13,370 Hours @ $9/Hour	$120,330
Power	
1,673,000 kWh @ $0.02/kWh	$ 33,460
Fuel	
21 x 10^6 SCF @ $1.50/TCF	$ 31,500
Maintenance Materials	$ 24,400
Chemicals	
Makeup Alum	
42 Tons @ $70/Ton	$ 2,940
Makeup Carbon	
127 Tons @ $650/Ton	$ 83,000
Lime	
228 Tons @ $37/Ton	$ 8,436
Polymer, Wastewater	
6,044 lb @ $0.30/lb	$ 1,813
Polymer, Sludge	
5,183 lb @ $2/lb	$ 10,366
Sulfuric Acid	
456 Tons @ $57.30/Ton	$ 26,129
Chlorine	
4.6 Tons @ $220/Ton	$ 1,012
TOTAL	$620,515

Cost/MG @ Capacity = $\frac{\$620,515}{365 \times 1}$ = $1,700/MG

TABLE 96

BATTELLE PROCESS, 5 MGD

TOTAL ANNUAL COSTS	
Amortized Capital	
6,166,000 x 0.09439	$ 582,000
Labor	
22,860 Hours @ $9/Hour	$ 205,740
Power	
6,262,700 kWh @ $0.02/kWh	$ 125,254
Fuel	
84 x 10^6 SCF @ $1.50/TCF	$ 126,000
Maintenance Materials	$ 49,180
Chemicals	
Alum	
210 Tons @ $70/Ton	$ 14,700
Carbon	
635 Tons @ $650/Ton	$ 431,800
Lime	
1,140 Tons @ $37/Ton	$ 42,180
Polymer, Wastewater	
30,220 lb @ $0.30/lb	$ 9,066
Polymer, Sludge	
25,915 lb @ $2/lb	$ 51,830
Sulfuric Acid	
2,280 Tons @ $57.30/Ton	$ 130,644
Chlroine	
23 Tons @ $220/Ton	$ 5,060
TOTAL	$1,773,454

$$\text{Cost/MG @ Capacity} = \frac{\$1,773,454}{365 \times 5} = \$972/\text{MG}$$

TABLE 97

BATTELLE PROCESS, 10 MGD

TOTAL ANNUAL COSTS

Amortized Capital	
10,016,850 x 0.09439	$ 945,490
Labor	
33,200 Hours @ $9/Hour	$ 298,800
Power	
13,123,300 kWh @ $0.02/kWh	$ 262,466
Fuel	
168 x 10^6 @ $1.50/TCF	$ 252,000
Maintenance Materials	$ 71,510
Chemicals	
Alum	
420 Tons @ $70/Ton	$ 29,400
Carbon	
1,270 Tons @ $650/Ton	$ 825,500
Lime	
2,280 Tons @ $37/Ton	$ 84,360
Polymer, Wastewater	
60,440 lb @ $0.30/lb	$ 18,132
Polymer, Sludge	
51,830 lb @ $2/lb	$ 103,660
Sulfuric Acid	
4,560 Tons @ $57.30/Ton	$ 261,288
Chlorine	
46 Tons @ $220/Ton	$ 10,120
TOTAL	$3,162,726

$$\text{Cost/MG @ Capacity} = \frac{\$3,162,726}{365 \times 10} = \$867/\text{MG}$$

TABLE 98

BATTELLE PROCESS, 25 MGD

TOTAL ANNUAL COSTS	
Amortized Capital	
20,353,000 x 0.09439	$1,921,120
Labor	
72,900 Hours @ $9/Hour	$ 656,100
Power	
27,281,000 kWh @ $0.02/kWh	$ 545,620
Fuel	
385 x 10^6 SCF @ $1.50/TCF	$ 577,500
Maintenance Materials	$ 113,390
Chemicals	
Alum	
1,050 Tons @ $70/Ton	$ 73,500
Carbon	
3,175 Tons @ $650/Ton	$2,063,750
Lime	
5,700 Tons @ $37/Ton	$ 210,900
Polymer, Wastewater	
151,100 lb @ $0.30/lb	$ 45,330
Polymer, Sludge	
129,575 lb @ $2/lb	$ 259,150
Sulfuric Acid	
11,400 Tons @ $57.30/Ton	$ 653,220
Chlorine	
115 Tons @ $100/Ton	$ 11,500
TOTAL	$7,131,080

$$\text{Cost/MG @ Capacity} = \frac{\$7,131,080}{365 \times 25} = \$781/\text{MG}$$

TABLE 99

BATTELLE PROCESS, 50 MGD

TOTAL ANNUAL COSTS

Amortized Capital	
36,293,000 x 0.09439	$ 3,425,696
Labor	
90,290 Hours @ $9/Hour	$ 812,610
Power	
47,497,000 kWh @ $0.02/kWh	$ 949,940
Fuel	
630 x 10^6 SCF @ $1.50/TCF	$ 945,000
Maintenance Materials	$ 159,250
Chemicals	
Alum	
2,100 Tons @ $70/Ton	$ 147,000
Carbon	
6,350 Tons @ $650/Ton	$ 4,127,500
Lime	
11,400 Tons @ $37/Ton	$ 421,800
Polymer, Wastewater	
302,200 lb @ $0.30/lb	$ 90,660
Polymer, Sludge	
259,150 lb @ $2/lb	$ 518,300
Sulfuric Acid	
22,800 Tons @ $57.30/Ton	$ 1,306,440
Chlorine	
230 Tons @ $100/Ton	$ 23,000
TOTAL	$12,925,196

$$\text{Cost/MG @ Capacity} = \frac{\$12{,}925{,}196}{365 \times 50} = \$708/\text{MG}$$

TABLE 100

BATTELLE PROCESS, ANNUAL COST SUMMARY

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	277	582	945	1,921	3,426
Labor	120	206	299	656	813
Power	33	125	262	546	950
Fuel	32	126	252	578	945
Maintenance Materials	24	49	72	113	159
Chemicals					
Alum	3	15	29	74	147
Carbon	83	431	825	2,064	4,127
Lime	8	42	84	211	422
Polymer, Wastewater	1.8	9	18	45	91
Polymer, Sludge	10	52	104	259	518
Sulfuric Acid	26	131	261	653	1,306
Chlorine	1	5	10	11	23
TOTAL	620	1,773	3,163	7,131	12,925
Costs/1,000 Gals (Operating @ Capacity)	$1.70	$0.97	$0.87	$0.78	$0.71

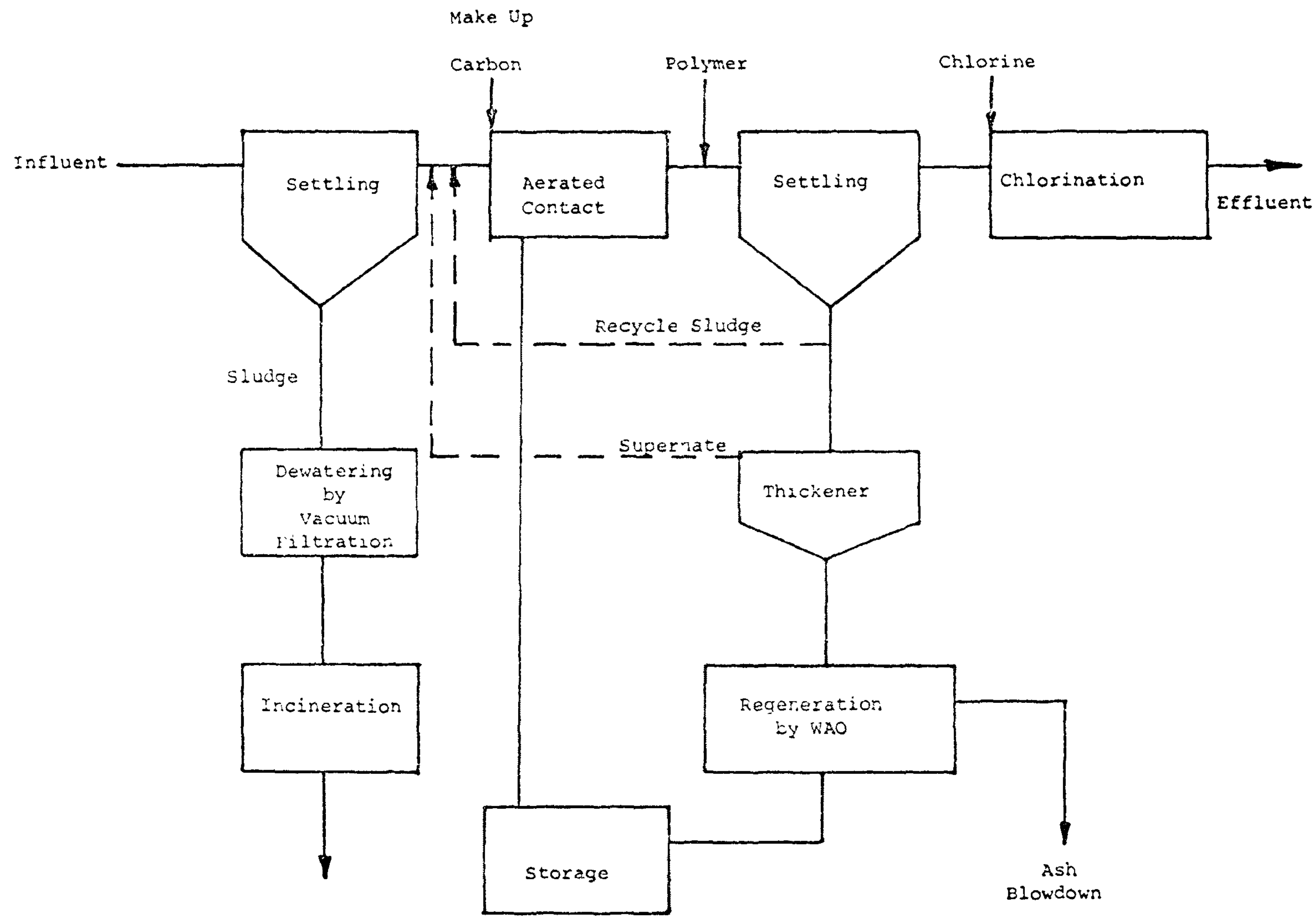


FIGURE 27. FLOW SHEET FOR BIO-PHYSICAL PROCESS WITH WET AIR OXIDATION

TABLE 101

DESIGN PARAMETERS FOR BIO-PHYSICAL PROCESS WITH WET AIR OXIDATION

<u>Primary Sedimentation</u>	
Surface Loading Rate, gpd/ft^2	800
Detention Time, Hour	2.5
Solids Removal Efficiency, %	65
Sludge Moisture, %	95
Sludge Specific Gravity	1.03
<u>Activated Sludge</u>	
Air Rate, scfm/MGD	1,275
Recycle, %	50
Mixed Liquor Solids, mg/l	
Volatile	4,000
Carbon	8,000
Total	13,000
Growth Yield Coefficient, lb vs/lb BOD	0.5
Return Sludge Solids, mg/l	
VSS	12,000
Carbon	24,000
Total	39,000
Detention Time, Hour	4.5
Sludge Age, Days	12.5
<u>Secondary Sedimentation</u>	
Overflow Rate, gpd/ft^2	400
Polymer Dose, mg/l	5
Flow to Thickener, gal/MG	5,000
<u>Gravity Thickener</u>	
Loading Rate, lb/ft^2/ day	10
Thickened Sludge, % Solids	8
<u>Wet Oxidation System</u>	
Temperature, °F	450
Pressure, psi	700
Blowdown	
Volume, gal/MG	100
Solids, lb/MG	166
Ash Content of Solids, %	75

TABLE 101 (Cont'd)

Carbon Losses mg/l	
Blowdown	5
Oxidation	7
Effluent	5
Carbon Dose mg/l	
Makeup Carbon	17
Regenerated Carbon	103
Primary Sludge Dewatering	
Vacuum Filtration, $lb/ft^2/hr$	6
Polymer, lb/Ton	1
Primary Sludge Disposal	
Multiple Hearth Incinerator, $lb/ft^2/hr/hr$	7

Zimpro were adjusted to reflect housing, miscellaneous, and contingency costs. The costs of carbon handling and storage included by Zimpro were deducted and the CWC costs for this item were used. Zimpro's estimates of labor, power, and fuel were used for O&M costs. Zimpro felt the regeneration system would be thermally self-sustaining except for startup and shutdown periods. Thus, fuel requirements are minimal. Table 102 presents the unit process sizes. Table 103-114 present the cost estimates.

TABLE 102

UNIT PROCESS SIZES, BIO-PHYSICAL

Unit Process Component	Plant Capacity, MGD				
	1	5	10	25	50
Primary Sedimentation, ft^2	1,250	6,250	12,500	31,250	62,500
Primary Sludge Pumping, gpm	15	75	150	375	750
Primary Sludge Thickener, ft^2	54.2	271	542	1,355	2,710
Vacuum Filtration, ft^2	113(1)	113(1)	113(1)	225	450
Multiple Hearth Incineration, ft^2	79(2)	184	268	920	1,840
Chemical Feed					
Carbon, lb/Hour	41.6	208	416	1,040	2,080
Polymer, lb/Hour	1.74	8.69	17.4	43.4	86.9
Polymer (Vac. Filter), lb/Hour	3.05	3.05	4.88	12.2	24.4
Aeration Basin, ft^3	25,100	125,500	251,000	627,500	1,255,000
Aerators Equipment, hp	70	350	700	1,750	3,500
Sedimentation, ft^2	2,500	12,500	25,000	62,500	125,000
Return Sludge Pumping Station, MGD (Ave/Peak)	0.5/0.75	2.5/3.75	2.5/7.5	12.5/18.7	25/37
Thickener, ft^2	163	815	1,630	4,075	8,150
Air Oxidation System, gpm	12	12	24	60	120
Chlorine Contact Basin, ft^3	4,180	20,900	41,800	104,500	209,000
Chlorine Feed Equipment, Tons/Year Average/Peak (3)	4.56/11.4	22.8/57.0	45.6/114	114/285	228/570

(1) Smallest practical unit is 113 ft^2 - operation times will be less for small plants, polymer feed systems are sized larger to compensate.

(2) Smallest available unit.

(3) Average flow is used to determine power requirements and maintenance materials cost. Peak Peak flow is used to determine construction cost and labor requirement.

TABLE 103

CAPITAL COSTS, BIO-PHYSICAL PROCESS

	MGD				
	1	5	10	25	50
Primary Sedimentation Tanks	70,000	260,000	440,000	940,000	1,600,000
Primary Sludge Pumping	44,000	93,000	140,000	200,000	290,000
Primary Sludge Thickener	60,000	72,000	90,000	130,000	160,000
Vacuum Filtration	200,000	200,000	200,000	290,000	430,000
Incineration	1,000,000	1,100,000	1,500,000	2,300,000	3,200,000
Chemical Feed Systems:					
Carbon	49,000	134,000	170,000	280,000	423,000
Polymer, Wastewater	27,000	110,000	200,000	530,000	1,100,000
Polymer, Sludge	42,000	42,000	61,000	150,000	300,000
Aeration Basins	170,000	440,000	650,000	1,100,000	1,700,000
Aerators	130,000	450,000	800,000	1,500,000	2,200,000
Secondary Sedimentation Basins	130,000	450,000	800,000	1,700,000	2,800,000
Return Sludge Pumping Stations	60,000	160,000	230,000	390,000	540,000
Gravity Thickener	63,000	100,000	130,000	190,000	260,000
Wet Air Oxidation	1,000,000	1,000,000	1,400,000	2,500,000	4,500,000
Chlorine Contact Basin	51,000	140,000	200,000	340,000	530,000
Chlorine Feed Equipment	7,000	22,000	38,000	69,000	110,000
SUBTOTAL	3,103,000	4,773,000	7,049,000	12,609,000	20,143,000
Yardwork	434,000	668,000	987,000	1,765,000	2,820,000
TOTAL CONSTRUCTION COST	$3,537,000	$5,441,000	$ 8,036,000	$14,374,000	$22,963,000
Engineering, Fiscal and Legal	424,000	653,000	964,000	1,725,000	2,756,000
Interest During Construction	354,000	544,000	804,000	1,437,000	2,296,000
TOTAL CAPITAL COSTS	$4,315,000	$6,638,000	$ 9,804,000	$17,536,000	$28,015,000

TABLE 104

BIO-PHYSICAL, 1 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	570	3,300	-	400
Primary Sludge Pumping	63	300	-	610
Primary Thickening	400[1]	-	-	100[1]
Vacuum Filtration	319	15,900	-	2,200
Incineration	1,300	26,000	2.5×10^6	3,200
Chemical Feed Systems				
Carbon	995	37,400	-	2,350
Polymer, Wastewater	520	2,800	-	210
Polymer, Sludge	94	570	-	50
Aeration Basins	-	-	-	-
Aerators	1,700	370,000	-	4,000
Secondary Sedimentation	730	3,300	-	800
Return Sludge Pumping	720	10,000	-	460
Gravity Thickening	400[1]	-	-	100[1]
Wet Air Oxidation[2]	600	110,000	0.02×10^6	2,000
Chlorine Contact Basin	-	-	-	-
Chlorine Feed Equipment	390	-	-	300
Filtration	-	-	-	-
TOTAL	8,201	469,570	2.52×10^6	16,820

[1]Assumed minimum labor of 400 manhours/year and minimum maintenance material costs of $100/year.

[2]Based on operation 20% of the time.

TABLE 105

BIO-PHYSICAL, 5 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	1,200	3,300	-	1,600
Primary Sludge Pumping	130	1,500	-	1,900
Primary Thickening	400	-	-	140
Vacuum Filtration	1,300	55,000	-	8,000
Incineration	2,300	60,000	6.6×10^6	4,000
Chemical Feed Systems				
Carbon	1,700	170,000	-	2,500
Polymer, Wastewater	700	6,700	-	590
Polymer, Sludge	470	2,900	-	250
Aeration Basins	-	-	-	-
Aerators	3,600	1,800,000	-	8,100
Secondary Sedimentation	1,700	3,300	-	2,800
Return Sludge Pumping	930	42,000	-	840
Gravity Thickening	400	-	-	210
Wet Air Oxidation	3,000	550,000	0.06×10^6	10,000
Chlorine Contact Basin	-	-	-	-
Chlorine Feed Equipment	610	-	-	1,800
Filtration	-	-	-	-
TOTAL	18,440	2,694,700	6.66×10^6	42,730

TABLE 106

BIO-PHYSICAL, 10 MGD O&M

	Annual Labor, Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	1,800	3,300	-	2,700
Primary Sludge Pumping	170	3,000	-	3,000
Primary Thickening	420	-	-	240
Vacuum Filtration	2,700	140,000	-	18,000
Incineration	3,600	120,000	15×10^6	5,200
Chemical Feed Systems				
Carbon	1,700	350,000	-	3,600
Polymer, Wastewater	800	11,000	-	900
Polymer, Sludge	640	4,500	-	410
Aeration Basins	-	-	-	-
Aerators	5,600	3,600,000	-	11,000
Secondary Sedimentation	2,600	6,600	-	4,700
Return Sludge Pumping	1,100	78,000	-	1,300
Gravity Thickening	440	-	-	350
Wet Air Oxidation	3,500	1,000,000	0.09×10^6	14,000
Chlorine Contact Basin	-	-	-	-
Chlorine Feed Equipment	890	-	-	2,200
Filtration	-	-	-	-
TOTAL	25,960	5,316,400	15.09×10^6	67,600

TABLE 107

BIO-PHYSICAL, 25 MGD O&M

	Annual Labor, Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	3,100	6,600	-	5,600
Primary Sludge Pumping	250	7,500	-	5,600
Primary Thickening	480	-	-	490
Vacuum Filtration	5,000	330,000	-	36,000
Incineration	6,300	300,000	40×10^6	8,300
Chemical Feed Systems				
Carbon	2,000	900,000	-	6,100
Polymer, Wastewater	2,000	22,000	-	1,600
Polymer, Sludge	750	8,600	-	710
Aeration Basins	-	-	-	-
Aerators	11,000	8,600,000	-	17,000
Secondary Sedimentation	4,600	13,200	-	9,500
Return Sludge Pumping	1,500	170,000	-	2,600
Gravity Thickening	560	-	-	700
Wet Air Oxidation	5,000	2,500,000	0.2×10^6	25,000
Chlorine Contact Basin	-	-	-	-
Chlorine Feed Equipment	1,600	7,500	-	2,800
Filtration	-	-	-	-
TOTAL	44,140	13,464,800	40.2×10^6	122,000

TABLE 108

BIO-PHYSICAL, 50 MGD O&M

	Annual Labor Hours	Annual Power Consumption kWh	Annual Fuel Consumption SCF, Natural Gas	Annual Cost of Maintenance Materials, Dollars
Primary Sedimentation	4,900	13,200	-	9,500
Primary Sludge Pumping	340	15,000	-	9,000
Primary Thickening	600	-	-	800
Vacuum Filtration	7,900	600,000	-	57,000
Incineration	10,000	600,000	88×10^6	13,000
Chemical Feed Systems				
Carbon	2,500	1,800,000	-	10,000
Polymer, Wastewater	3,900	38,000	-	2,600
Polymer, Sludge	1,200	14,000	-	1,100
Aeration Basins	-	-	-	-
Aerators	21,000	17,000,000	-	23,000
Secondary Sedimentation	7,000	66,000	-	16,000
Return Sludge Pumping	2,000	340,000	-	5,000
Gravity Thickening	820	-	-	1,200
Wet Air Oxidation	7,000	4,500,000	0.4×10^6	45,000
Chlorine Contact Basin	-	-	-	-
Chlorine Feed Equipment	2,300	15,000	-	3,500
Filtration	-	-	-	-
TOTAL	71,460	25,001,200	88.4×10^6	196,700

TABLE 109

BIO-PHYSICAL PROCESS, ANNUAL COST SUMMARY, 1 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
4,315,000 x 0.09439	$407,293
Labor	
8,201 Hours @ $9/Hour	$ 73,809
Power	
469,570 kWh @ $0.02/kWh	$ 9,391
Fuel	
2.52 x 10^6 SCF @ $1.50/TCF	$ 3,780
Maintenance Materials	$ 17,900
Chemicals	
Carbon	
26 Tons @ $650/Ton	$ 16,900
Polymer	
15,200 lb @ $0.30/lb	$ 4,560
Chlorine	
4.6 Tons @ $220/Ton	$ 1,012
TOTAL	$533,745

Cost/MG @ Capacity = $\frac{\$533,745}{365 \times 1}$ = $1,462/MG

TABLE 110

BIO-PHYSICAL PROCESS, ANNUAL COST SUMMARY, 5 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
6,638,000 x 0.09439	$ 626,561
Labor	
18,440 Hours @ $9/Hour	$ 165,960
Power	
2,694,700 kWh @ $0.02/kWh	$ 53,894
Fuel	
6.66×10^6 SCF @ $1.50/TCF	$ 9,990
Maintenance Materials	$ 42,730
Chemicals	
Carbon	
130 Tons @ $650/Ton	$ 84,500
Polymer	
76,100 lb @ $0.30/lb	$ 22,830
Chlorine	
23 Tons @ $220/Ton	$ 5,060
TOTAL	$1,011,525

$$\text{Cost/MG @ Capacity} = \frac{\$1,011,525}{365 \times 5} = \$554/\text{MG}$$

TABLE 111

BIO-PHYSICAL PROCESS, ANNUAL COST SUMMARY, 10 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years	
9,804,000 x 0.09439	$ 925,400
Labor	
25,960 Hours @ $9/Hour	$ 233,640
Power	
5,316,400 kWh @ $0.02/kWh	$ 106,328
Fuel	
15.09 x 10^6 SCF @ $1.50/TCF	$ 23,635
Maintenance Materials	$ 67,600
Chemicals	
Carbon	
260 Tons @ $650/Ton	$ 169,000
Polymer	
152,205 lb @ $0.30/lb	$ 45,660
Chlorine	
46 Tons @ $220/Ton	$ 10,120
TOTAL	$1,580,383

Cost/MG @ Capacity = $\frac{\$1,580,383}{365 \times 10}$ = $433/MG

TABLE 112

BIO-PHYSICAL PROCESS, ANNUAL COST SUMMARY, 25 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years 17,536,000 x 0.09439	$1,655,223
Labor 44,140 Hours @ $9/Hour	$ 397,260
Power 13,464,800 kWh @ $0.02/kWh	$ 269,296
Fuel 40.2×10^6 SCF @ $1.50/TCF	$ 60,300
Maintenance Materials	$ 122,000
Chemicals	
Carbon 650 Tons @ $650/Ton	$ 424,500
Polymer 280,512 lbs @ $0.30/lb	$ 114,153
Chlorine 115 Tons @ $100/Ton	$ 11,500
TOTAL	$3,052,232

$$\text{Cost/MG @ Capacity} = \frac{\$3{,}052{,}232}{365 \times 25} = \$334/\text{MG}$$

TABLE 113

BIO-PHYSICAL PROCESS, ANNUAL COST SUMMARY, 50 MGD

TOTAL ANNUAL COSTS	
Amortized Capital @ 7%, 20 Years 28,015,000 x 0.09439	$2,634,335
Labor 71,460 Hours @ $9/Hour	$ 643,140
Power 25,001,200 kWh @ $0.02/kWh	$ 500,024
Fuel 88.4 x 10^6 SCF @ $1.50/TCF	$ 132,600
Maintenance Materials	$ 132,600
Maintenance Materials	$ 196,700
Chemicals	
Carbon 1,300 Tons @ $650/Ton	$ 845,000
Polymer 761,025 lbs @ $0.30/lb	$ 228,300
Chlorine 230 Tons @ $100/Ton	$ 23,000
TOTAL	$5,203,099

Cost/MG @ Capacity = $\frac{\$5,203,099}{365 \times 50}$ = $286/MG

TABLE 114

BIO-PHYSICAL PROCESS, ANNUAL COST SUMMARY

Annual Cost ($1,000)

	Capacity, MGD				
	1	5	10	25	50
Amortized Capital	407	626	925	1,655	2,634
Labor	74	166	234	397	643
Power	9	54	106	269	500
Fuel	4	10	23	60	133
Maintenance Materials	17	43	68	122	197
Chemicals:					
Carbon	17	84	169	423	845
Polymer	4	23	46	114	228
Chlorine	1	5	10	11	23
TOTAL	533	1,011	1,580	3,052	5,203
Costs/1,000 Gals (Operating @ Capacity)	$1.46	$0.55	$0.43	$0.33	$0.29

SECTION 9

EVALUATION OF RELATIVE ECONOMICS

Because of the fact that the powdered carbon processes are still in the developmental stage, the preceding cost estimates are based on assumptions some of which may prove to be either overly optimistic or pessimistic. Thus, it is the purpose of this section to evaluate the potential impact of some key assumptions on relative costs.

ACTIVATED SLUDGE AND GRANULAR CARBON SYSTEMS

The following summarized the costs calculated previously for activated sludge and granular carbon systems:

	$/1,000 Gallons				
	1 MGD	5 MGD	10 MGD	25 MGD	50 MGD
Activated Sludge					
Conventional	1.02	0.49	0.38	0.29	0.24
Single Stage Nitrification	1.10	0.51	0.41	0.31	0.26
Two Stage Nitrification	1.21	0.59	0.46	0.35	0.29
Conventional with Coagulation and Filtration	1.49	0.71	0.55	0.44	0.37
Granular Carbon System	1.84	0.73	0.58	0.46	0.40

Independent physical chemical treatment utilizing the granular carbon system is clearly not economically competitive with conventional activated sludge systems. However, if effluent standards require high degrees of removal of phosphorus and suspended solids, then the granular carbon system is comparable in costs to activated sludge treatment followed by coagulation and filtration for plants of 5 mgd or greater in capacity. The potential impact of savings in land costs should also be considered. As an example, if one assumes a land savings of 10 acres for the 10 MGD capacity, the cost savings which result from a land price (land amortized at 7 percent, 20 years) of $1,000/acre would be only $0.00025/1,000 gallons or at $50,000/acre, only $0.0125/1,000 gallons. Thus, unless land costs are extremely high, the cost savings from reduced space requirements are not significant in the relative economics of biological processes and purely physical chemical processes.

BIOLOGICAL NITRIFICATION, TWO STAGE

Detailed estimates of conventional activated sludge and single stage nitrification were presented earlier. In order to determine the potential economic position of the bio-physical powdered carbon process (which is claimed to provide stable nitrification), it proved desirable to also estimate the cost of two-stage biological nitrification -- a commonly used approach. Table 115 summarized the results of this calculation. The costs are based on providing aeration (three hour detention), final sedimentation (600 gpd/ft^2), and return sludge pumping (50 percent Q) downstream of conventional activated sludge. Costs were determined using the appropriate cost curves in the Appendix.

EIMCO SYSTEM

The basic Eimco process is based on two stages of carbon contact preceded by chemical coagulation and sedimentation. Although carbon requirements would increase, capital costs and O&M costs would be decreased by eliminating the second stage contactors. The maximum potential gain for cost savings in a single stage system would be represented by the costs using the same carbon dosage used in the two-stage system -- realizing that some of this potential gain would probably be offset by increased carbon costs. Table 116 summarizes the results of the calculations. Total annual cost savings of 4-6 percent resulted -- not enough to significantly alter the competitive position of the process relative to granular carbon or biological processes.

Eimco's work indicated that carbon dosages as low as 100 mg/l may be practical (while producing an effluent quality of 5 mg/l COD, 5 mg/l SS, and 0.3 mg/l phosphorus) under some conditions. Thus, costs were also calculated for the system based on a 100 mg/l carbon dosage. Table 117 summarizes the results. The lower carbon dosage has a significant impact on the economics and would place the two-stage system in a comparable but competitive position with granular carbon systems. Should the single stage system be successful at a 100 mg/l carbon dosage, then the Eimco system would be lower in cost than the granular carbon system. Some work is being done on generating powdered activated carbon from waste materials which might provide a carbon low enough in cost that it could be used on a throwaway basis. Table 118 shows the impact that use of 5¢/lb and 1¢/lb throwaway carbon (300 mg/l dosage) would have on the two-stage Eimco system. The cost would have to be 1¢/lb for the system to be competitive with the granular carbon system. It was assumed that the carbon sludge would be dewatered and hauled (40 mile haul) to a disposal site.

TABLE 115

ANNUAL COST SUMMARY TWO-STAGE NITRIFICATION
Annual Cost ($1000)

	MGD				
	1	5	10	25	50
Amortized Capital	315	694	1,030	1,809	2,774
Labor	78	178	267	481	780
Power	9	48	96	227	447
Fuel	6	36	75	210	450
Maintenance Materials	19	48	65	137	211
Chemicals					
Chlorine	3	17	33	38	76
Polymer	13	64	129	321	642
TOTAL	443	1,085	1,695	3,223	5,380
Costs/1,000 Gallons	$1.21	$0.59	$0.46	$0.35	$0.29

TABLE 116

ANNUAL COST SUMMARY EIMCO - SINGLE STAGE

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	444	771	1,167	2,064	3,517
Labor	118	221	303	477	738
Power	23	86	152	374	660
Fuel	28	85	142	340	645
Maintenance Materials	26	69	113	220	338
Chemicals*					
Powdered Carbon	45	224	448	1,121	2,242
Alum	12	66	133	332	665
Polymer, Wastewater	0.2	1.14	2.3	5.7	11.4
Polymer, Carbon Sludge	10	70	140	350	702
Chlorine	1	5	10	11.5	23
Lime, Primary Sludge	6	28	57	142	283
TOTAL	714	1,626	2,667	5,437	9,824
Costs/1,000 Gals (Operating @ Capacity)	$1.96	$0.89	$0.73	$0.60	$0.54
Two Stage Costs/1,000 Gals	$2.08	$0.94	$0.77	$0.62	$0.56
% Reduction	6	5	5	3	4

*Unchanged from Two Stage System in order to determine maximum potential savings from eliminating second stage of carbon contact.

TABLE 117

ANNUAL COST SUMMARY EIMCO SYSTEM AT 100 MG/L CARBON

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	464	743	1,110	1,837	3,000
Labor	120	217	295	459	703
Power	23	45	84	190	346
Fuel	23	51	84	193	352
Maintenance Materials	23	60	102	205	323
Chemicals:					
Powdered Carbon	15	75	150	374	747
Alum	13	66	133	332	665
Polymer, Wastewater	0.2	1.14	2.3	5.7	11.4
Polymer, Carbon Sludge	3	23	46	117	234
Chlorine	1	5	10	11.5	23
Lime, Primary Sludge	6	28	57	142	283
TOTAL	691	1,314	2,073	3,866	6,687
Costs/1,000 Gals (Operating @ Capacity)	$1.89	$0.72	$0.57	$0.42	$0.37

TABLE 118

ANNUAL COST SUMMARY
EIMCO SYSTEM WITH THROWAWAY (5¢/lb) CARBON (300 MG/L)

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	351	642	982	1,590	2,675
Labor	111	222	315	482	748
Power	4	32	58	132	260
Fuel	13	32	48	109	195
Maintenance Materials	24	70	117	234	370
Sludge Handling	35	82	150	300	520
Chemicals:					
Powdered Carbon	46	228	456	1,140	2,281
Alum	13	66	133	332	665
Polymer, Wastewater	0.2	1.14	2.3	5.7	11.4
Polymer, Carbon Sludge	10	70	140	350	702
Chlorine	1	5	10	11.5	23
Lime, Primary Sludge	6	28	57	142	283
TOTAL	614	1,478	2,468	4,828	8,733
Costs/1,000 Gals (Operating @ Capacity)	$1.68	$0.81	$0.68	$0.53	$0.48
Costs/1,000 Gals @ 1¢/lb	$1.58	$0.71	$0.58	$0.43	$0.38

As noted earlier, the FBF regeneration system costs (Appendix curves 28, 99-102) are based on loadings recommended independently by two manufacturers. Because the independently determined loading rates (higher than the three lb/hr indicated by the Battelle-Northwest study[1]) were virtually identical, they were used as the basis of the FBF costs in the basic cases of each process. Although this assumption appears reasonable, the impact of using a loading rate of three $lb/ft^2/hr$ was determined as shown in Table 119. The impact is quite significant and the process costs would be substantially higher should the lower FBF loading rate prove necessary.

The impact that a 50 percent reduction in labor, power, and fuel costs would have on overall costs is shown in Table 120. Such a large reduction is not likely but Table 120 indicates that even such a major reduction would still not place the process in a competitive position with the granular carbon process. Should the cost of powdered activated carbon be reduced by 50 percent, approaching the levels of 2-3 years ago, a savings of 6¢/1,000 gallons would result for all capacities.

BATTELLE PROCESS

A dominant factor in determining the cost of the basic Battelle process is the large carbon (600 mg/l) and alum (200 mg/l) dosages specified. These, in turn, affect the cost of sludge handling and regeneration facilities. The costs using the same alum dosages (125 mg/l) used in the Eimco process and a carbon dosage of 200 mg/l were calculated. Table 121 presents the results. The impact on costs is dramatic -- providing about a 50 percent reduction in capacities of 5 MGD or more. The reduction places the costs significantly (20-34 percent) below the costs of the granular carbon system.

The potential for economic gains through use of cheap, throwaway carbon is limited with this process because of the questionable practicality of disposing of the sludge (a mixture of raw sewage solids, alum sludge, and carbon) after merely dewatering. If incineration were practiced (so as to be comparable to the other processes), the savings resulting from elimination of the FBF would be largely offset by the costs of incineration. If the price of carbon were reduced 50 percent, the cost of the basic Battelle process (600 mg/l carbon) would be reduced 12¢/1,000 gallons. At a carbon dosage of 200 mg/l, the lower carbon price would result in a savings of 4¢/1,000 gallons.

The Battelle data indicate that the need for effluent filtration is marginal. If effluent filtration were eliminated, the following savings would result (cost/1,000 gallons): 1 MGD - 22¢; 5 MGD - 7¢; 10 MGD - 5¢; 25 MGD - 3.4¢; 50 MGD - 2.4¢.

TABLE 119

ANNUAL COST SUMMARY
EIMCO SYSTEM WITH FBF LOADING = 3 lb/ft^2/hr

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	531	1,033	1,639	3,033	5,430
Labor	131	254	348	584	855
Power	24	166	258	692	1,220
Fuel	32	130	248	634	1,245
Maintenance Materials	28	76	128	248	389
Chemicals					
Powdered Carbon	45	224	448	1,121	2,242
Alum	13	66	133	332	665
Polymer, Wastewater	0.2	1.14	2.3	5.7	11.4
Polymer, Carbon Sludge	10	70	140	350	702
Chlorine	1	5	10	11.5	23
Lime, Primary Sludge	6	28	57	142	283
TOTAL	825	2,053	3,411	7,153	13,065
Costs/$1,000 Gals (Operating @ Capacity)	$2.26	$1.12	$0.93	$0.78	$0.72
Basic Eimco Process Cost	$2.08	$0.94	$0.77	$0.62	$0.56
% Increase	8.5	19	21	26	29

TABLE 120

ANNUAL COST SUMMARY
EIMCO, 50% REDUCTION IN LABOR, POWER, FUEL

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	464	837	1,285	2,248	3,859
Labor	70	119	164	260	400
Power	12	45	78	192	340
Fuel	14	42	71	170	322
Maintenance Materials	27	73	122	241	380
Chemicals					
Powdered Carbon	45	224	448	1,121	2,242
Alum	13	66	133	332	665
Polymer, Wastewater	0.2	1.14	2.3	5.7	11.4
Polymer, Carbon Sludge	10	70	140	350	702
Chlorine	1	5	10	11.5	23
Lime, Primary Sludge	6	28	57	142	283
TOTAL	662	1,510	2,510	5,073	9,227
Cost/1,000 Gals (Operating @ Capacity)	$1.81	$0.83	$0.69	$0.56	$0.51
Granular Carbon Process @ 1500 lbs/mg	$1.84	$0.73	$0.58	$0.46	$0.40

TABLE 121

BATTELLE PROCESS WITH 200 MG/L CARBON AND 125 MG/L ALUM

Annual Costs ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	220	412	603	1,137	1,863
Labor	102	137	185	415	495
Power	23	76	154	286	575
Fuel	11	48	94	210	409
Maintenance Materilas	17	35	54	80	114
Chemicals					
Alum	2	9	18	46	92
Carbon	27	144	275	688	1,375
Lime	5	26	53	131	263
Polymer, Wastewater	1.8	9	18	45	91
Polymer, Sludge	5	26	52	130	209
Sulfuric Acid	16	82	163	408	816
Chlorine	1	5	10	11	23
TOTAL	430	1,009	1,679	3,587	6,325
Costs/1,000 Gals (Operating @ Capacity)	$1.18	$0.55	$0.46	$0.39	$0.35

BIO-PHYSICAL PROCESS

The criteria used for the basic version of this process are reported to reliably provide nitrification and also represent the basis on which most of the available data on this process have been collected. Zimpro advised CWC that the system could be designed to provide carbonaceous oxygen demand removal without nitrification. They suggested reducing the aeration time to 1.4 hours with an accompanying reduction in aerator size. Sludge yields were expected to increase from 0.5 lb VS/lb BOD removed to 0.7 lb VS/lb BOD removal. Makeup carbon requirements were expected to be 12 mg/l rather than the 17 mg/l used in the basic case. Table 122 summarizes the results of the cost calculations. The following compares the bio-physical process with the activated sludge process.

	$/1,000 Gallons				
	1 MGD	5 MGD	10 MGD	25 MGD	50 MGD
Activated Sludge					
Conventional	1.02	0.49	0.38	0.29	0.24
Single Stage Nitrification	1.10	0.51	0.41	0.31	0.20
Two-Stage Nitrification	1.21	0.59	0.46	0.35	0.29
Bio-Physical					
Basic Process	1.46	0.55	0.43	0.33	0.29
Carbonaceous Carbon	1.43	0.52	0.39	0.30	0.26

If the bio-physical process provides a degree of stability of nitrification comparable to two-stage activated sludge, the bio-physical process would offer an economic advantage for plants of 5 MGD capacity or larger. It does not offer an economic advantage over single-stage nitrification. With the carbonaceous criteria, the bio-physical process is comparable in costs to conventional activated sludge.

If powdered carbon costs were reduced by 50 percent, the costs of the process would be reduced by 2¢/1,000 gallons.

COST SENSITIVITY TO CARBON LOSSES

Table 123 illustrates the effects that substantial reductions in carbon losses would have on process economics for the powdered carbon processes. Reduction in losses to 5% would represent a very significant improvement over the 14-16% values reported in the pilot studies to dates. Even if the losses, including blow-down, could be reduced to this low level, the powdered carbon

TABLE 122

ANNUAL COST SUMMARY
BIO-PHYSICAL PROCESS, CARBONACEOUS CRITERIA

	MGD				
	1	5	10	25	50
Amortized Capital	392	606	868	1,587	2,586
Labor	79	161	222	370	589
Power	12	44	82	220	390
Fuel	4	10	23	60	133
Maintenance Materials	17	43	68	129	217
Chemicals					
Carbon	12	59	118	295	592
Polymer	4	23	46	114	228
Chlorine	1	5	10	11	23
TOTAL	521	951	1,437	2,786	4,758
Costs/1,000 Gals (Operating @ Capacity)	$1.43	$0.52	$0.39	$0.30	$0.26

TABLE 123

PROCESS COSTS SENSITIVITY TO CARBON LOSS

Process	% Makeup Carbon	$/1,000 Gallons				
		1 MGD	5 MGD	10 MGD	25 MGD	50 MGD
Eimco						
Basic	15	2.08	0.94	0.77	0.62	0.56
Optimistic	5	1.99	0.85	0.68	0.54	0.48
Battelle						
Basic	14	1.70	0.97	0.87	0.78	0.71
Optimistic	5	1.55	0.82	0.72	0.63	0.55
Bio-Physical						
Basic	14.6	1.46	0.55	0.43	0.33	0.29
Optimistic	5	1.43	0.52	0.40	0.30	0.26

processes still would not be competitive with the granular carbon process costs. A comparison of costs and characteristics for commercially available powdered activated carbons is presented at the end of the appendix.

COMPOSITION OF PROCESS COSTS

Table 124 shows the composition of the total annual costs for the various basic processes evaluated in this study. The composition of costs for a capacity of 10 MGD is illustrative for capacities of 5 MGD - 50 MGD. Power and fuel costs are relatively insignificant indicating that "fine-tuning" of these parameters would not result in a significant change in process costs. Also, changes in labor costs by a factor as high as 2 would result in changes of only about 5-7 percent in most processes. A change in carbon dosage is one of the most significant variables in the IPC powdered carbon systems because it has a major, direct impact on chemical costs and the sludge handling and regeneration system costs -- which comprise a large portion of the capital costs, the single largest component of costs.

CARBON REGENERATION COSTS

Table 125 summarizes the costs of carbon regeneration for each of the basic processes. Costs of powdered carbon dewatering are not included as part of the regeneration costs. Dewatering of the carbon sludge would be required prior to disposal in any case. Thus, dewatering costs are not attributable to regeneration. The costs of granular carbon regeneration correspond closely to those projected in the EPA Technology Transfer manual on carbon adsorption.

SENSITIVITY TO SLUDGE DISPOSAL METHOD

As noted earlier, all cost estimations for comparative evaluation were based on the use of incineration. Relative economics would change with selection of alternate sludge disposal methods. Incineration is more costly than digestion and landfill, digestion and landspreading composting, or ocean dumping in most areas. Consequently, if these methods were considered, overall sludge disposal would be less costly. This reduction in cost would not be uniform between processes, however, since sludge disposal costs represent a different fraction of total costs for each alternative.

Specifically, sludge disposal represents 30-50 percent of capital costs for the activated sludge, nitrification, and granular carbon options. For PAC processes, sludge disposal accounts for 0-25 percent of capital costs. This difference is due to the lower quantities of sludge handled in PAC processes since much of the solids are routed through the carbon regeneration step. The implication here is that consideration of alternate sludge disposal options (less expensive) will tend to reduce economic incentive

TABLE 124

COMPOSITION OF PROCESS COSTS, 10 MGD

	Conventional Activated Sludge	Granular Carbon IPC System	Eimco Process	Battelle Process	Bio-Physical Process
Amortized Capital	58	56	46	30	59
Labor	16	13	12	9	15
Power	4	2	6	8	7
Fuel	5	5	5	8	1
Maintenance Materials	4	4	4	2	4
Chemicals	12	20	28	42	14

TABLE 125

CARBON REGENERATION COSTS

Annual Costs ($1,000)

	MGD				
	1	5	10	25	50
GRANULAR CARBON					
Amortized Capital	151	184	236	341	511
Labor	8.5	36	61	108	171
Power	0.9	4.0	6.5	16	20
Fuel	15	27	55	136	271
Maintenance Materials	2	6	8	12	16
Carbon Loss	22	109	219	547	1,096
TOTAL	199.4	366	585	1,160	2,085
1,000 lbs Carbon Regenerated Per Year	547.5	2,737	5,474	13,685	27,370
Cost/lb Regenerated Carbon	36.4¢	13.4	10.7	8.5	7.6
POWDERED CARBON SYSTEMS					
Eimco					
Amortized Capital	111	196	301	655	1,179
Labor	8	15	22	38	54
Power	14	57	98	252	420
Fuel	10	52	95	231	450
Maintenance Materials	2	4	5	7	10
Carbon Loss	45	224	448	1,121	2,242
TOTAL	190	548	969	2,304	4,355
1,000 lb Carbon Regenerated Per Year	913	4,565	9,130	22,825	45,650
Cost/lb Regenerated Carbon	20.8¢	12.0¢	10.6¢	10.1¢	9.5¢

TABLE 125 (Cont'd.)

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Battelle					
Amortized Capital	144	314	537	1,179	2,227
Labor	11	27	31	54	76
Power	27	98	210	420	700
Fuel	30	126	252	577	945
Maintenance Materials	4	7	9	13	17
Carbon Loss	83	432	825	2,064	4,127
TOTAL	299	1,004	1,864	4,307	8,092
1,000 lbs Carbon Regenerated Per Year	1,826	9,132	18,264	45,662	91,323
Cost/lb Regenerated Carbon	16.4	11.0	10.2	9.4	8.9
Bio-Physical					
Amortized Capital	131	131	183	238	589
Labor	5	27	32	45	63
Power	2	11	20	50	90
Fuel	0.03	0.1	0.13	0.3	0.6
Maintenance Materials	2	10	14	25	45
Carbon Loss	17	85	169	423	845
TOTAL	157	264	418	871	1,632
1,000 lbs Carbon Regenerated Per Year	350	1,750	3,500	8,750	17,500
Cost/lb Regenerated Carbon	45¢	15¢	11.9¢	9.9¢	9.3¢

for PAC processes even further and, therefore, more strongly endorse the alternative processes. Among the PAC processes themselves, lower sludge disposal costs would render the Eimco and Bio-Physical Processes more competitive with the Battelle Northwest process. The latter utilizes no sludge disposal since the entire waste stream is routed through the fluidized bed regeneration facility. Hence, while reductions in sludge disposal costs would decrease costs for the Eimco and Bio-Physical processes, they would have no effect on the Battelle-Northwest process. Annual operating costs changes would have a similar effect since they are tied directly to the volume of sludge processed.

With respect to the size of the facility, it is clear that less costly sludge disposal would have a greater effect on the economics of smaller plants since sludge disposal accounts for a large fraction of total costs in these facilities than in larger plants. This trend holds throughout the facility sizes evaluated. The effects would be greatly different for plants where regeneration was not employed. Here, sludge disposal would be a major cost factor and reduced costs would improve relative process economics with respect to activated sludge and nitrification.

COMPARISON OF TOTAL ANNUAL COST COMPONENTS FOR 10 MGD IPC SYSTEMS

In order to summarize the underlying causes of the non-competive economic position of the basic IPC powdered carbon systems, Table 126 was prepared.

Eimco vs Granular Carbon

The three clarifier system results in slightly higher capital costs and labor costs for the Eimco system. Power requirements are higher primarily due to the FBF power demands. Fuel requirements are higher primarily because the weight of carbon involved is significantly higher for the Eimco system. About 65 percent of the total cost difference occurs in the area of chemical costs -- primarily related to the higher Eimco carbon dosage (2,500 lb/MG vs 1,500 lb/MG and higher carbon losses (14 percent vs 8 percent). The need for polymer conditioning of the powdered carbon sludge while granular carbon readily dewaters without conditioning accounts for another major cost difference ($140,160/year of polymer costs).

Battelle vs Granular Carbon

The capital costs of the Battelle system are quite favorable because there is only one step of clarification and the organic, chemical, and carbon sludges are handled in one system -- eliminating duplication of dewatering and thermal equipment.

TABLE 126

COMPARISON OF TOTAL ANNUAL COST COMPONENTS, 10 MGD IPC SYSTEMS

	Granular Carbon	Eimco	Battelle
Amortized Capital	$1,195,638	$1,284,648	$ 945,490
Labor	284,000	327,600	298,800
Power	45,500	156,118	262,466
Fuel	102,600	142,500	252,000
Maintenance Materials	76,600	121,970	71,510
Chemicals			
Makeup Carbon	219,000	448,500	825,500
Alum	133,000	133,000	29,400
Polymer, Wastewater	2,300	2,300	18,132
Polymer, Sludge	-	-	103,660
Polymer, Carbon Sludge	-	140,160	-
Lime	56,700	56,700	84,360
Chlorine	10,120	10,120	10,120
Sulfuric Acid	-	-	261,288
TOTAL	$2,125,378	$2,823,616	$3,162,726
Cost/MG @ Capacity	$ 582	$ 774	$ 867

The limited capital facilities also result in comparable labor costs. Power and fuel costs are higher due to the FBF demands -- which are further aggravated by the very large quantities of carbon involved (5,000 lb/MG vs 1,500 lb/MG. The net difference in costs results primarily from the higher chemical costs. The costs of recovered alum are higher than the cost of fresh alum. In addition, the basic case assumed a 200 mg/l alum dosage as compared to 125 mg/l in the granular carbon system. The high carbon dose not only results in higher chemical and operating costs but adversely affects the capital cost of the dewatering and regeneration equipment. As shown earlier, reduction of the carbon dosage to 200 mg/l and alum dosage to 125 mg/l in itself would reduce the cost of the Battelle system to a value significantly lower than the granular carbon system.

SENSITIVITY OF GRANULAR CARBON COSTS TO CARBON DOSAGE

The costs of the granular carbon IPC system presented throughout the report are based on a carbon dosage of 1,500 lb/million gallons. At a carbon loading of 0.5 lb COD/lb carbon, this corresponds to a situation where a 90 mg/l of COD is being removed by the carbon. There are cases where the carbon loading may be higher, the applied COD may be lower, or both of these conditions may occur. Thus, Tables 127 and 128 were prepared to show the impact that carbon dosages of 750 lb/MG and 200 lb/MG have on costs.

MULTIPLE-HEARTH REGENERATION OF POWDERED CARBON

Multiple-hearth regeneration of powdered carbon is planned for duPont's large, full-scale bio-physical plant. Thus, data were requested from Nichols Corporation, the manufacturer of the dePont furnace. Available data on powdered carbon regeneration in multiple-hearth furnaces are limited and, thus, a significant degree of uncertainty is associated with the estimates made in this report. The following summarizes the key information supplied by Nichols for this project:

	Process		
	Eimco	Battelle	Bio-Physical
Square Feet of Hearth, Effective area/MGD	130	162	60
Fuel, 10^6BTU/hr/MGD	1.2	1.6	0.67

Nichols based their information on use of pressure filtration to achieve a 50 percent solids concentration prior to regeneration.

TABLE 127

GRANULAR CARBON PROCESS AT 750 LB CARBON PER MG

	Annual Cost ($1,000) Capacity, MGD				
	1	5	10	25	50
Amortized Capital	444	751	1,141	2,063	3,534
Labor	103.0	182.8	257.0	399.1	639.2
Power	4.0	23.44	42.2	96.4	184.0
Fuel	40.0	46.0	75.0	177.0	330.0
Maintenance Materials	17.5	44.9	72.7	141.4	207.4
Chemicals					
Makeup Carbon	11.0	54.5	110.0	274.0	548.0
Alum	13.3	66.5	133.0	322.5	665.0
Polymer, Wastewater	0.23	1.14	2.3	5.7	11.4
Chlorine	1.0	5.06	10.12	11.50	23.0
Lime, Primary Sludge	5.66	28.34	56.7	141.7	283.42
TOTAL	639.7	1,203.7	1,900.0	3,632.3	6,425.4
Costs/1,000 Gals (Operating @ Capacity)	$1.75	$0.66	$0.52	$0.40	$0.35

TABLE 128

GRANULAR CARBON PROCESS AT 200 LB CARBON PER MG

	Annual Cost ($1,000) Capacity, MGD				
	1	5	10	25	50
Amortized Capital	444	751	1,109	1,984	3,350
Labor	101	190.5	234.5	373.8	599.1
Power	6.8	21.9	39.5	90.2	171.5
Fuel	33.75	35.8	55.2	127.5	231.0
Maintenance Materials	17.5	42.9	69.7	138.1	202.0
Chemicals					
Makeup Carbon	3.0	14.5	29.1	72.8	146.0
Alum	13.3	66.5	133.0	322.5	665.0
Polymer, Wastewater	0.23	1.54	2.3	5.7	11.4
Chlorine	1.0	5.06	10.12	11.50	23.0
Lime, Primary Sludge	5.66	28.34	56.7	141.7	283.42
TOTAL	626.2	1,157.6	1,739.1	3,267.8	5,682.4
Costs/1,000 Gals (Operating @ Capacity)	$1.72	$0.64	$0.48	$0.36	$0.31

Cost, power, labor, and maintenance material curves developed by CWC for multiple-hearth furnaces and filter presses were used to develop the cost information present in Tables 129-131.

Eimco

The capital costs of the filter press and multiple-hearth furnace were higher (about 30 percent) than the costs of the vacuum filter and FBF. Labor requirements were slightly higher. The power requirements were reduced drastically by a factor of about 10. Fuel requirements for carbon regeneration were higher with the difference becoming greater as the plant capacity increased (50 percent more at 5 MGD to 70 percent more at 50 MGD). This latter trend resulted from the fact that Nichols stated the fuel requirements per pound of carbon were fixed over the entire range of multiple-hearth sizes with no fuel economies resulting in the larger furnaces. The FBF fuel consumption/lb of carbon decreased with increasing furnace size. Nichols conclusions on makeup carbon quantities agreed with the quantities presented earlier. Maintenance materials were not affected significantly. The net effect was a slight (5-6 percent) increase in overall costs as the savings in power costs were more than offset by the increases in the other categories.

Battelle

The regeneration capital costs were 4-8 percent higher using the filter press and multiple-hearth furnace. Labor requirements were not affected significantly. Power consumption was again reduced drastically. Fuel costs were comparable at 1 MGD but increased as plant size increased (as noted above). Maintenance materials decreased. The savings in power and maintenance materials resulted in a new reduction in costs of up to 7.5 percent in plants 5 MGD or larger. Nichols felt that about 50 percent of the makeup carbon requirements previously noted would be met by carbon manufactured from the raw sewage solids as they passed through the multiple-hearth furnace. As noted in Table 30, this could provide a savings of 12¢/1,000 gallons (7-17 percent of total costs) if, in fact, this level of carbon production occurs.

Bio-Physical

Costs and labor increases result primarily from the addition of a carbon sludge dewatering step not present in the original flowsheet. Fuel consumption also shows a marked increase but it should be kept in mind that the base case was based on Zimpro's wet-oxidation process with an assumption of no significant supplemental fuel required -- perhaps an optimistic assumption. Power savings achieved by replacing the wet air oxidation process with the multiple-hearth process more than offset the power requirements of the filter press. The net result was a 11-14

TABLE 129

EIMCO ANNUAL PROCESS WITH MULTIPLE HEARTH REGENERATION

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	508	934	1,376	2,455	4,426
Labor	148	284	399	608	909
Power	12	35	64	146	288
Fuel	34	111	207	505	987
Maintenance Materials	27	76	120	226	357
Chemicals					
Powdered Carbon	45	224	448	1,121	2,242
Alum	13	66	133	332	665
Polymer, Wastewater	0.2	1.14	2.3	5.7	11.4
Polymer, Carbon Sludge	9	70	140	350	702
Chlorine	1	5	10	11.5	23
Lime, Primary Sludge	6	28	57	142	283
TOTAL	805	1,834	2,956	5,901	10,893
Costs/1,000 Gals (Operating @ Capacity)	$2.21	$1.00	$0.81	$0.65	$0.60
Multiple Hearth Sizing					
Diameter	9'3"	16'9"	22'3"	2-25'9"	4-25'9"
No. Hearths	4	4	5	5	5

TABLE 130

BATTELLE PROCESS WITH MULTIPLE HEARTH REGENERATION

Annual Cost ($1,000)

	MGD				
	1	5	10	25	50
Amortized Capital	303	586	886	1,844	3,184
Labor	121	213	293	683	863
Power	8	30	55	140	276
Fuel	21	105	210	525	1,050
Maintenance Materials	19	40	54	98	154
Chemicals					
Alum	3	15	29	74	147
Carbon	83	431	825	2,064	4,127
Lime	8	42	84	211	422
Polymer, Wastewater	1.8	9	18	45	91
Polymer, Sludge	10	52	104	259	518
Sulfuric Acid	26	131	261	653	1,306
Chlorine	1	5	10	11	23
TOTAL	604.8	1,659	2,829	6,607	12,161
Costs/1,000 Gals (Operation @ Capacity)	$1.66	$0.91	$0.78	$0.72	$0.67
Potential Credit for Activated Carbon Manufacture in Multiple Hearth Furnace	$ 0.12	$ 0.12	$0.12	$0.12	$0.12
Multiple Hearth Sizing					
Diameter	9'3"	22'3"	25'9"	2-25'9"	4-25'9"
No. Hearths	5	3	5	5	5

TABLE 131

BIO-PHYSICAL PROCESS WITH MULTIPLE HEARTH REGENERATION

Annual Cost ($1,000)

	Capacity, MGD				
	1	5	10	25	50
Amortized Capital	464	711	1,039	1,785	2,865
Labor	80	181	288	482	807
Power	8	46	91	230	431
Fuel	13	55	112	285	582
Maintenance Materials	18	43	69	120	186
Chemicals					
Carbon	17	84	169	423	845
Polymer	4	23	46	114	228
Chlorine	1	5	10	11	23
TOTAL	605	1,148	1,819	3,450	5,958
Costs/1,000 Gals (Operating @ Capacity)	$1.66	$0.63	$0.50	$0.38	$0.33
Potential Credit for Activated Carbon Manufactured in Multiple Hearth Furnace	$0.02	$0.02	$0.02	$0.02	$0.02
Multiple Hearth Sizing					
Diameter	5'4"	14'3"	18'9"	25'9"	2-25'9"
No. Hearths	5	3	3	4	4

percent increase in overall process costs. As in the Battelle process, Nichols felt that production of powdered carbon would occur and Table 120 shows the potential savings.

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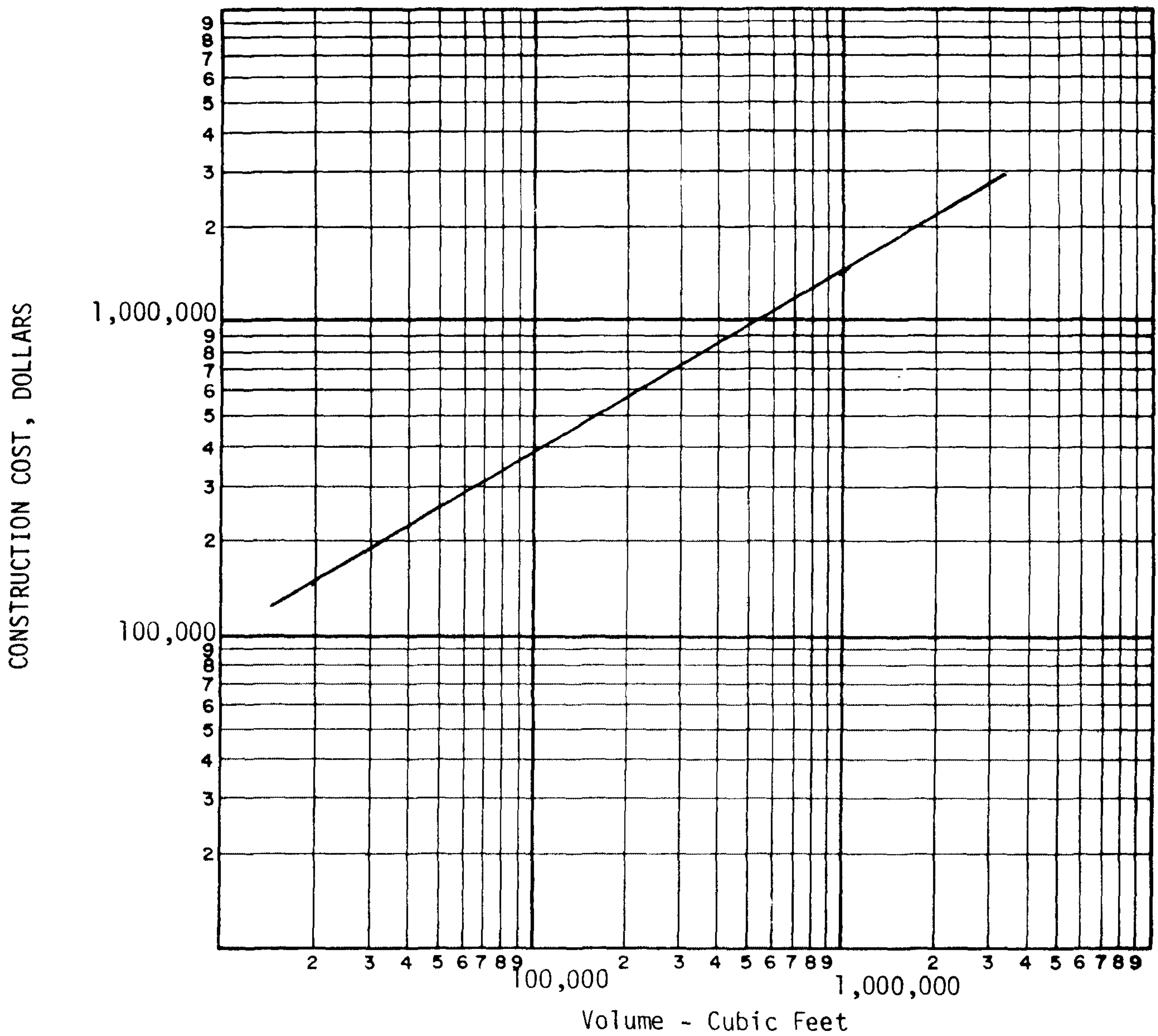
APPENDIX

COST CURVES

COST CURVE INDEX

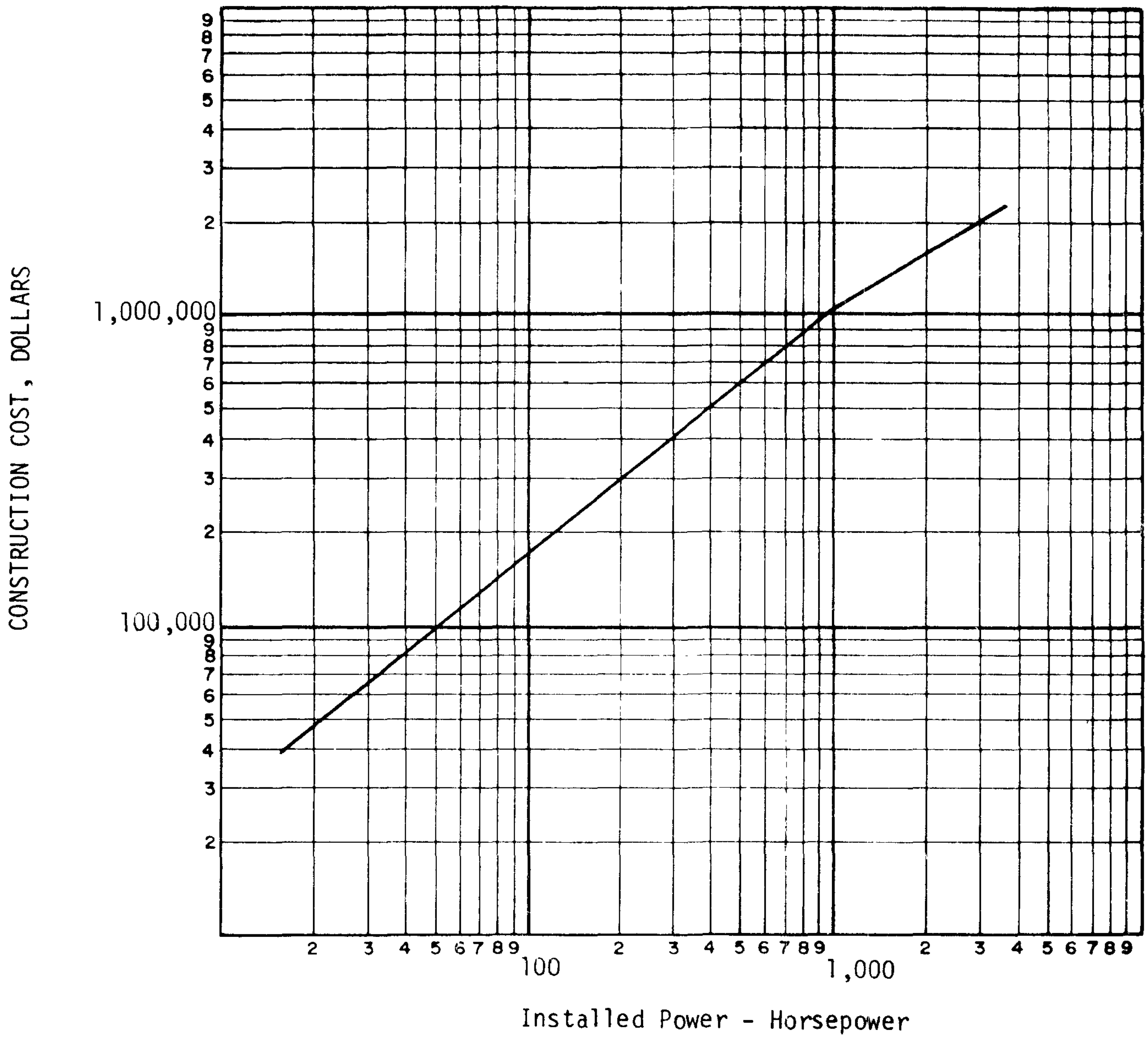
	Construction	Labor	Power	Fuel	Maintenance Materials
Aeration Basins	1	-	-	-	-
Mechanical Aeration	2	30	31	-	32
Intermediate and Return Act. Sl. Pump Stations	3	33	34	-	36
Rapid Mixing	4	37	38	-	39
Flocculation	5	40	41	-	42
Clarifier	6	43	44	-	45
Flocculator - Clarifier	7	46	47	-	48
Tube Settling Modules	8	-	-	-	-
Reactor Clarifier	9	49	50	-	51
Gravity Filtration	10	52	53	-	54
Granular Carbon Pumping	11	-	-	-	-
Granular Carbon Contactors	12	55	56	-	57
Chlorine Contact Basins	13	-	-	-	-
Chlorine Feed Equipment	14	58	-	-	59
Waste Sludge Pumping Stations	15	60	61	-	62
Chemical Sludge Pumping	16	63	64	-	65
Gravity Thickening	17	66	67	-	68
Floatation Thickening	18	69	70	-	71
Vacuum Filtration	19	72	73	-	74
Centrifuging	20	75	76	-	77
Multiple Hearth Furnaces	21	78	79	80	81
Alum Storage and Feeding	22	82	83	-	84
Powdered Activated Carbon Storage and Feeding	23	85	86	-	87
Lime Storage and Feeding	24	88	89	-	90
Polymer Storage and Feeding	25	91	92	-	93
Sulfuric Acid Storage and Feeding	26	94	95	-	96
Dry Chemical Feeders	27	97	-	-	98
Fluidized Bed Furnaces	28	99	100	101	102
Wet Air Oxidation Systems	29	103	104	105	106
Pressure Filtration	29A	107	108	-	109



AERATION BASINS

CONSTRUCTION COST

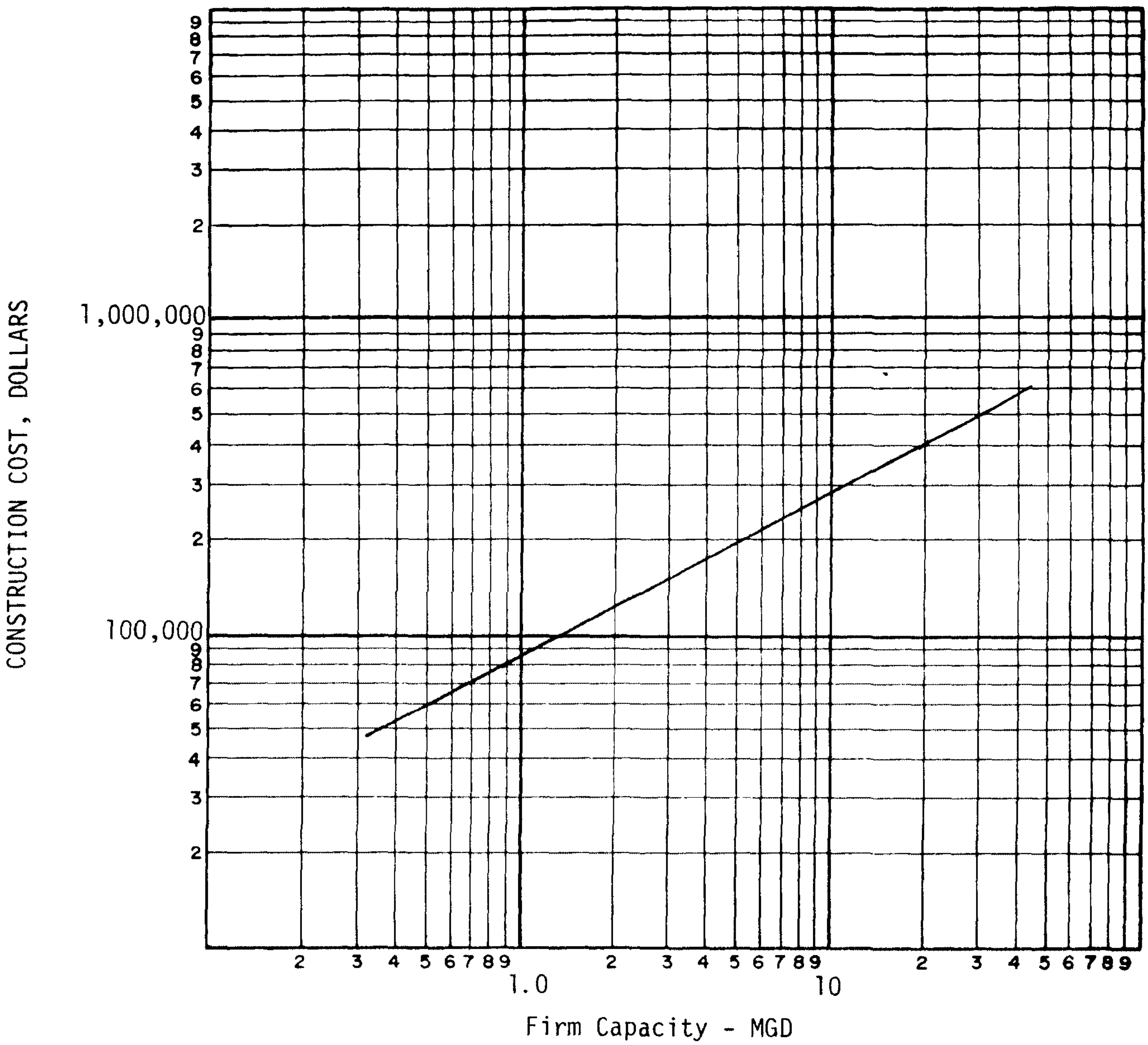
Curve 1



MECHANICAL AERATION

CONSTRUCTION COST

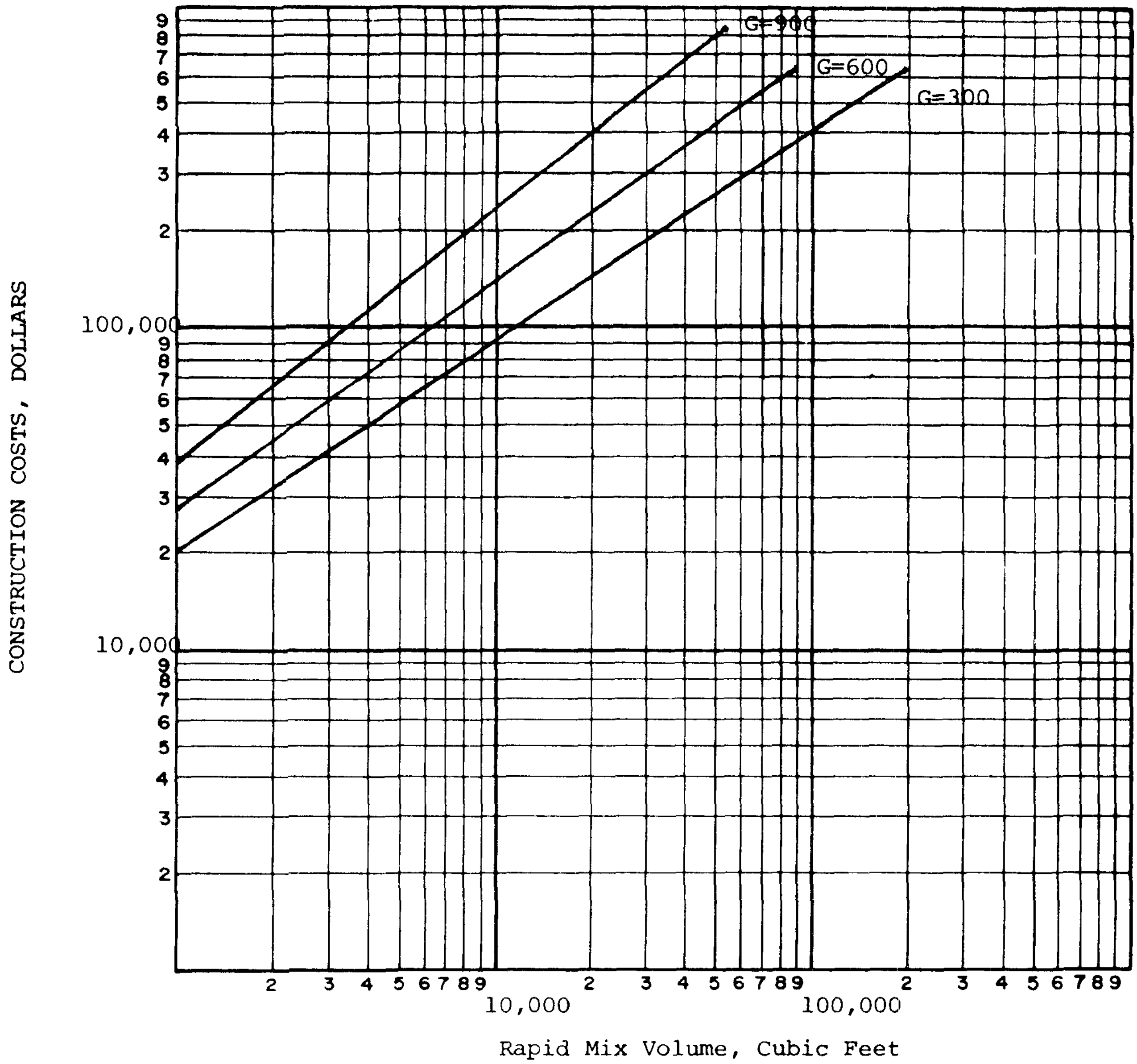
Curve 2



INTERMEDIATE OR RETURN ACTIVATED SLUDGE PUMPING STATIONS

CONSTRUCTION COST

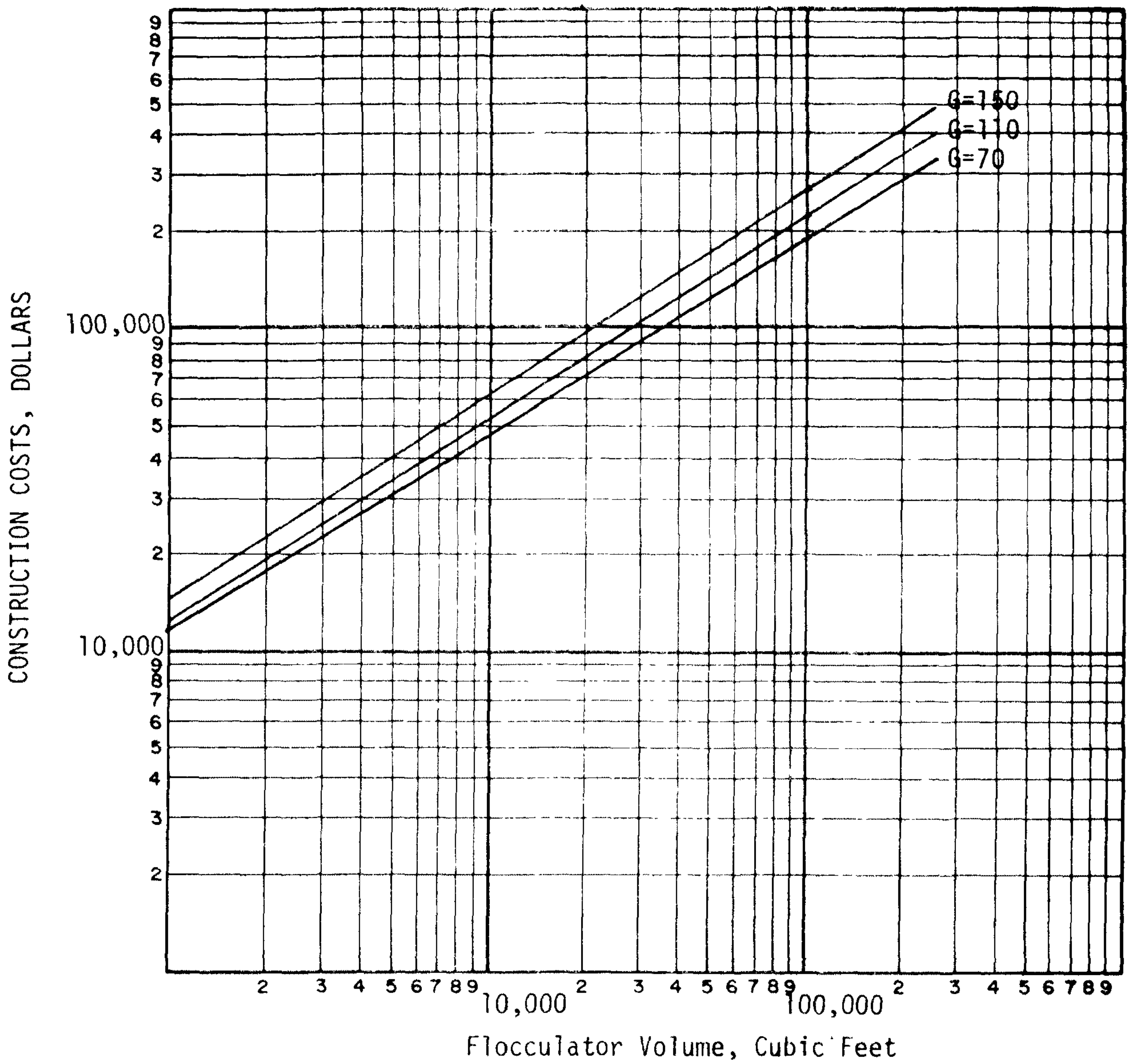
Curve 3



RAPID MIXING

CONSTRUCTION COSTS

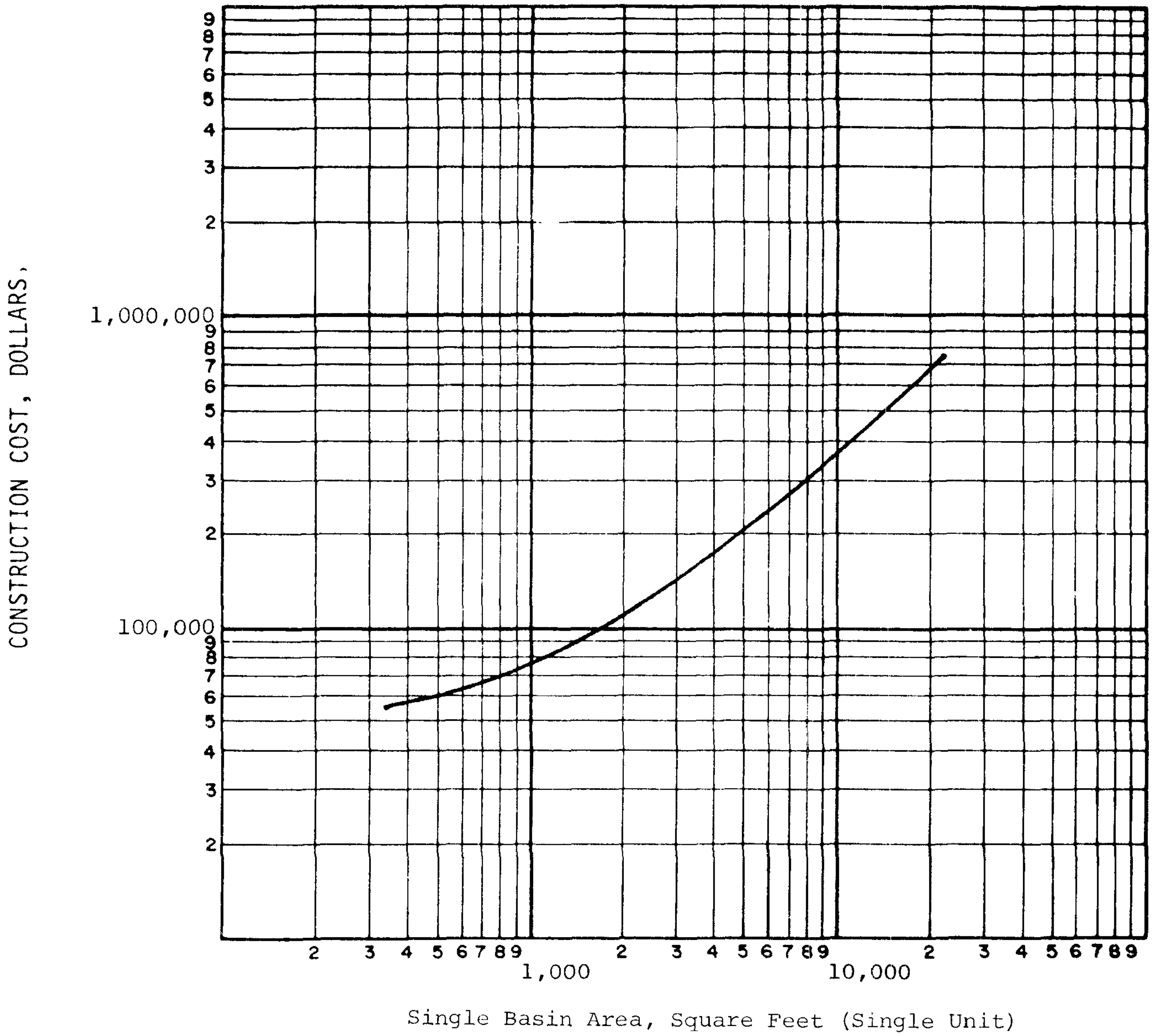
Curve 4



FLOCCULATION, VERTICAL TURBINE

CONSTRUCTION COSTS

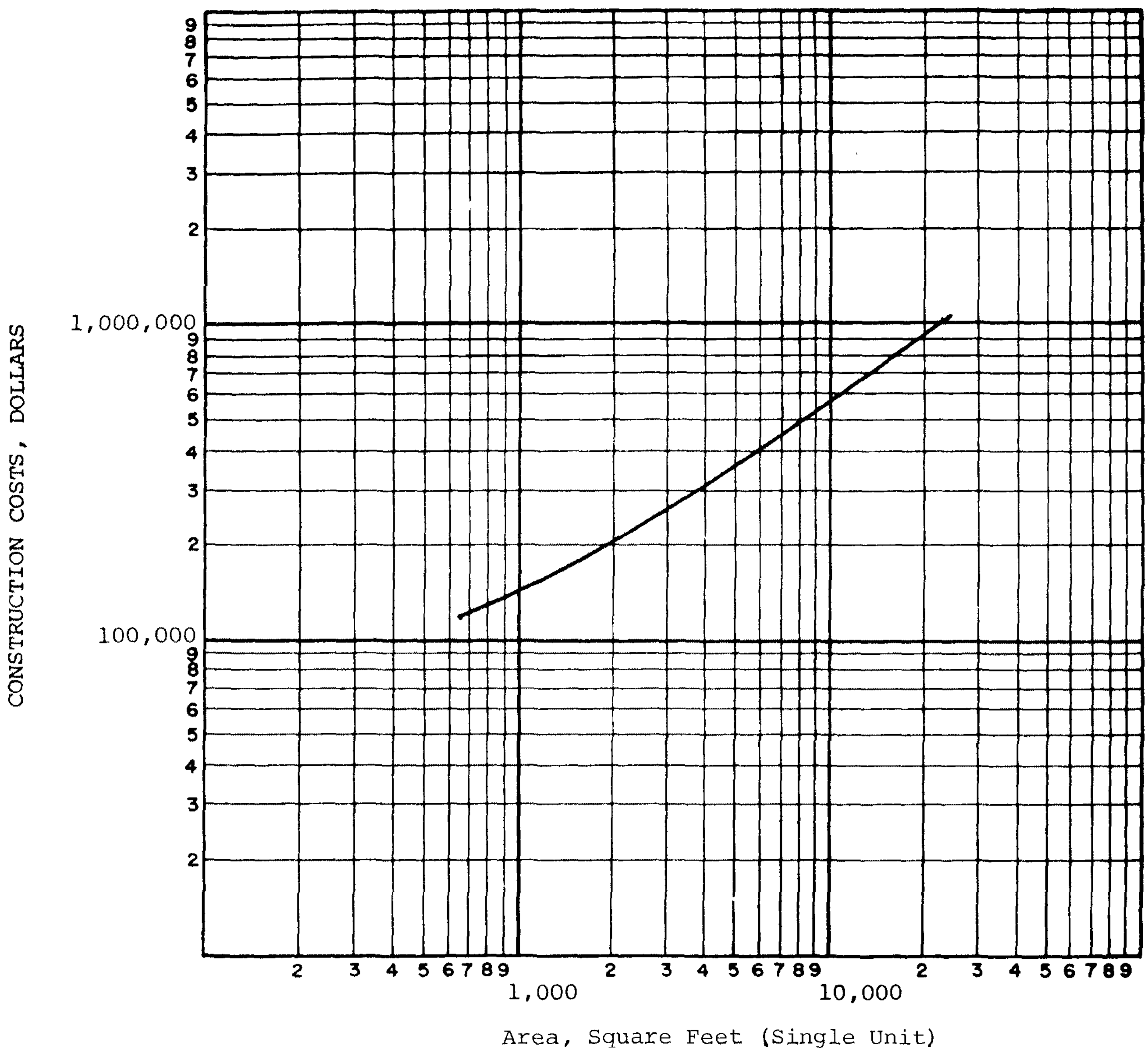
Curve 5



CLARIFIER

CONSTRUCTION COSTS

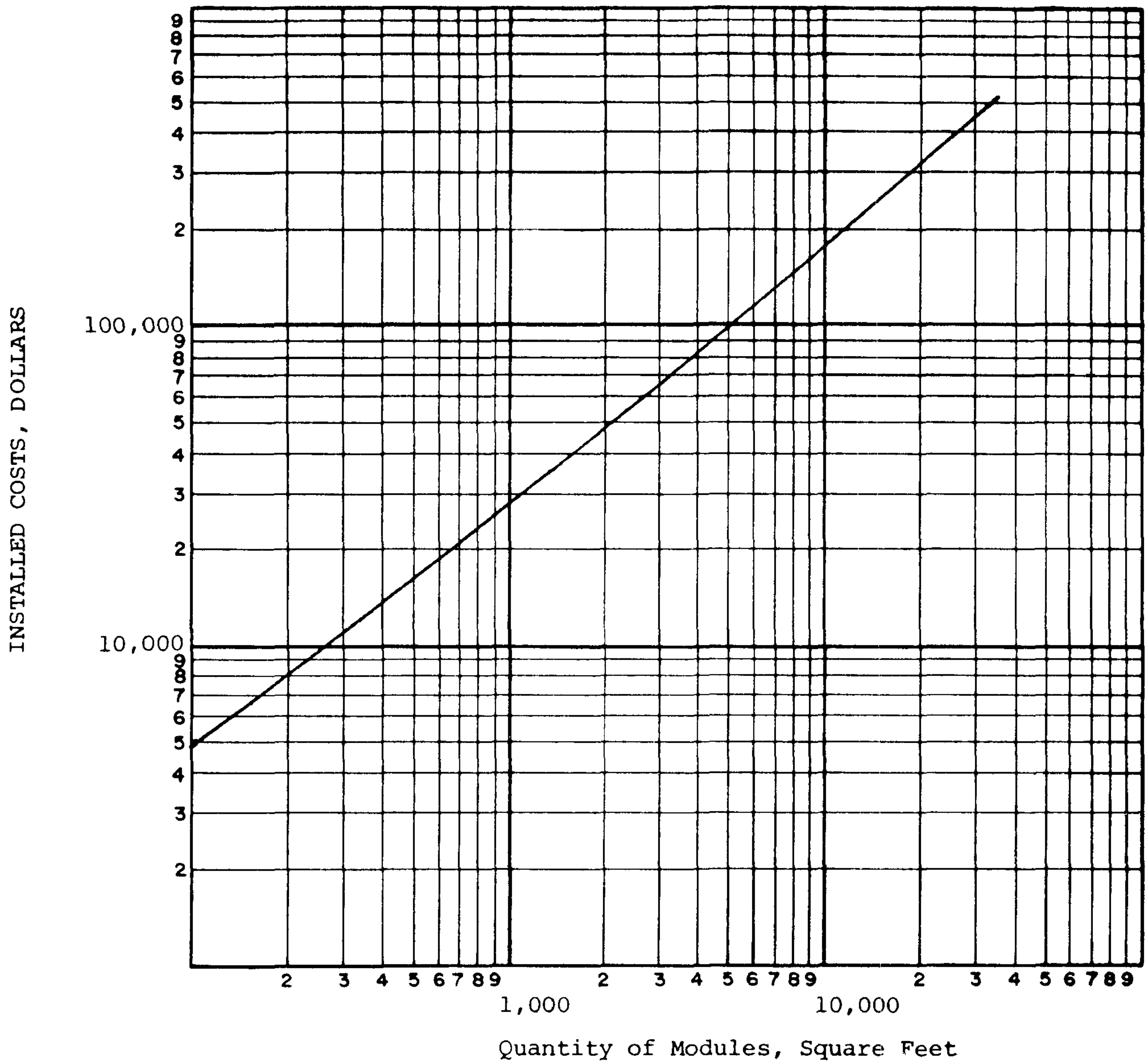
Curve 6



FLOCCULATOR - CLARIFIER

CONSTRUCTION COSTS

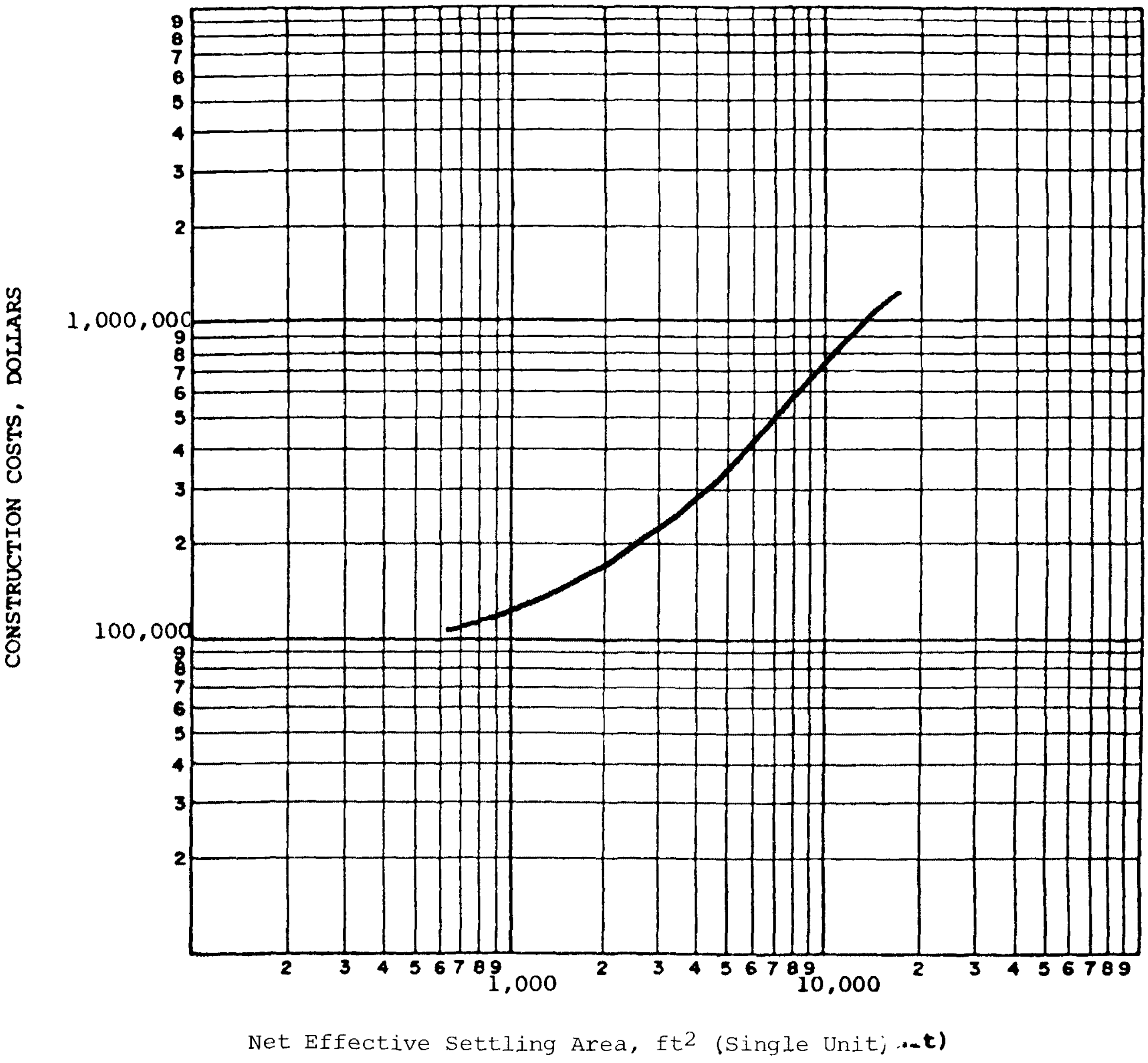
Curve 7



TUBE SETTLING MODULES

CONSTRUCTION COSTS

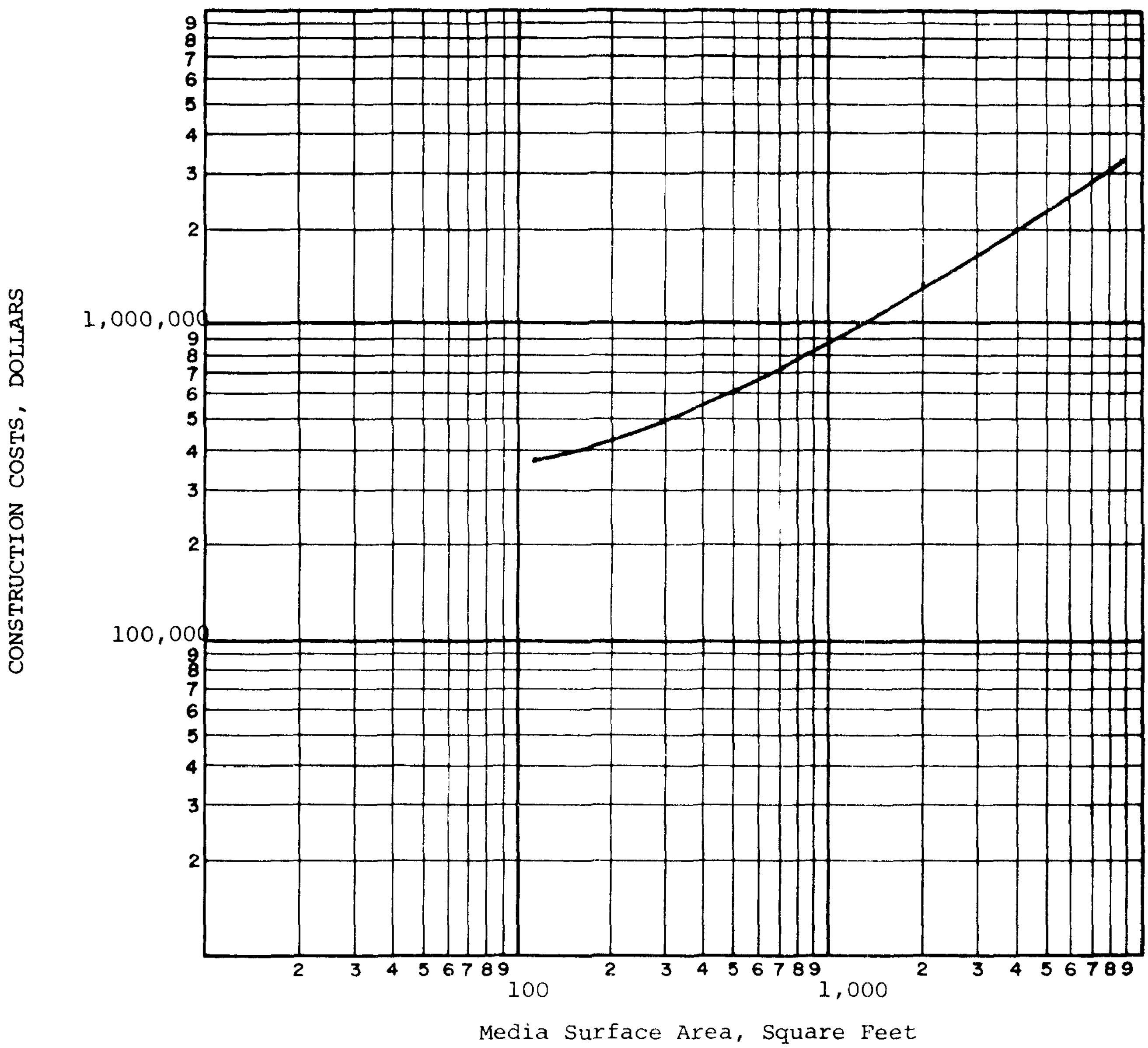
Curve 8



REACTOR - CLARIFIERS

CONSTRUCTION COSTS

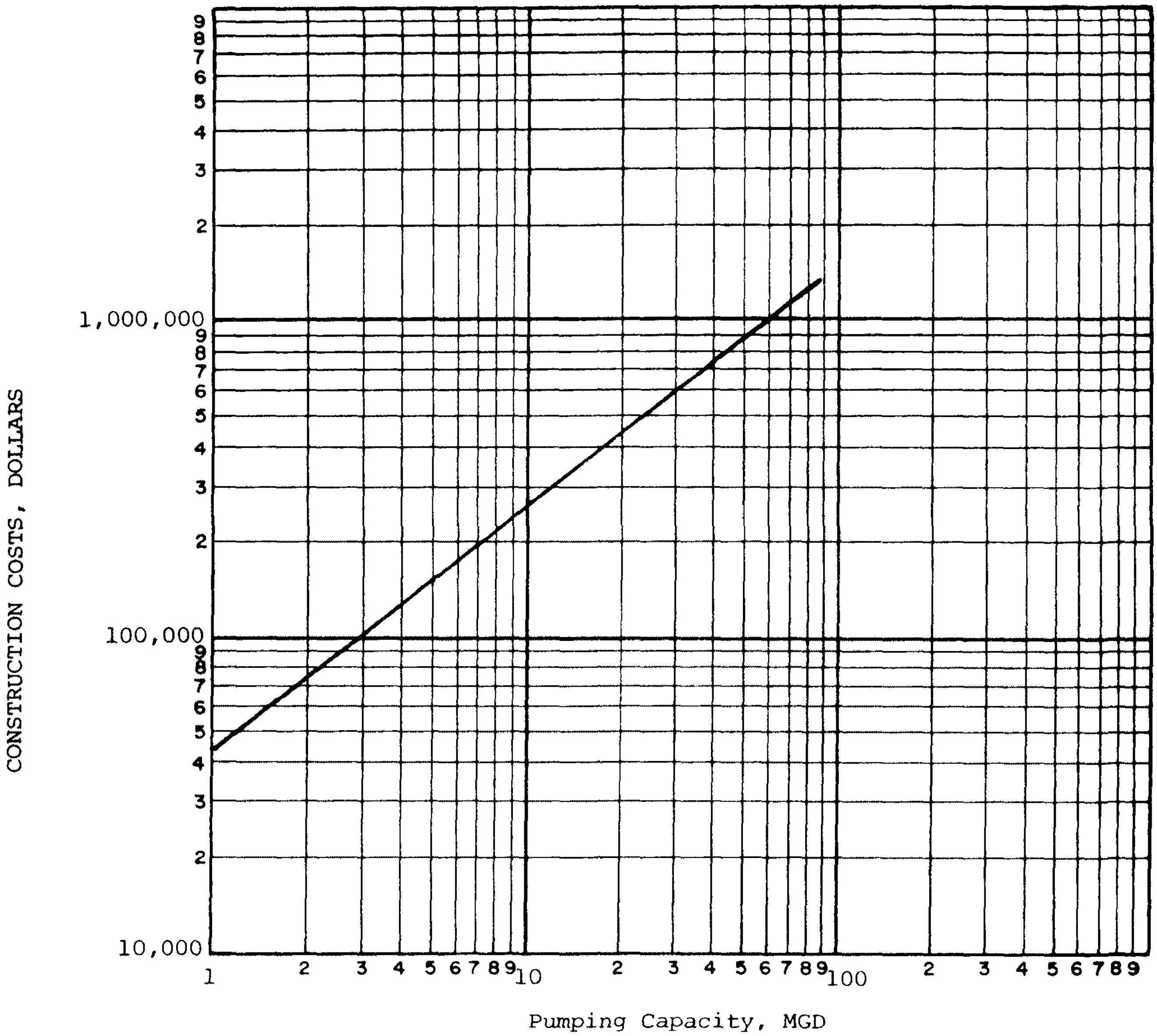
Curve 9



GRAVITY FILTRATION

CONSTRUCTION COSTS

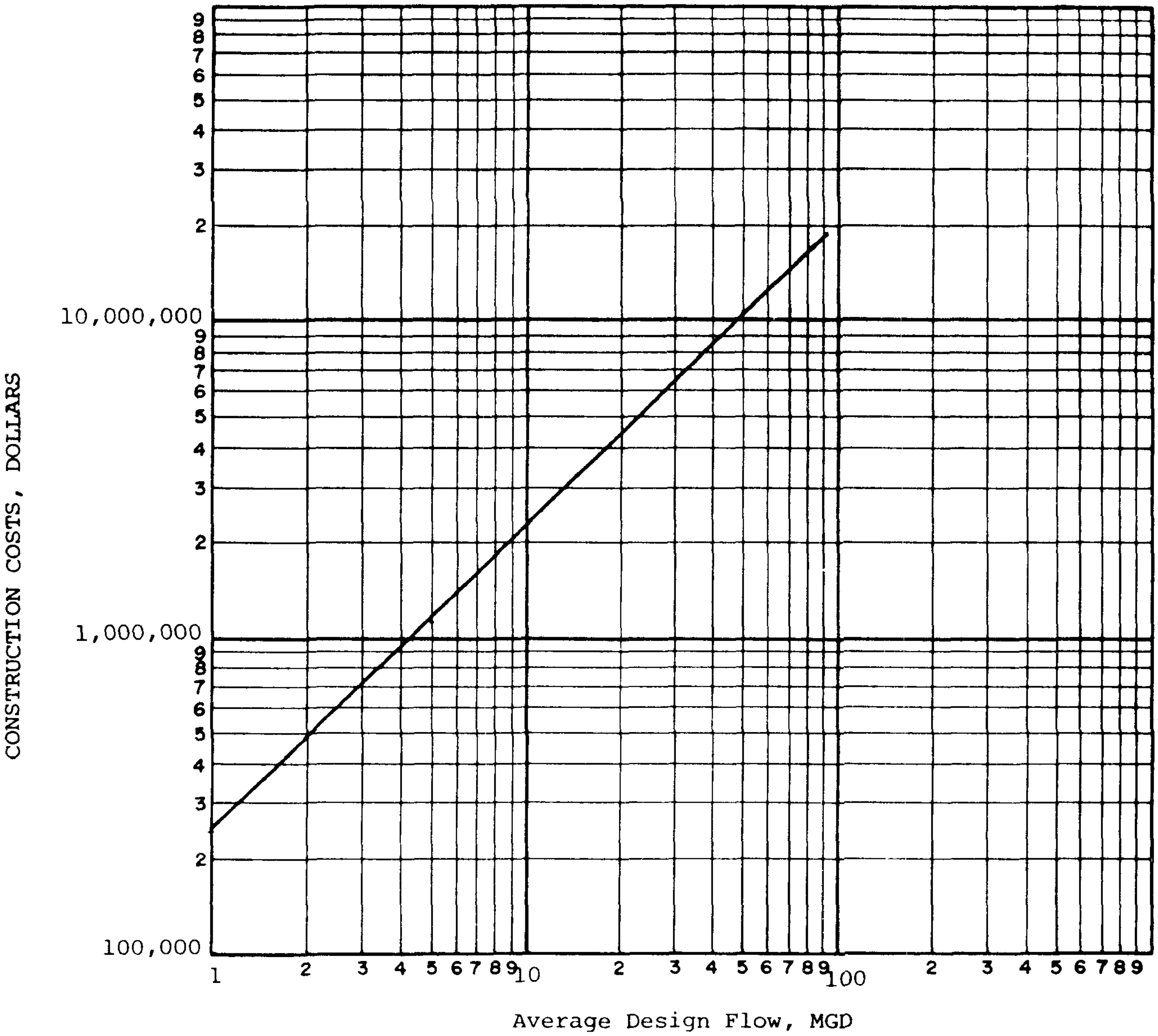
Curve 10



CARBON ADSORPTION PUMP STATION

CONSTRUCTION COSTS

Curve 11

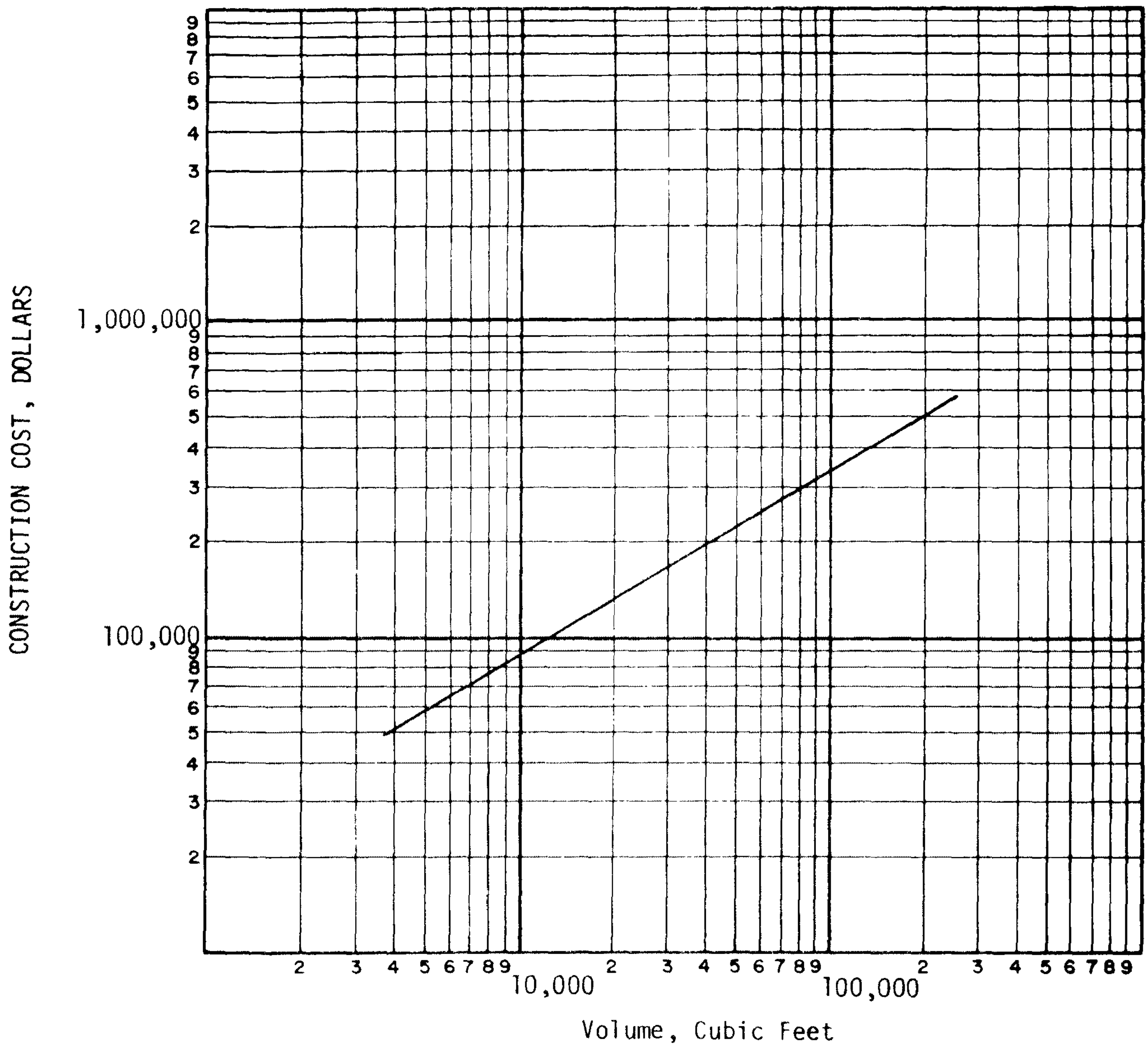


GRANULAR CARBON CONTACTOR SYSTEM

(30 minutes contact at design flow)

CONSTRUCTION COSTS

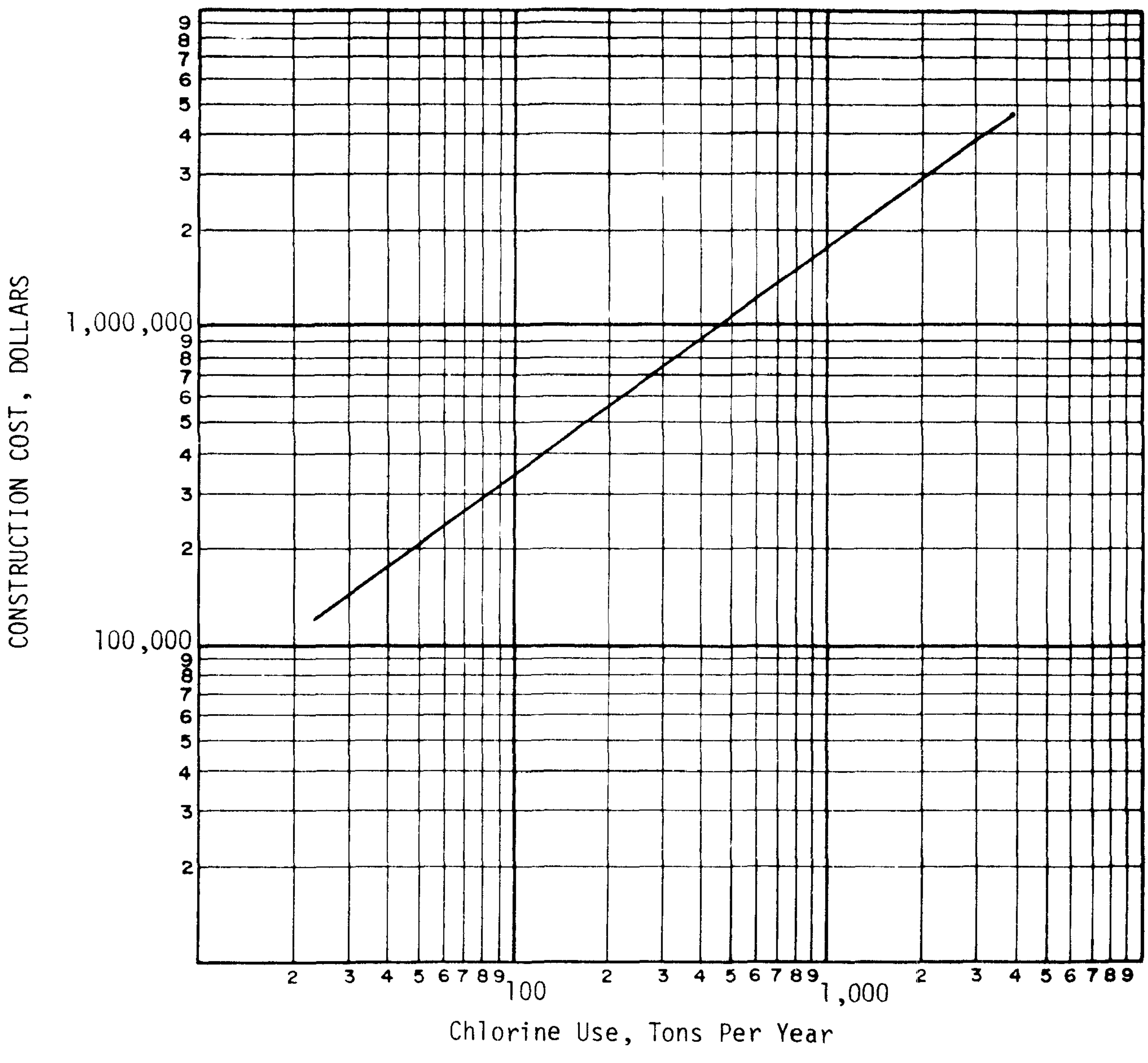
Curve 12



CHLORINE CONTACT BASINS

CONSTRUCTION COST

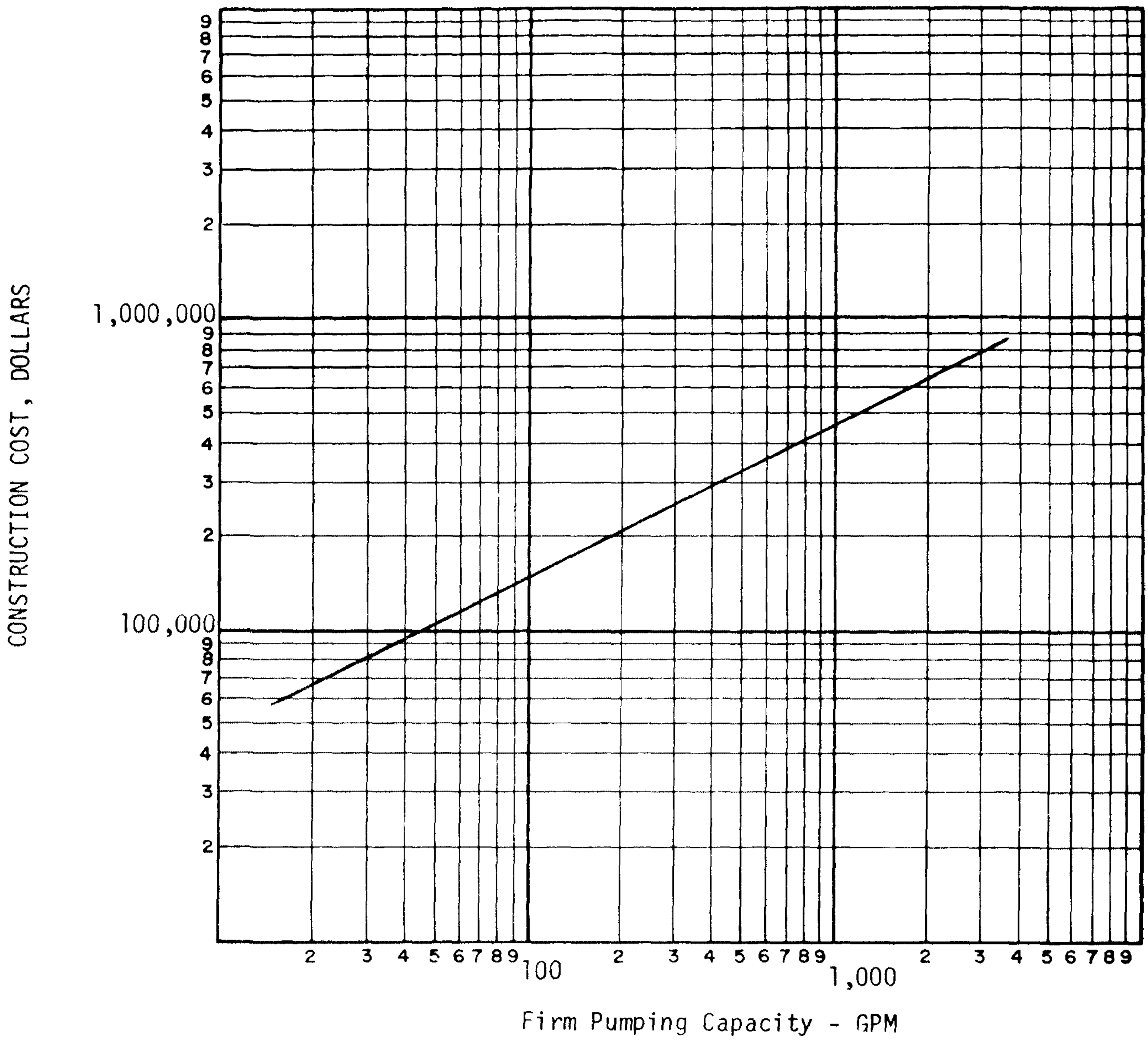
Curve 13



CHLORINE FEED EQUIPMENT

CONSTRUCTION COST

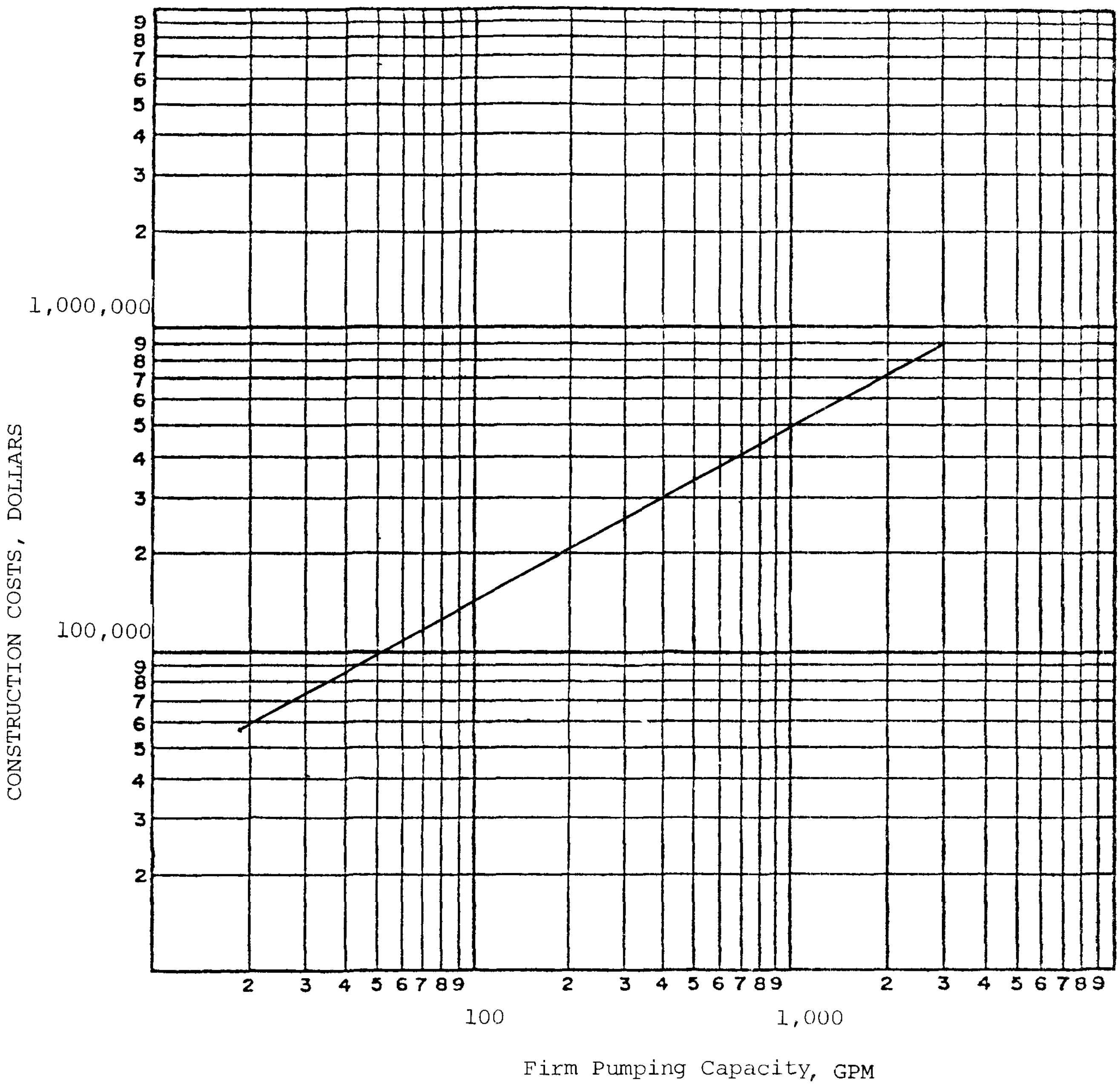
Curve 14



WASTE SLUDGE PUMPING STATIONS

CONSTRUCTION COST

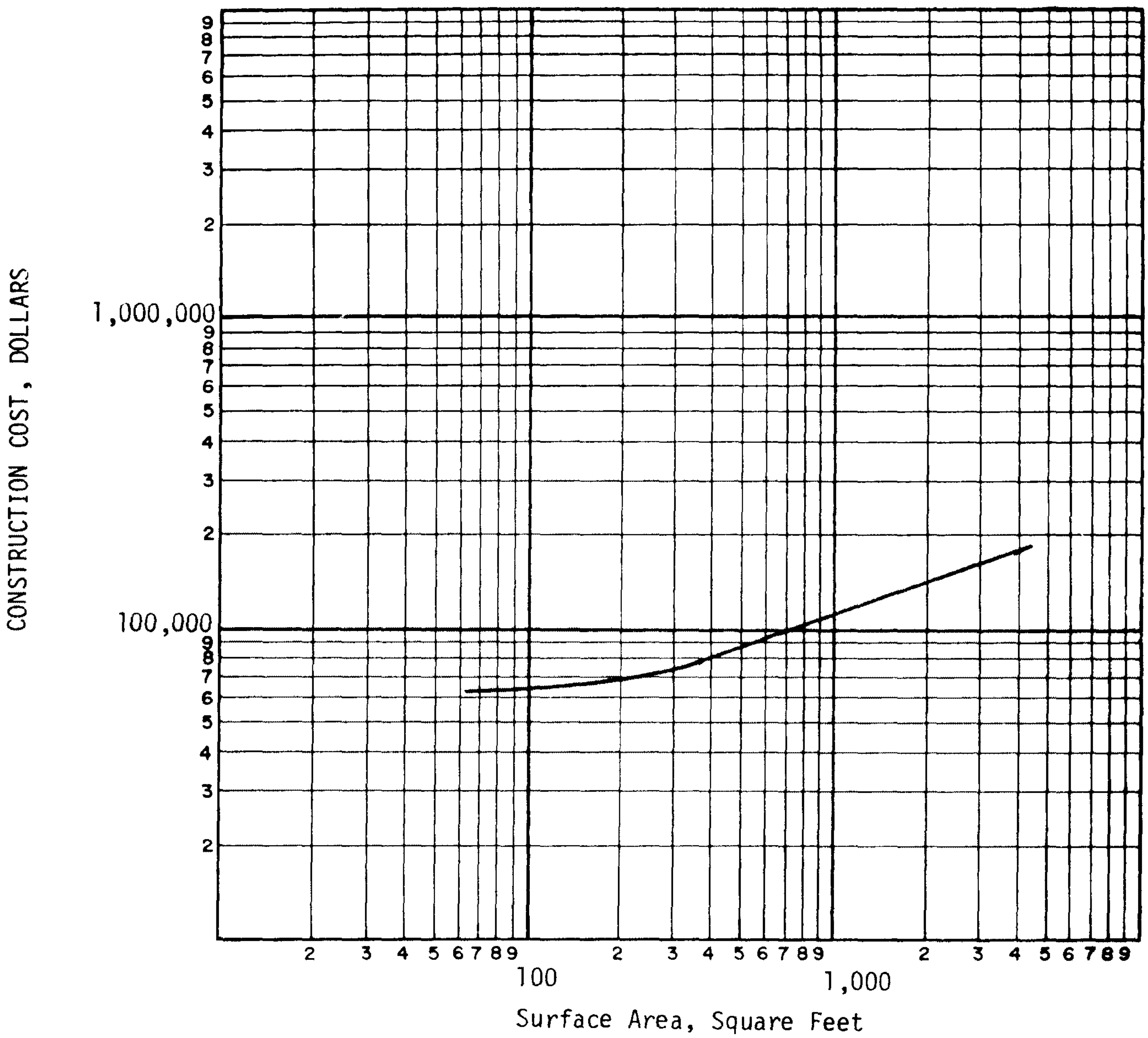
Curve 15



CHEMICAL SLUDGE PUMPING

CONSTRUCTION COSTS

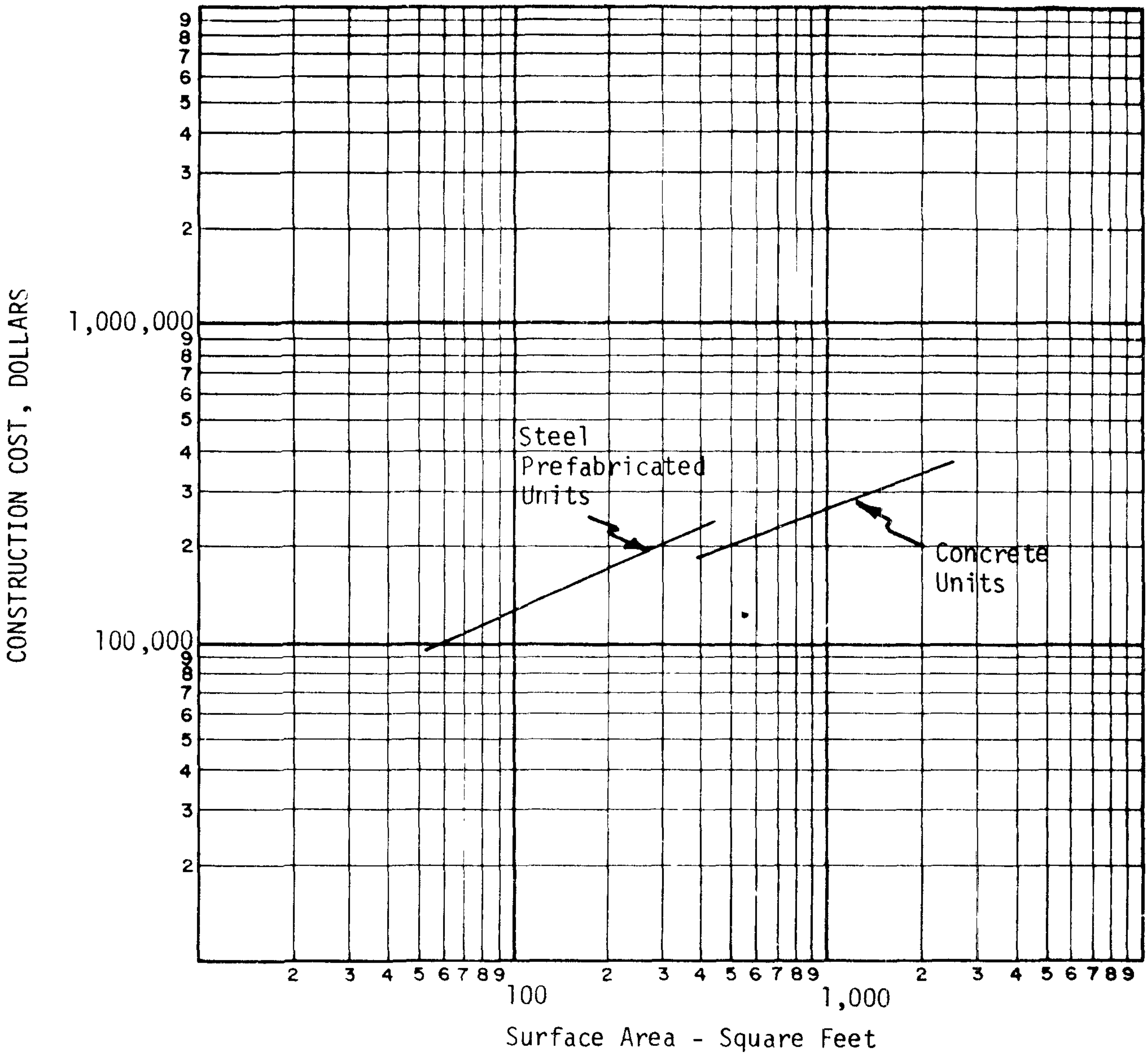
Curve 16



GRAVITY THICKENING

CONSTRUCTION COST

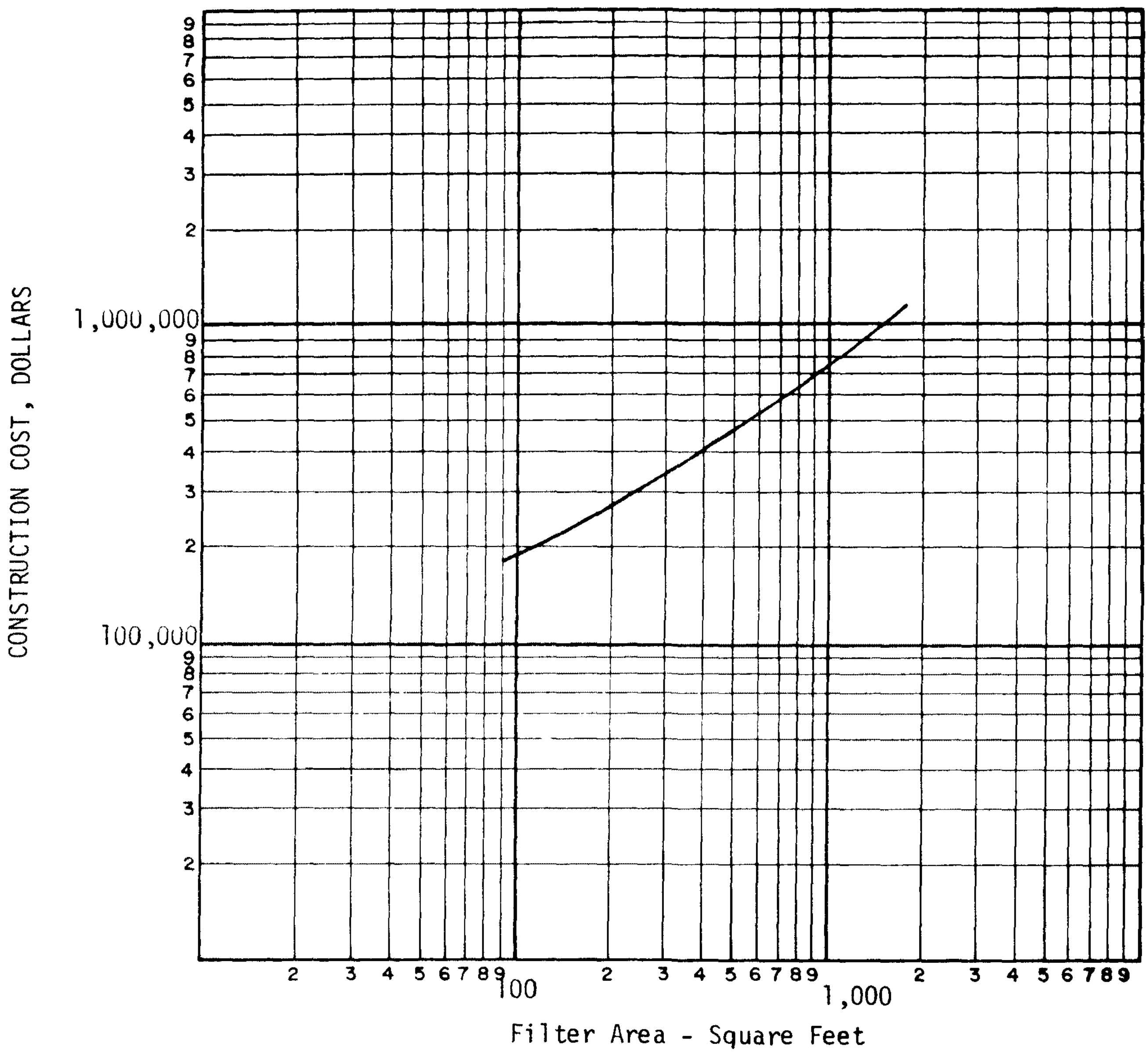
Curve 17



FLOTATION THICKENING

CONSTRUCTION COST

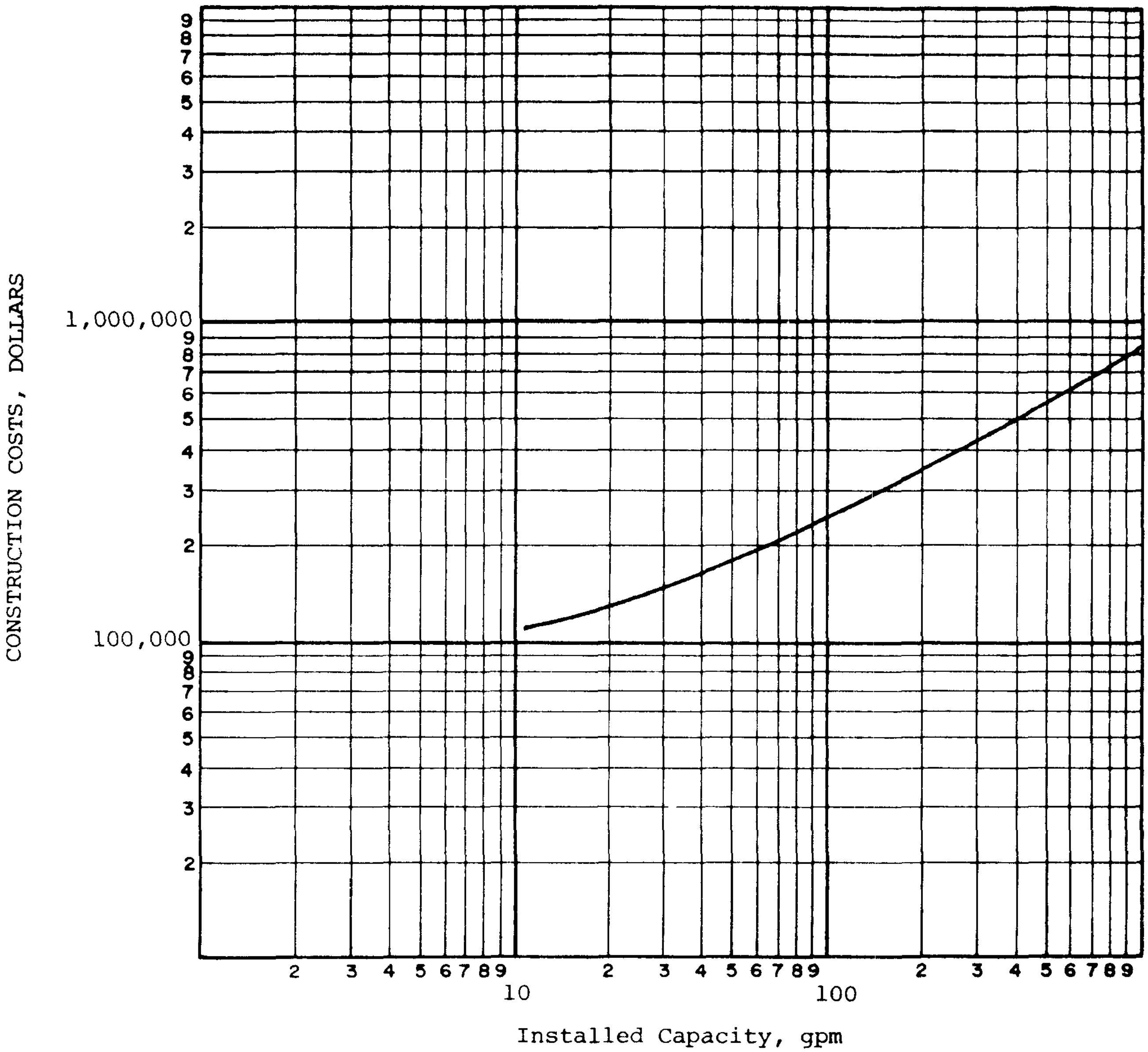
Curve 18



VACUUM FILTRATION

CONSTRUCTION COST

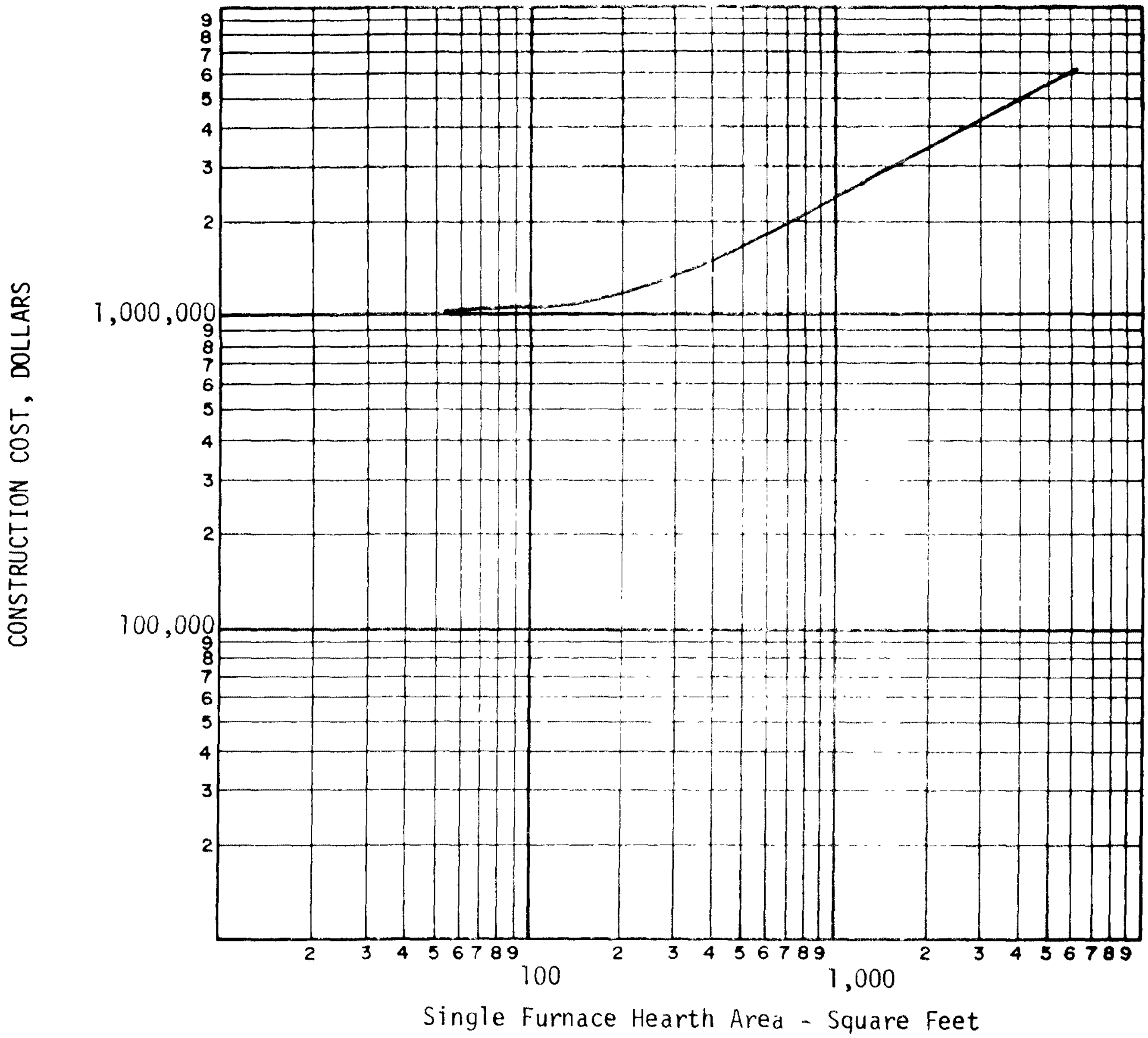
Curve 19



CENTRIFUGING

CONSTRUCTION COSTS

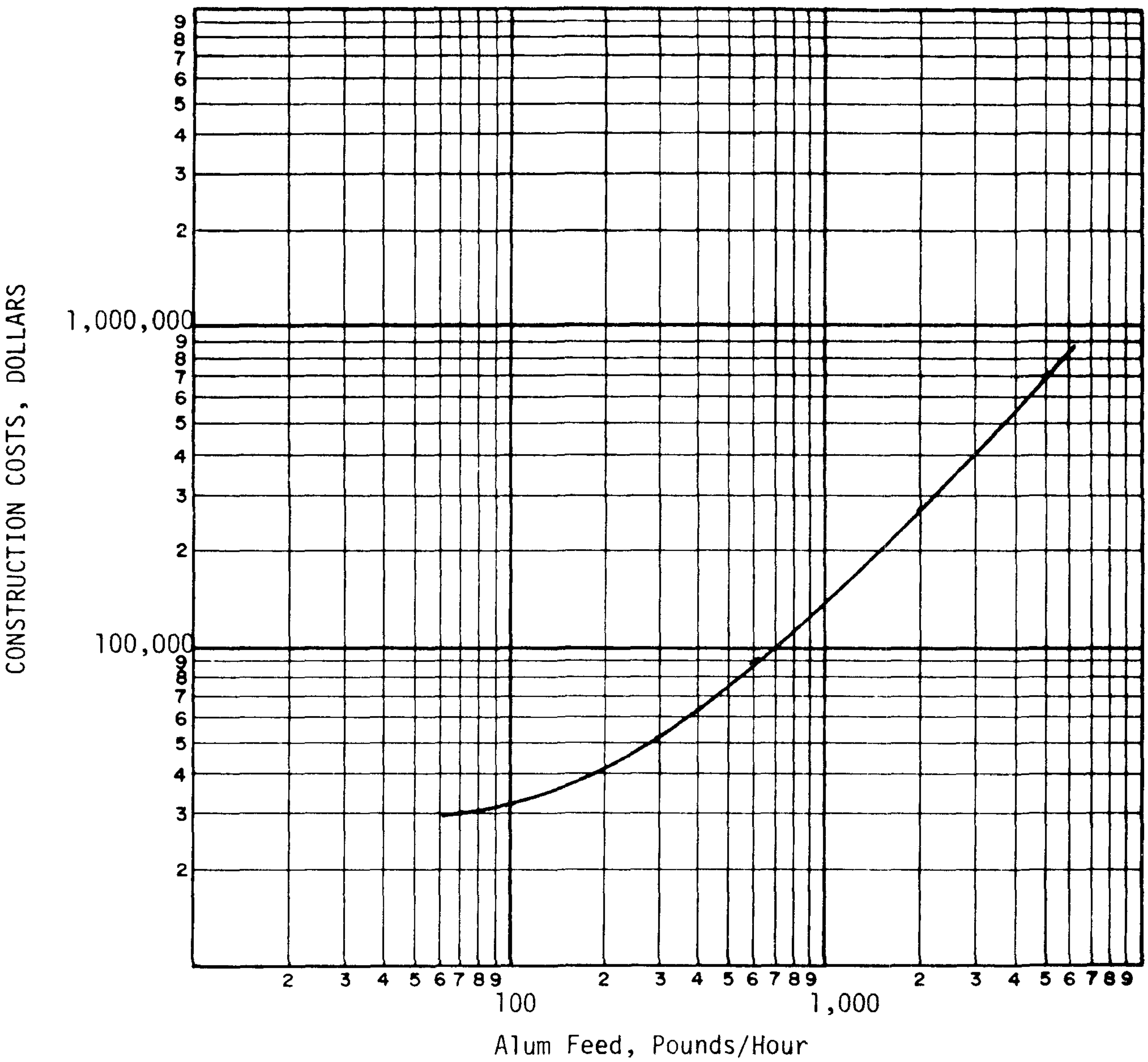
Curve 20



MULTIPLE HEARTH INCINERATION

CONSTRUCTION COST

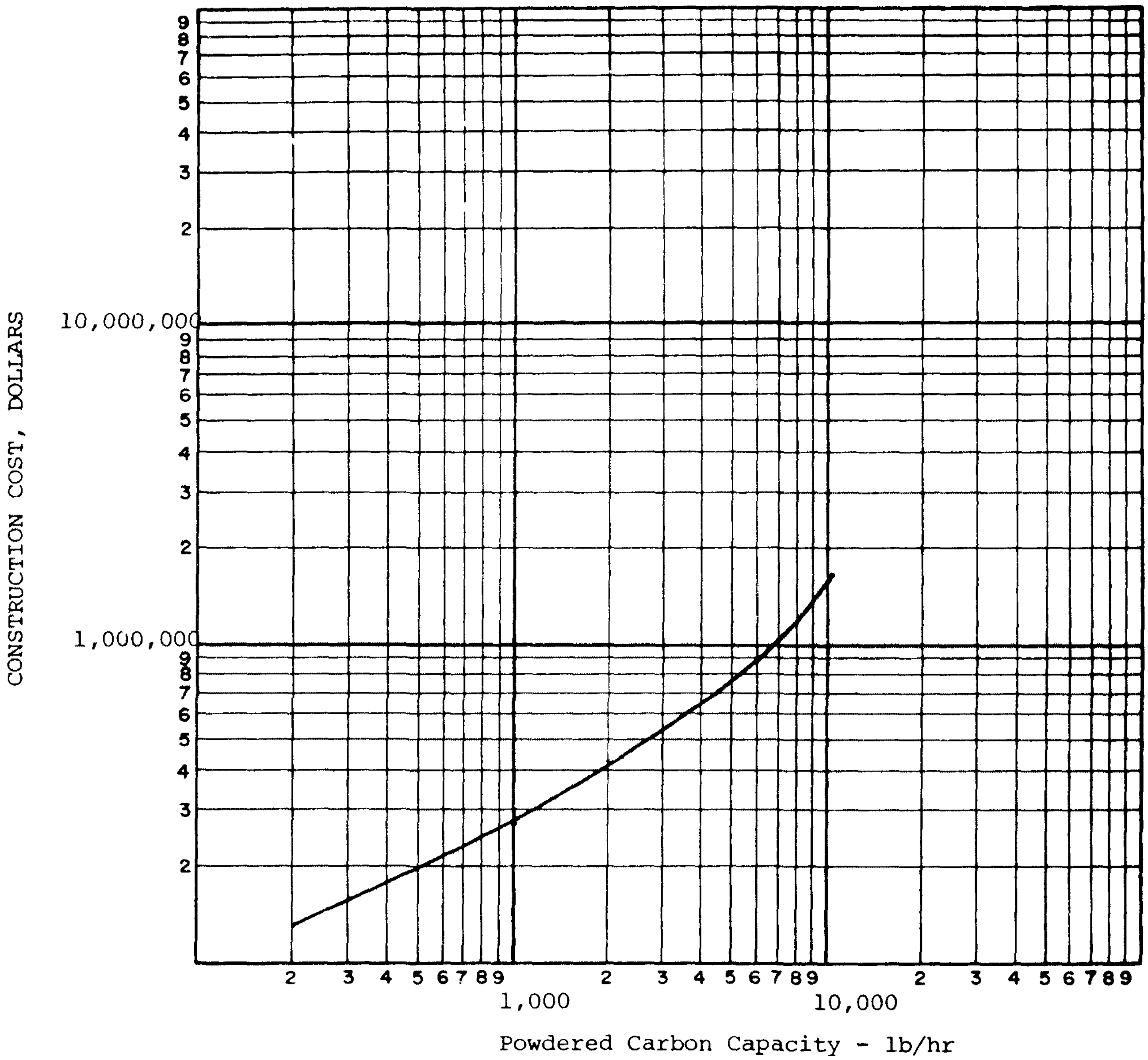
Curve 21



ALUM STORAGE & FEEDING

CONSTRUCTION COSTS

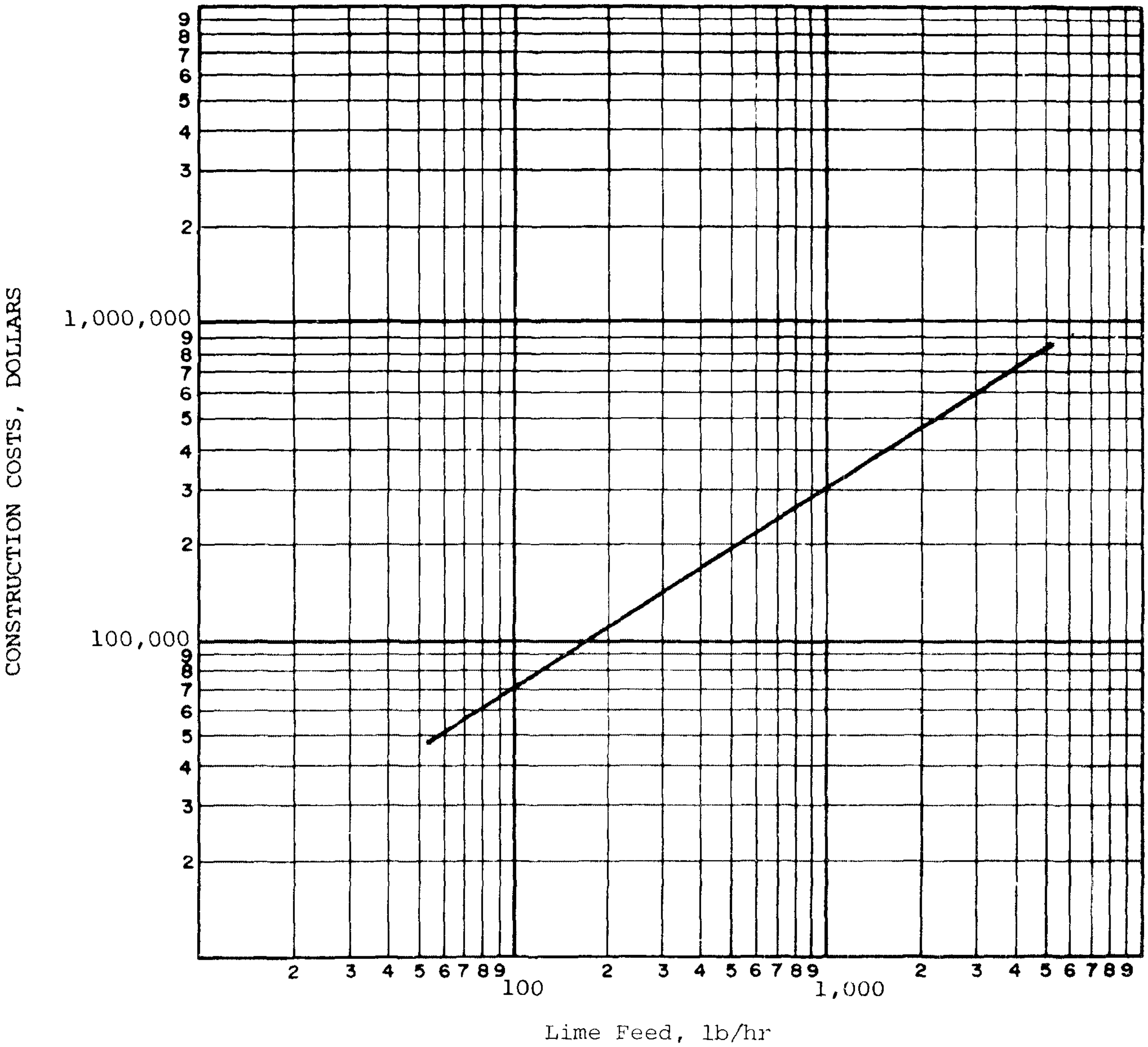
Curve 22



POWDERED ACTIVATED CARBON FEED SYSTEM

CONSTRUCTION COST

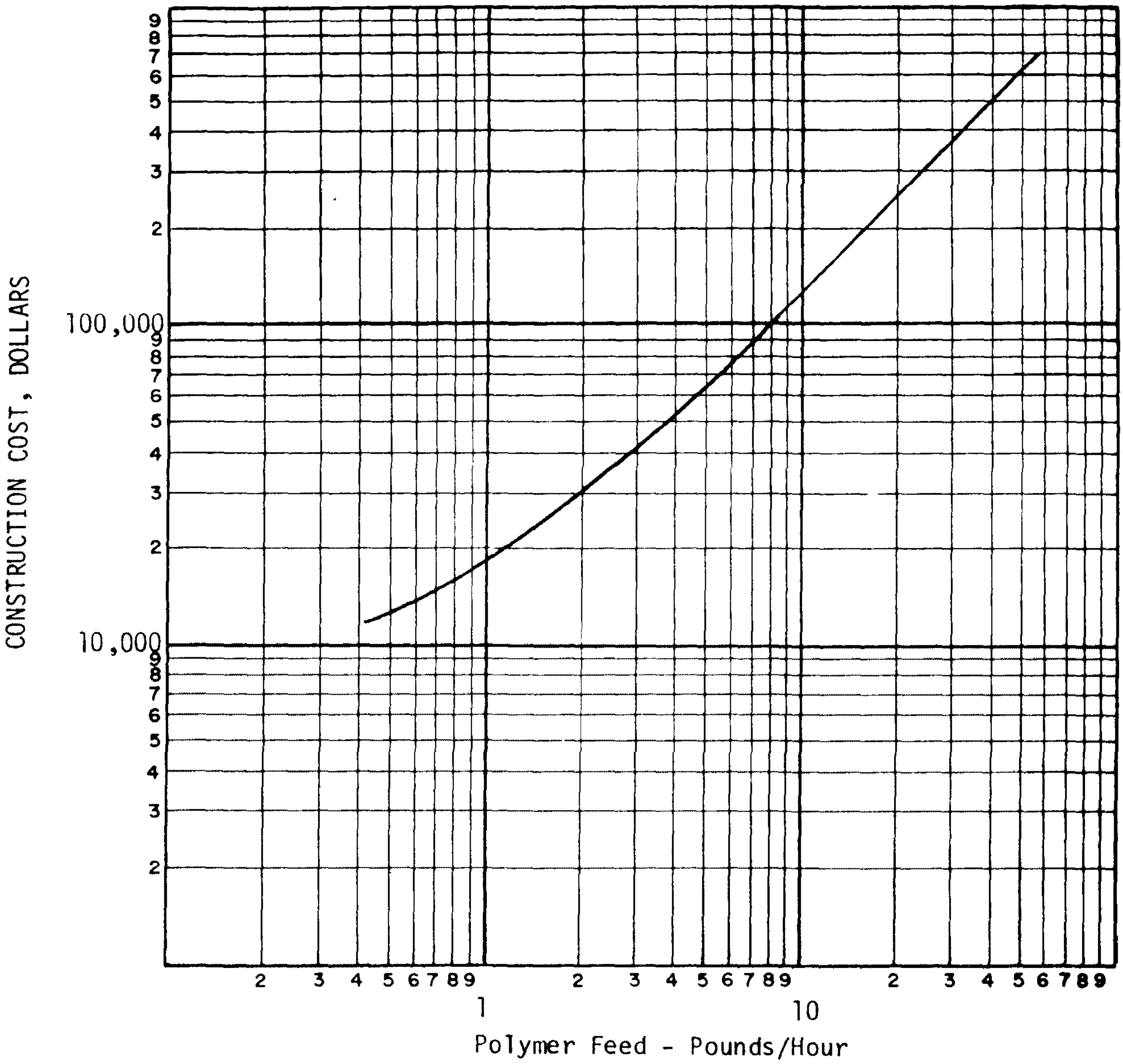
Curve 23



LIME STORAGE & FEEDING

CONSTRUCTION COSTS

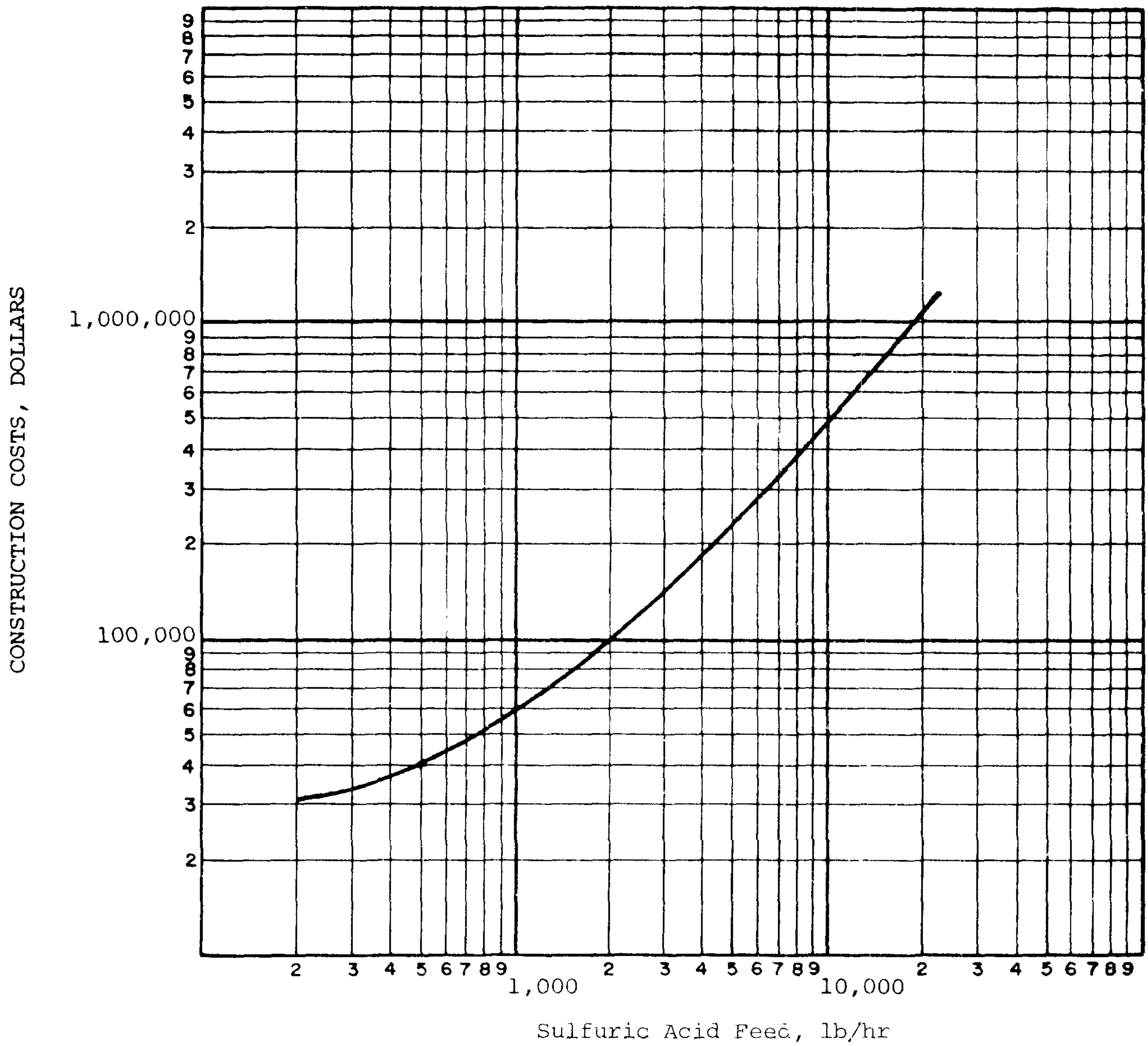
Curve 24



POLYMER STORAGE AND FEEDING

CONSTRUCTION COST

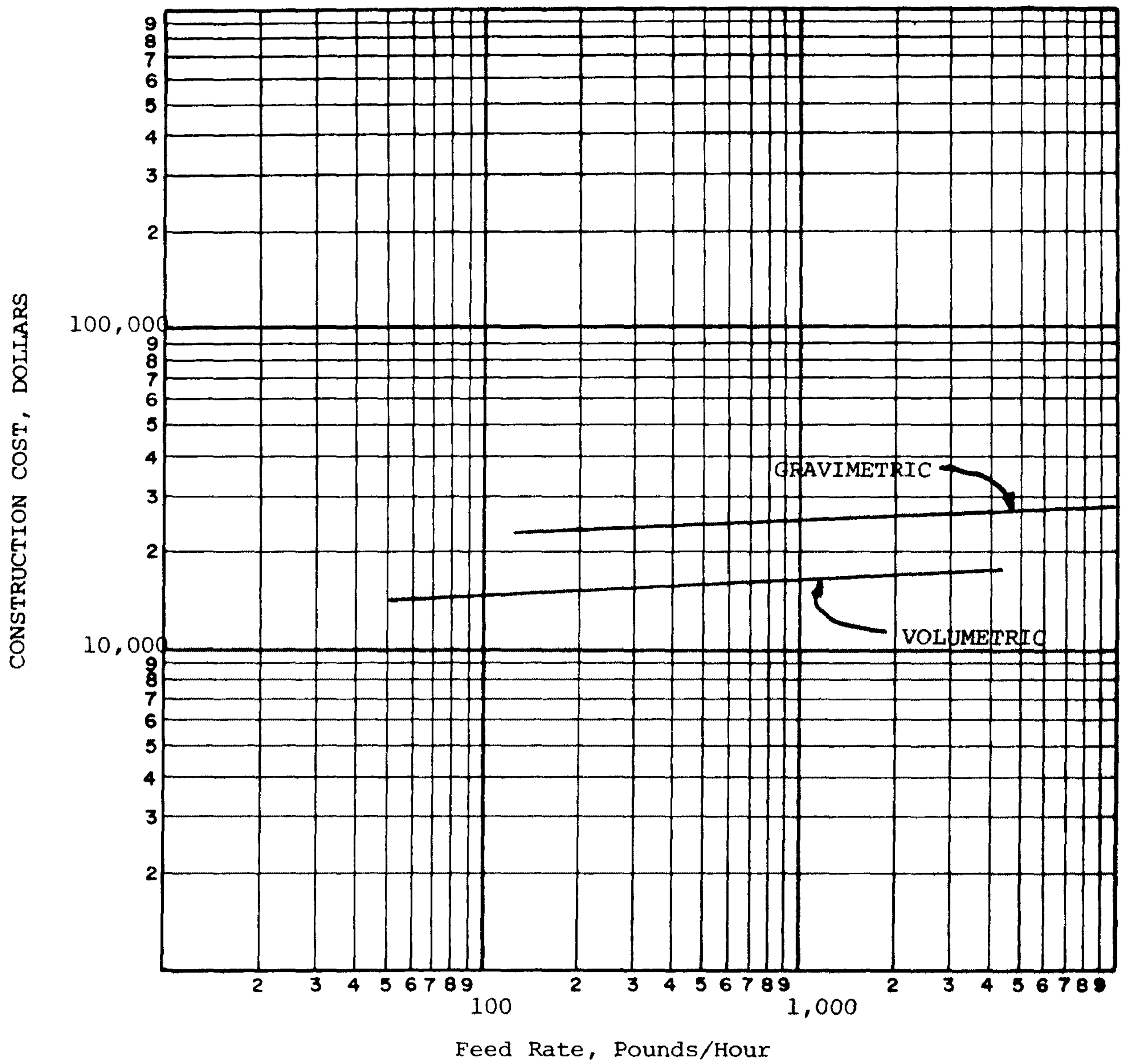
Curve 25



SULFURIC ACID STORAGE AND FEEDING

CONSTRUCTION COSTS

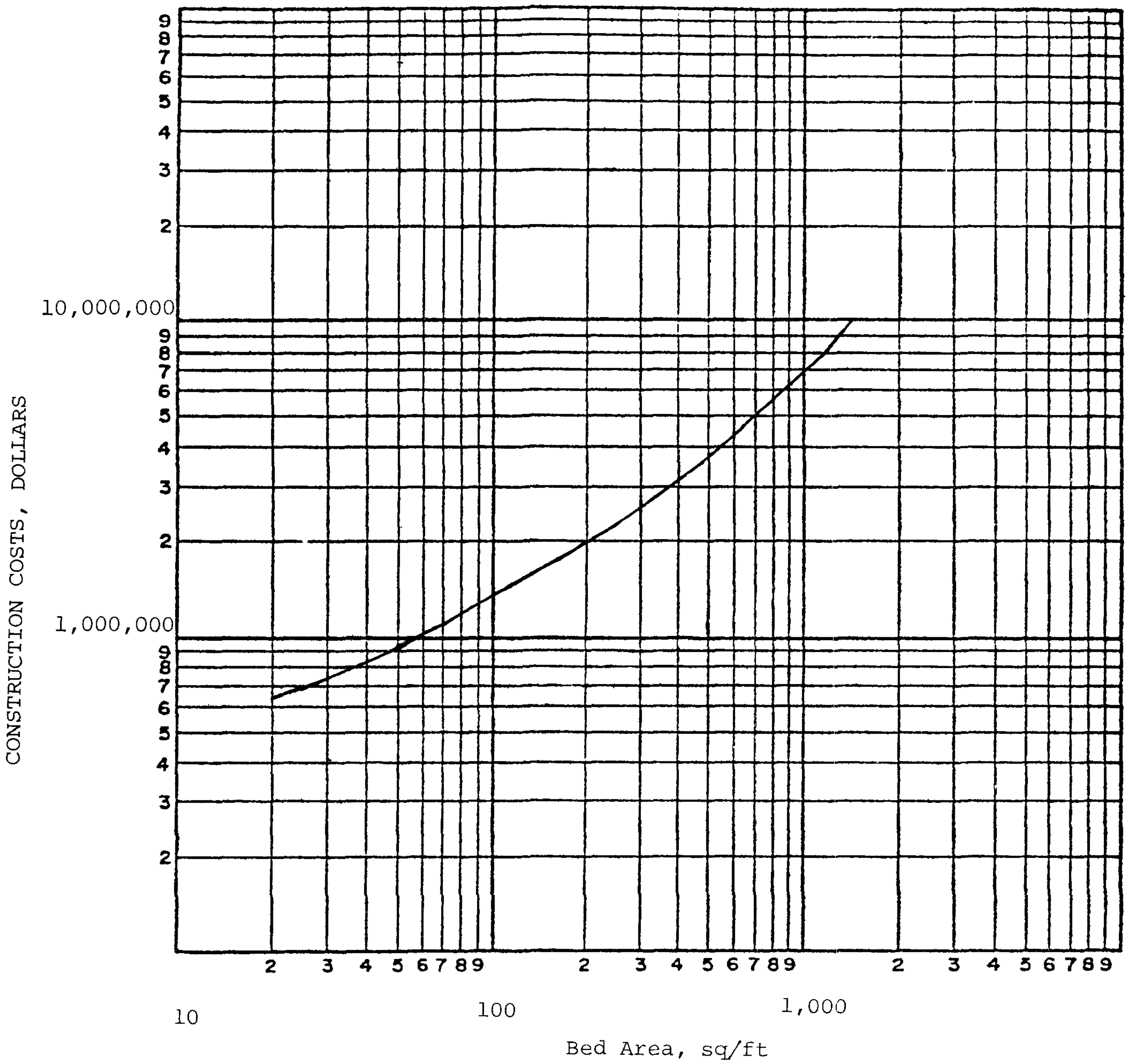
Curve 26



DRY CHEMICAL FEED SYSTEMS

CONSTRUCTION COSTS

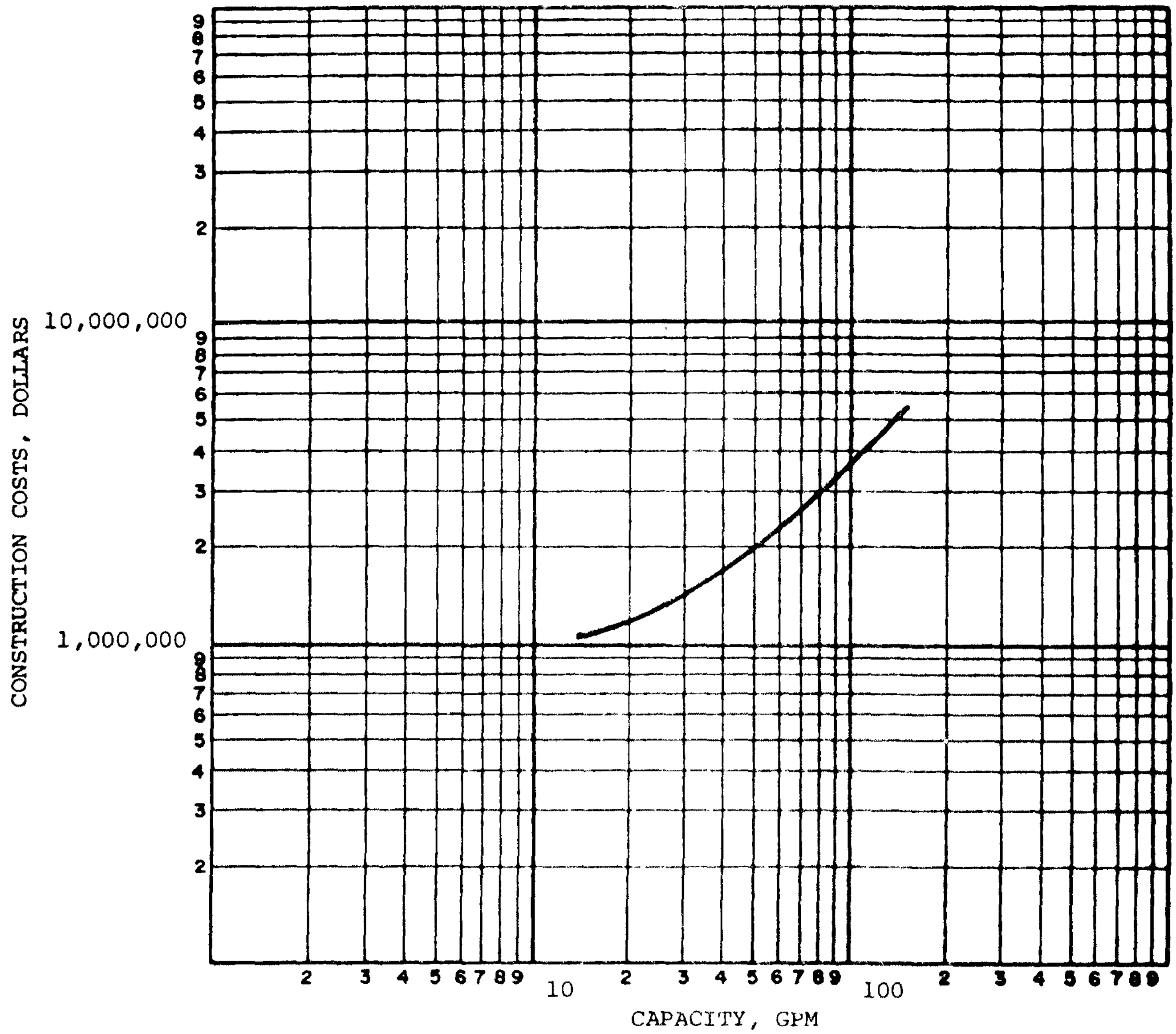
Curve 27



FLUIDIZED BED REGENERATION SYSTEM

CONSTRUCTION COSTS

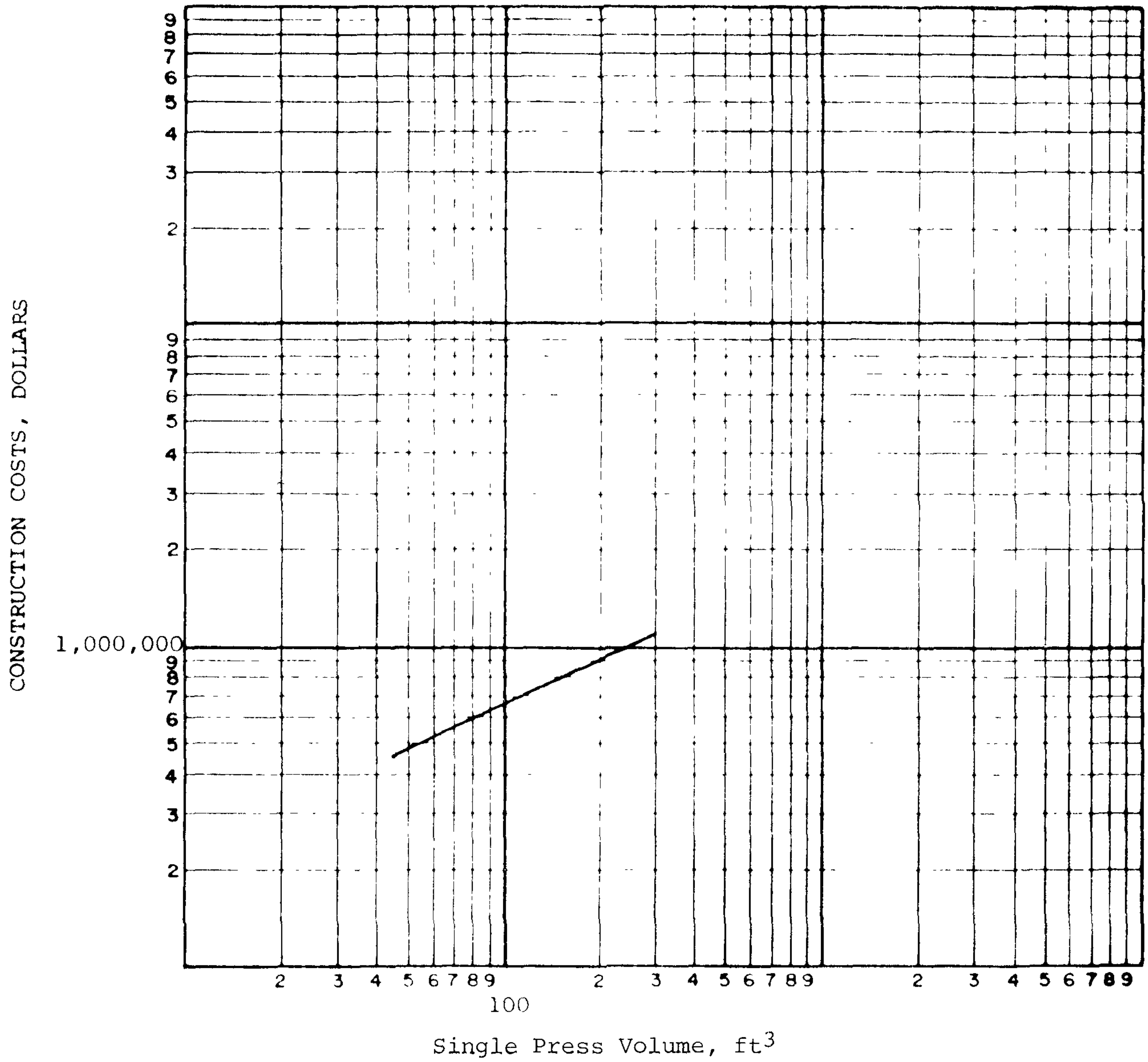
Curve 28



WET AIR REGENERATION SYSTEM

CONSTRUCTION COSTS

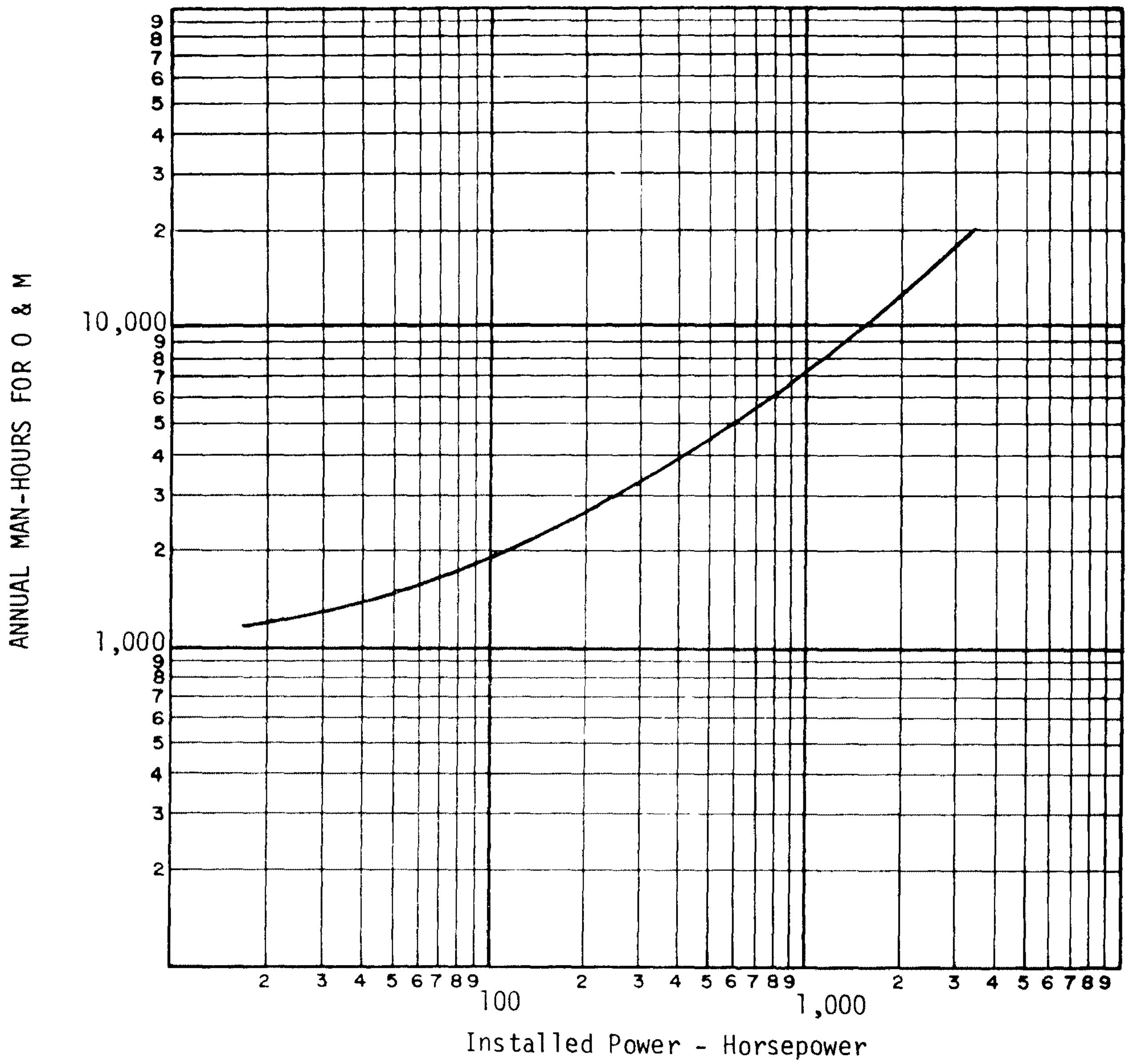
Curve 29



PRESSURE FILTRATION

CONSTRUCTION COSTS

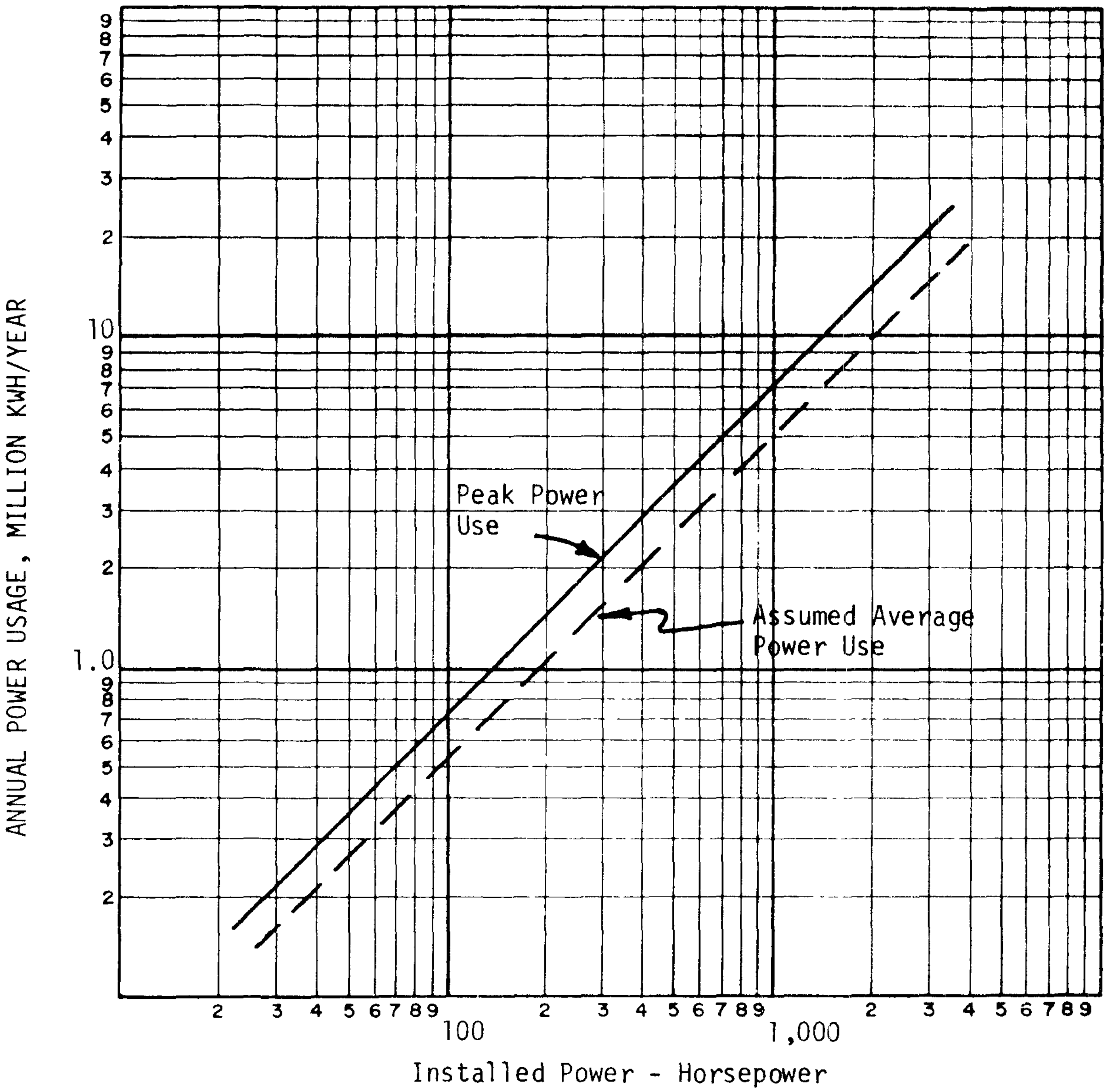
Curve 29A



MECHANICAL AERATION

MAN-HOUR REQUIREMENTS

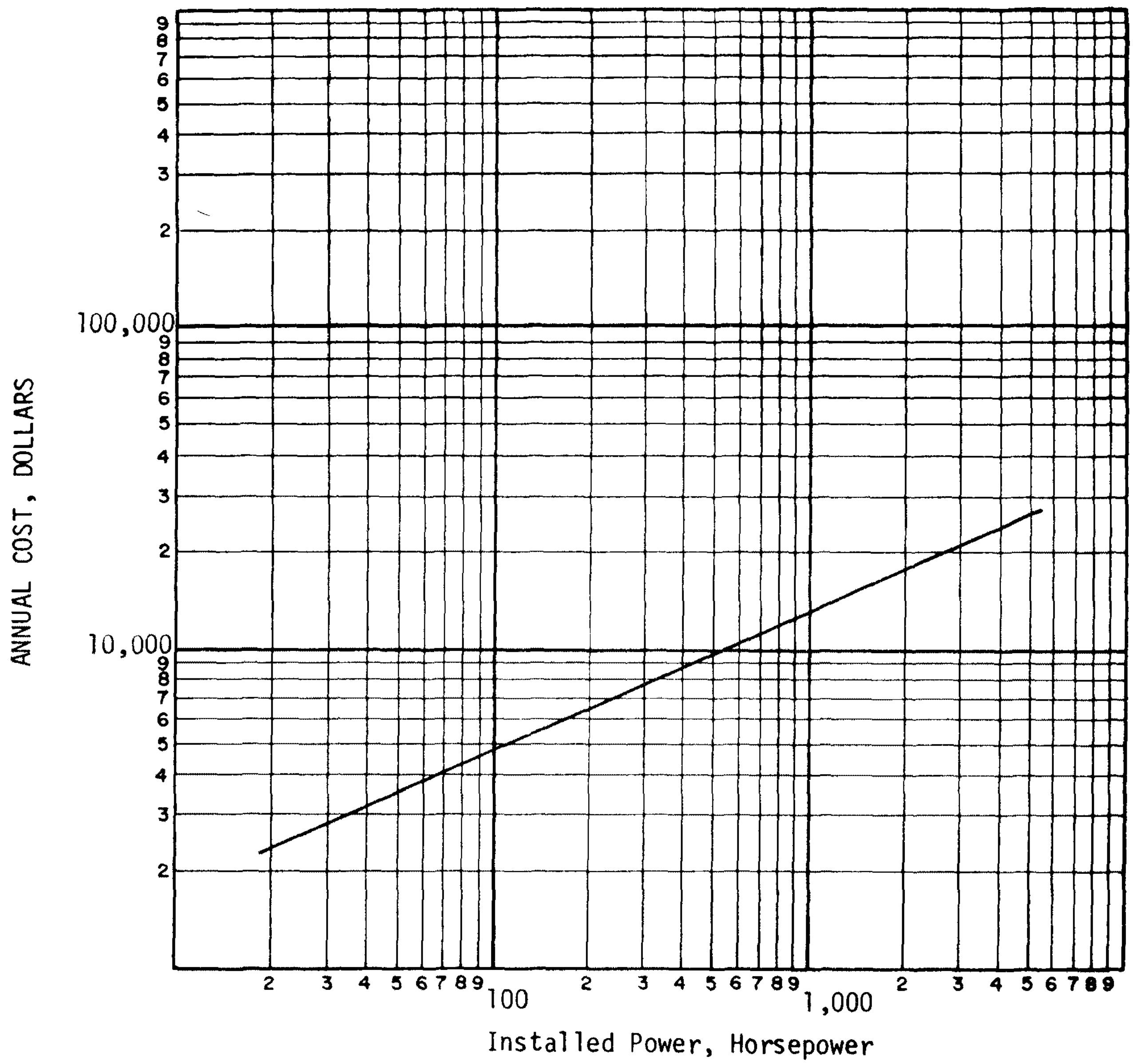
Curve 30



MECHANICAL AERATION

POWER REQUIREMENTS

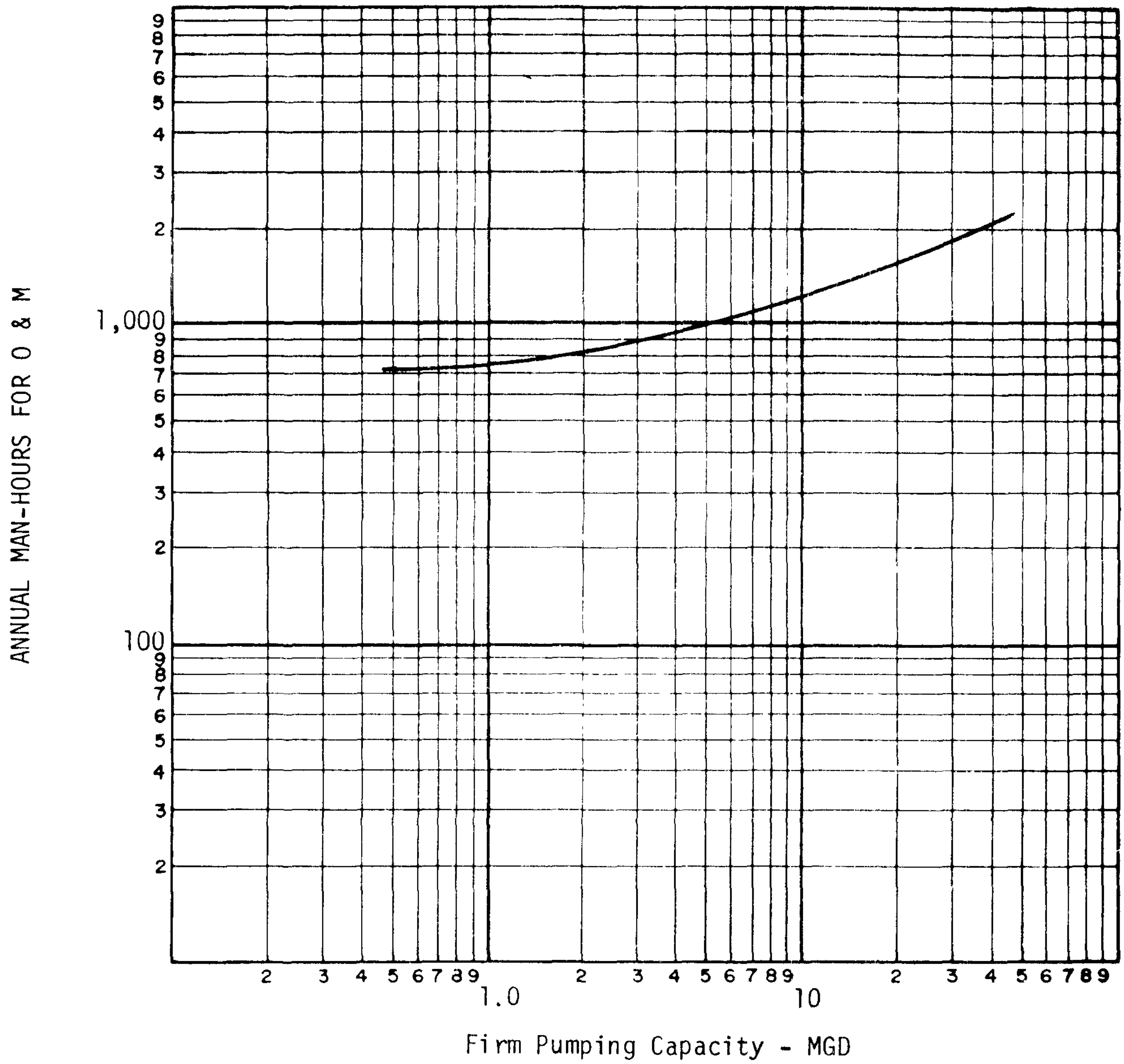
Curve 31



MECHANICAL AERATION

MAINTENANCE MATERIAL COSTS

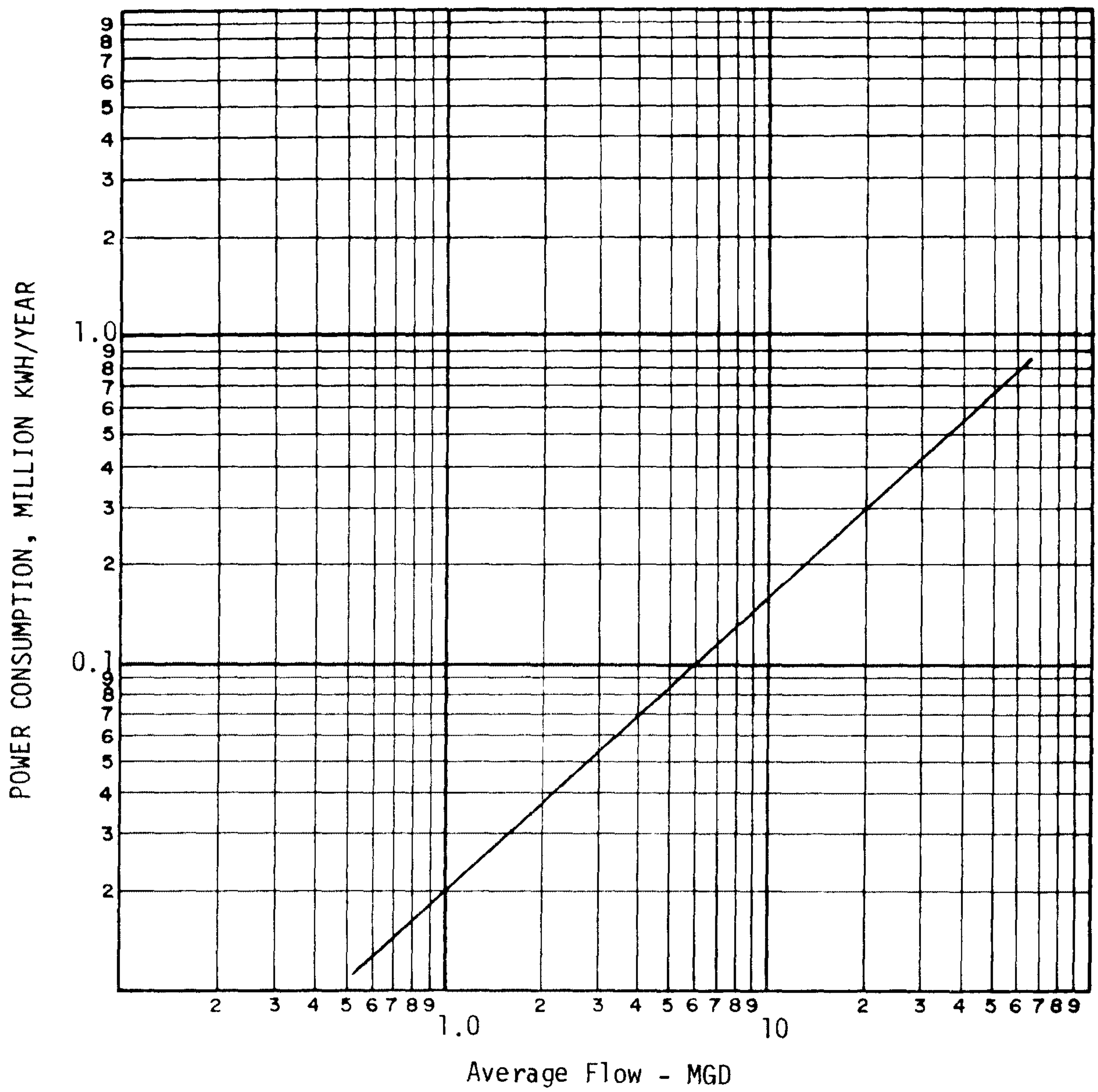
Curve 32



RETURN ACTIVATED SLUDGE PUMPING STATIONS

MAN-HOUR REQUIREMENTS

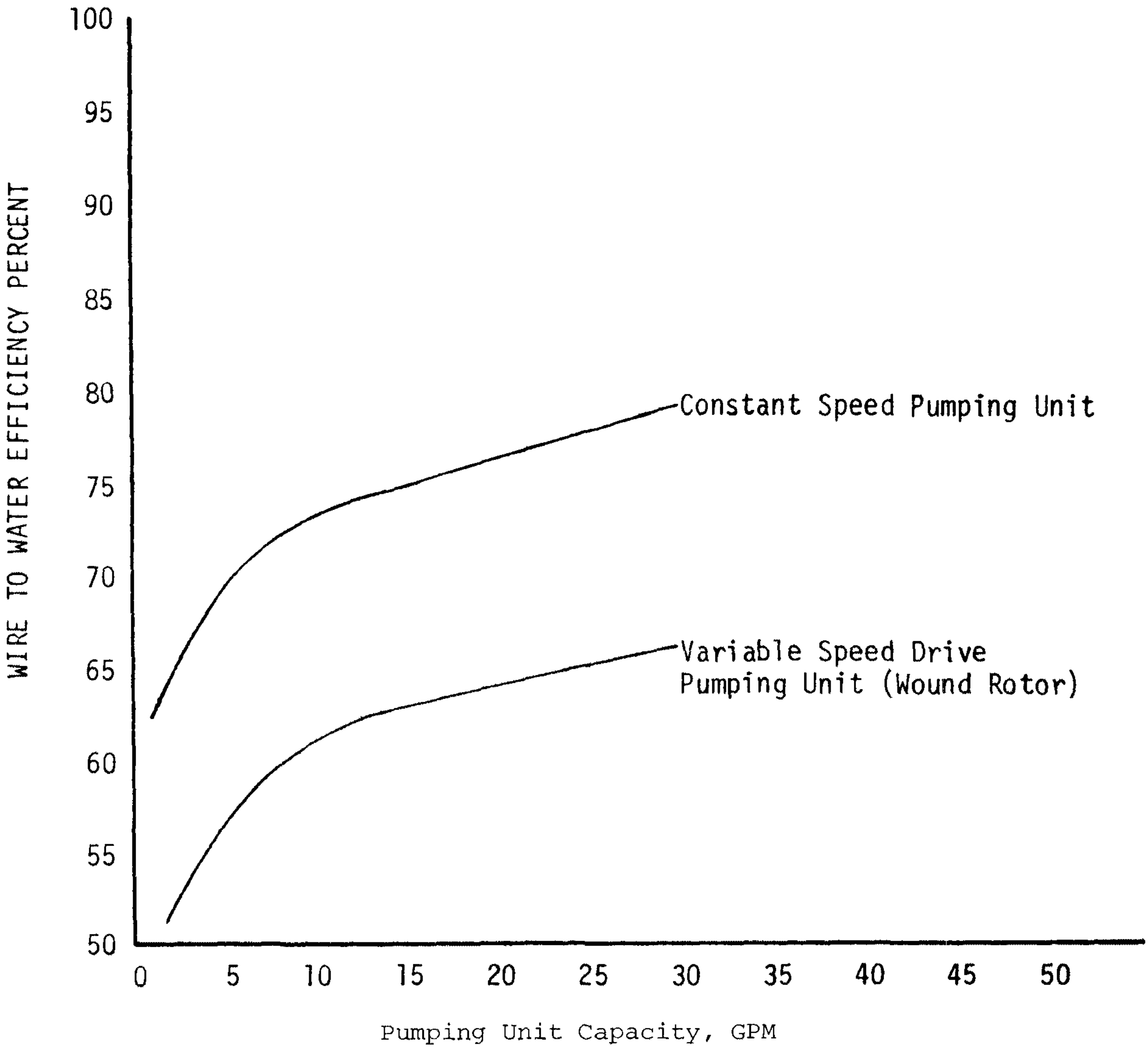
Curve 33



RETURN ACTIVATED SLUDGE PUMPING STATIONS

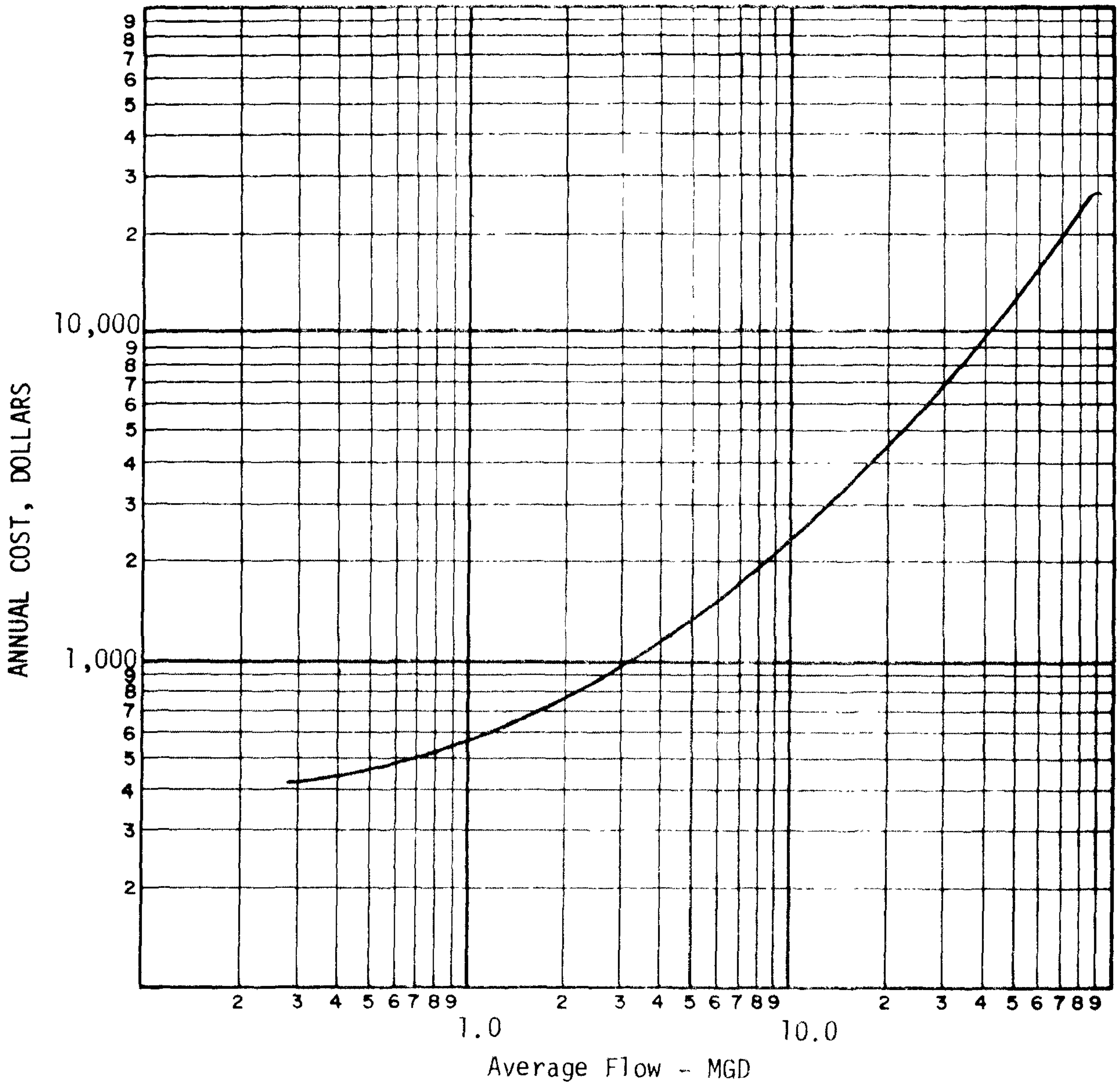
POWER REQUIREMENTS

Curve 34



PUMPING UNIT EFFICIENCY RELATED TO CAPACITY

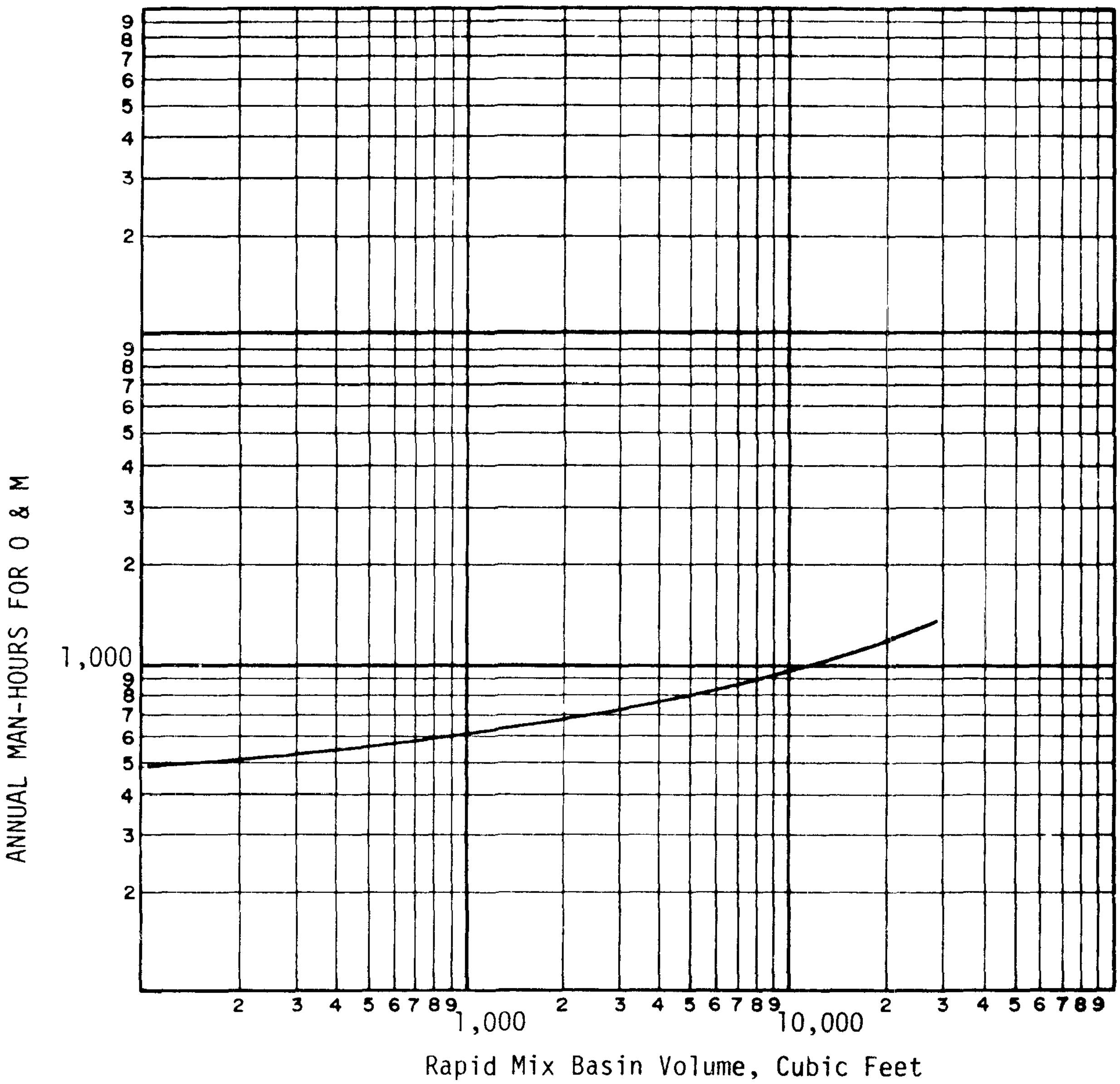
Curve 35



RETURN ACTIVATED SLUDGE PUMPING STATIONS

MAINTENANCE MATERIAL COSTS

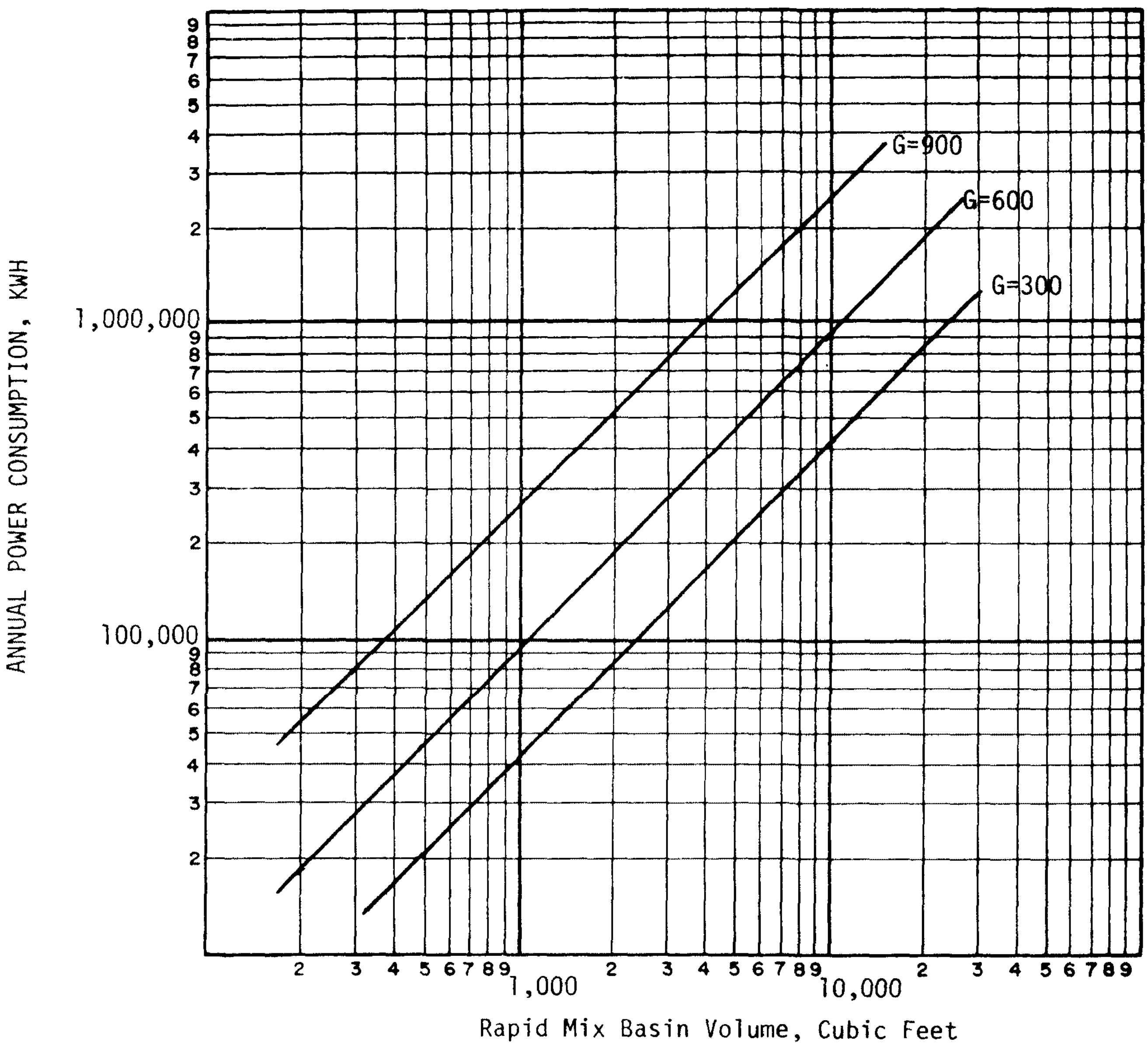
Curve 36



RAPID MIXING

MAN-HOUR REQUIREMENTS

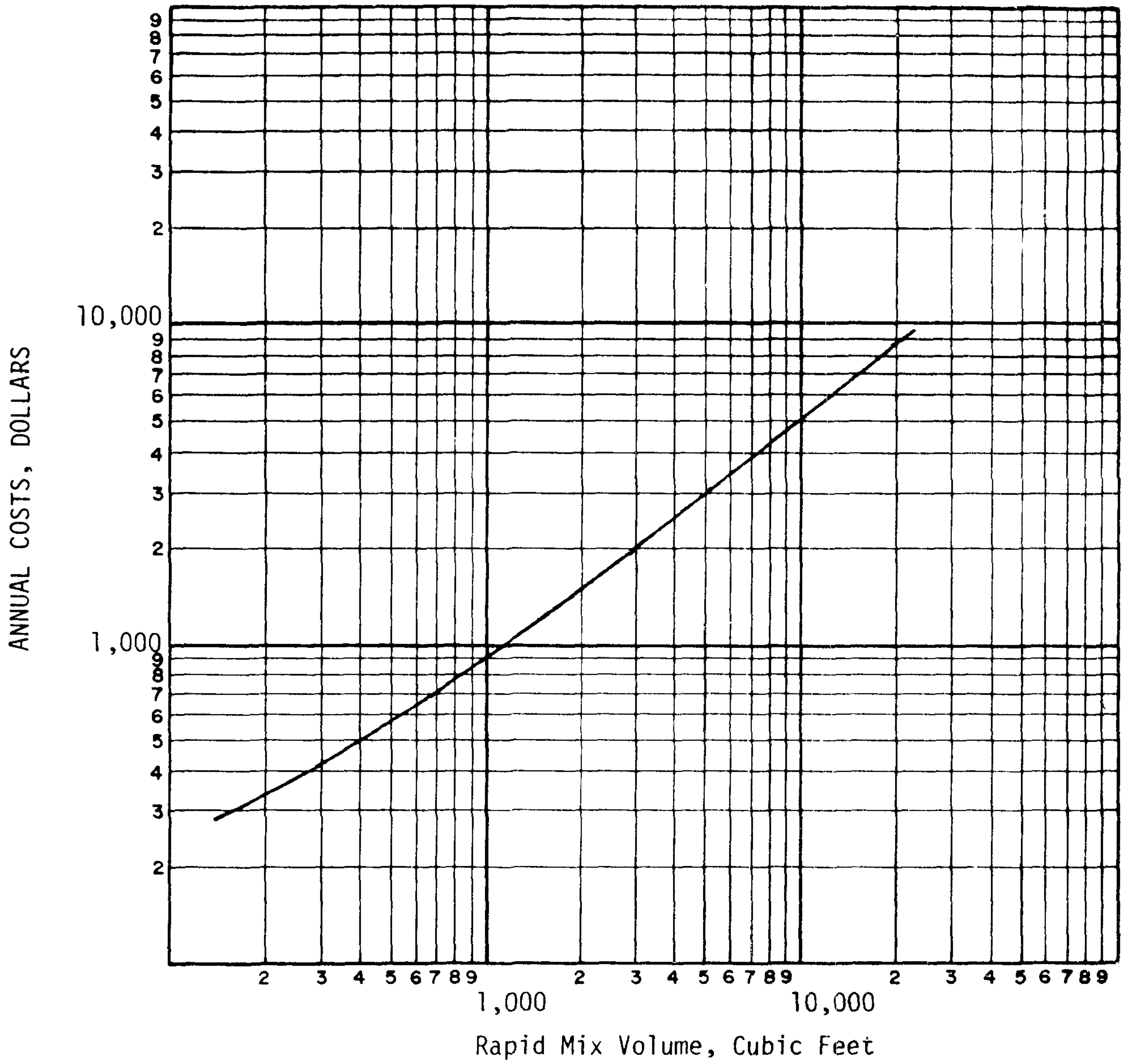
Curve 37



RAPID MIXING

POWER REQUIREMENTS

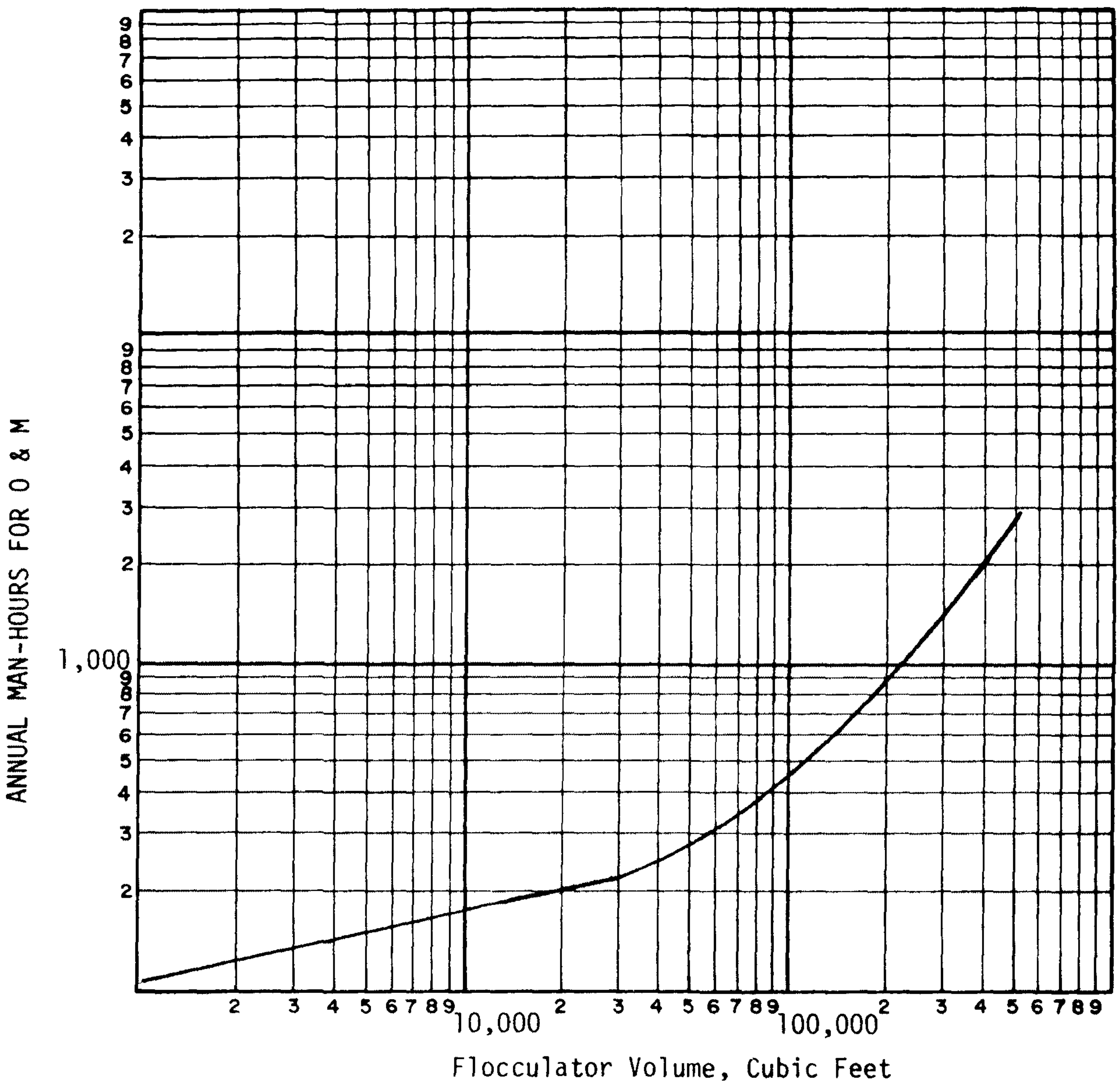
Curve 38



RAPID MIXING

MAINTENANCE MATERIAL COSTS

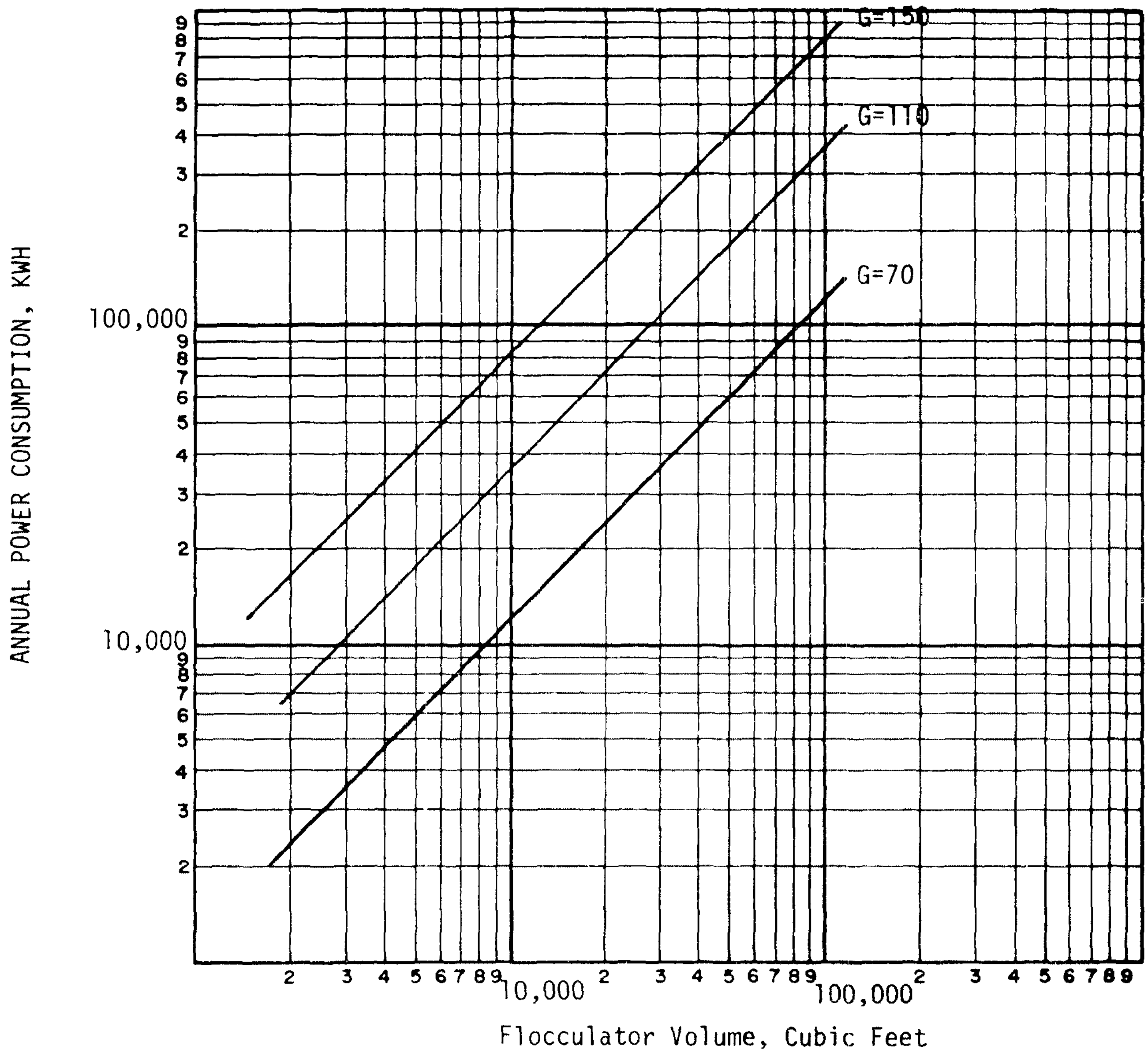
Curve 39



FLOCCULATION

MAN-HOUR REQUIREMENTS

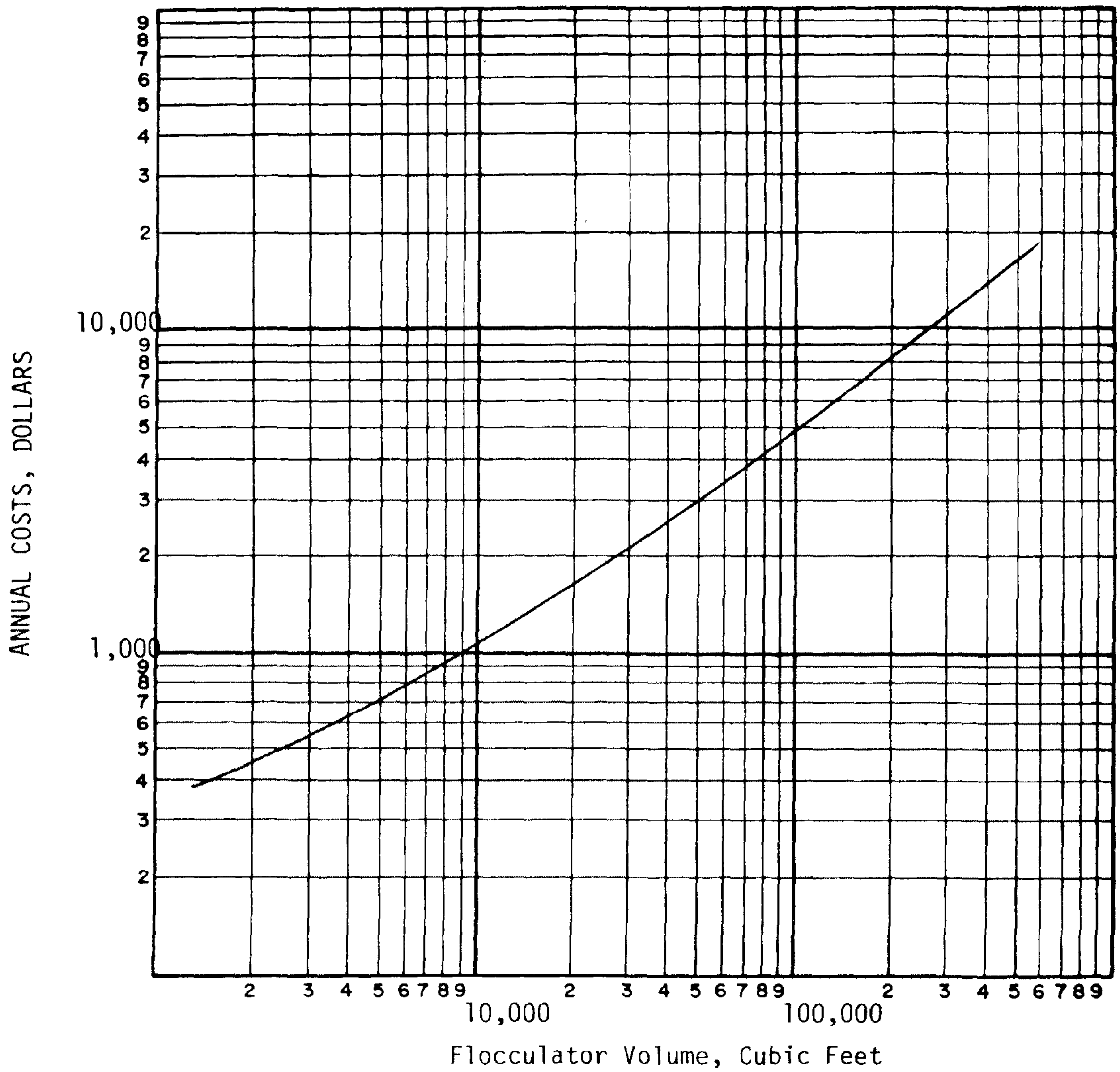
Curve 40



FLOCCULATION

POWER REQUIREMENTS

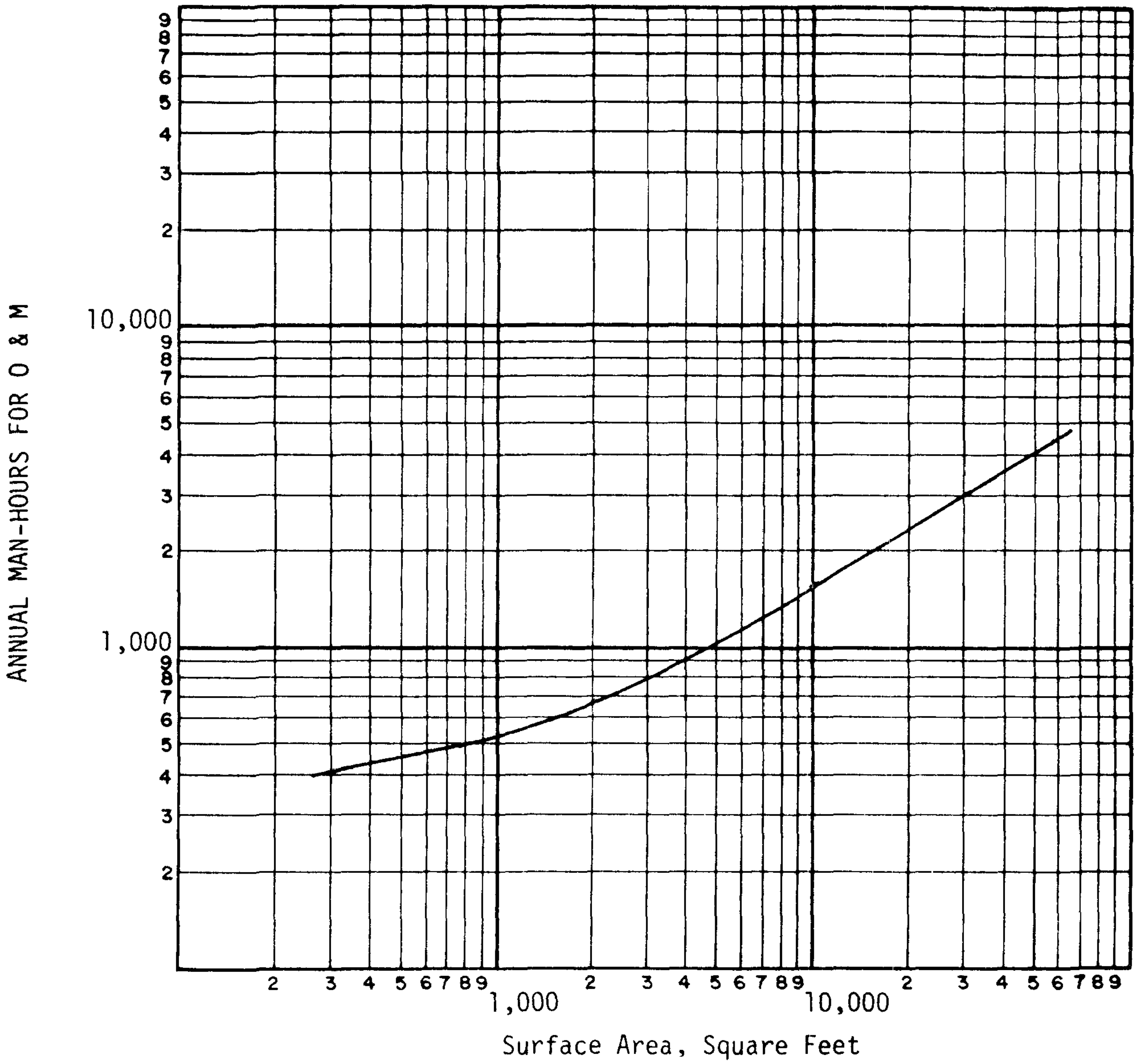
Curve 41



FLOCCULATION

MAINTENANCE MATERIAL COSTS

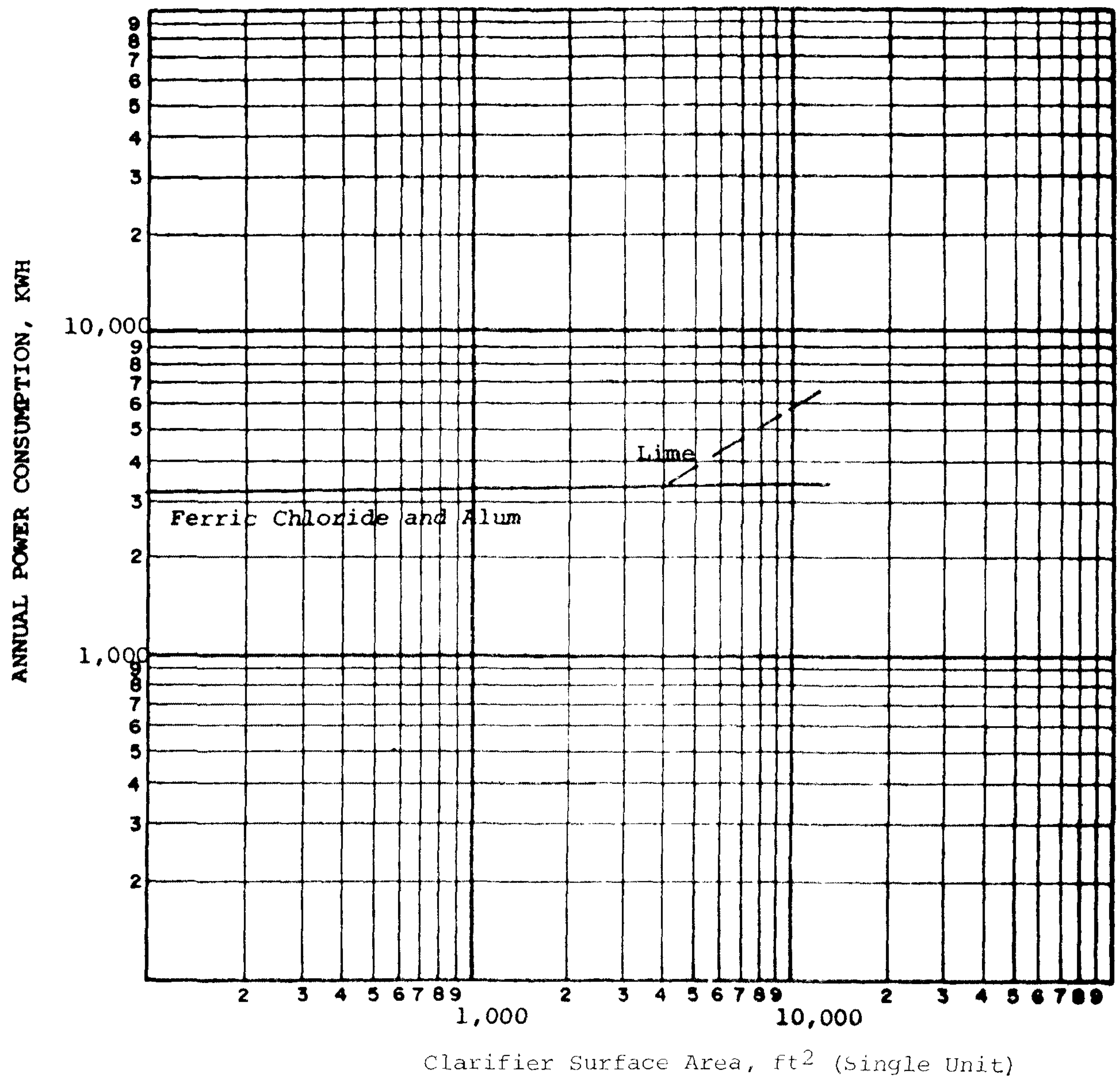
Curve 42



CLARIFIER

MAN-HOUR REQUIREMENTS

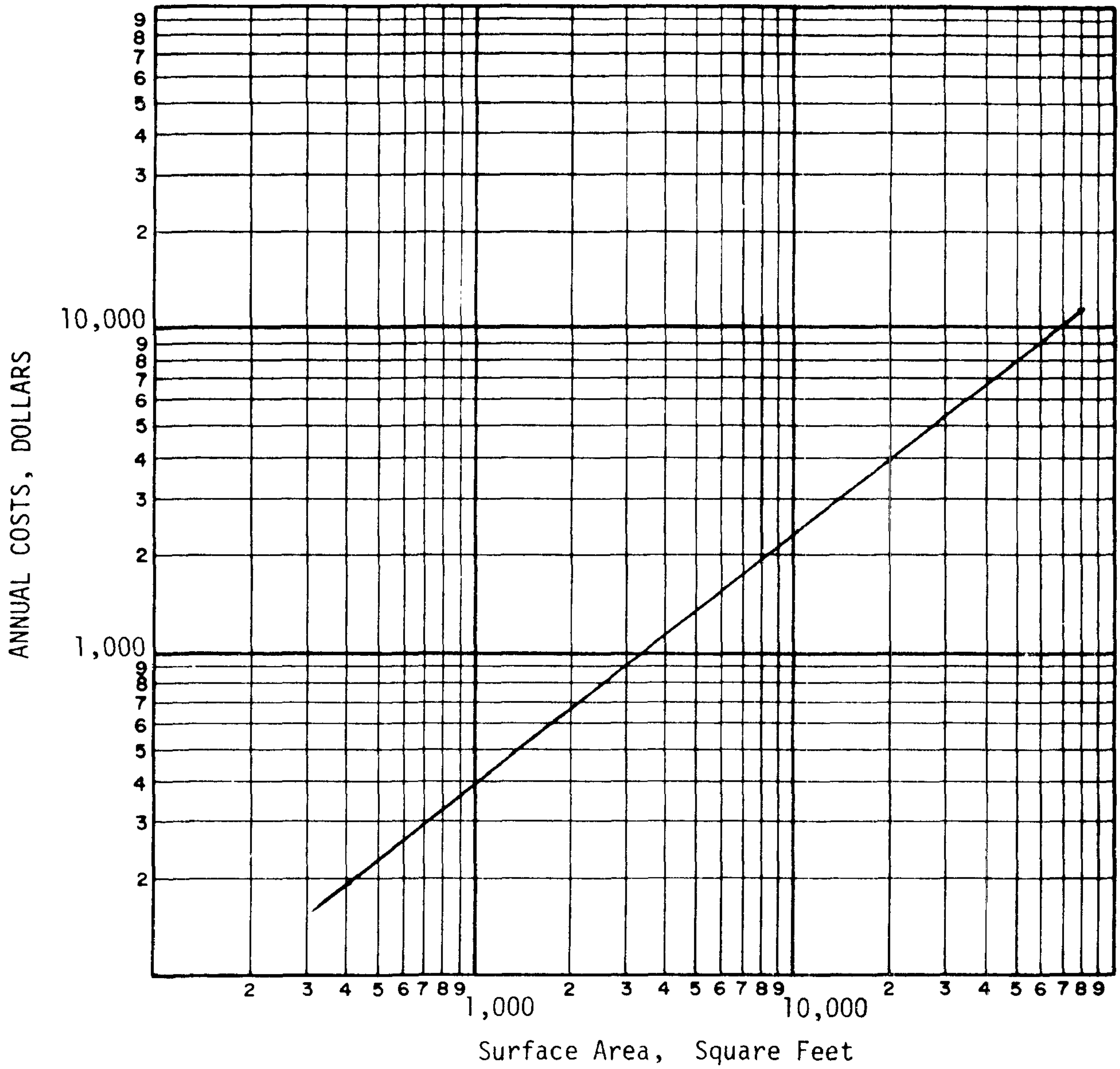
Curve 43



CLARIFIER

POWER REQUIREMENTS

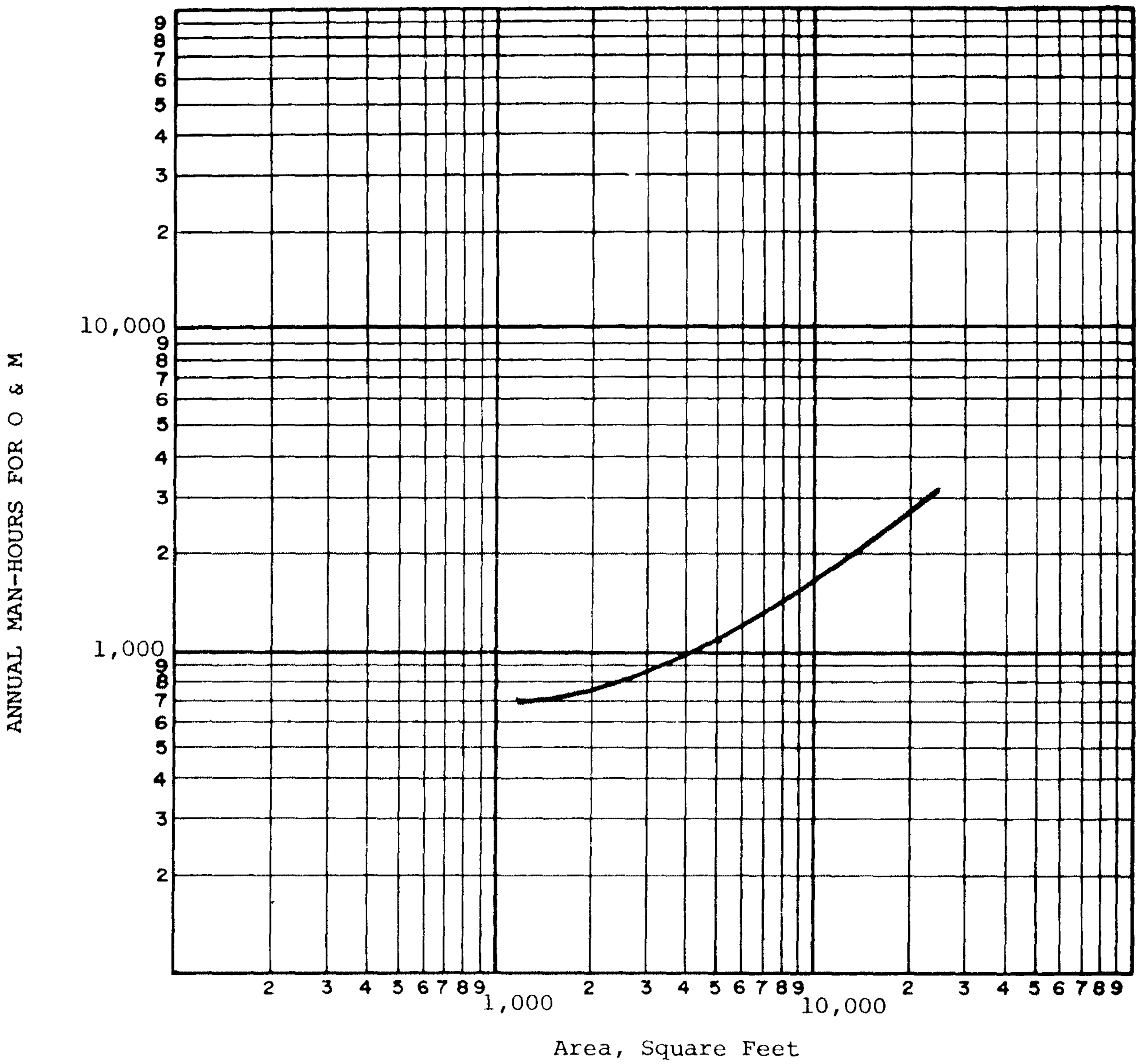
Curve 44



CLARIFIER

MAINTENANCE MATERIAL COSTS

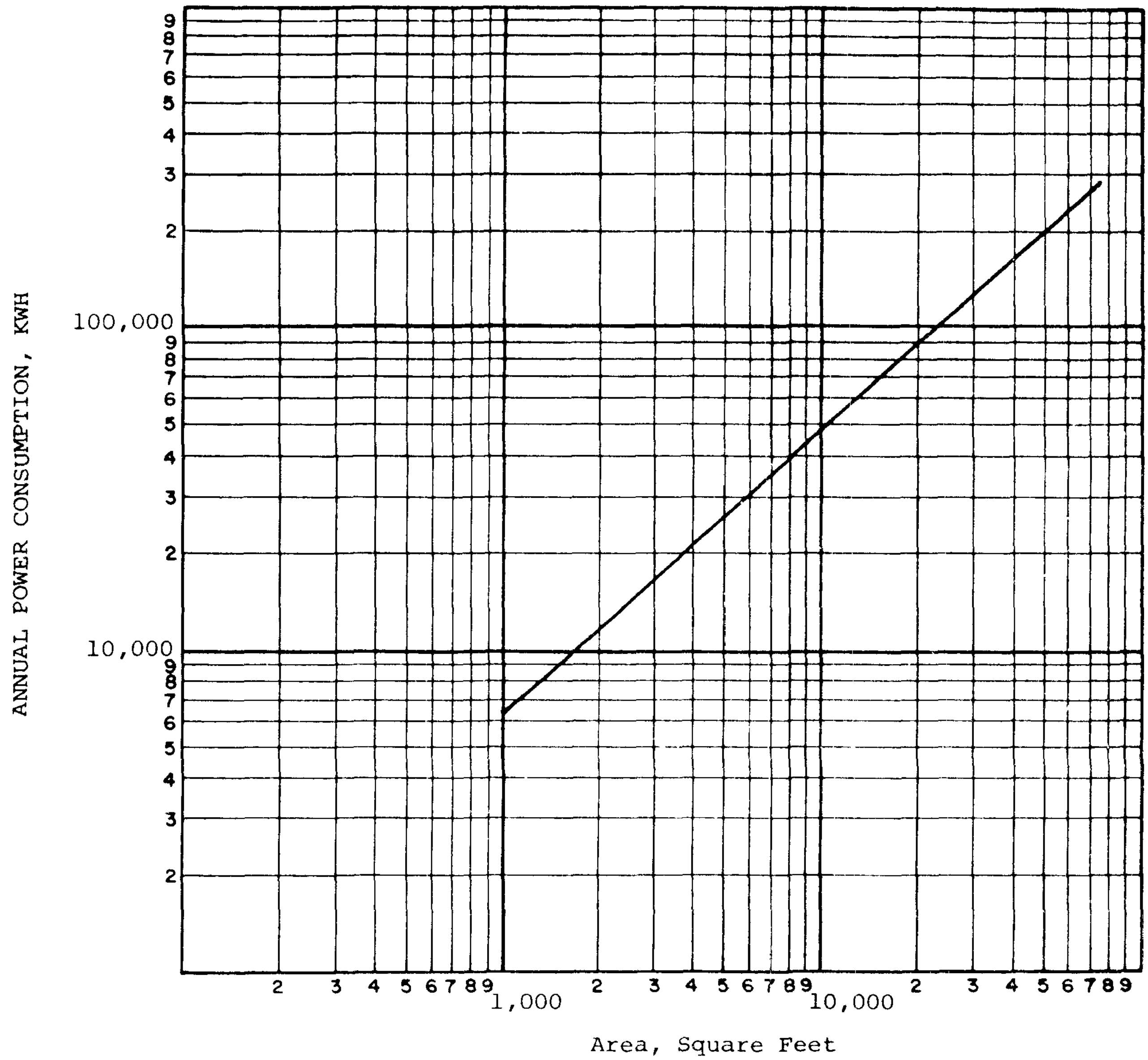
Curve 45



FLOCCULATOR - CLARIFIER

MAN-HOUR REQUIREMENTS

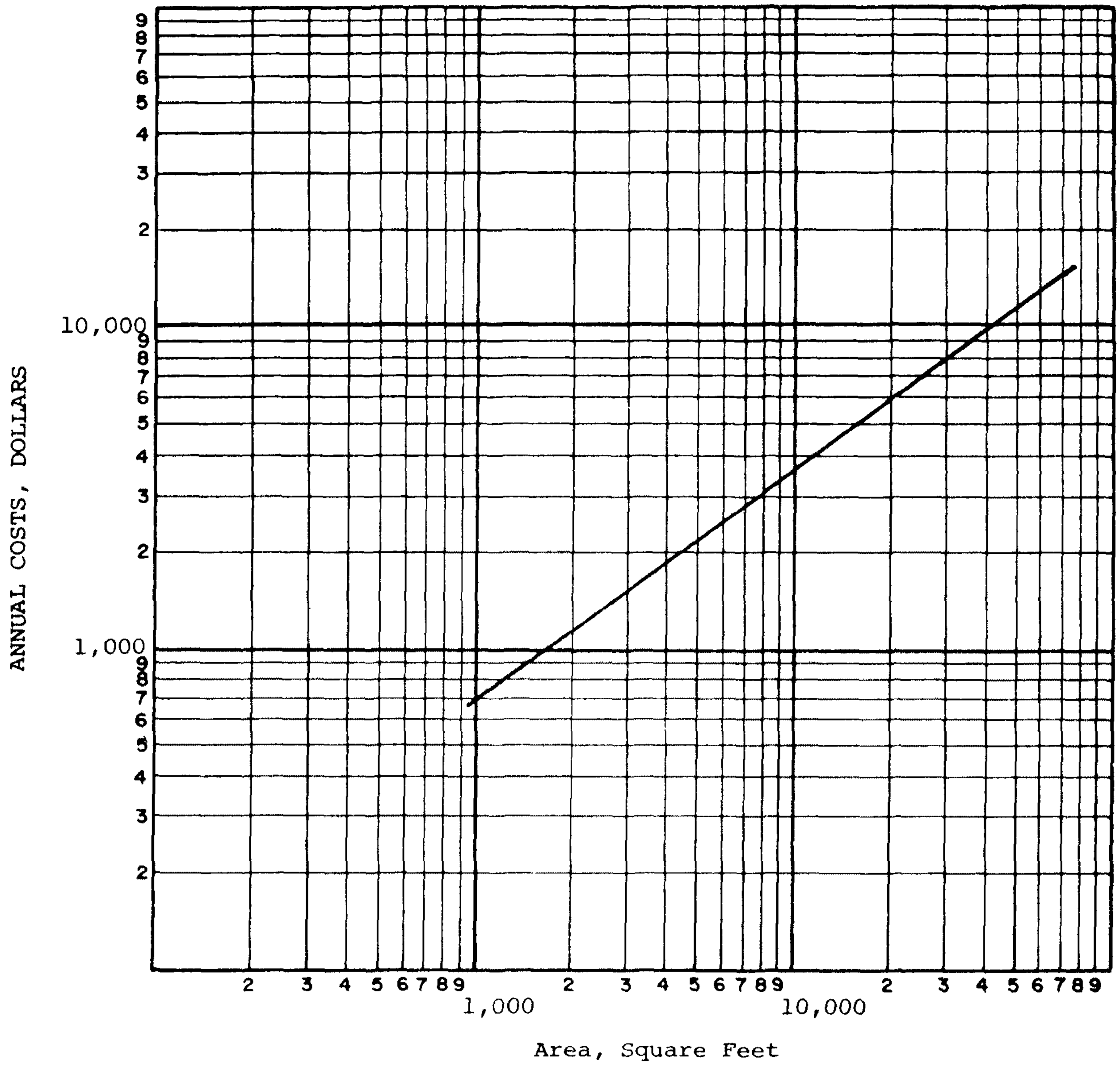
Curve 46



FLOCCULATOR - CLARIFIER

POWER REQUIREMENTS

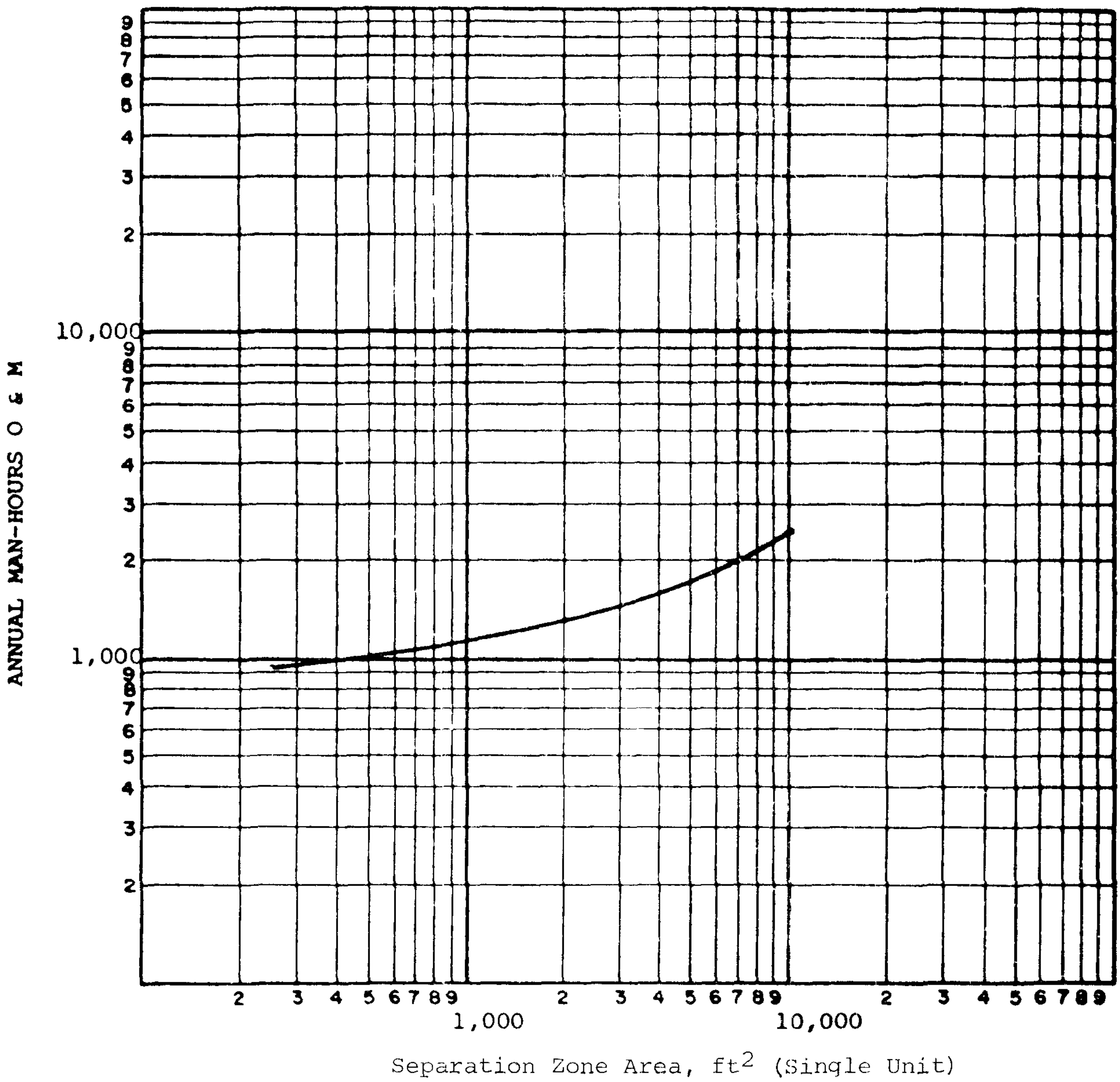
Curve 47



FLOCCULATOR - CLARIFIER

MAINTENANCE MATERIAL COSTS

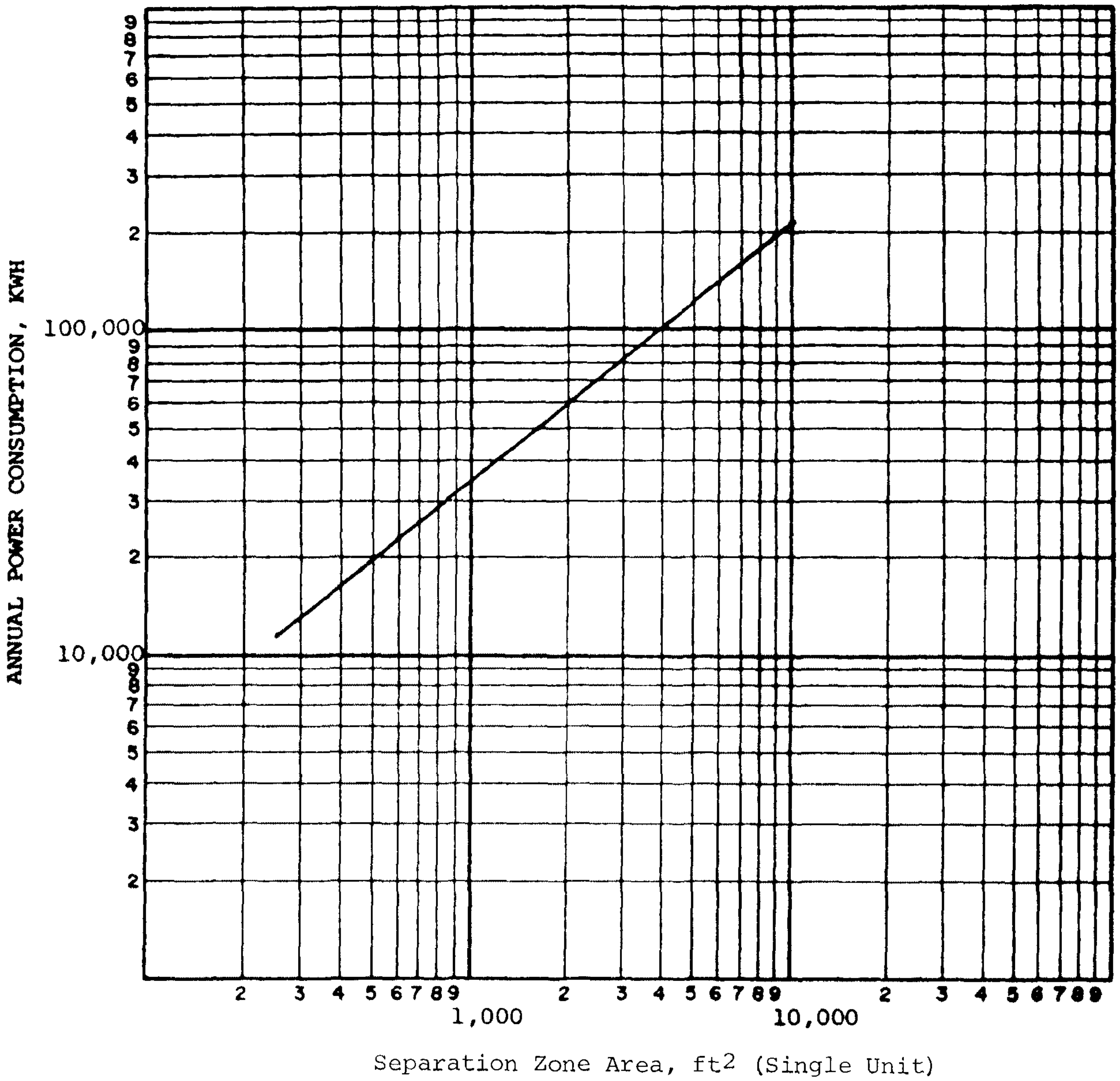
Curve 48



REACTOR CLARIFIER

MAN-HOUR REQUIREMENTS

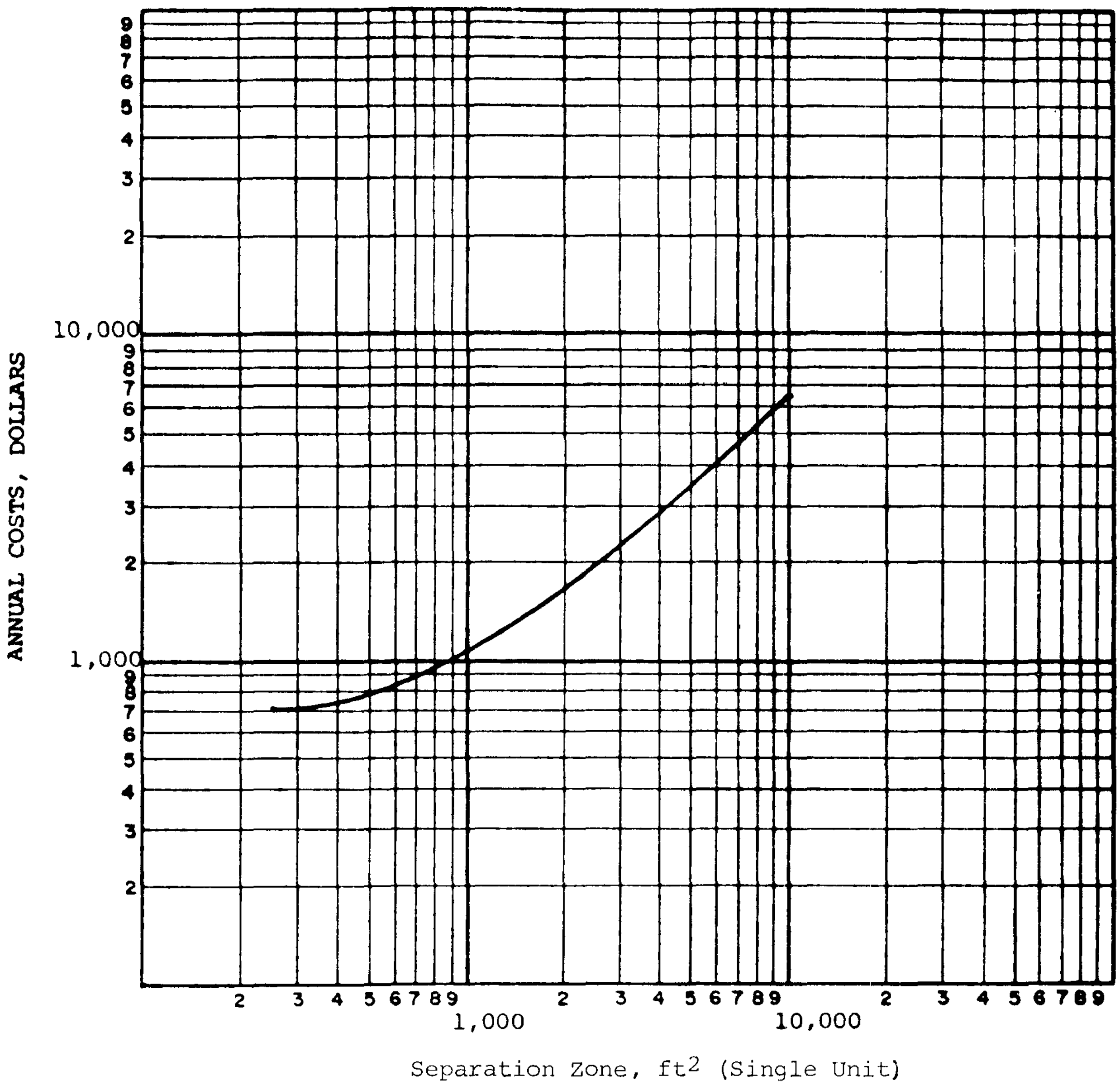
Curve 49



REACTOR CLARIFIER

POWER REQUIREMENTS

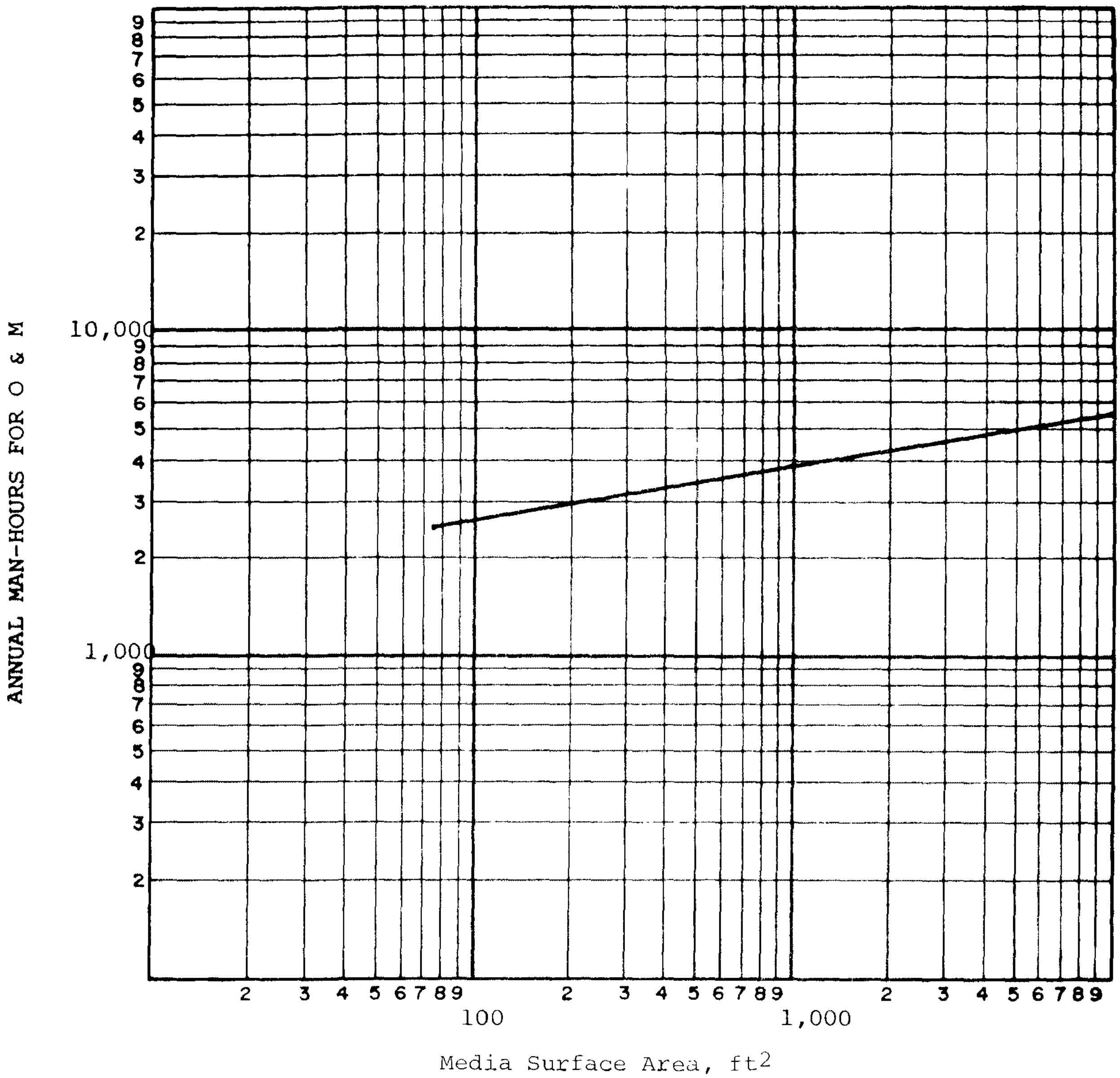
Curve 50



REACTOR CLARIFIER

MAINTENANCE MATERIAL COSTS

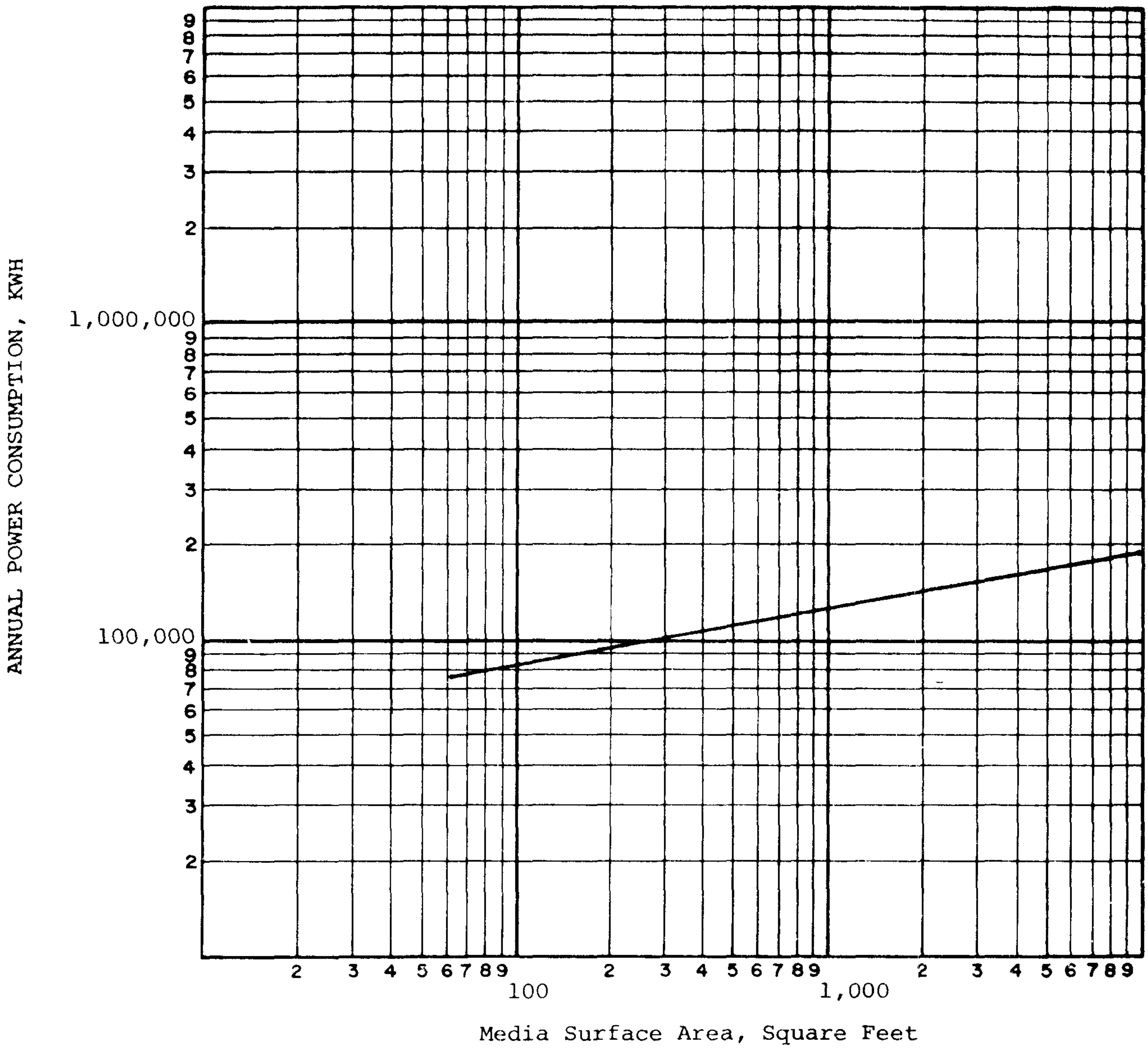
Curve 51



GRAVITY FILTRATION

MAN-HOUR REQUIREMENTS

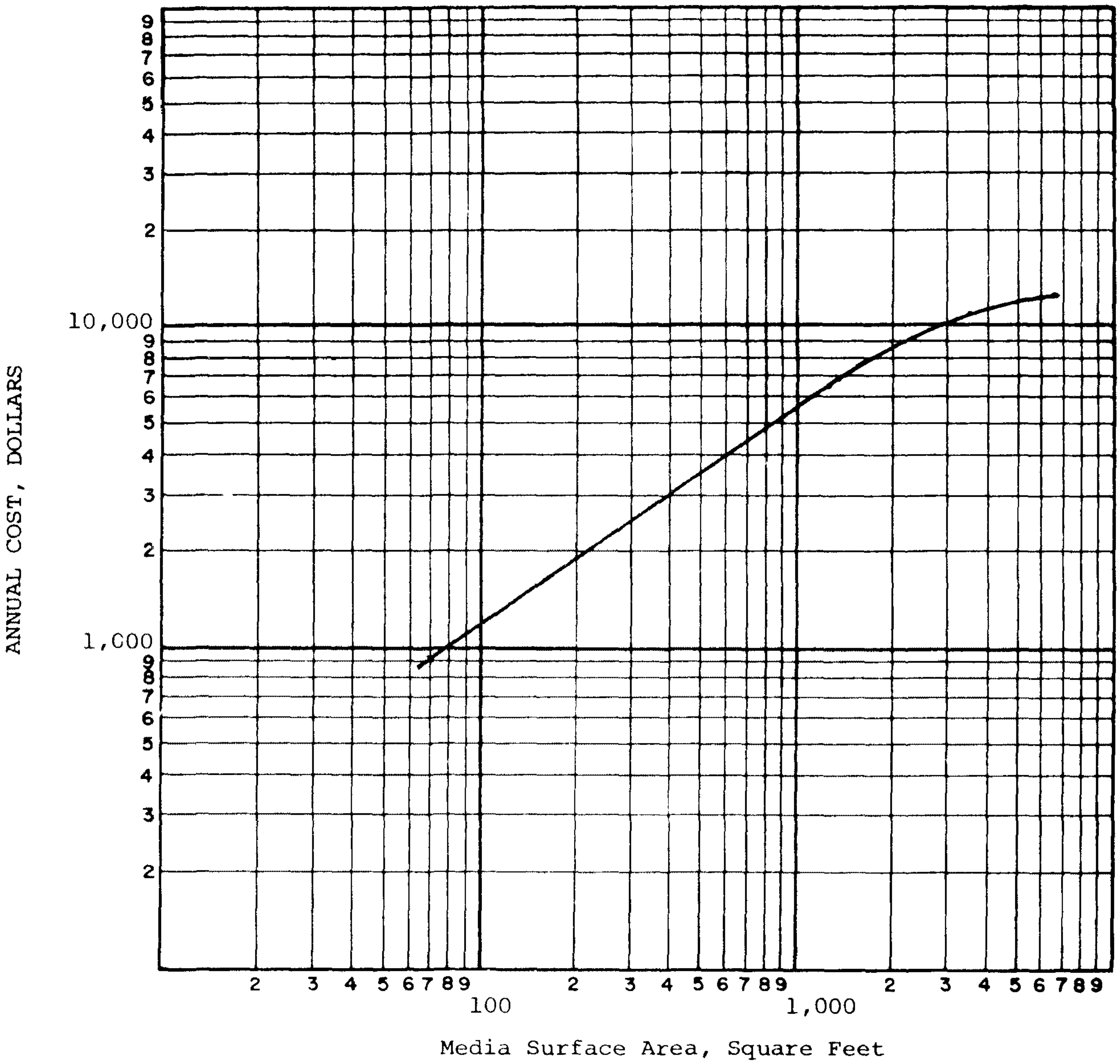
Curve 52



GRAVITY FILTRATION

POWER REQUIREMENTS
(Backwash - 2/24 Hours)

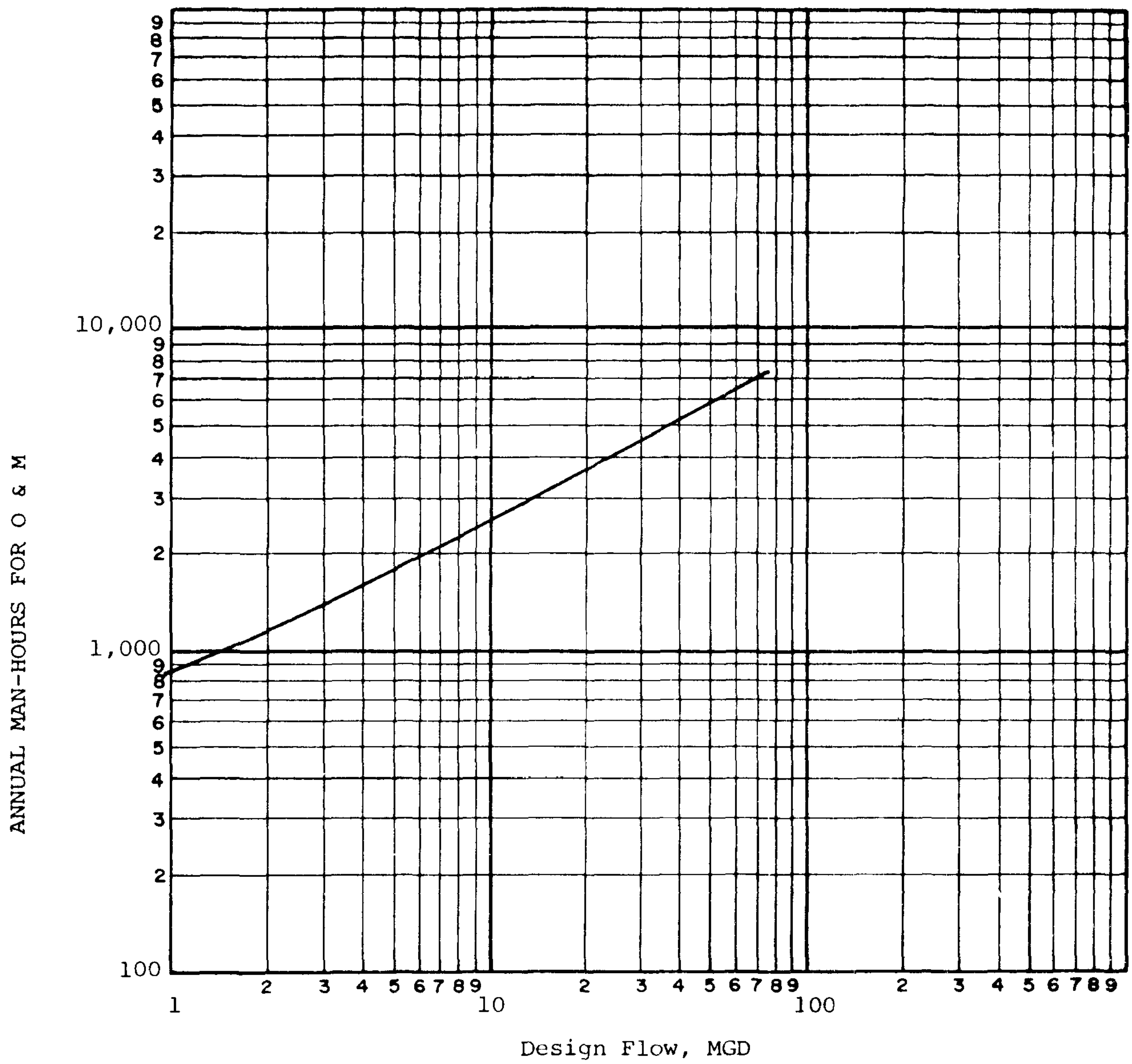
Curve 53



GRAVITY FILTRATION

MAINTENANCE MATERIAL COSTS

Curve 54

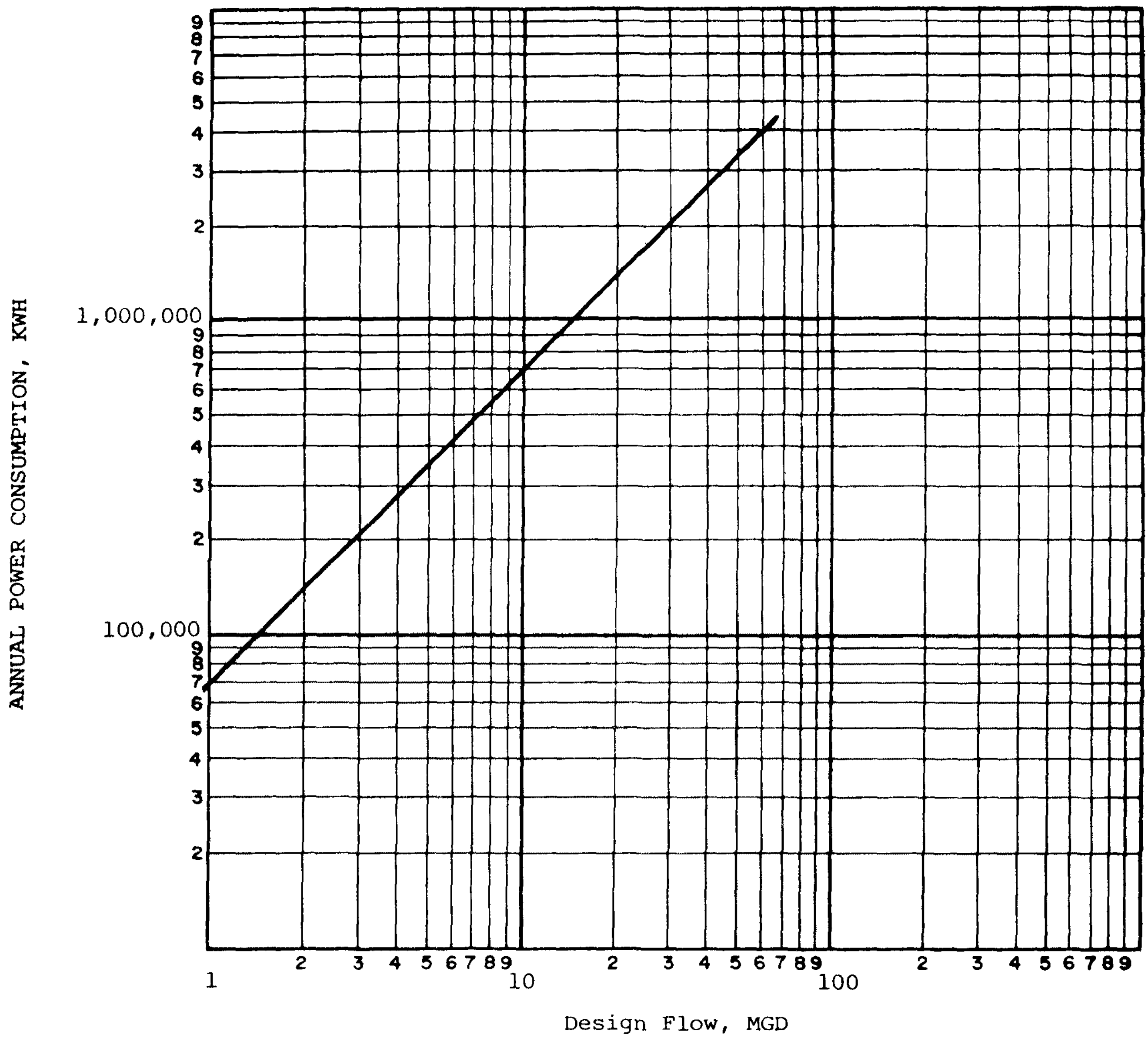


GRANULAR CARBON ADSORPTION AND PUMPING

(30 minutes contact)

MAN-HOUR REQUIREMENTS

Curve 55

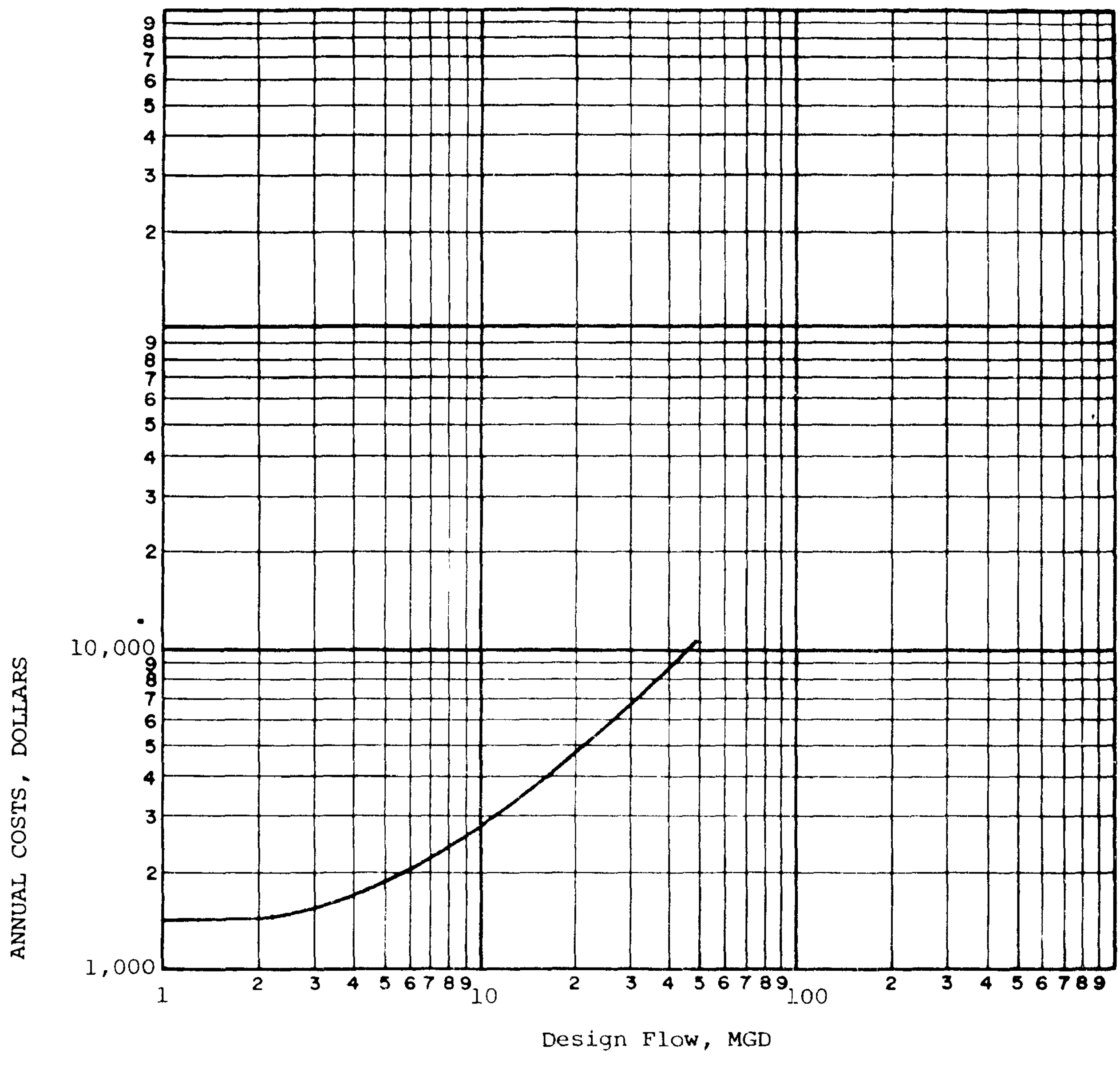


GRANULAR CARBON ADSORPTION AND PUMPING

(30 minutes contact)

POWER REQUIREMENTS

Curve 56

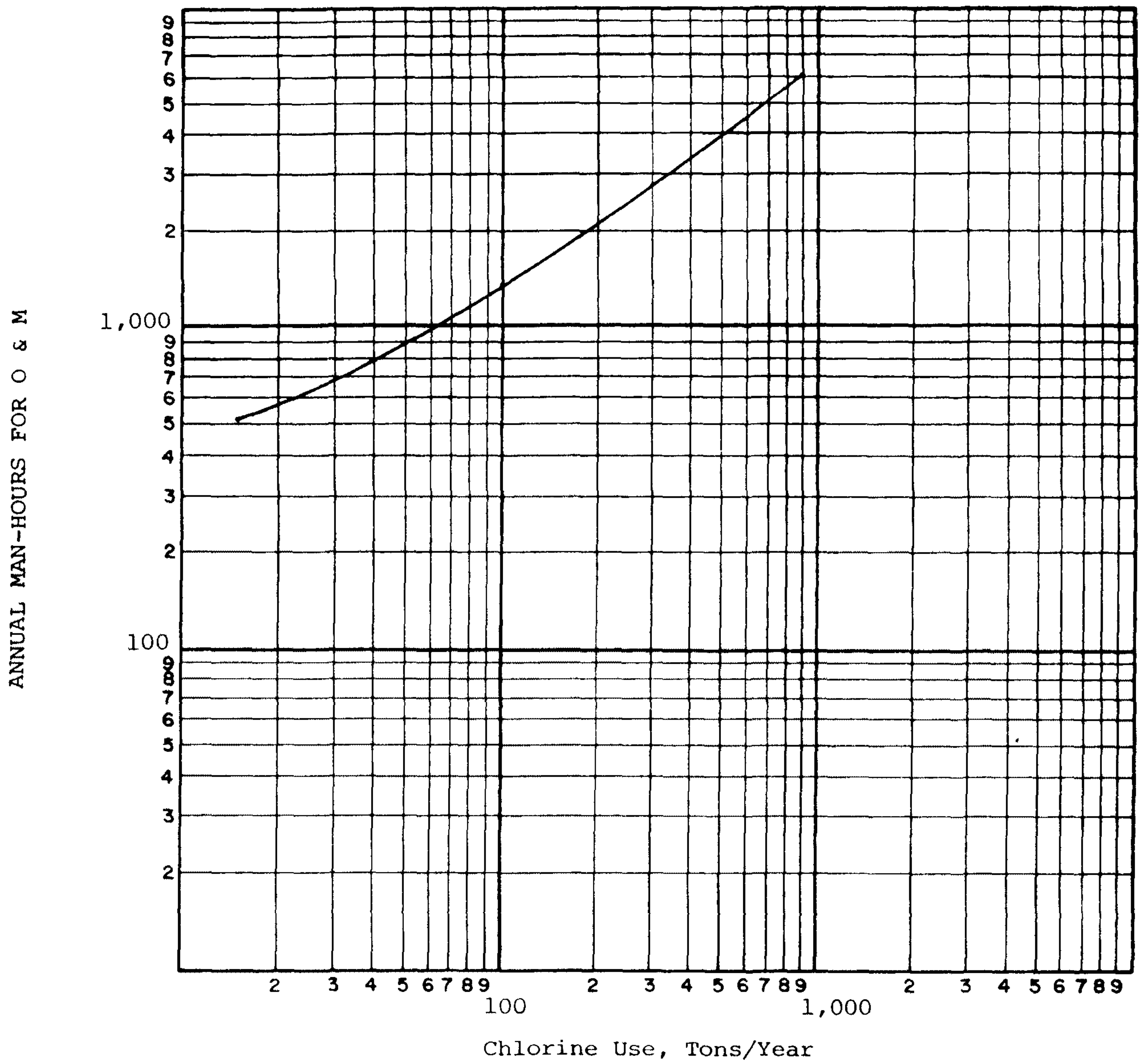


GRANULAR CARBON ADSORPTION AND PUMPING

(30 minutes contact)

MAINTENANCE MATERIALS

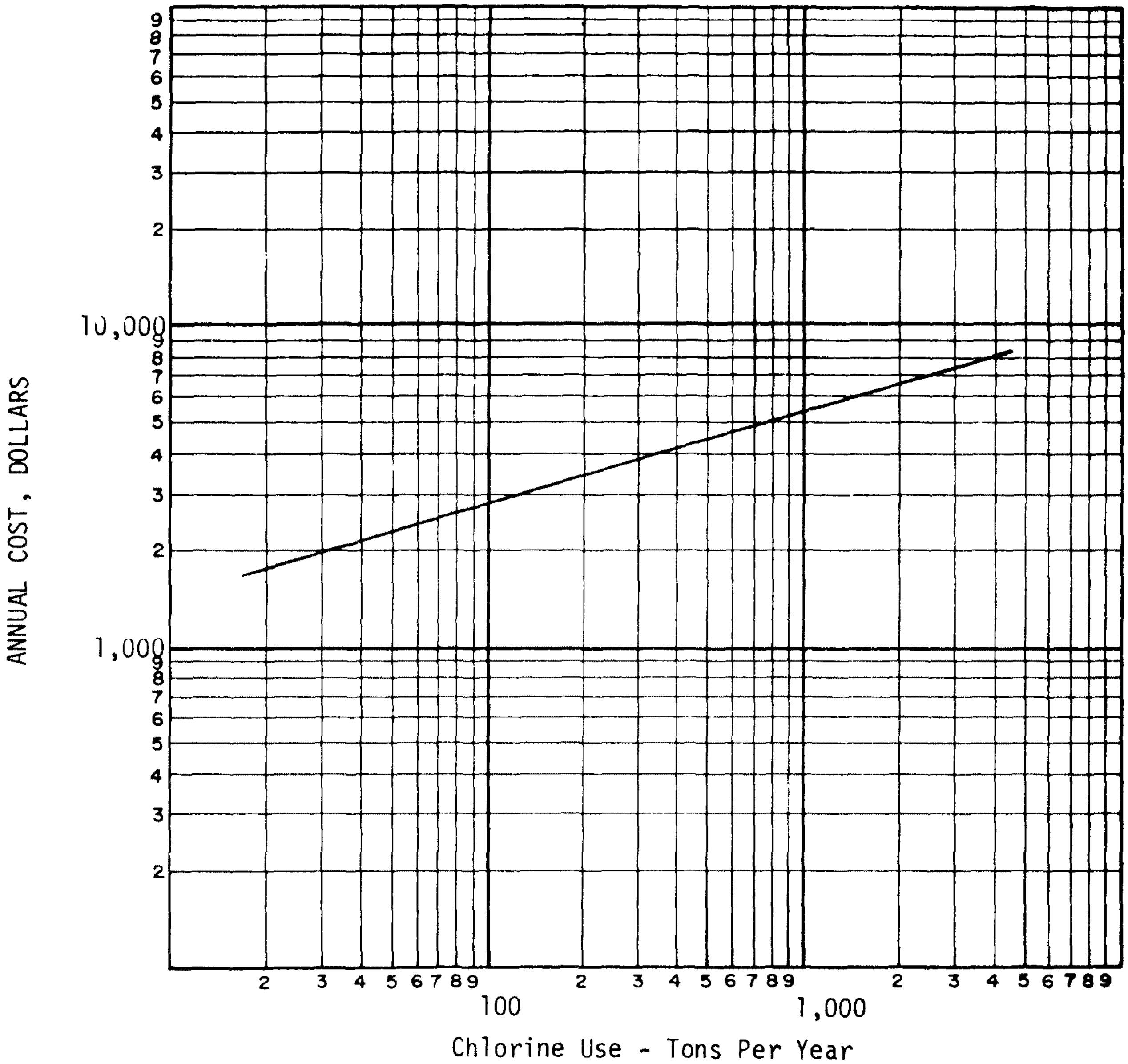
Curve 57



CHLORINATION

MAN-HOUR REQUIREMENTS

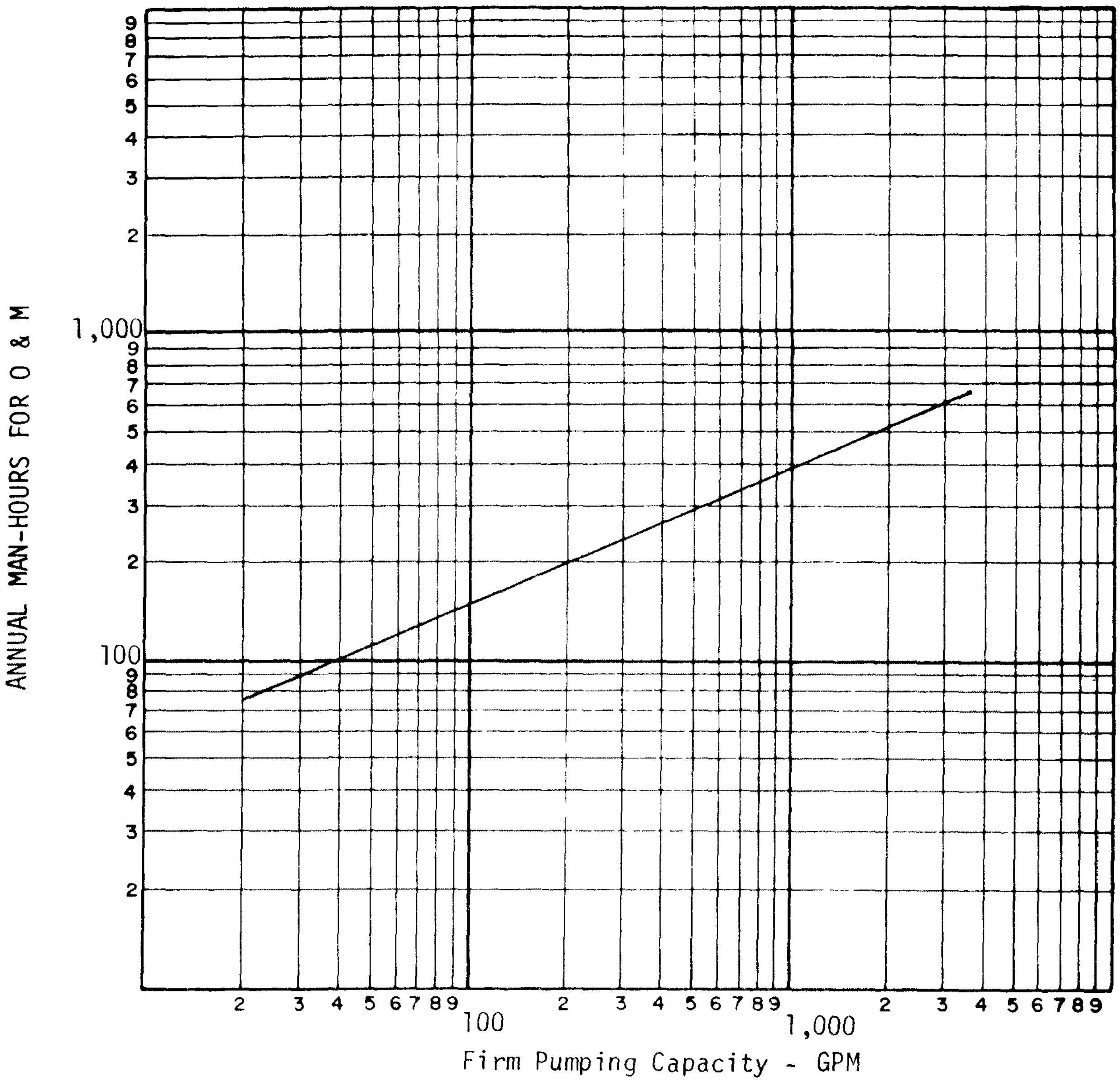
Curve 58



CHLORINATION

MAINTENANCE MATERIAL COSTS

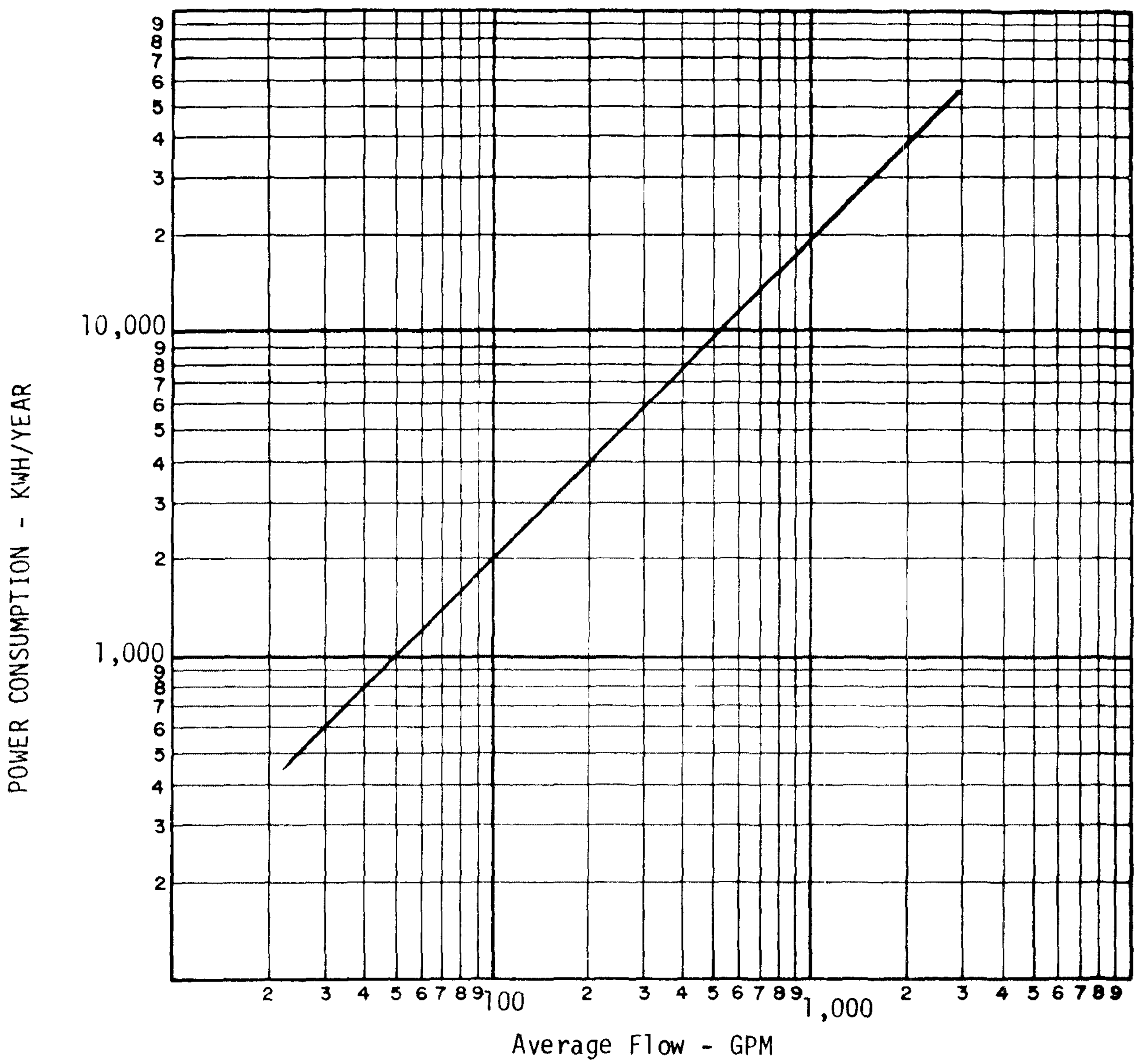
Curve 59



WASTE SLUDGE PUMPING

MAN-HOUR REQUIREMENTS

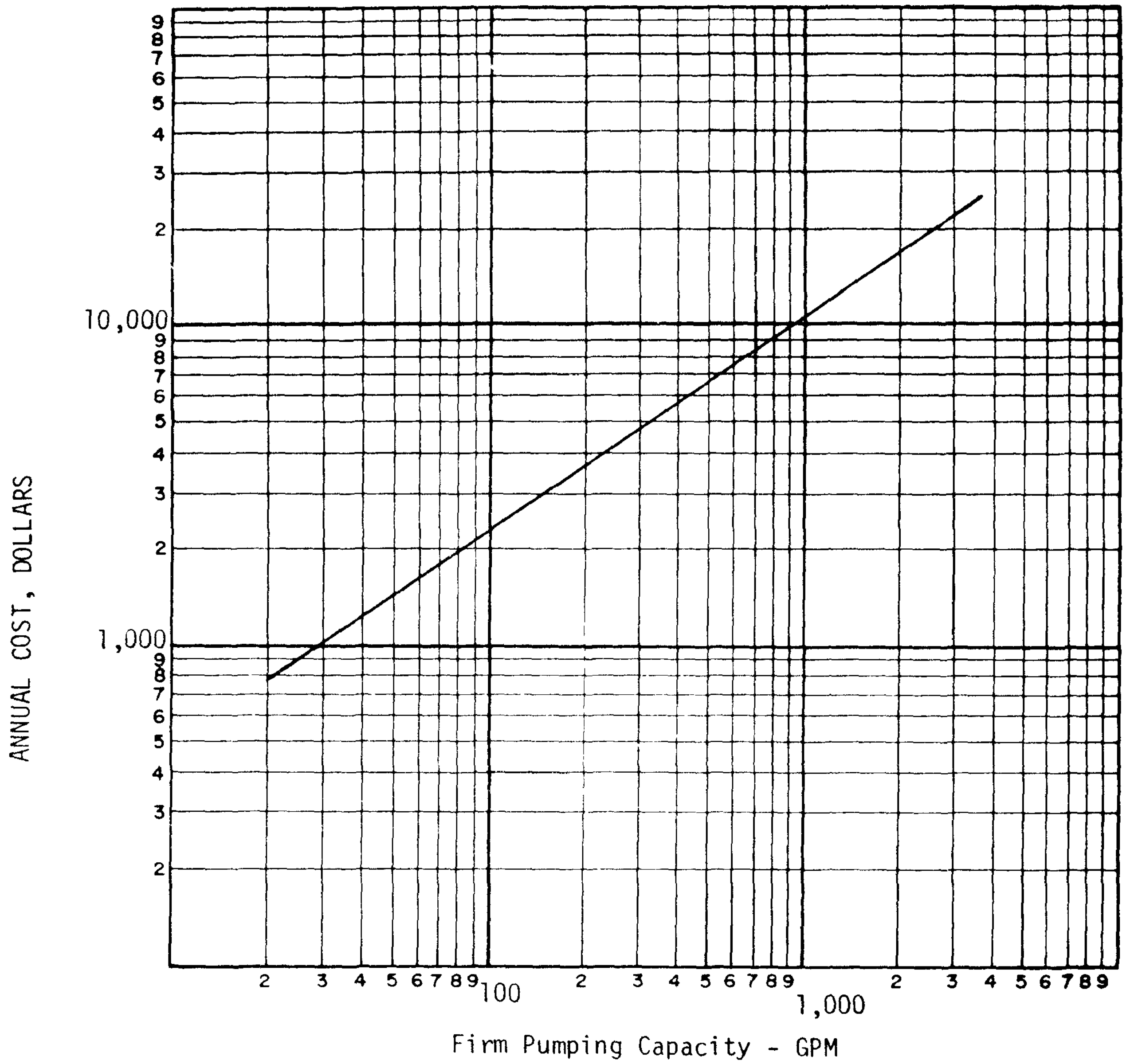
Curve 60



WASTE SLUDGE PUMPING

POWER REQUIREMENTS

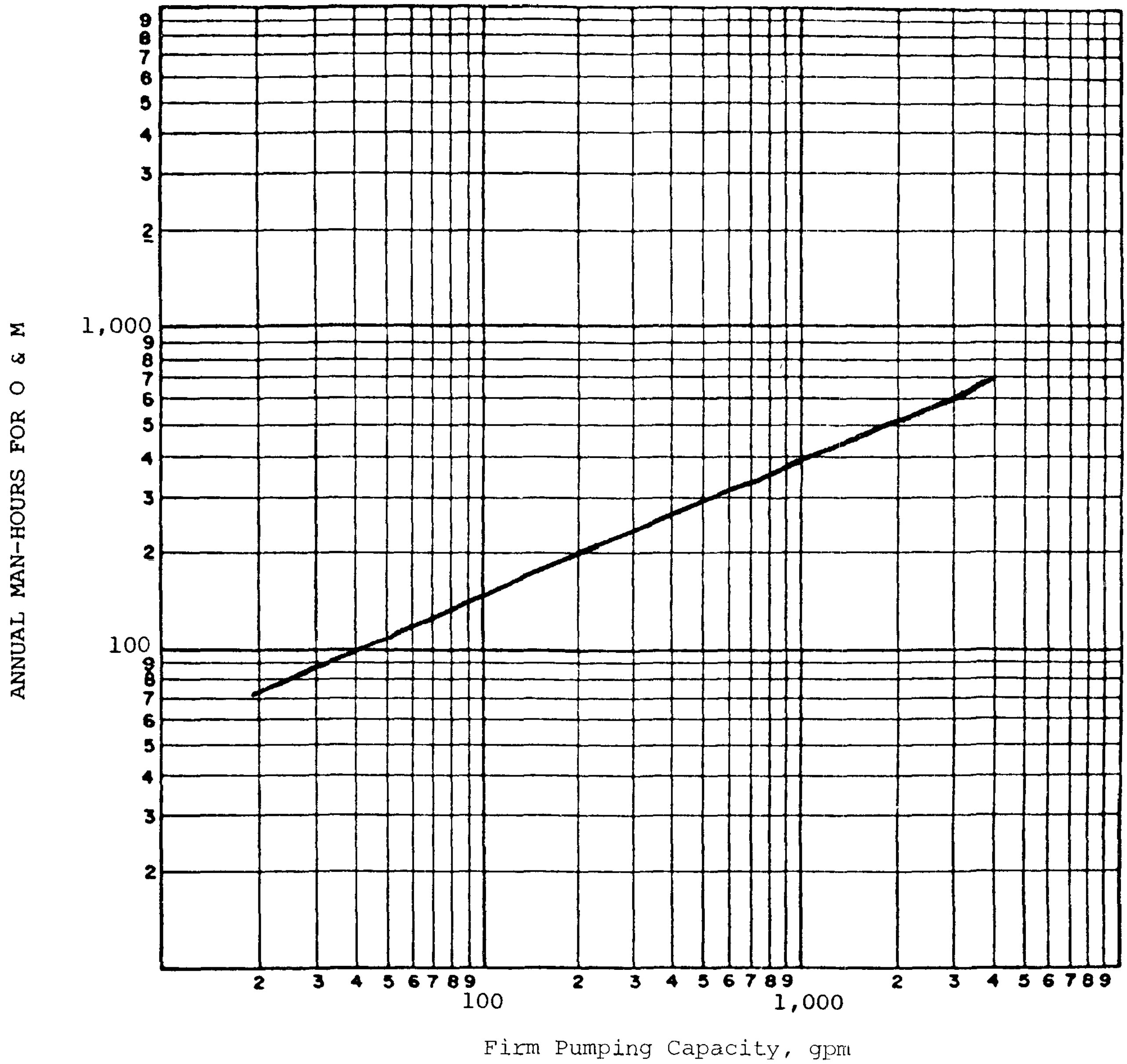
Curve 61



WASTE SLUDGE PUMPING

MAINTENANCE MATERIAL COSTS

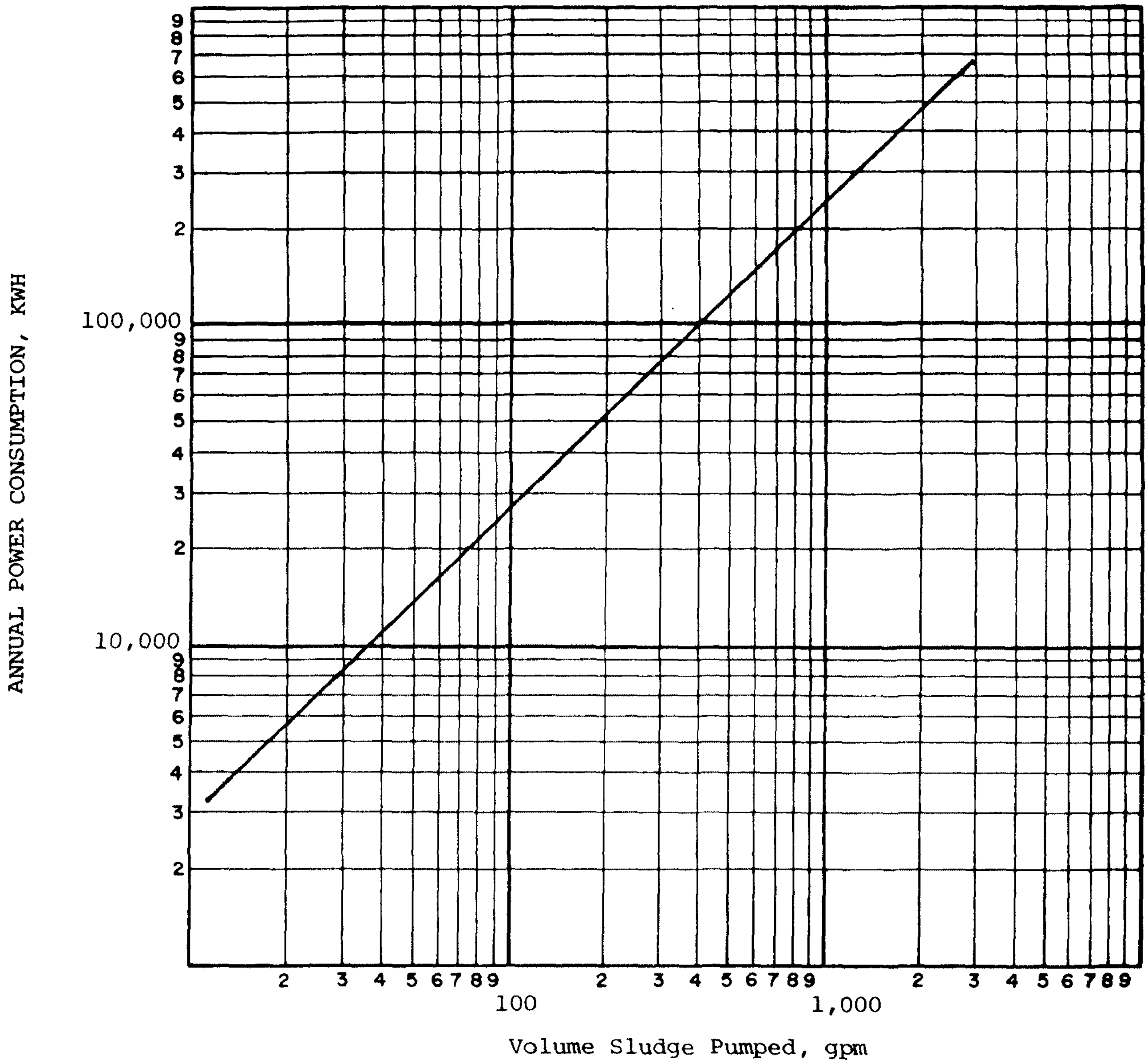
Curve 62



CHEMICAL SLUDGE PUMPING

MAN-HOUR REQUIREMENTS

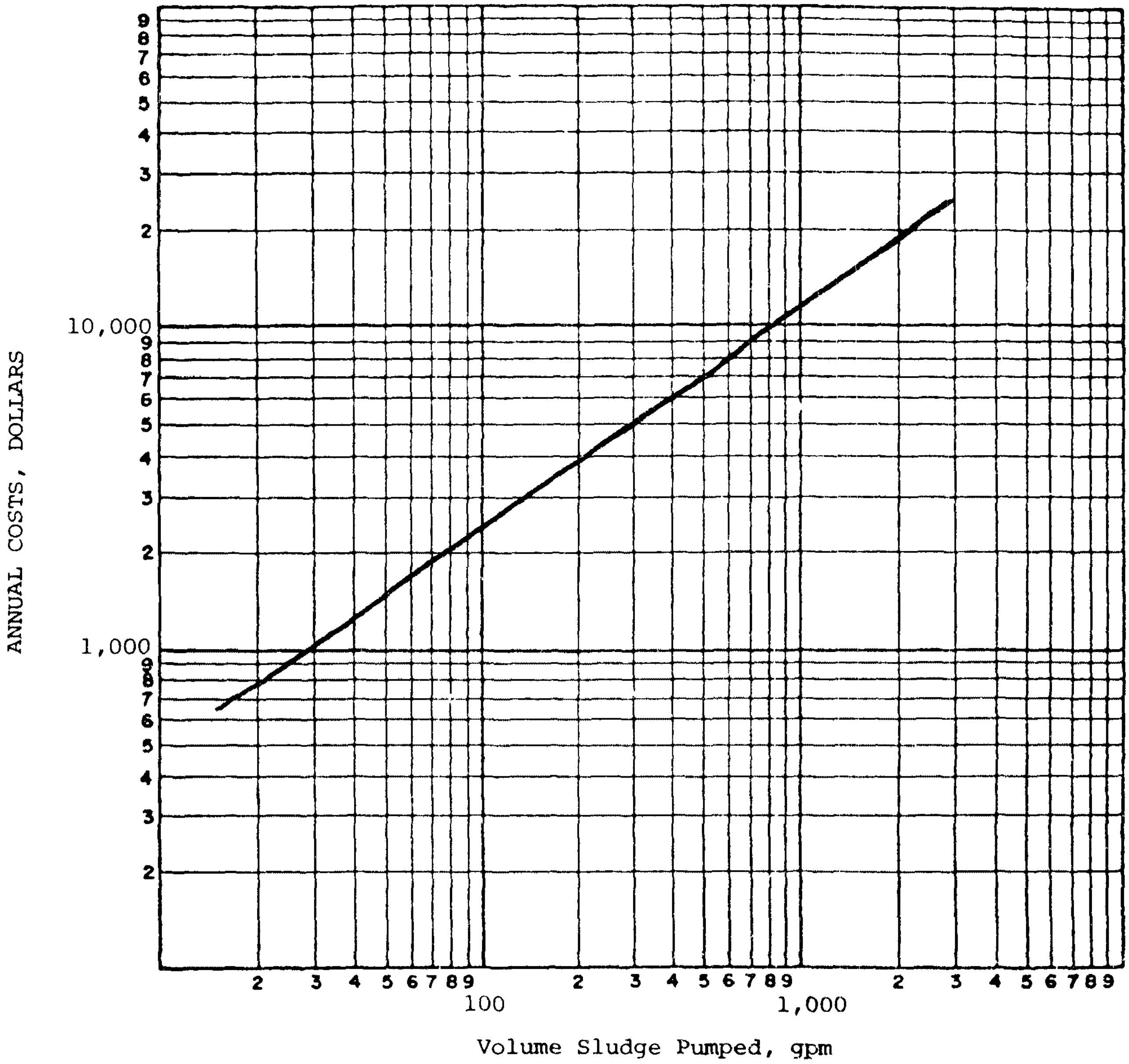
Curve 63



CHEMICAL SLUDGE PUMPING

POWER REQUIREMENTS

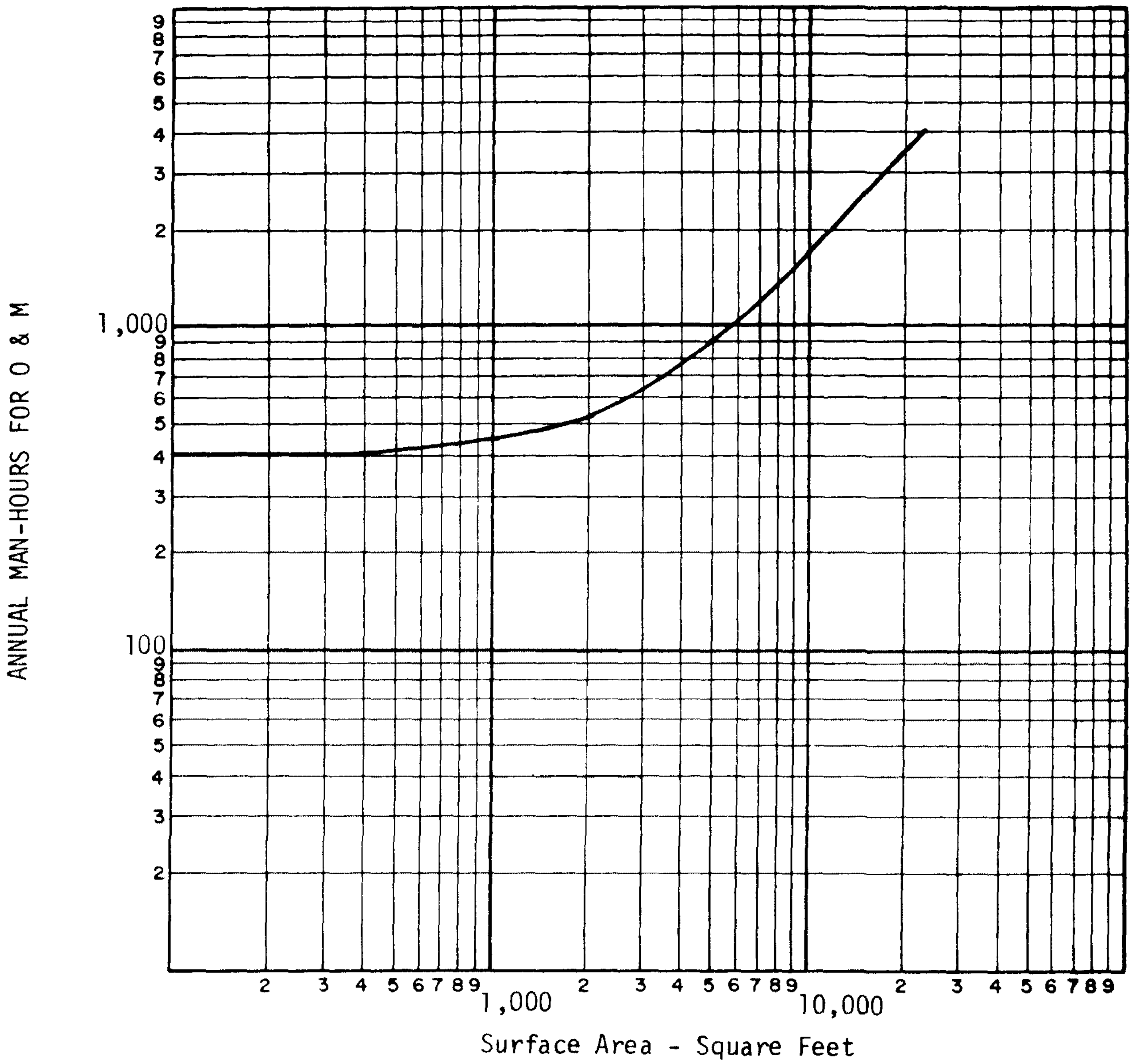
Curve 64



CHEMICAL SLUDGE PUMPING

MAINTENANCE MATERIAL COSTS

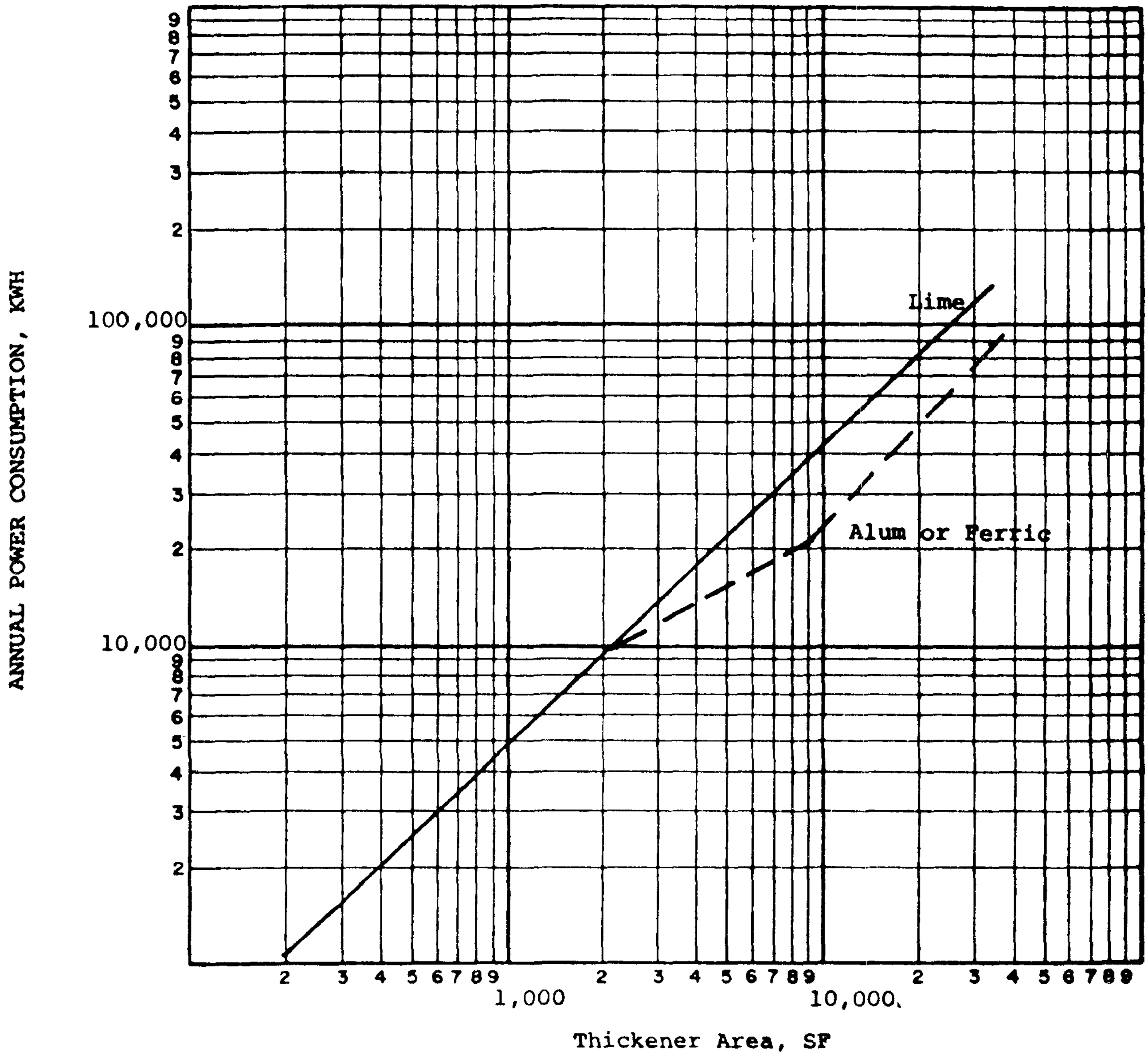
Curve 65



GRAVITY THICKENING

MAN-HOUR REQUIREMENTS

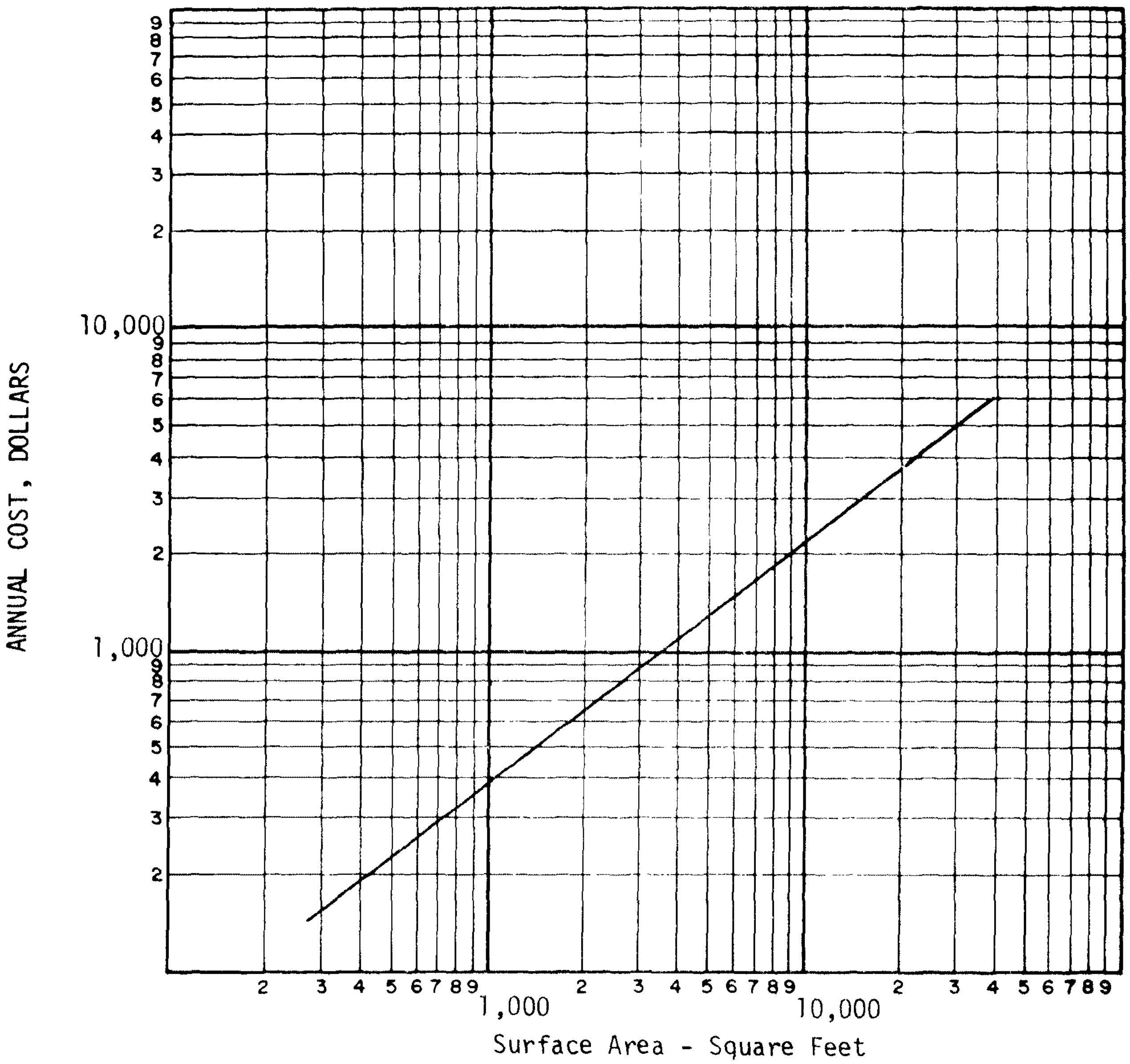
Curve 66



GRAVITY THICKENING

POWER REQUIREMENTS

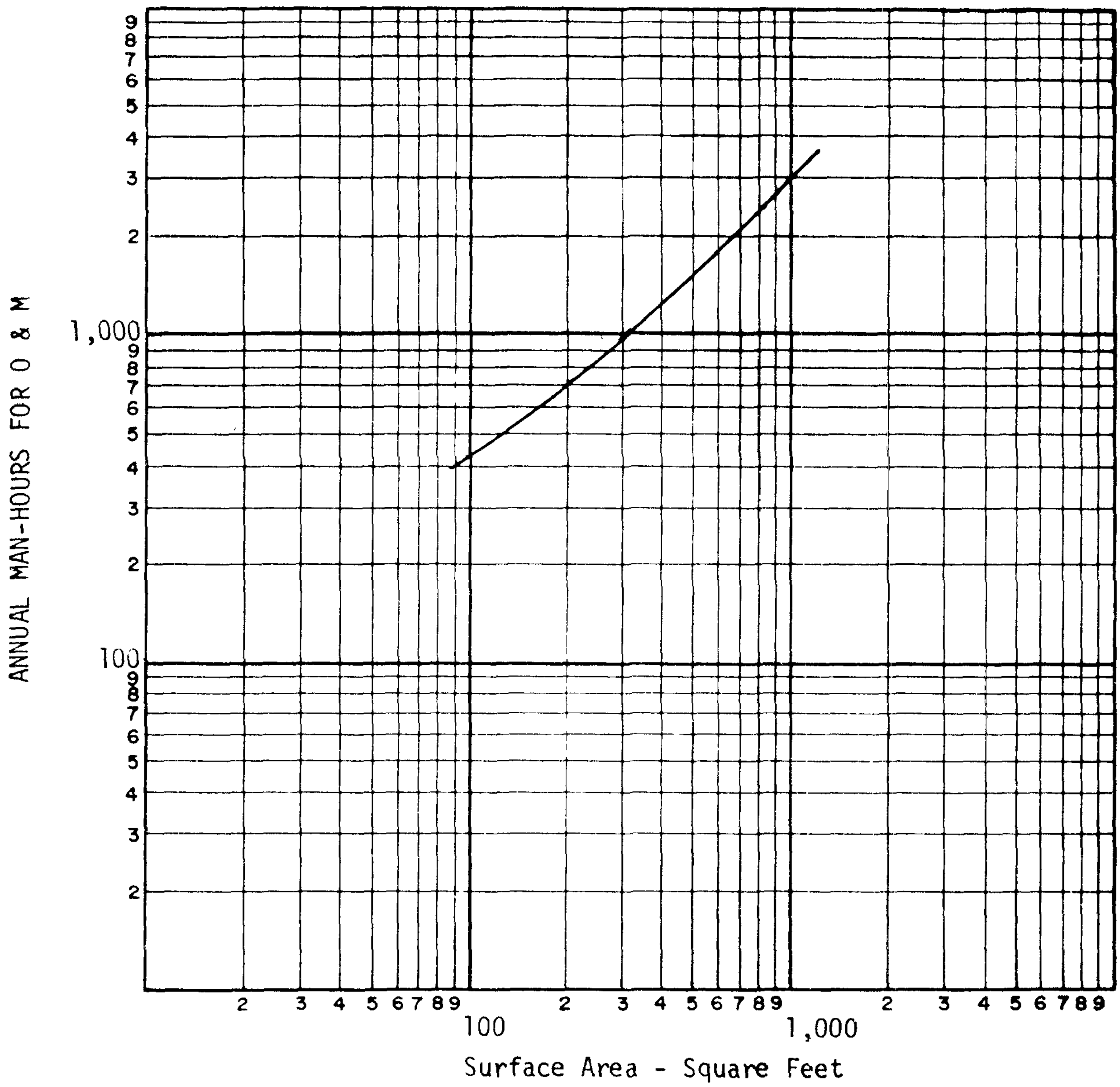
Curve 67



GRAVITY THICKENING

MAINTENANCE MATERIAL COSTS

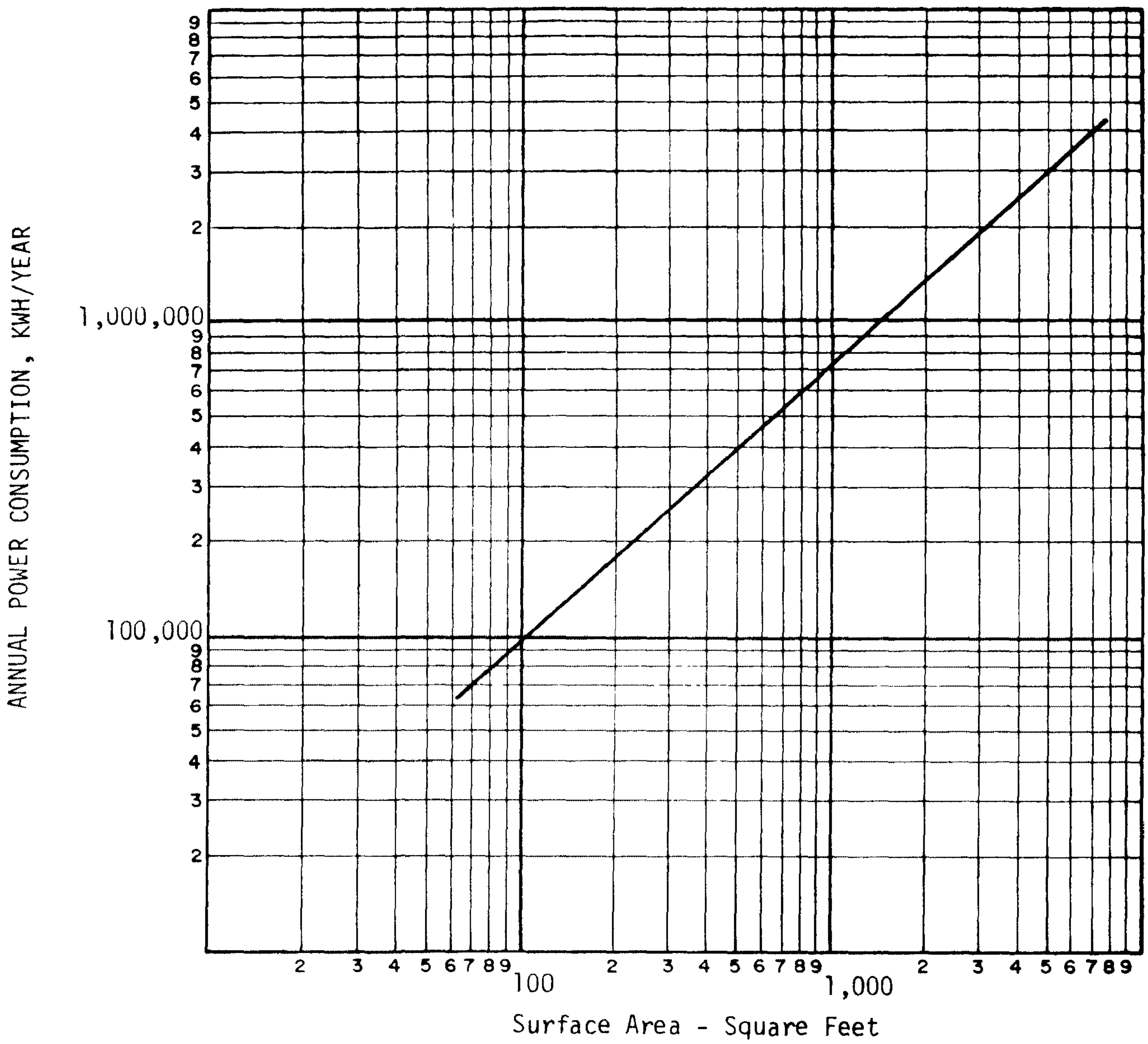
Curve 68



FLOTATION THICKENING

MAN-HOUR REQUIREMENTS

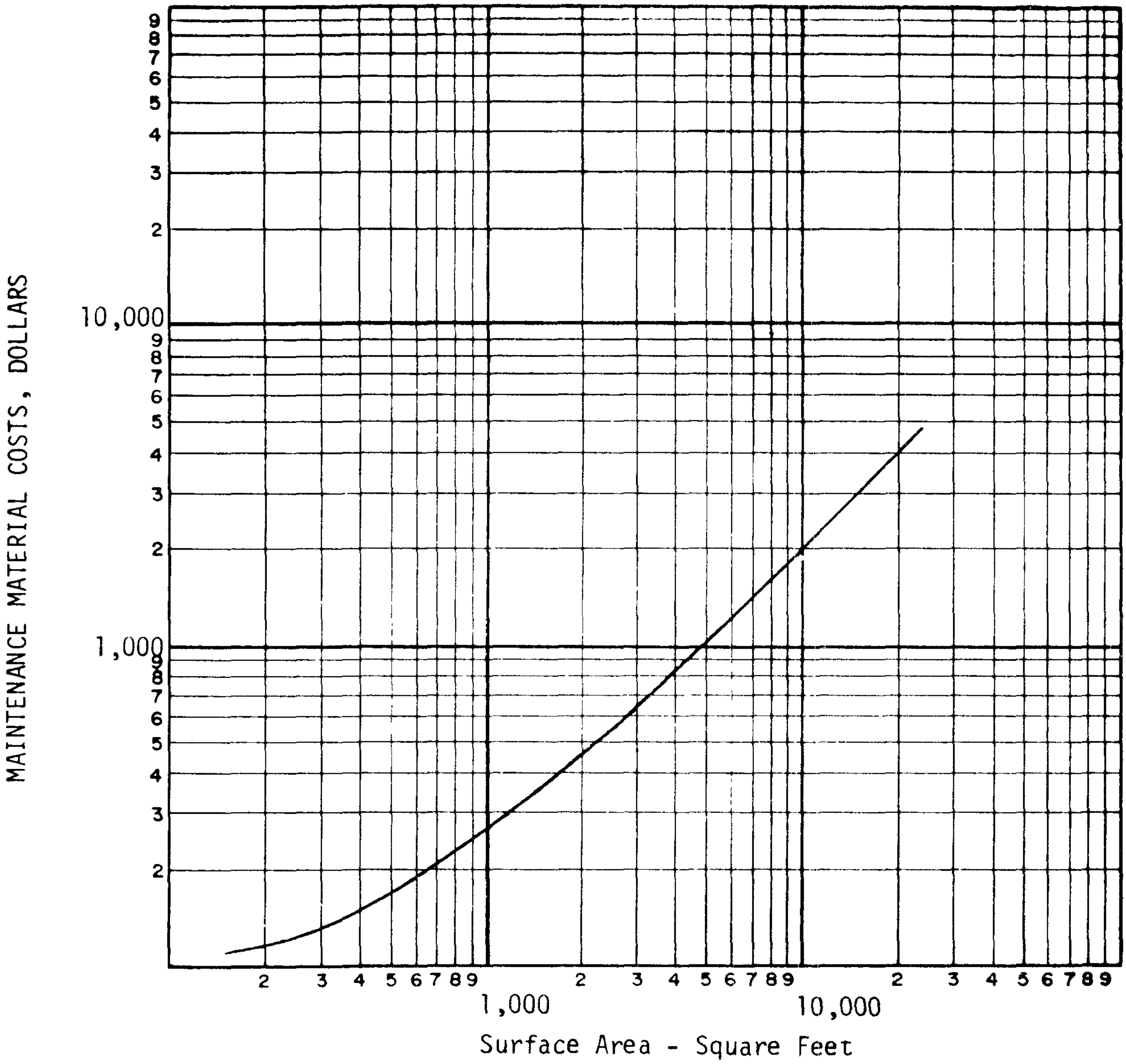
Curve 69



FLOTATION THICKENING

POWER REQUIREMENTS

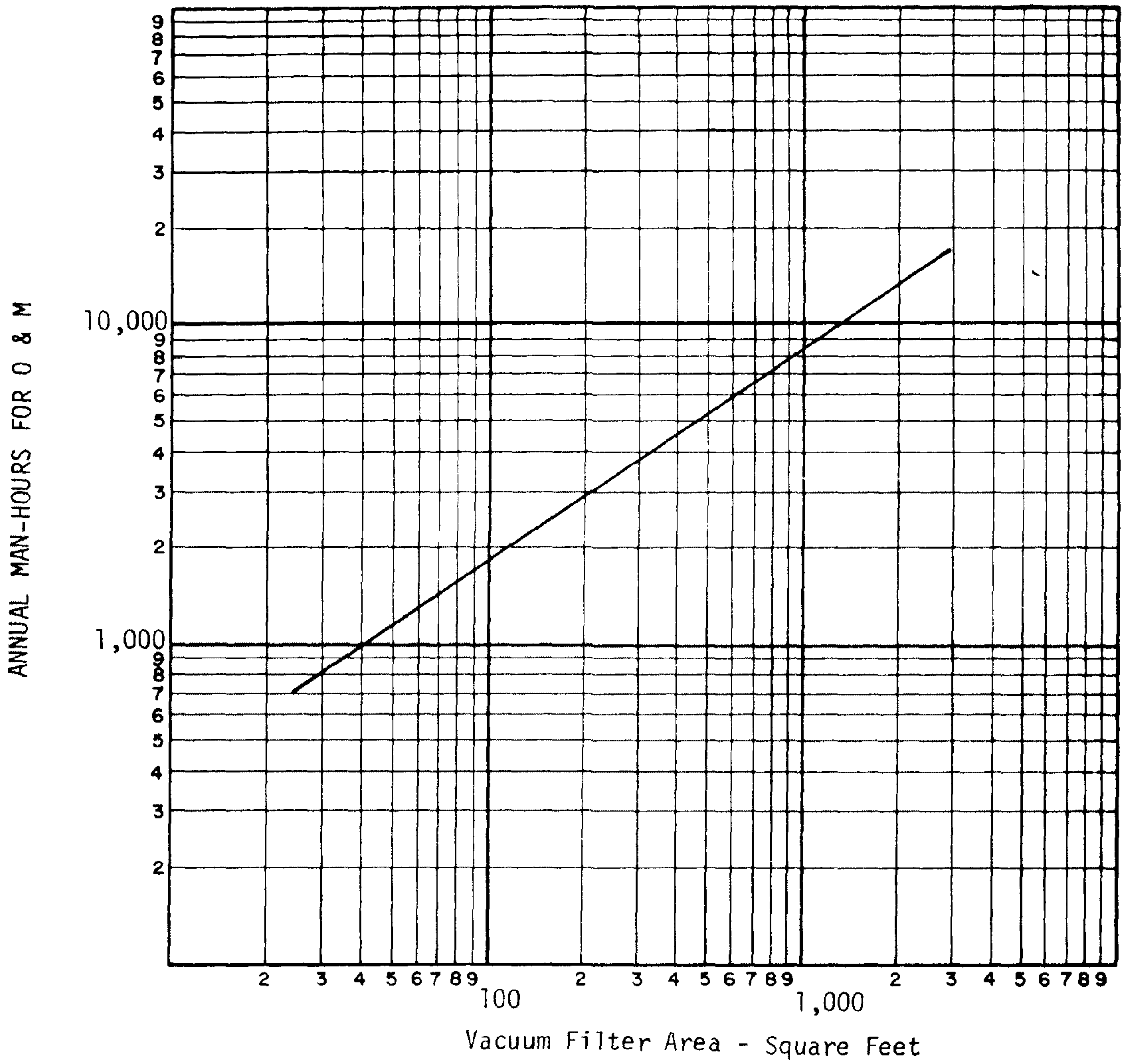
Curve 70



FLOTATION THICKENING

MAINTENANCE MATERIAL COSTS

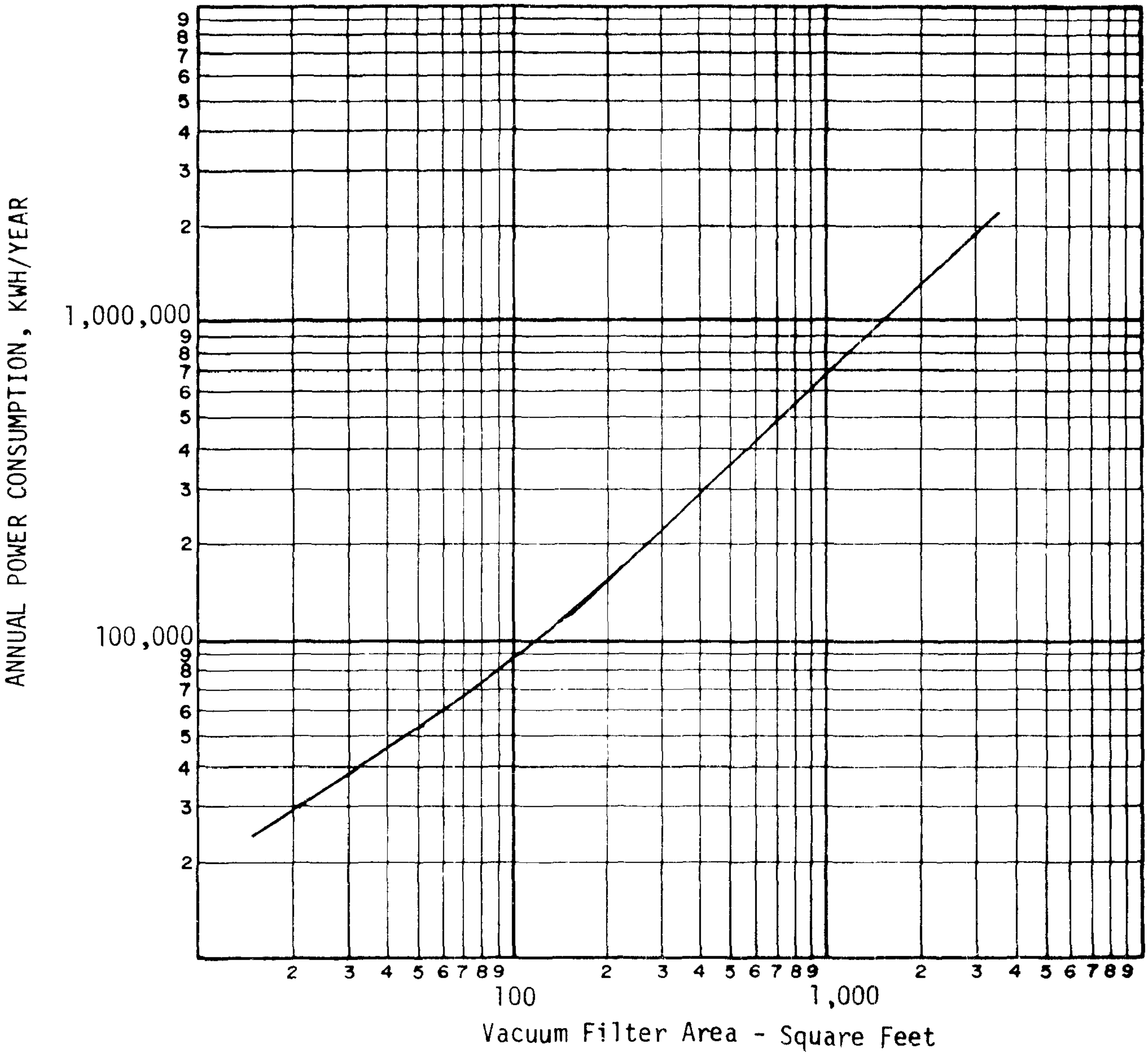
Curve 71



VACUUM FILTRATION

MAN-HOUR REQUIREMENTS
(20 hours/day operation)

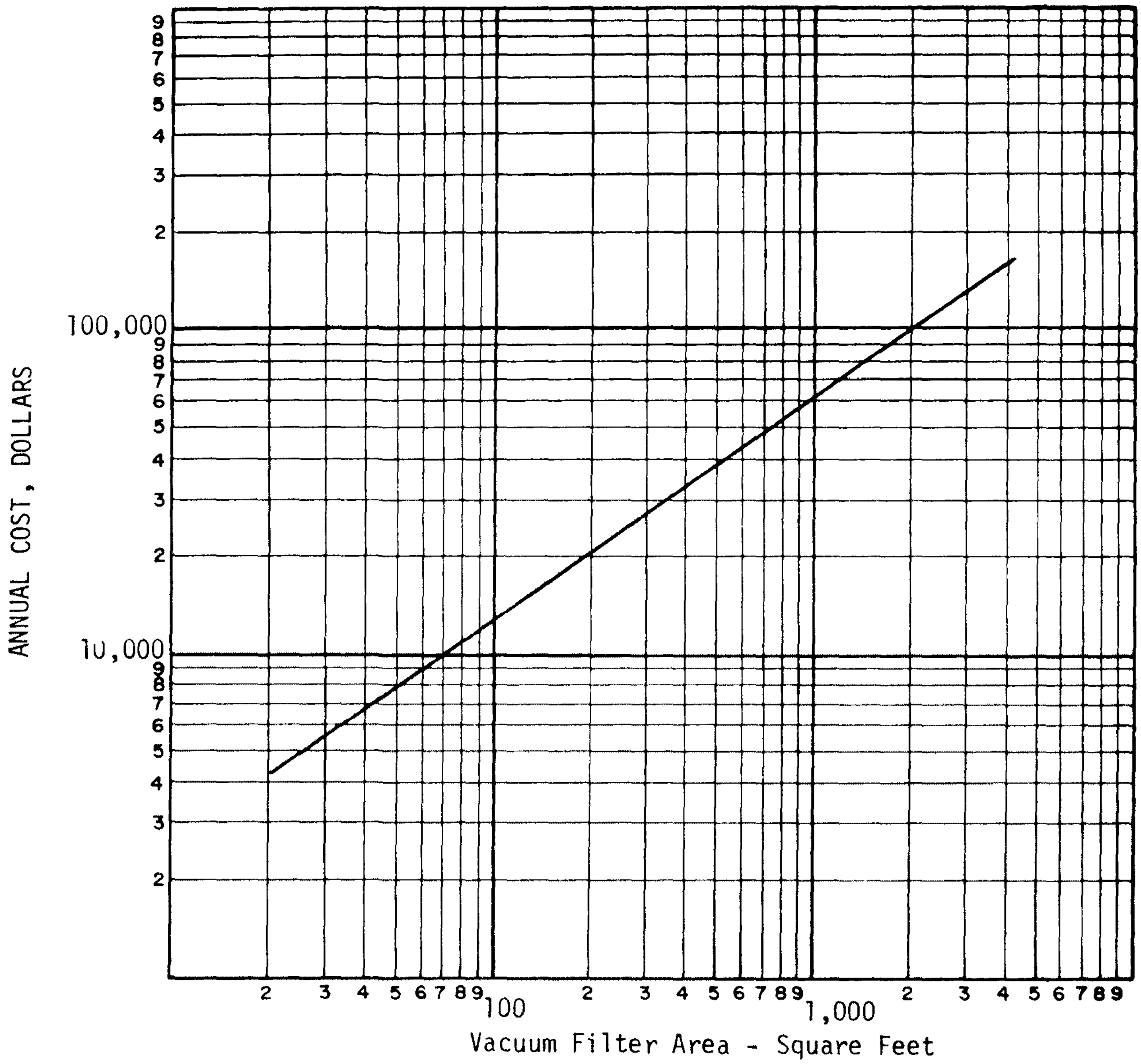
Curve 72



VACUUM FILTRATION

POWER REQUIREMENTS
(20 hours/day operation)

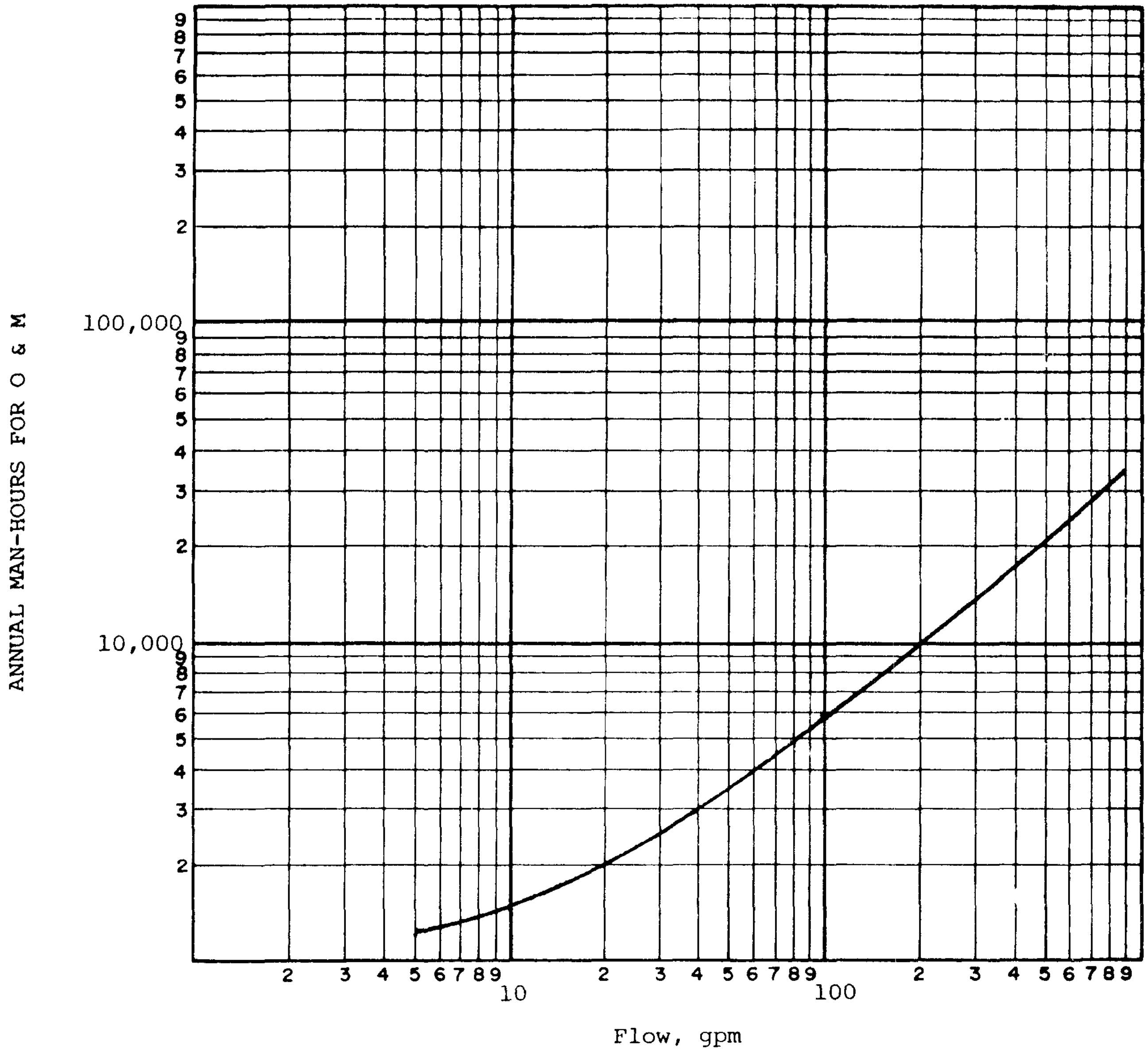
Curve 73



VACUUM FILTRATION

MAINTENANCE MATERIAL COSTS
(20 hours/day operation)

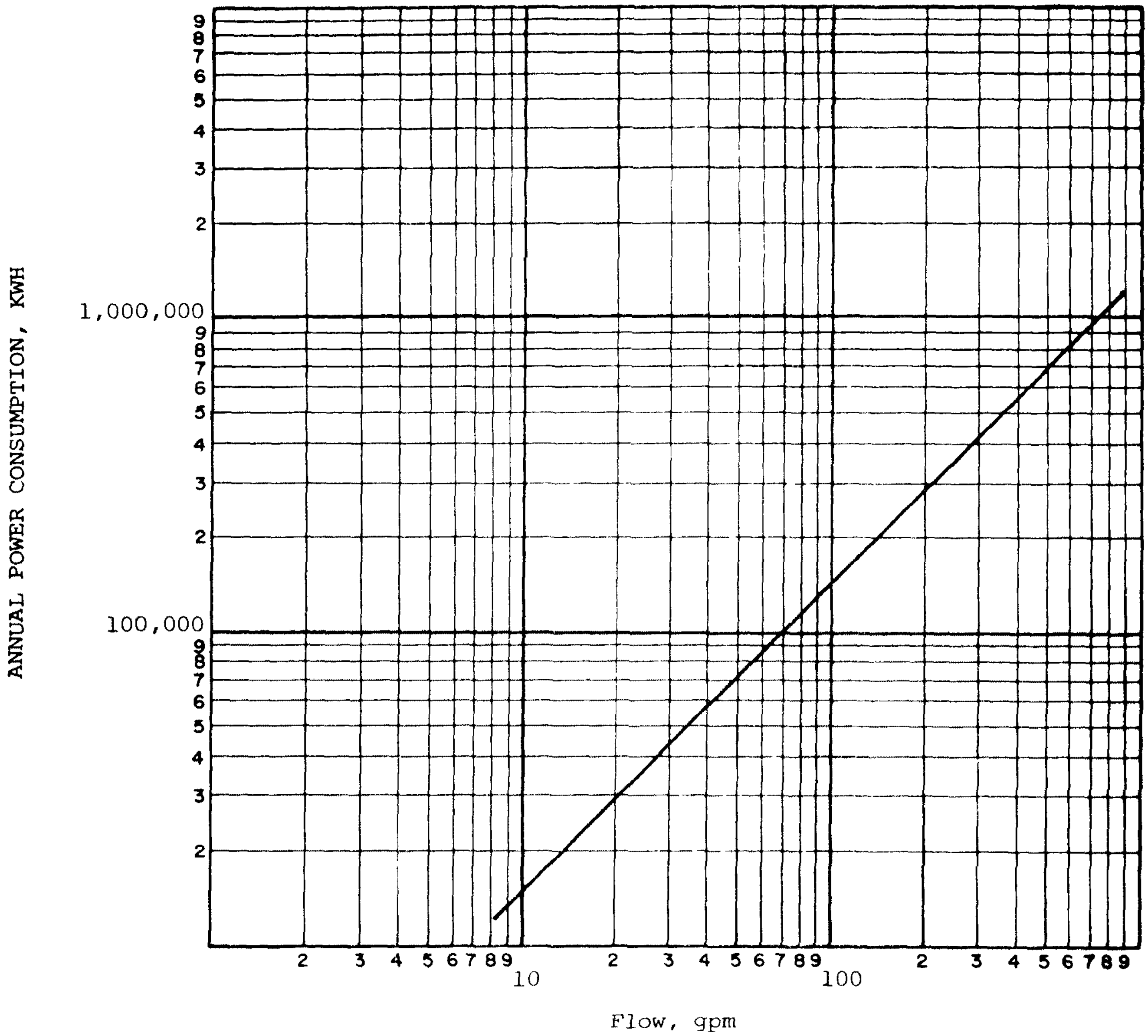
Curve 74



CENTRIFUGING

MAN-HOUR REQUIREMENTS
(Based on 70% Operation Run Time)

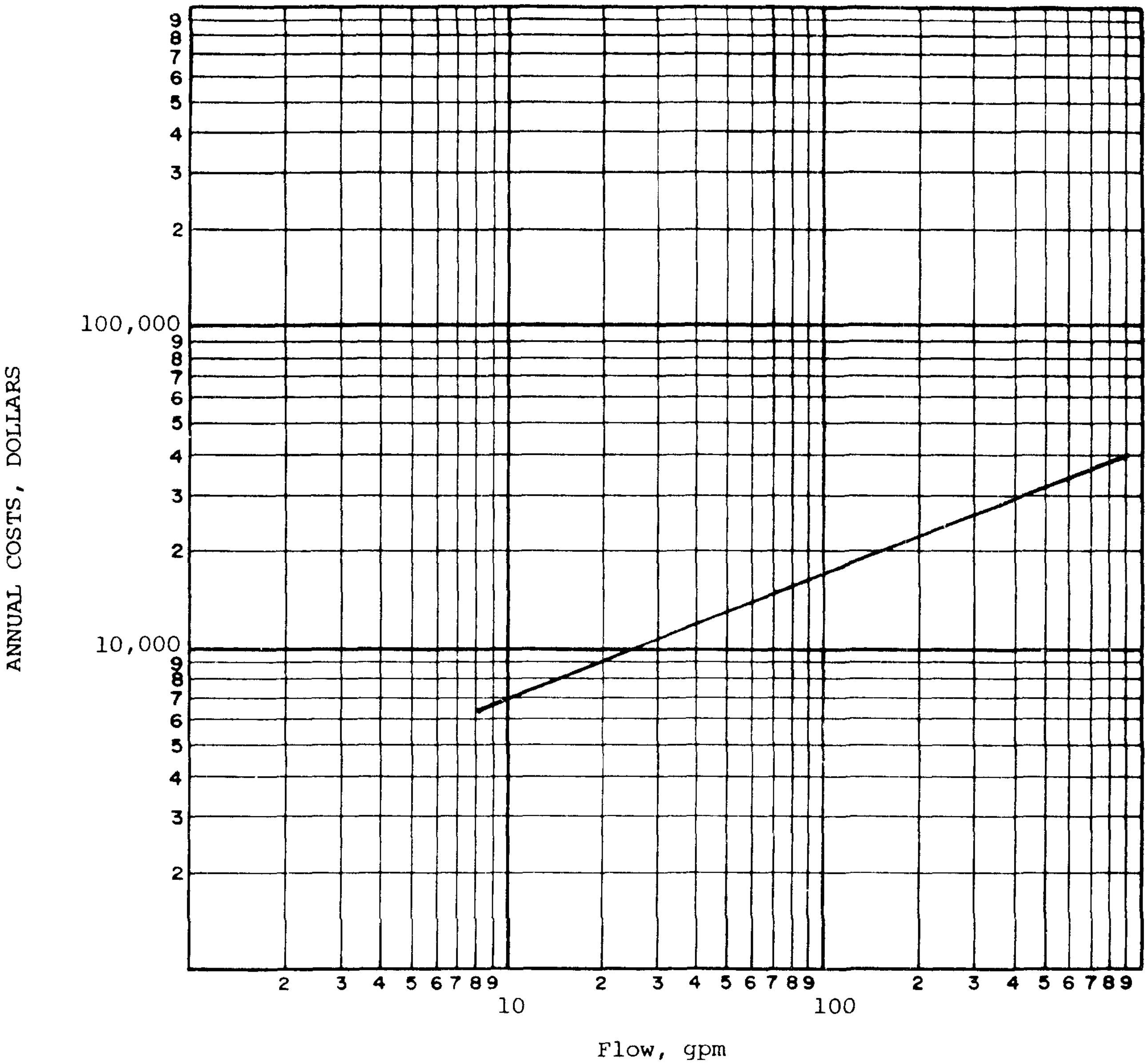
Curve 75



CENTRIFUGING

POWER REQUIREMENTS
(Based on 70% Operation Run Time)

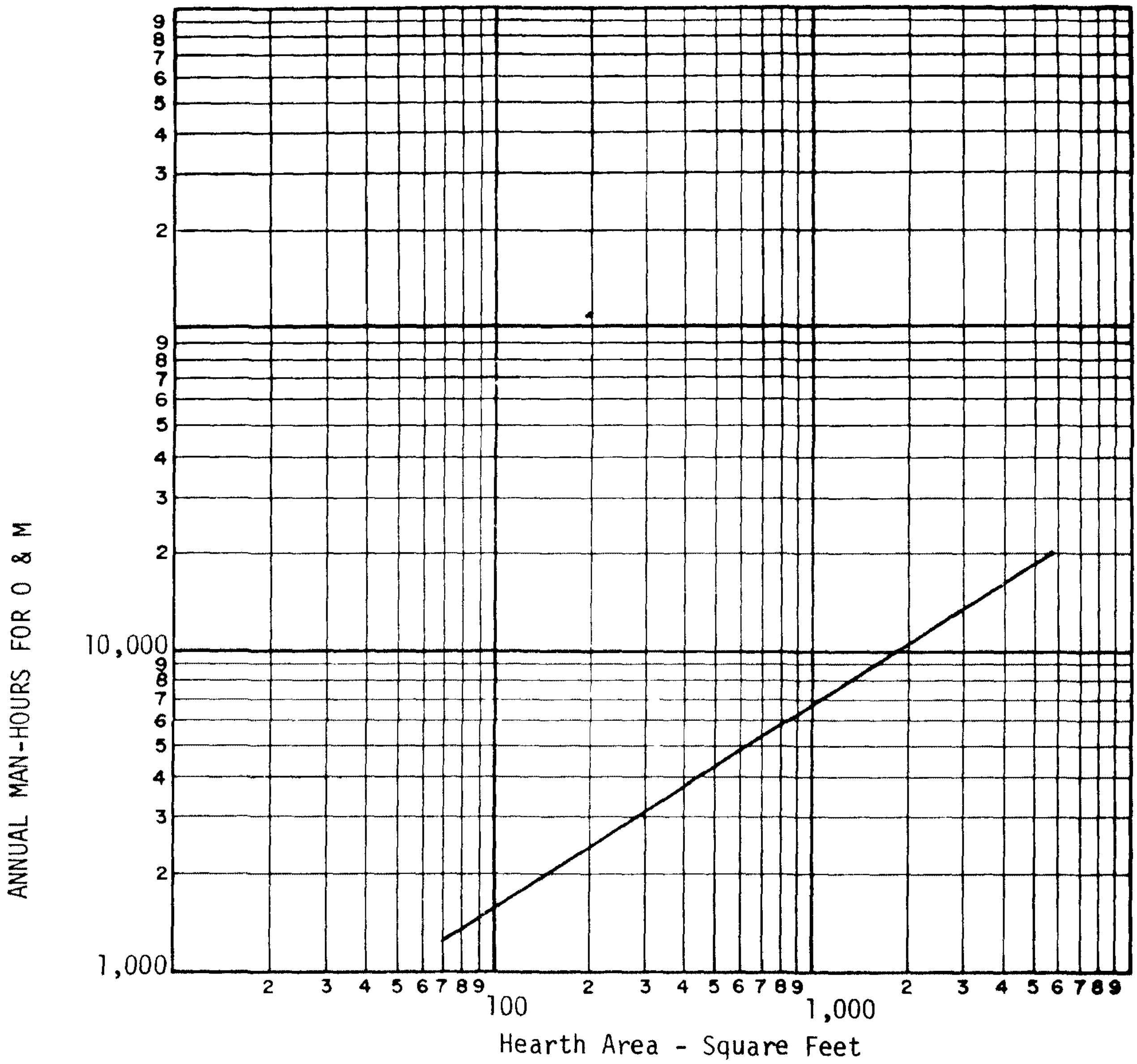
Curve 76



CENTRIFUGING

MAINTENANCE MATERIAL COSTS

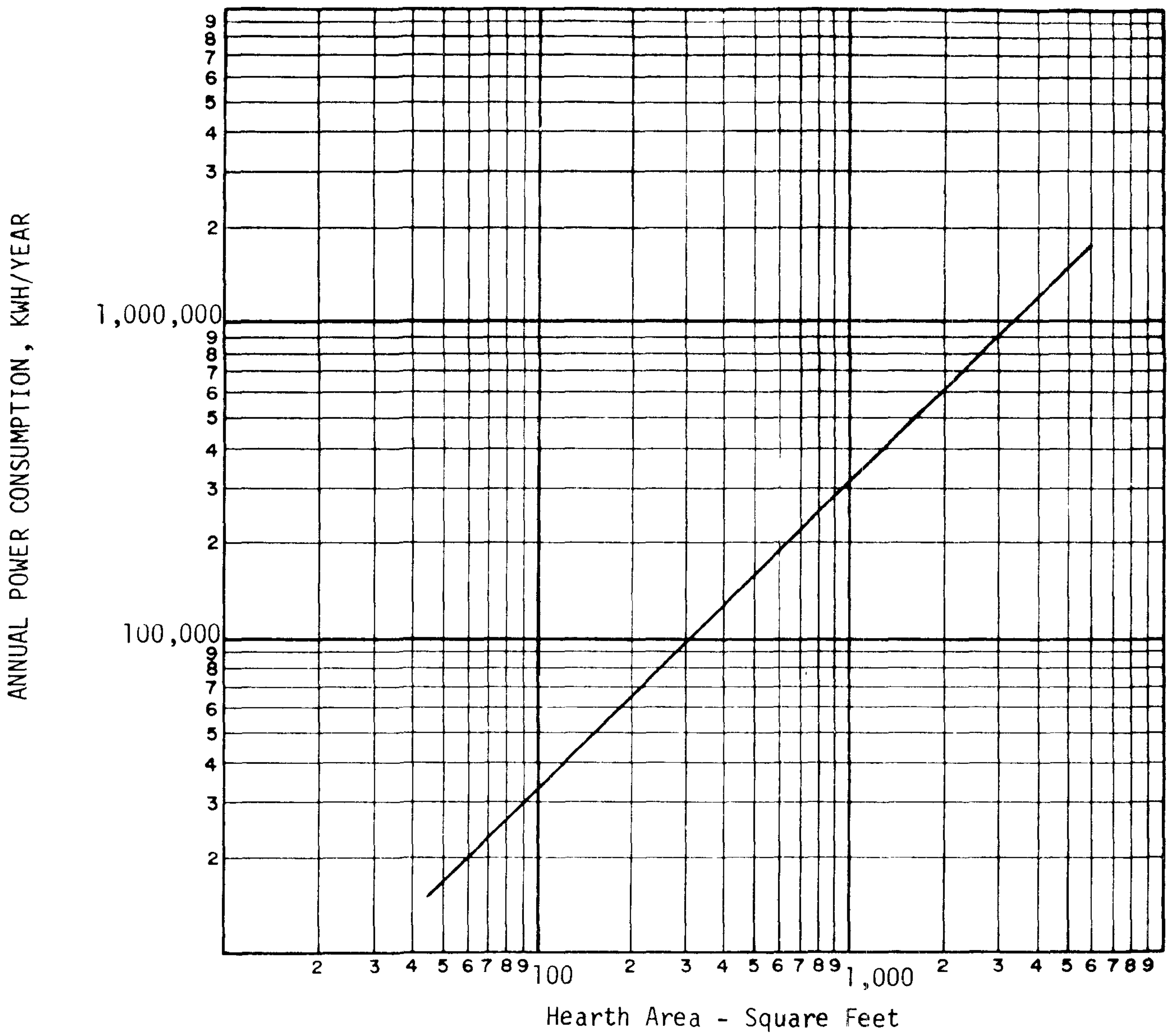
Curve 77



MULTIPLE HEARTH INCINERATION

MAN-HOUR REQUIREMENTS
(70% operation time, 6 pounds/square foot/hour loading-wet basis)

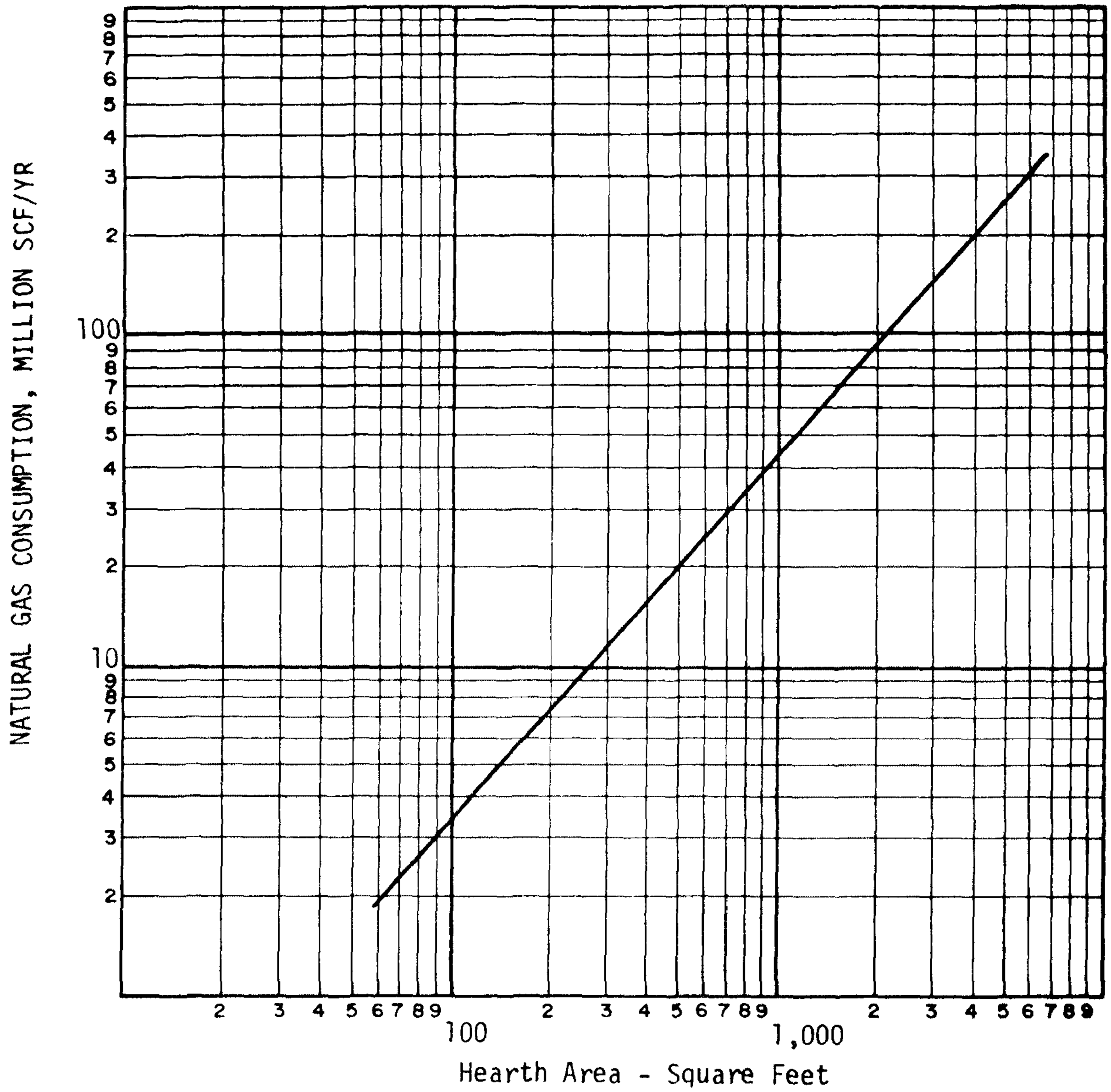
Curve 78



MULTIPLE HEARTH INCINERATION

POWER REQUIREMENTS
(70% operation time, 6 pounds/square foot/hour loading-wet basis)

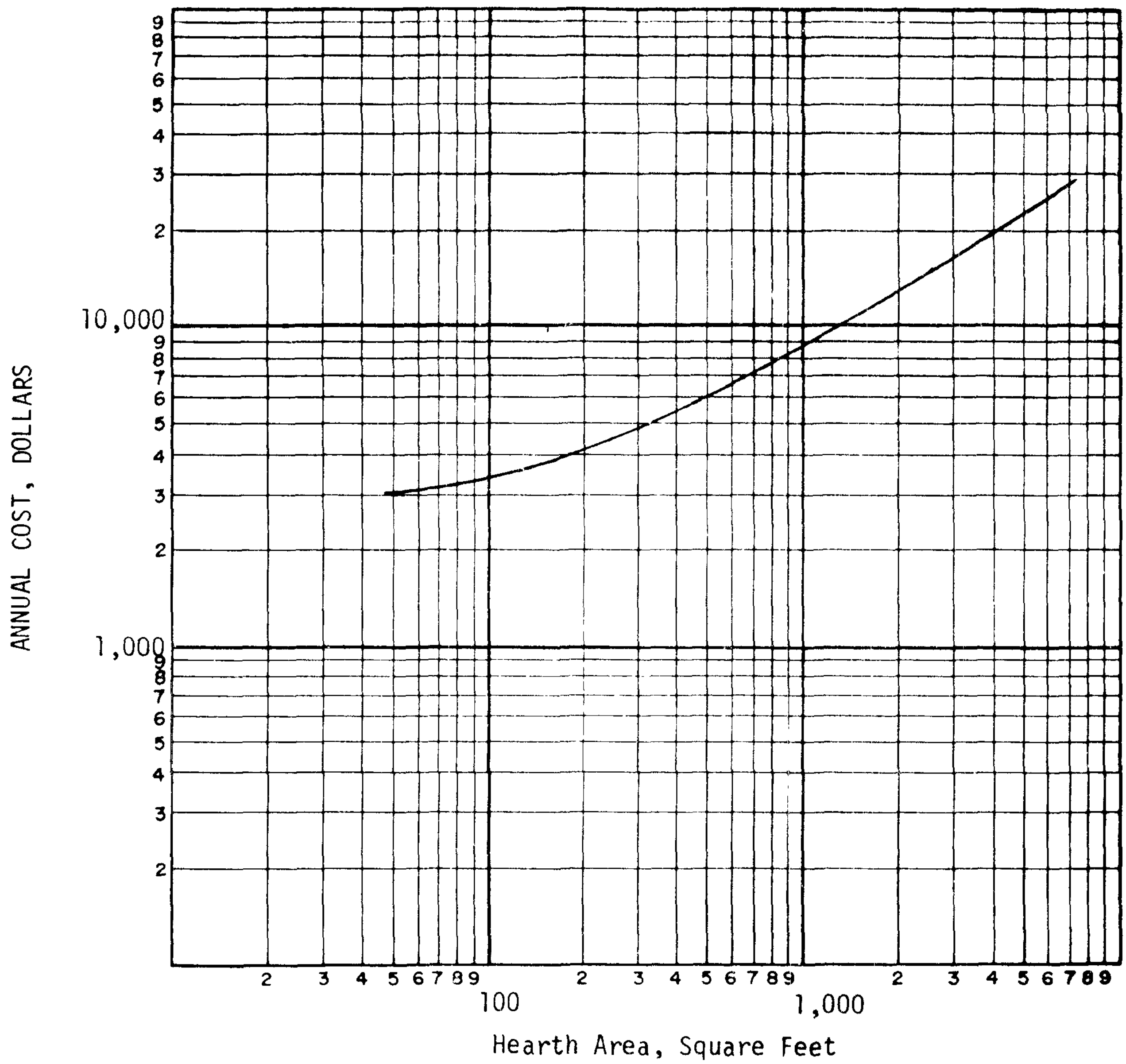
Curve 79



MULTIPLE HEARTH INCINERATION

FUEL REQUIREMENTS
(70% operation time, 6 pounds/square foot/hour loading-wet basis)

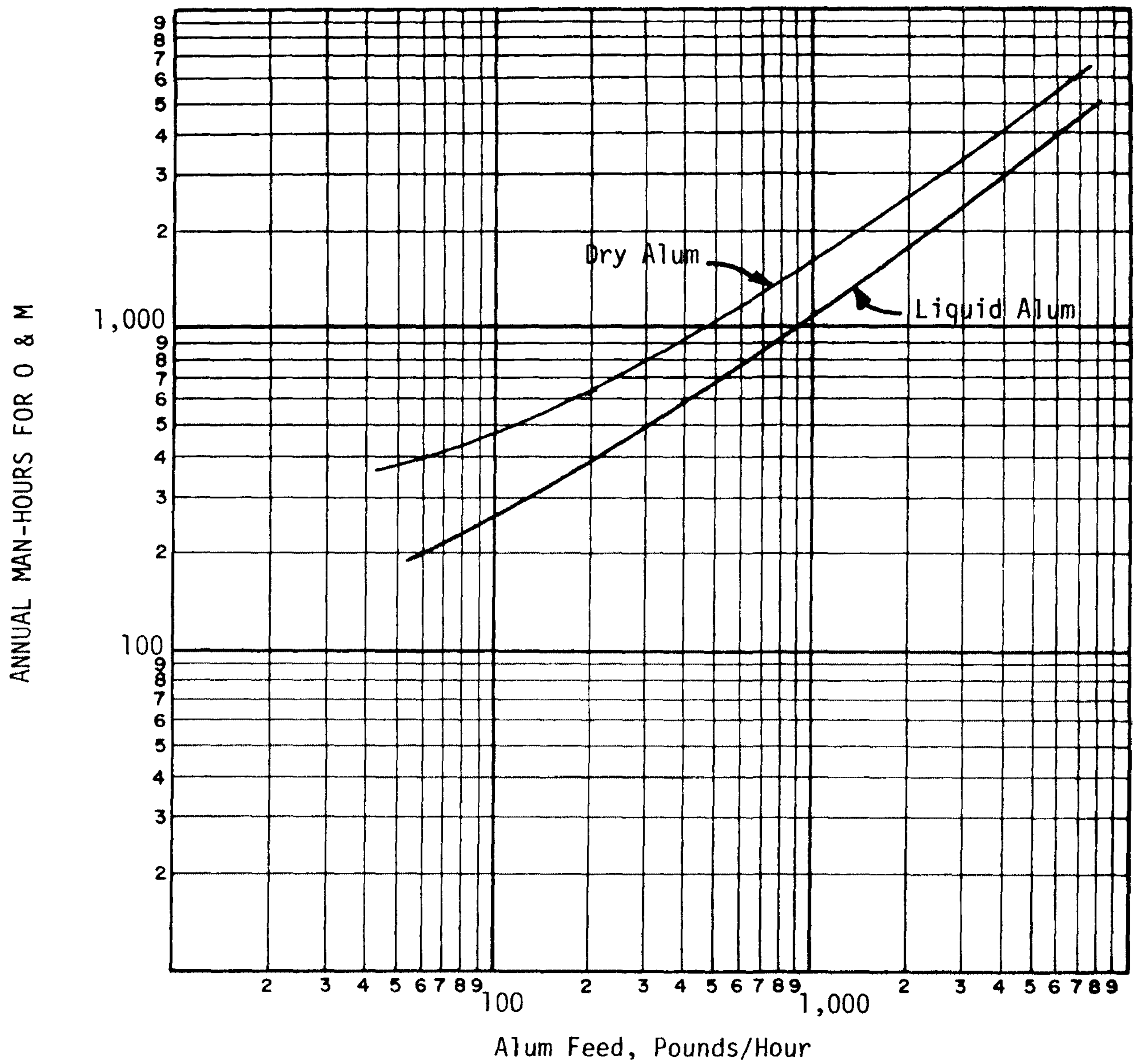
Curve 80



MULTIPLE HEARTH INCINERATION

MAINTENANCE MATERIAL COSTS
(70% operation time, 6 pounds/square foot/hour loading-wet basis)

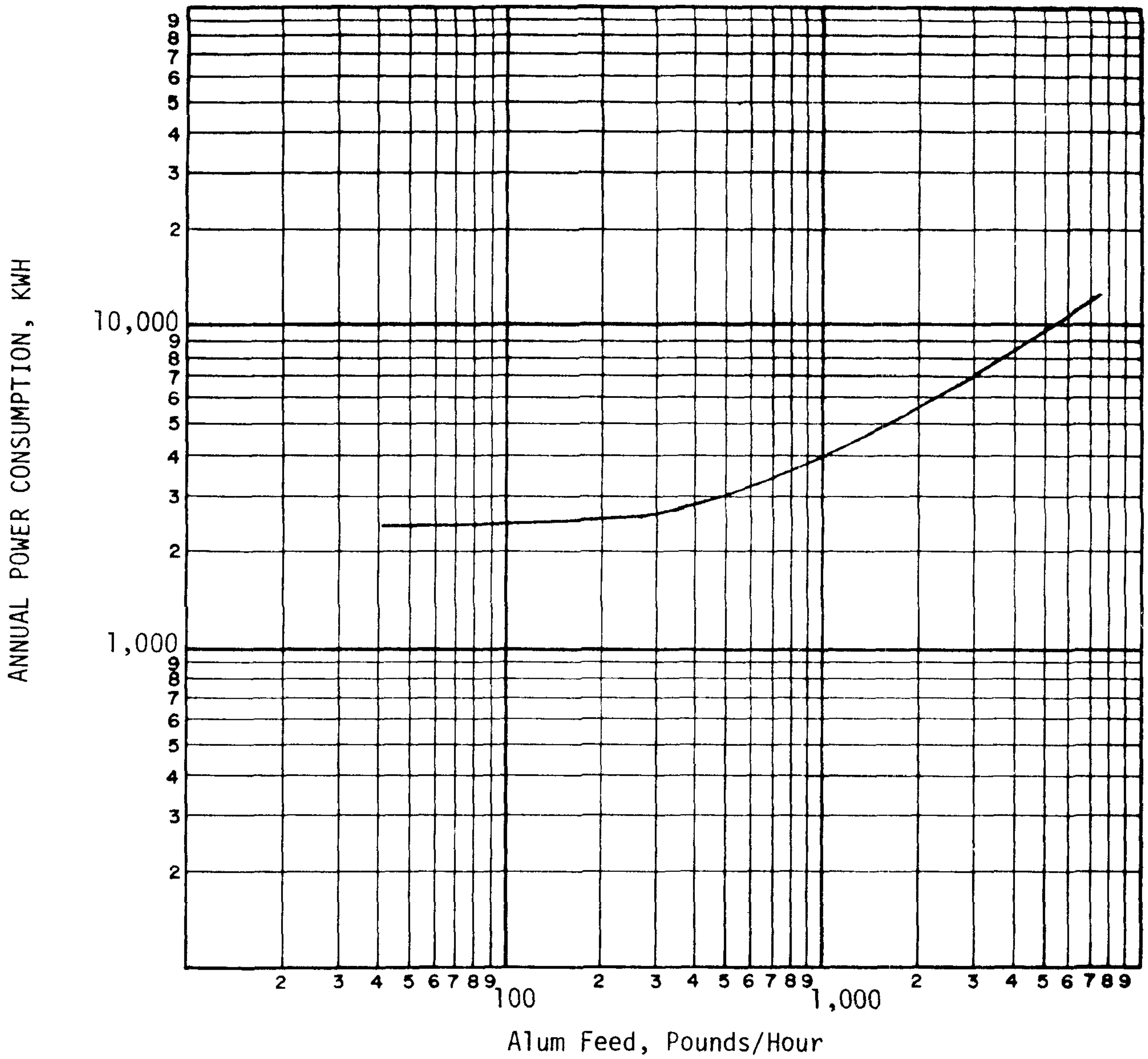
Curve 81



ALUM STORAGE AND FEEDING

MAN-HOUR REQUIREMENTS

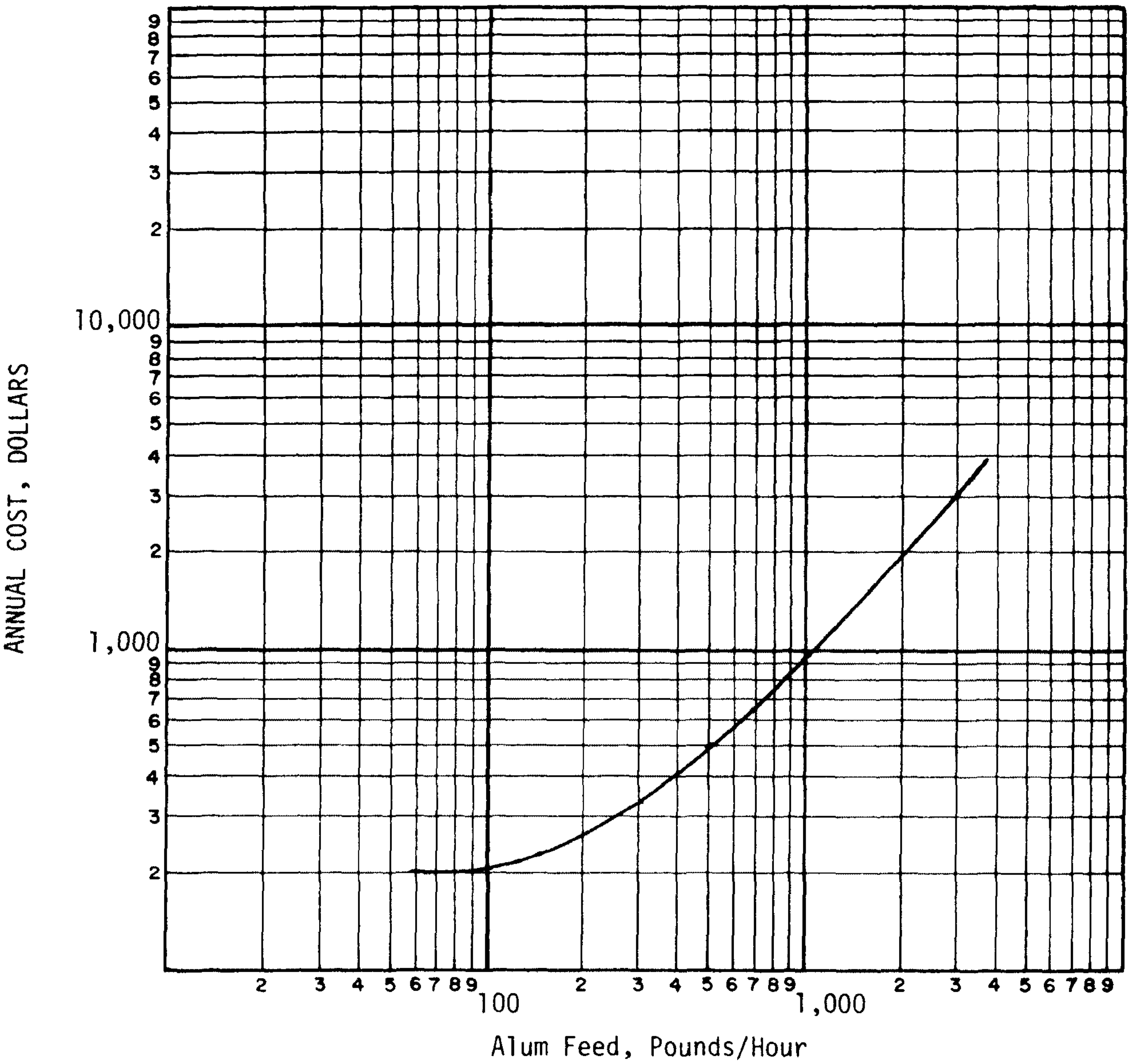
Curve 82



ALUM FEEDING

POWER REQUIREMENTS

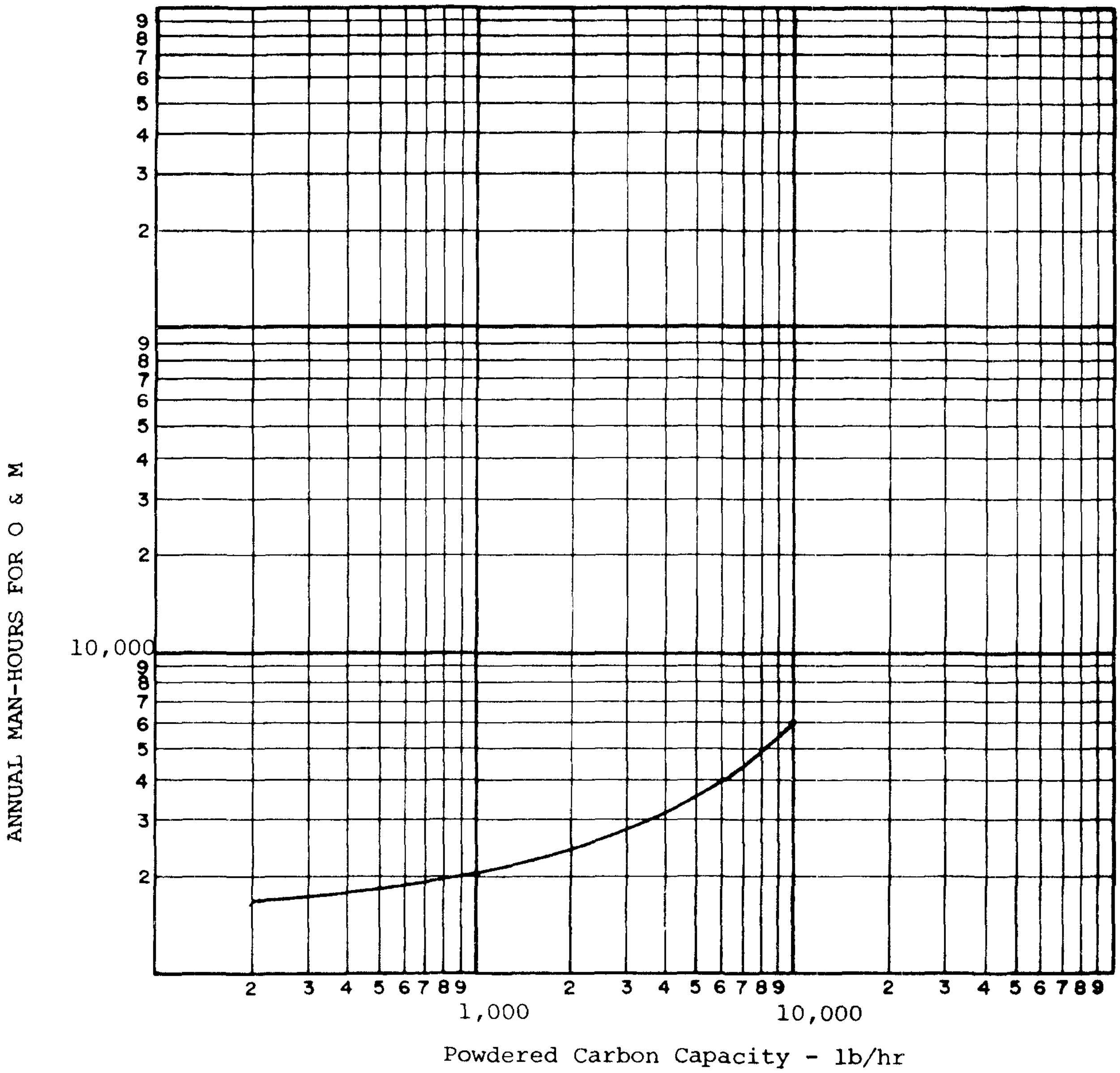
Curve 83



ALUM STORAGE AND FEEDING

MAINTENANCE MATERIAL COSTS

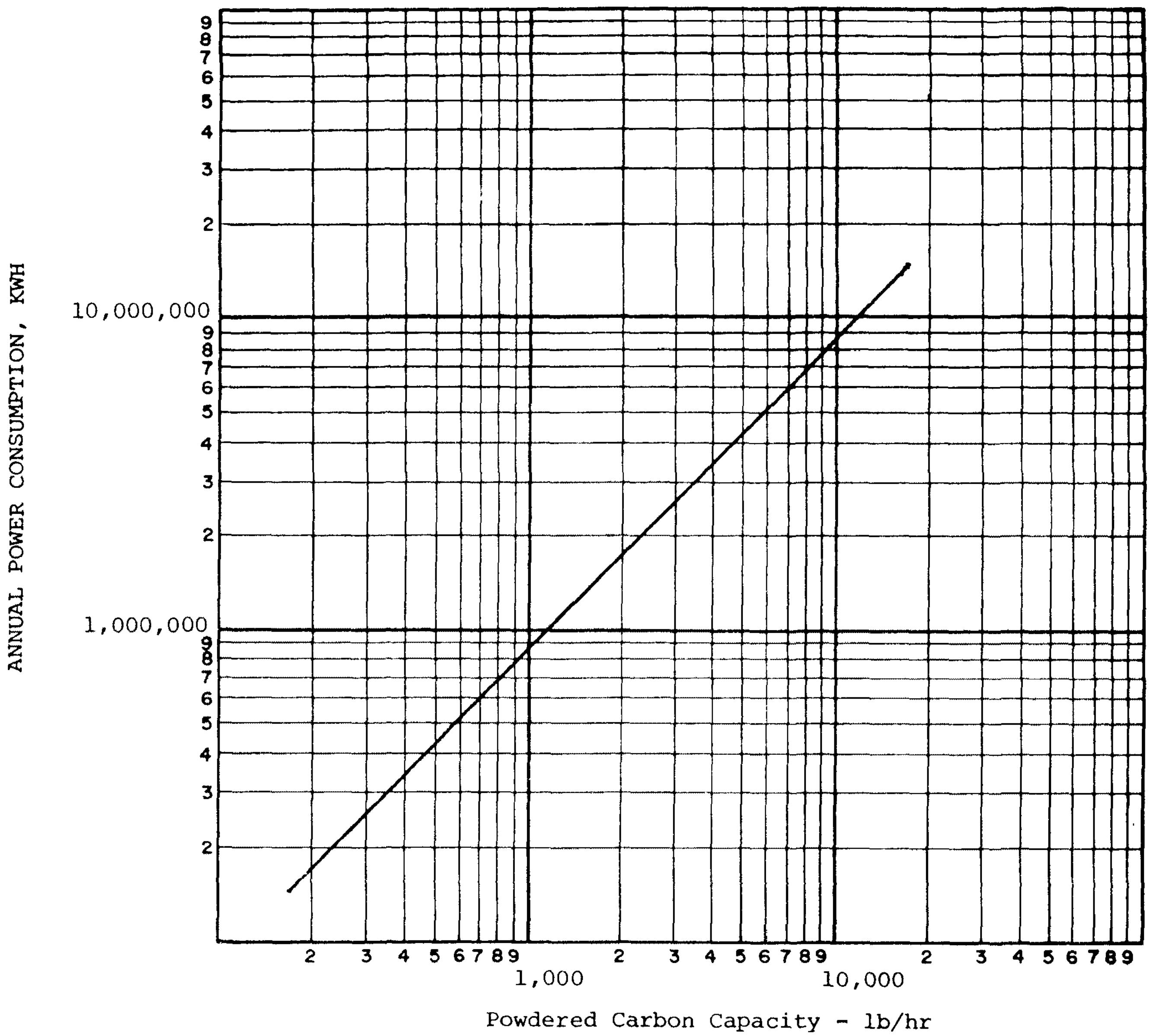
Curve 84



POWDERED ACTIVATED CARBON FEED SYSTEM

MAN-HOUR REQUIREMENTS

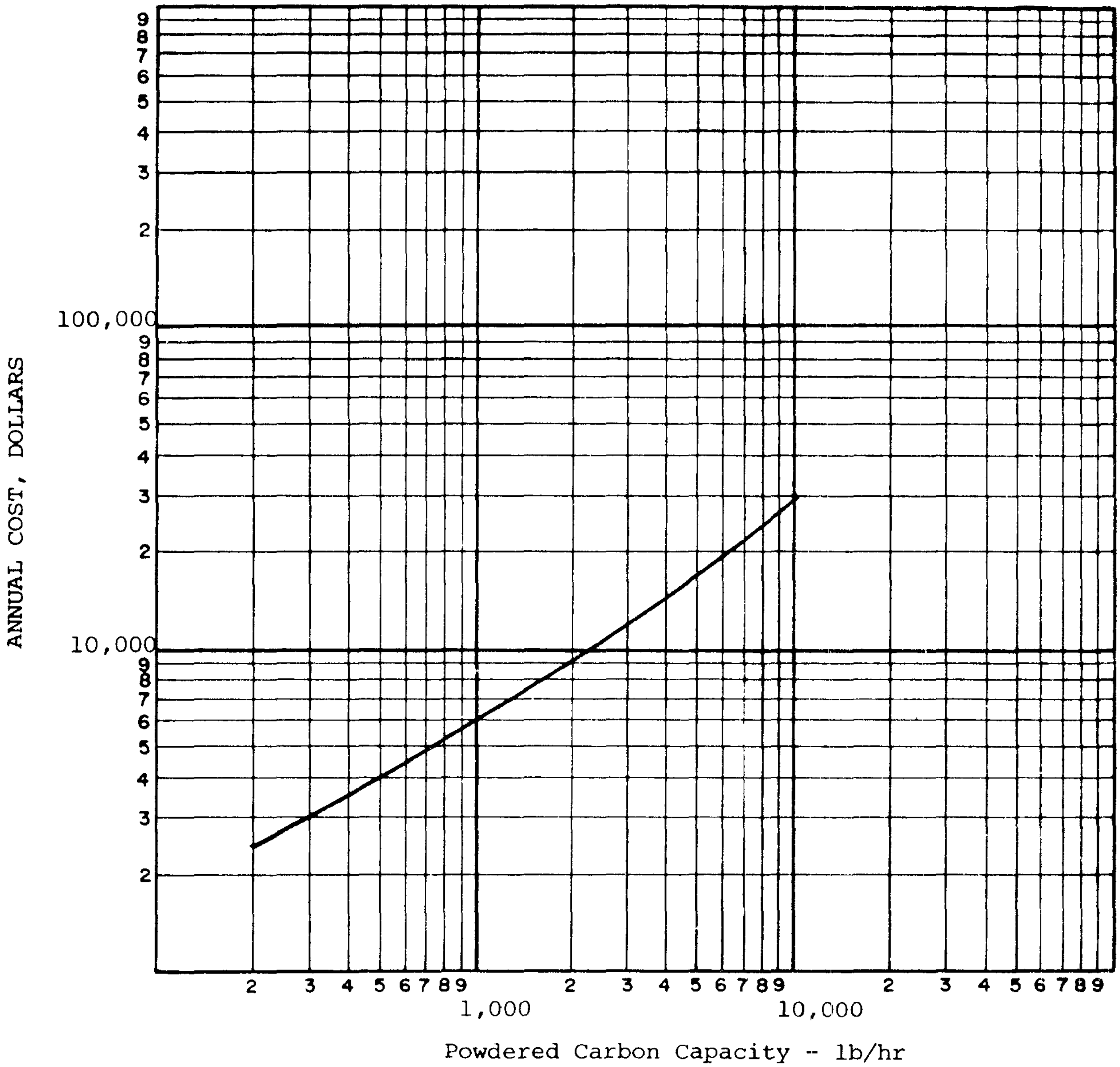
Curve 85



POWDERED ACTIVATED CARBON FEED SYSTEM

POWER REQUIREMENTS

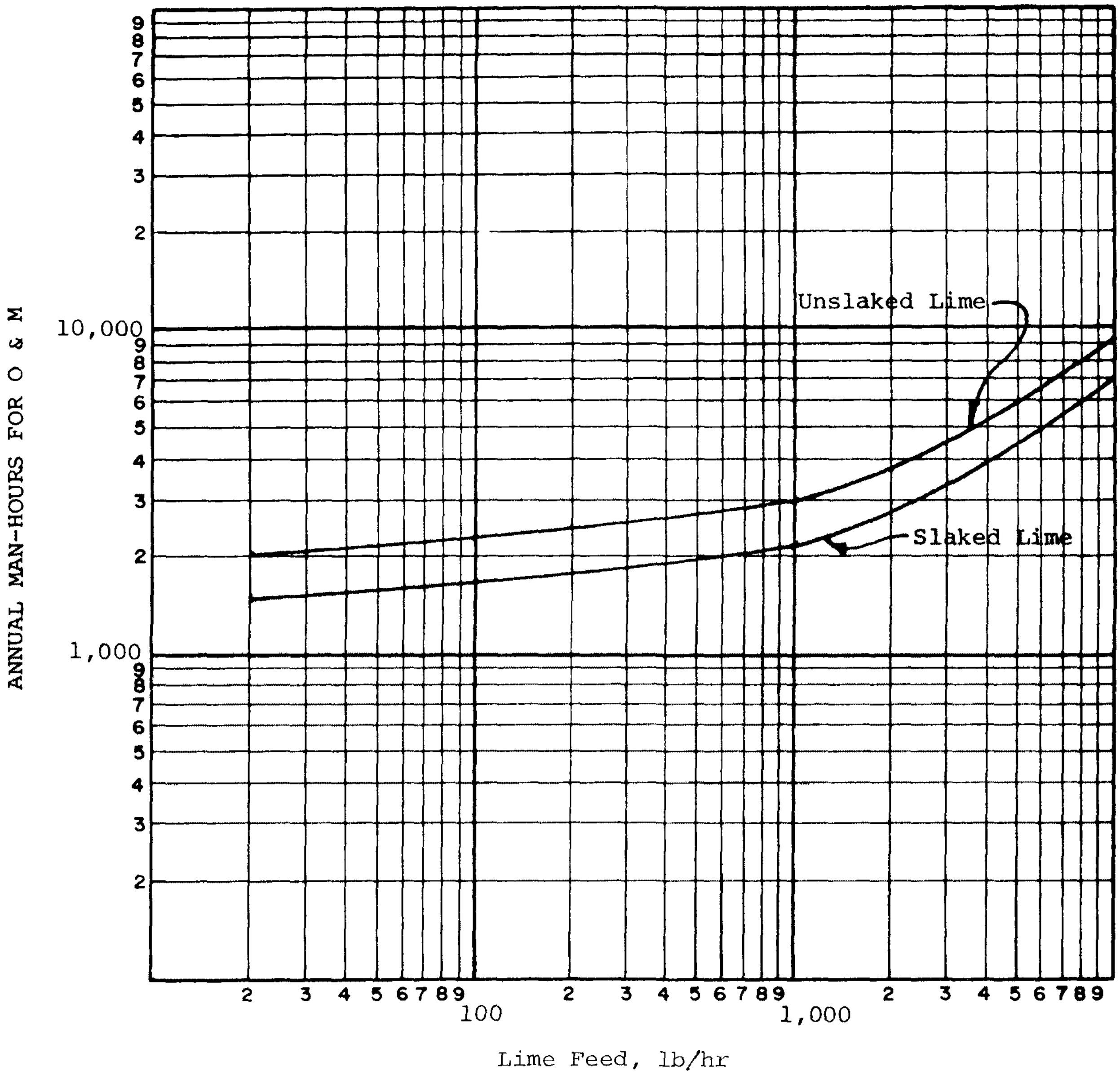
Curve 86



POWDERED ACTIVATED CARBON FEED SYSTEM

MAINTENANCE MATERIAL

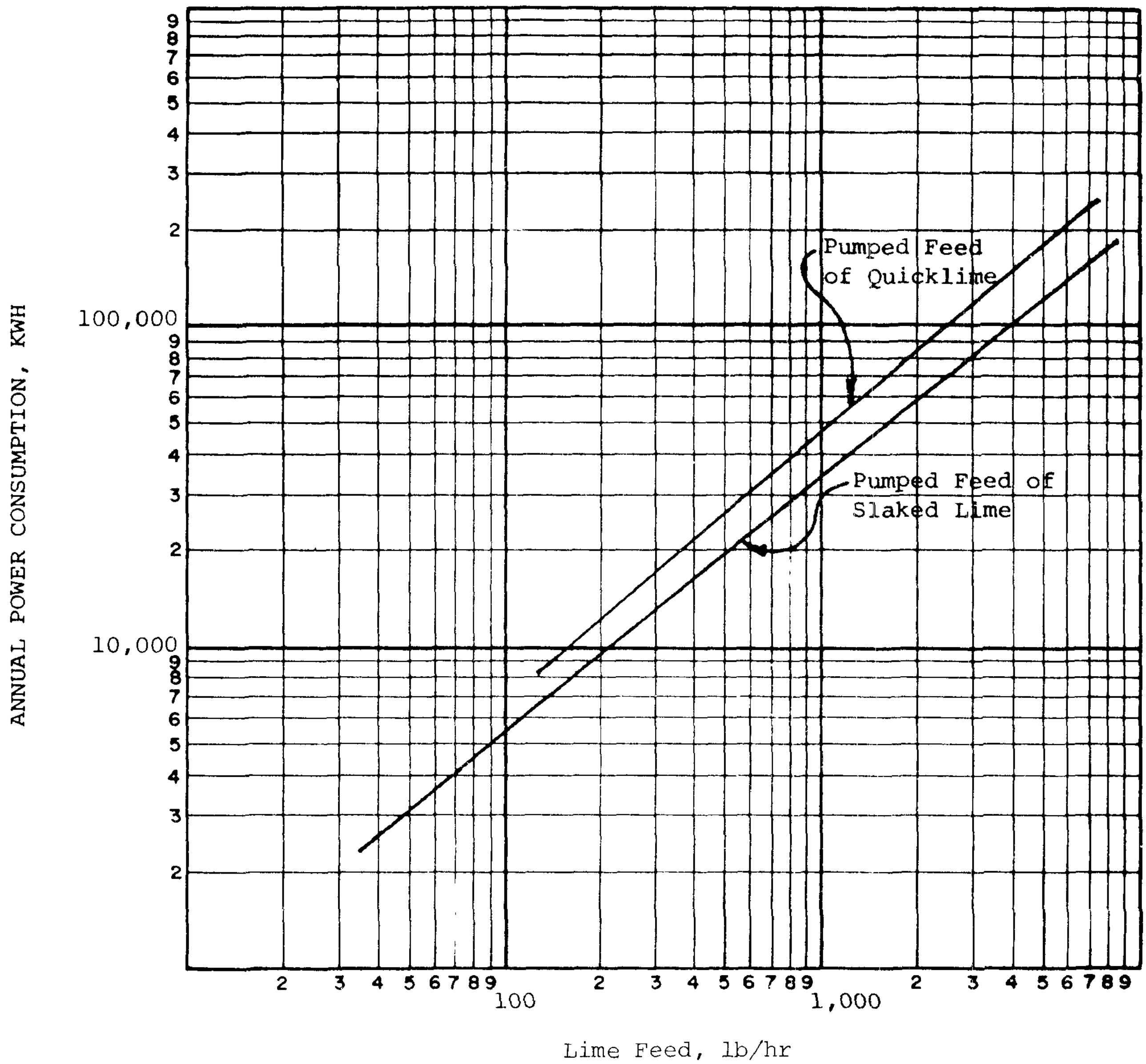
Curve 87



LIME STORAGE AND FEEDING

MAN-HOUR REQUIREMENTS

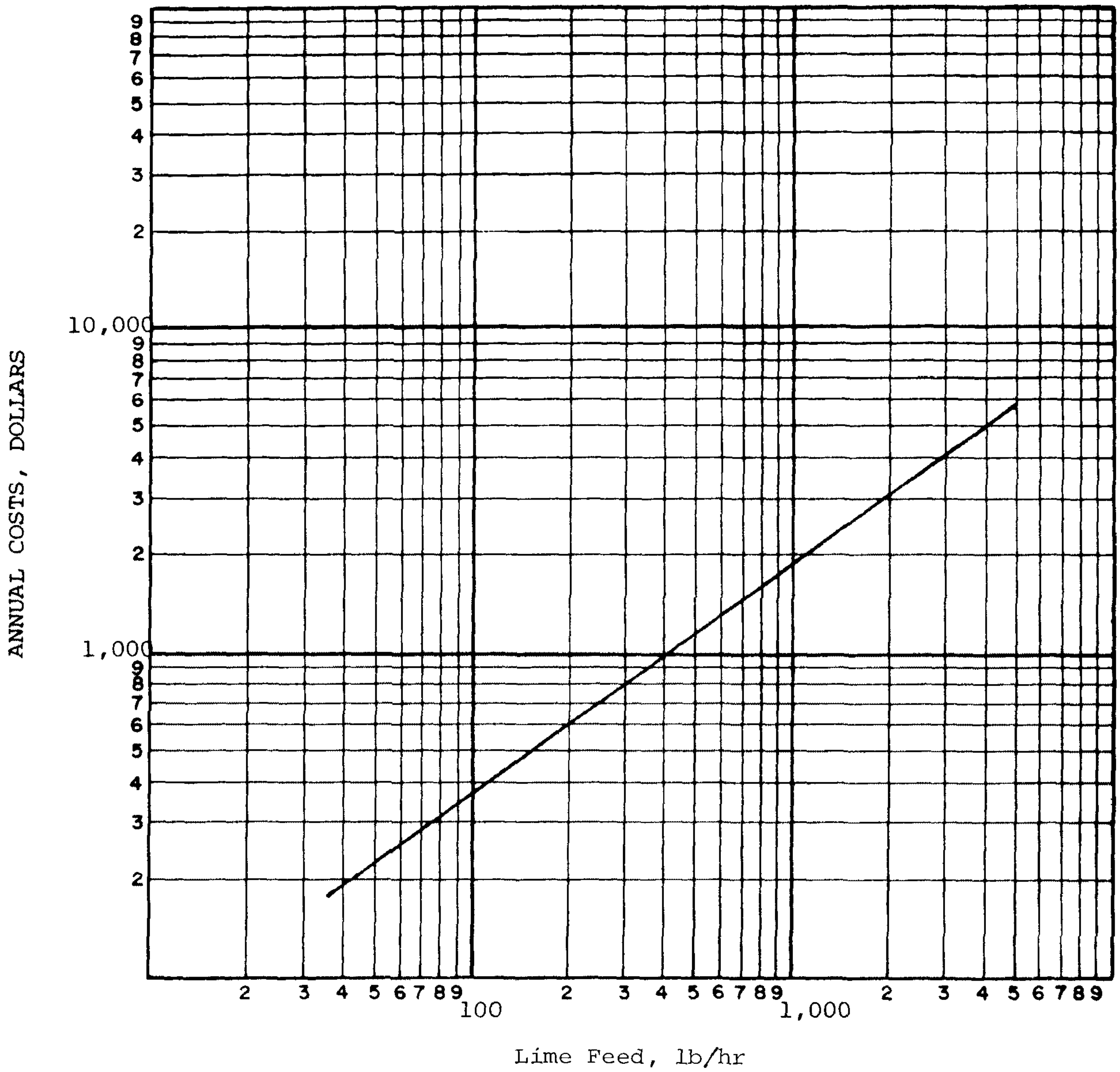
Curve 88



LIME FEEDING

POWER REQUIREMENTS

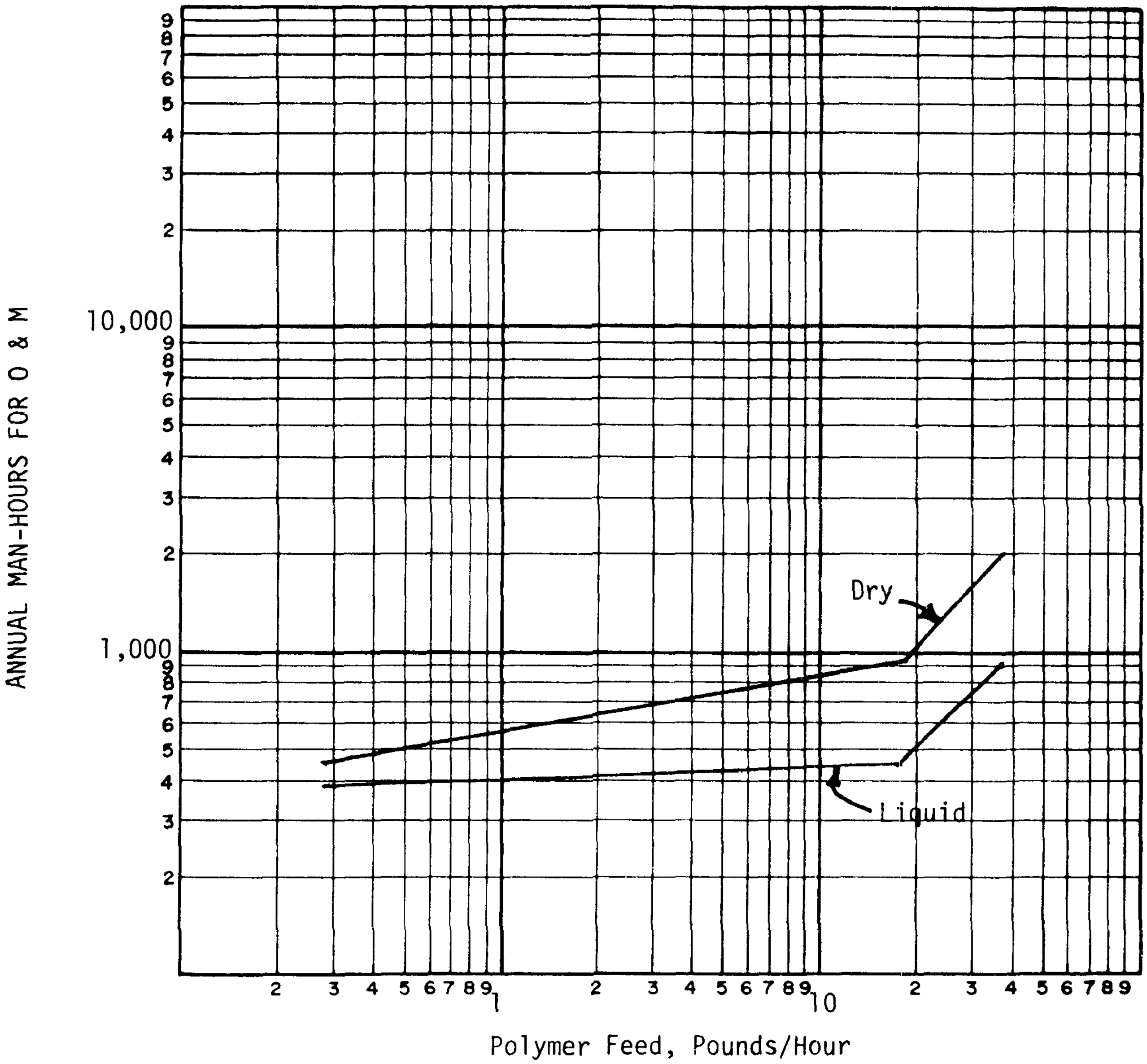
Curve 89



LIME STORAGE AND FEEDING

MAINTENANCE MATERIAL COSTS

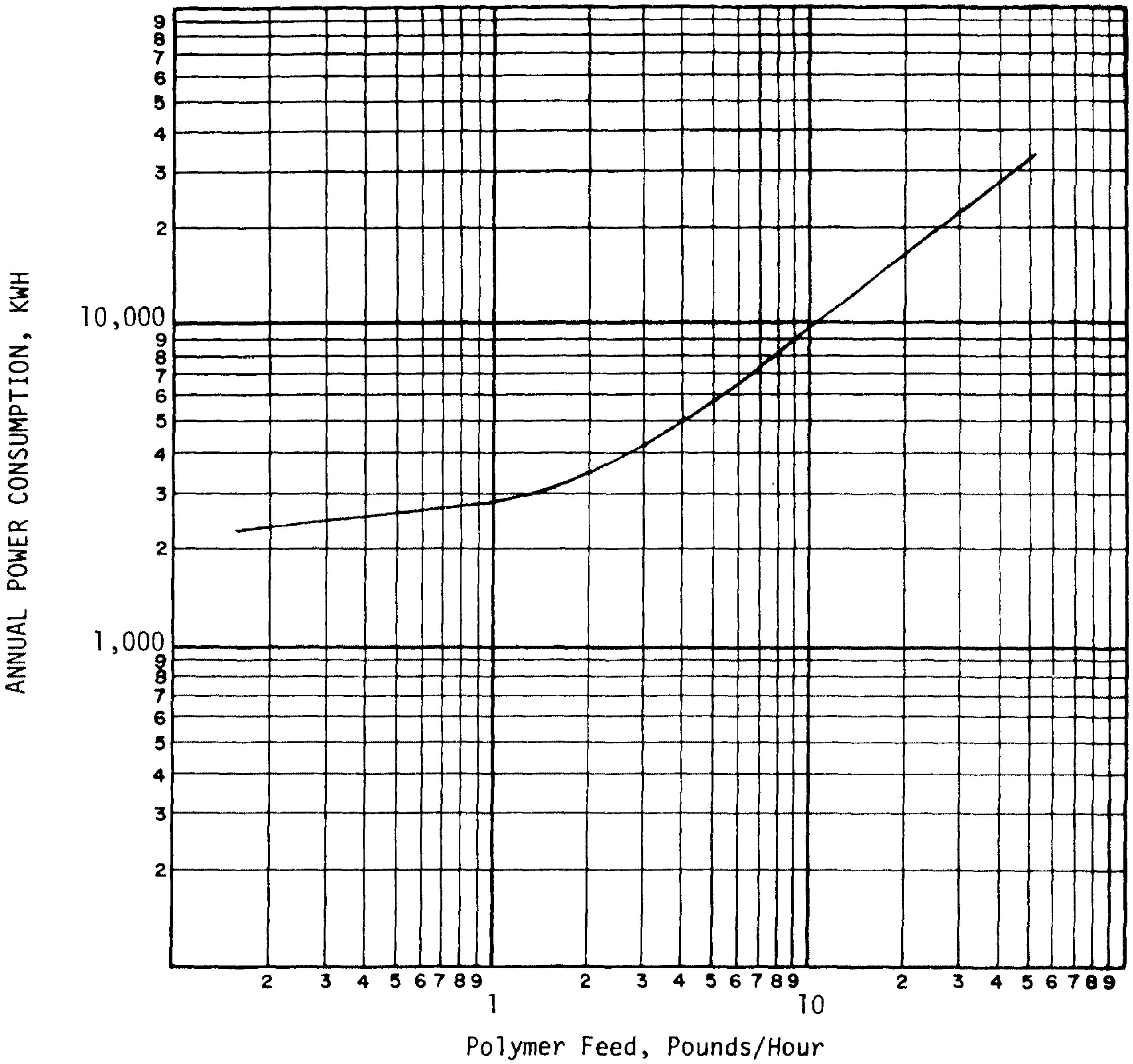
Curve 90



POLYMER FEEDING

MAN-HOUR REQUIREMENTS

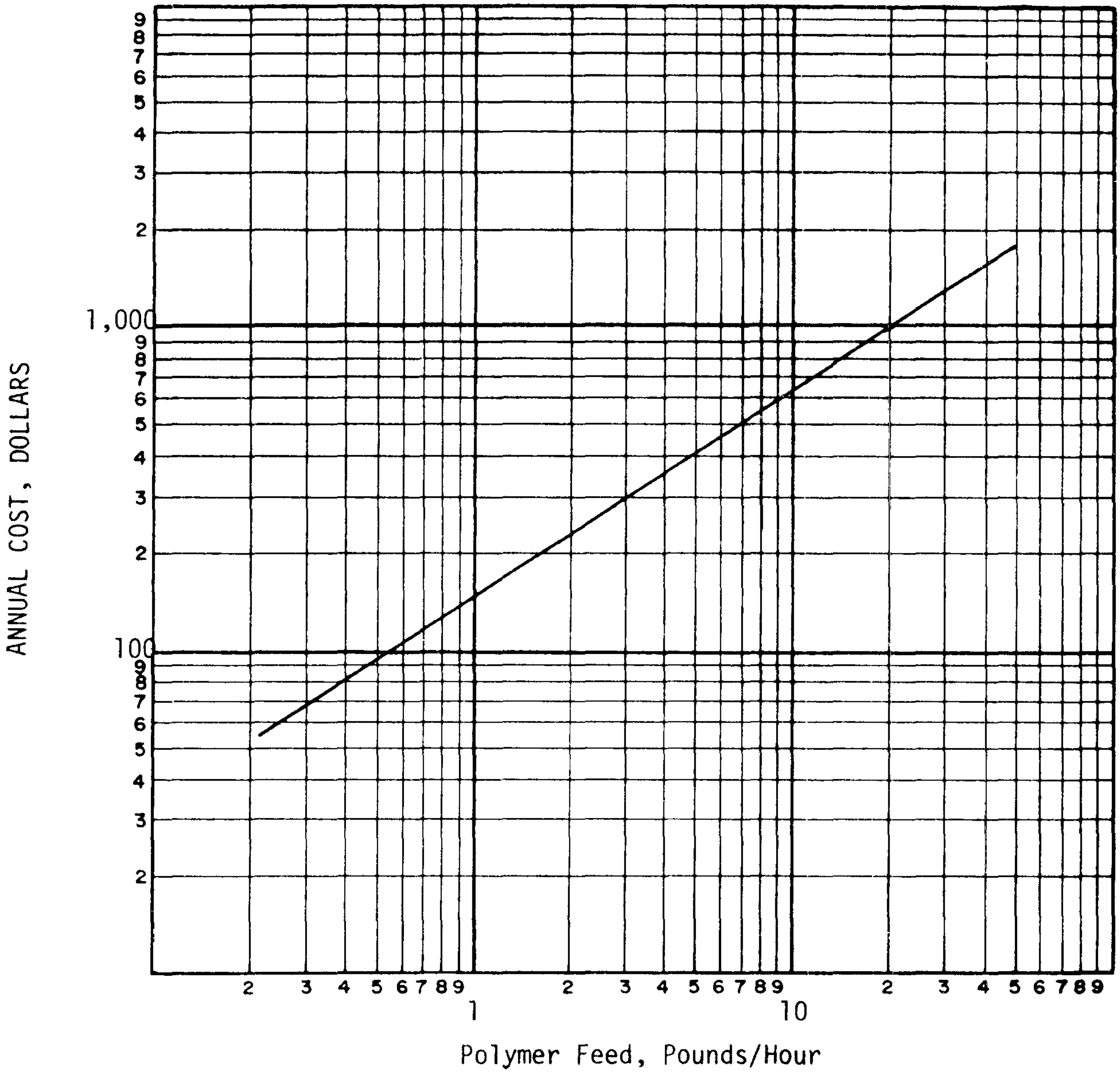
Curve 91



POLYMER MIXING AND FEEDING

POWER REQUIREMENTS

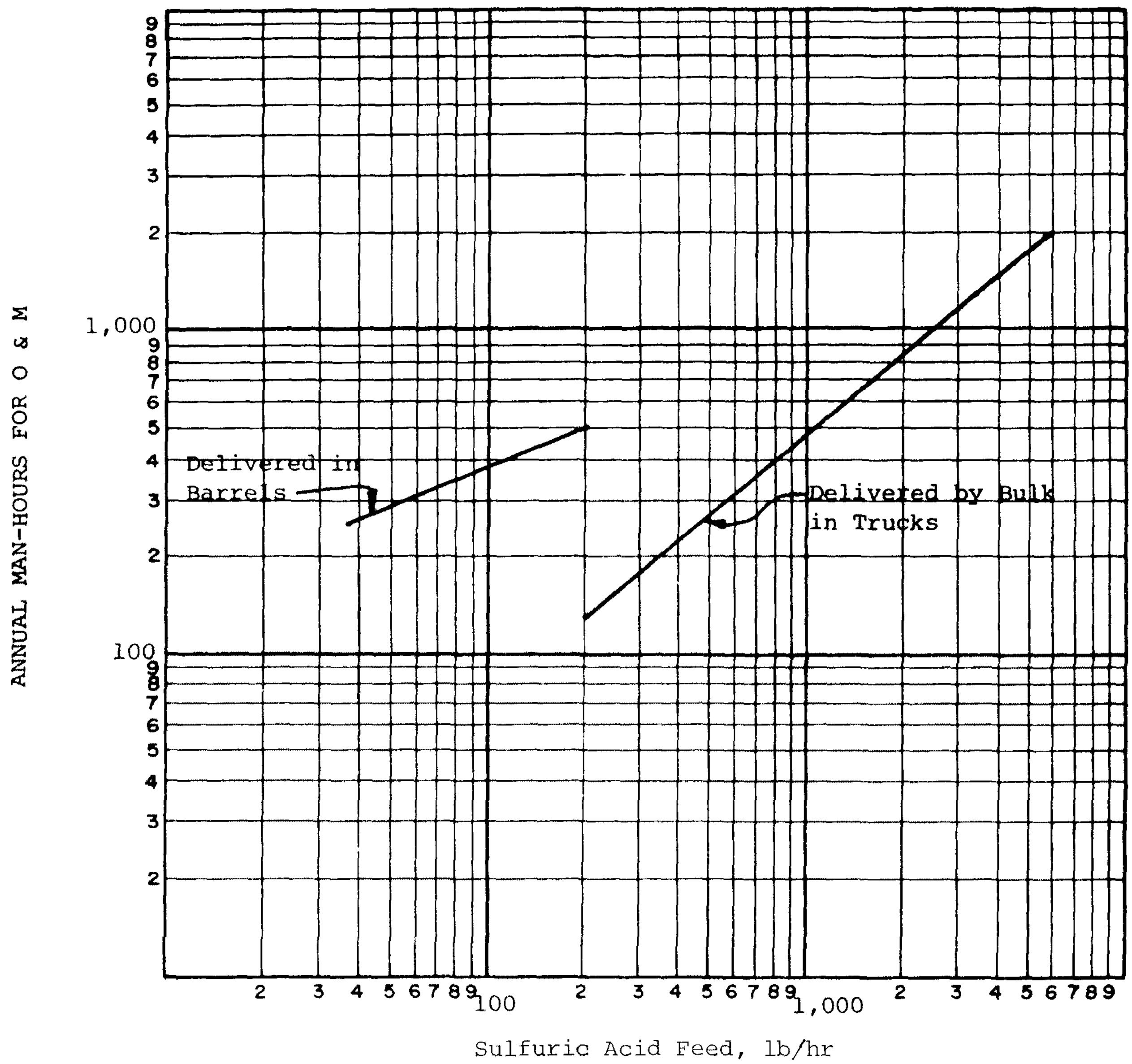
Curve 92



POLYMER STORAGE AND FEEDING

MAINTENANCE MATERIAL COSTS

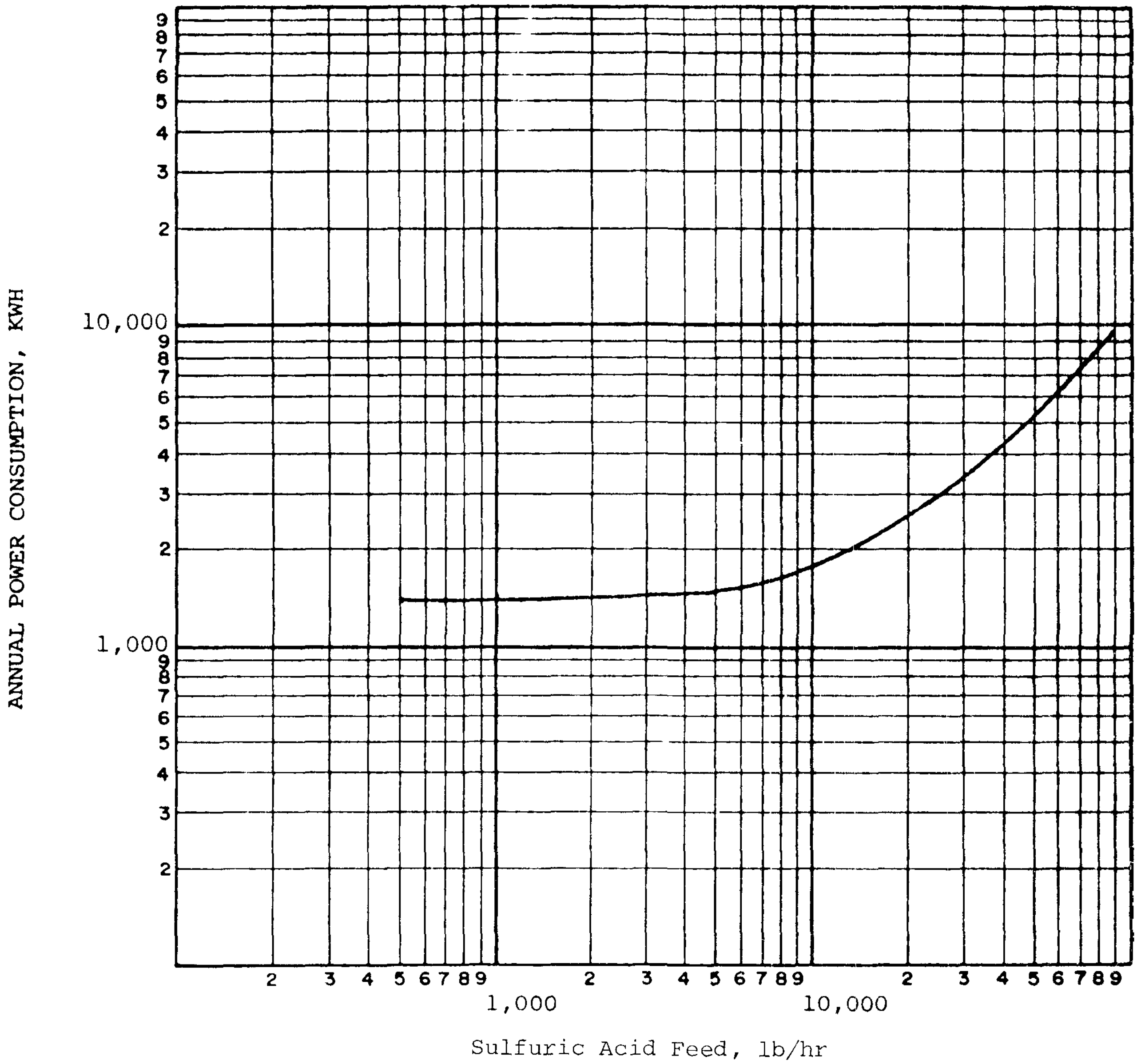
Curve 93



SULFURIC ACID FEED

MAN-HOUR REUQIREMENTS

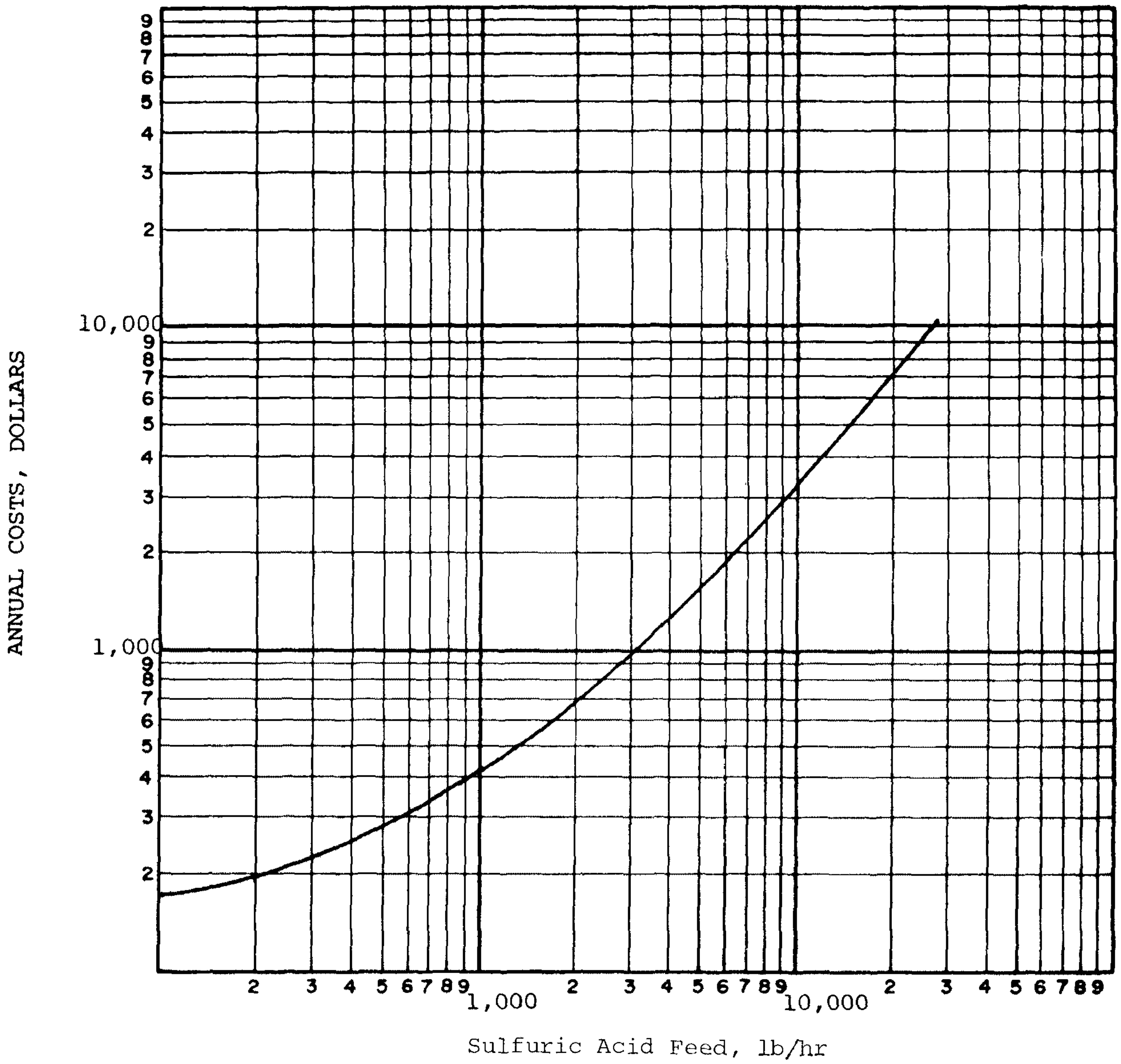
Curve 94



SULFURIC ACID FEED

POWER REQUIREMENTS

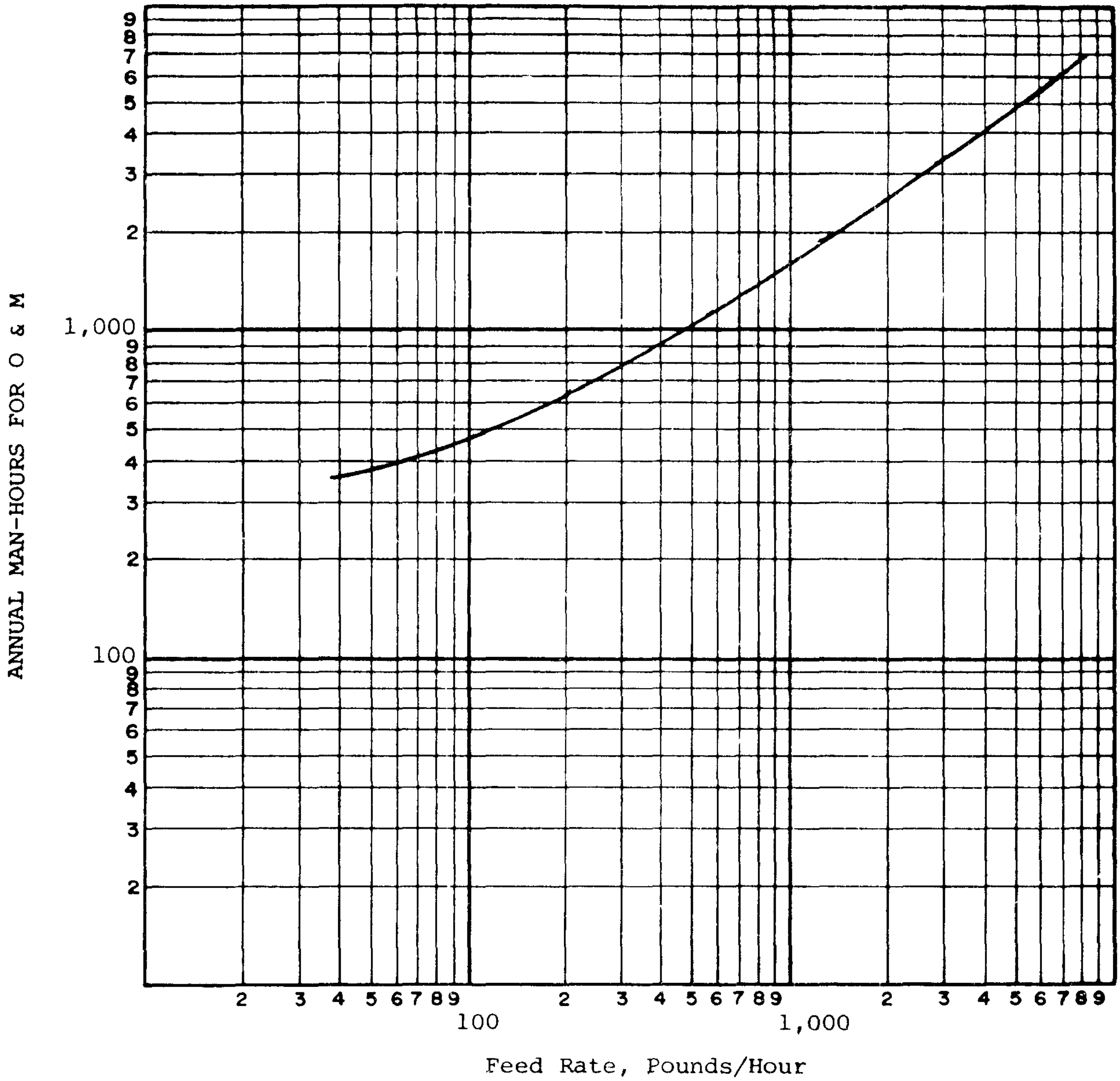
Curve 95



SULFURIC ACID STORAGE AND FEEDING

MAINTENANCE MATERIAL COSTS

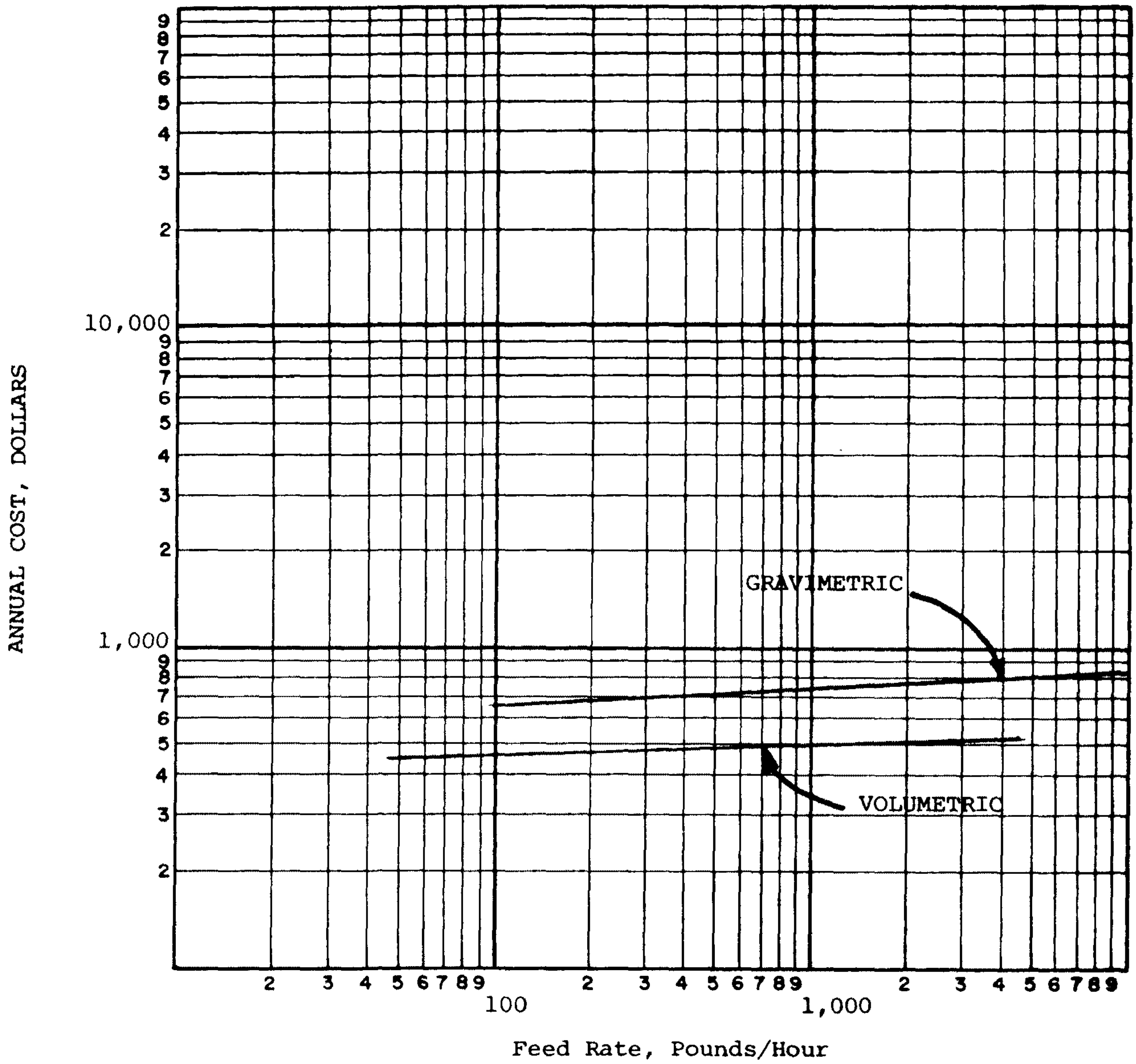
Curve 96



DRY CHEMICAL FEED SYSTEMS

MAN-HOUR REQUIREMENTS

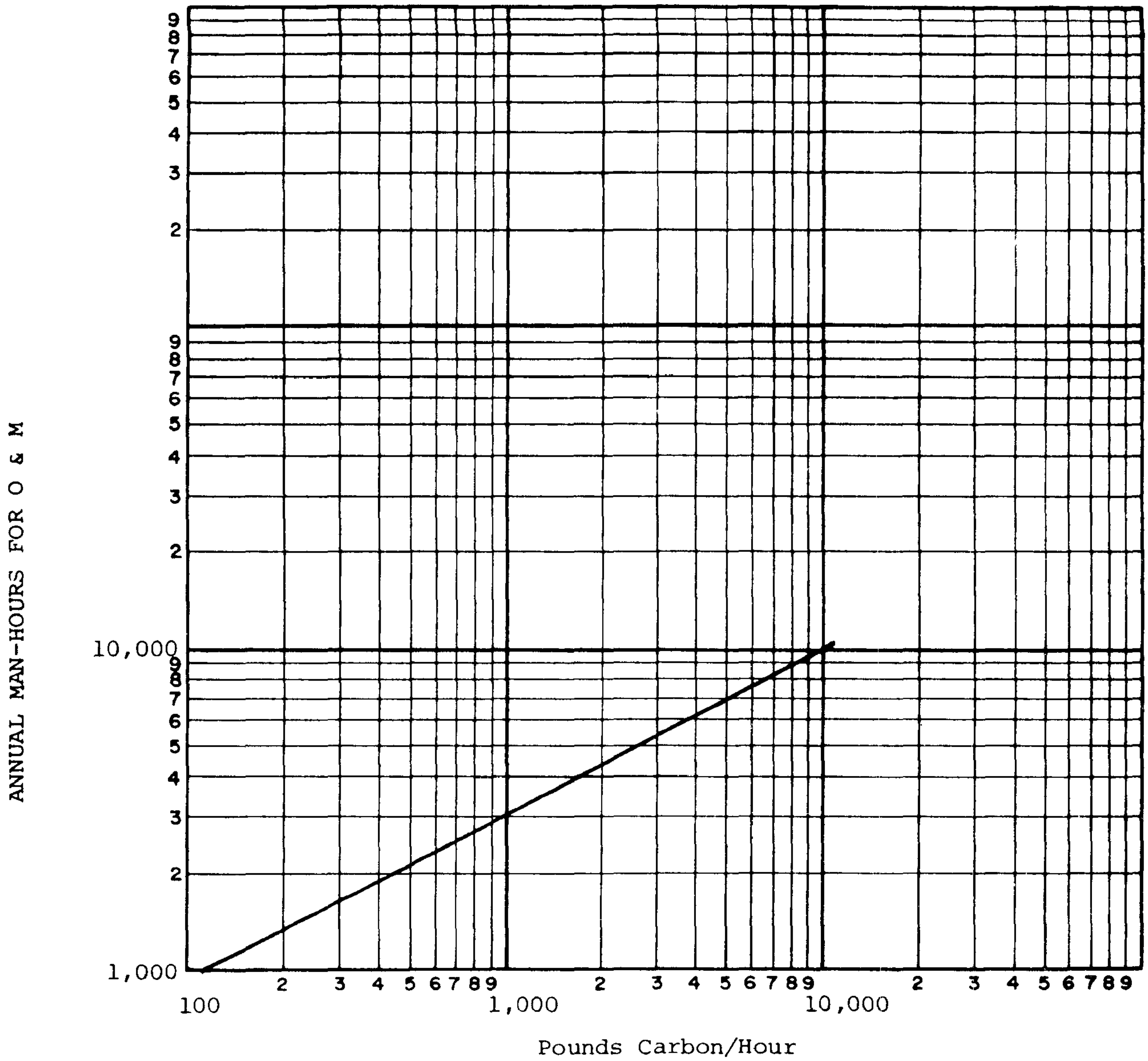
Curve 97



DRY CHEMICAL FEED SYSTEMS

MAINTENANCE MATERIAL COSTS

Curve 98

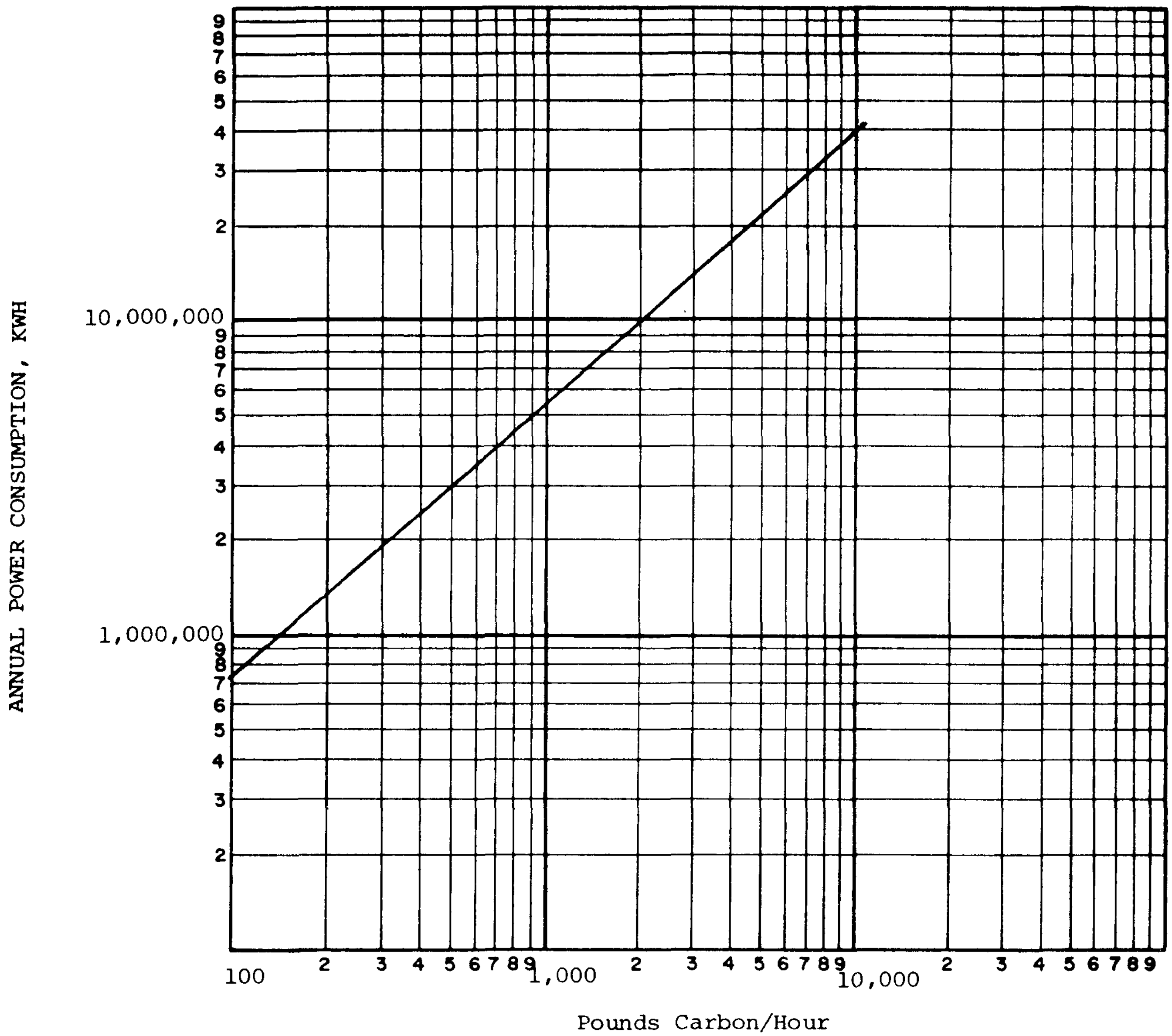


FLUIDIZED BED REGENERATION SYSTEM

MAN-HOUR REQUIREMENTS

(Based on Full Time Operation)

Curve 99

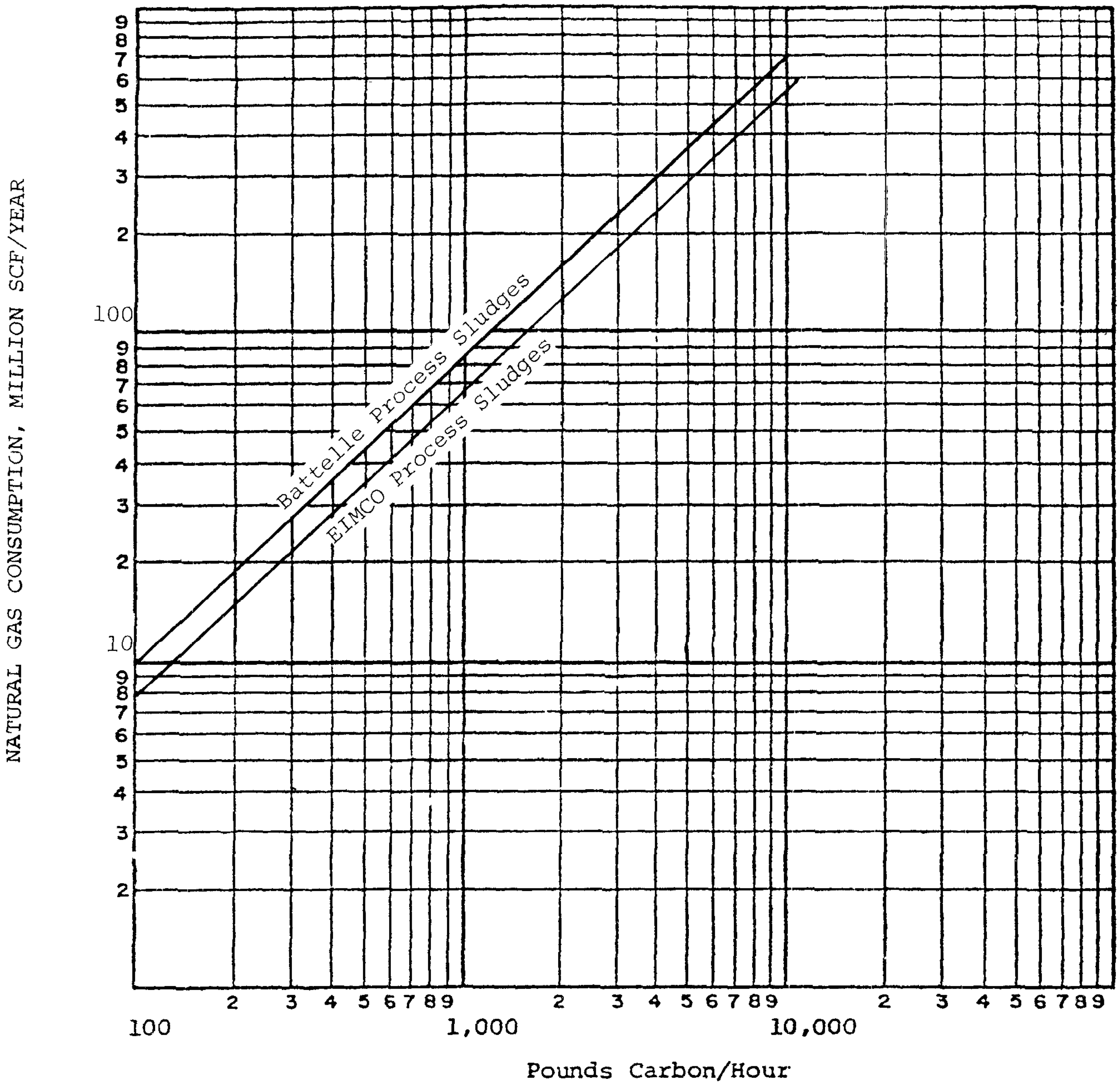


FLUIDIZED BED REGENERATION SYSTEM

POWER REQUIREMENTS

(Based on Full Time Operation)

Curve 100

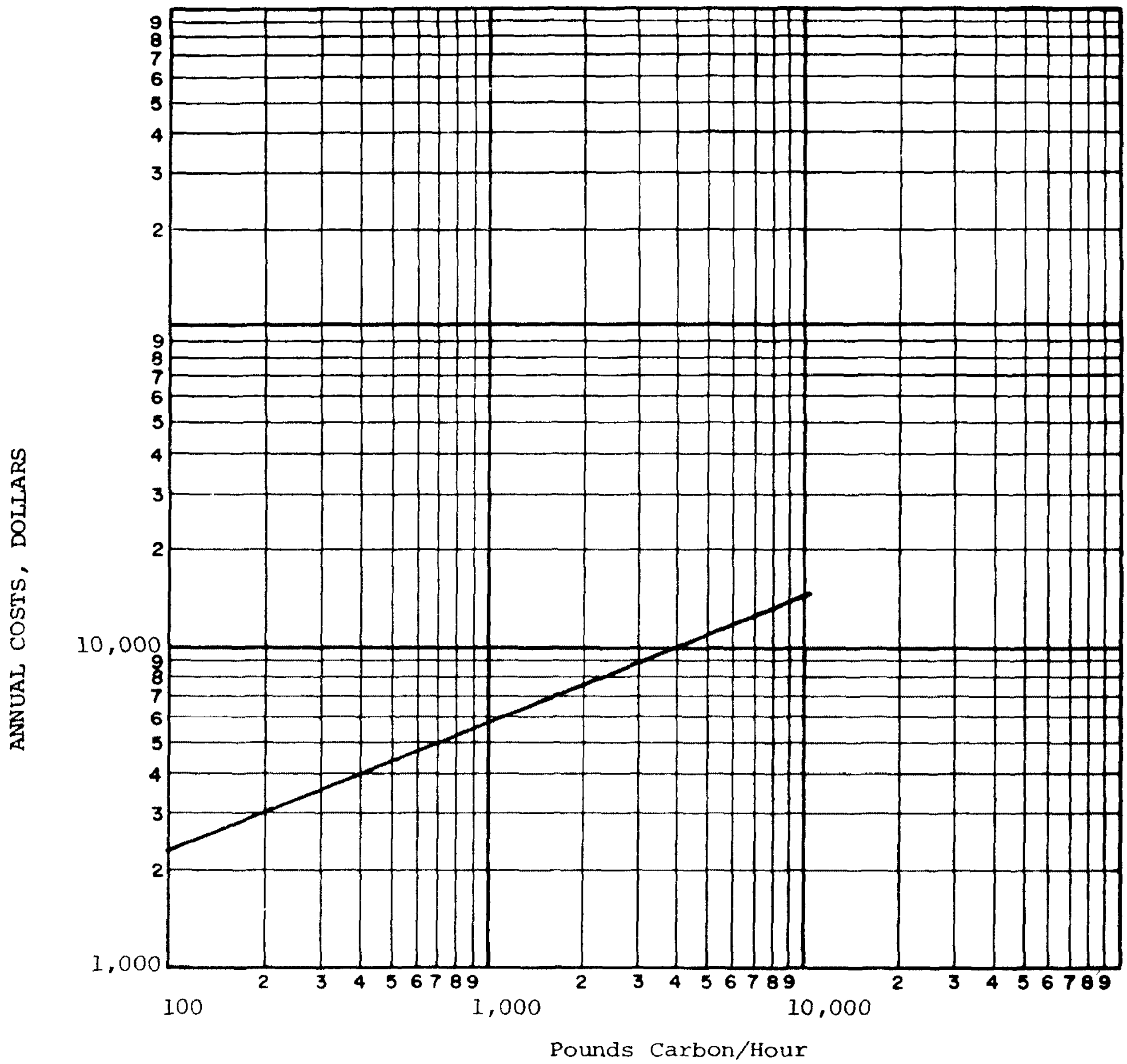


FLUIDIZED BED REGENERATION SYSTEM

FUEL REQUIREMENTS

(Based on Full Time Operation)

Curve 101

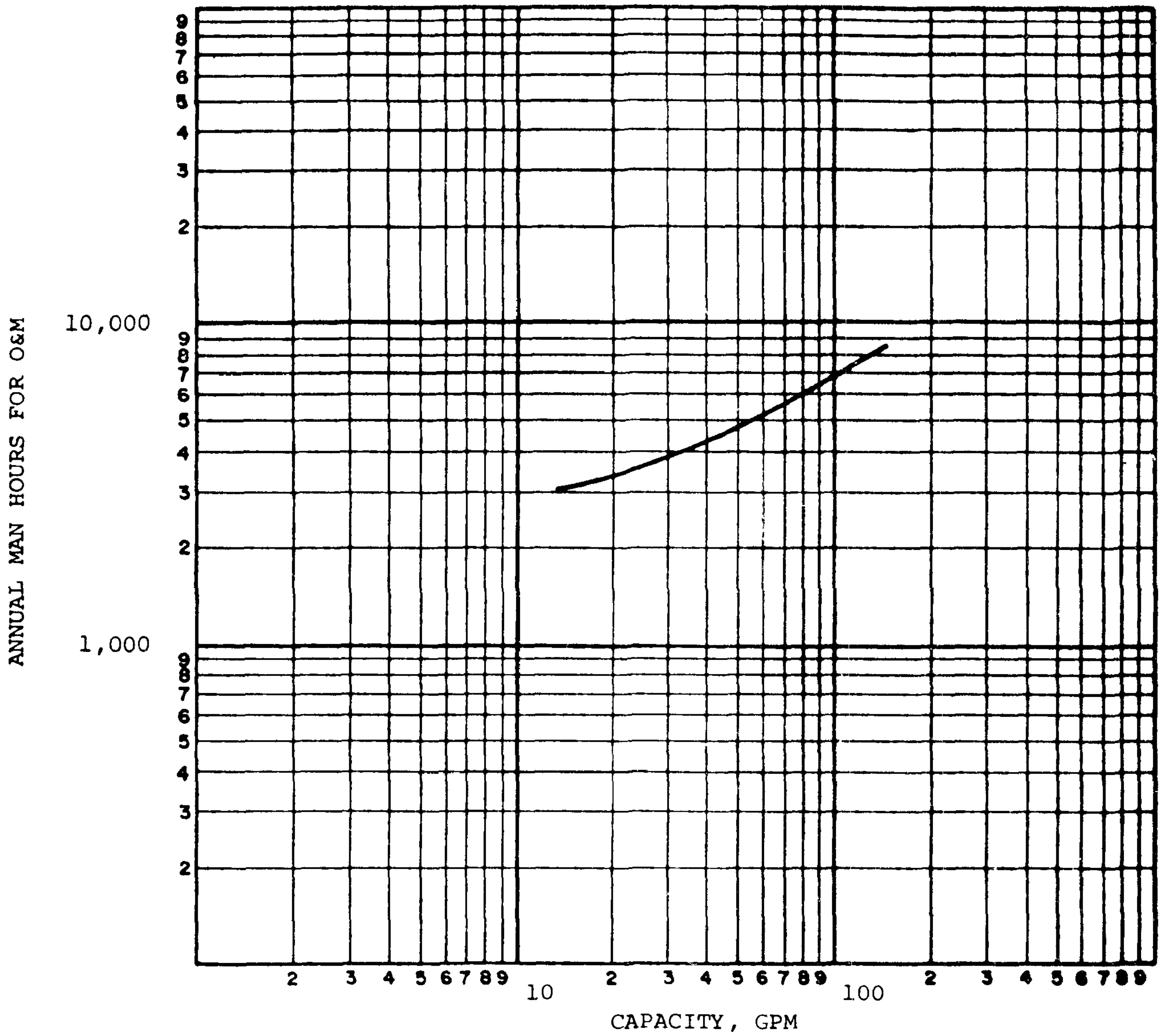


FLUIDIZED BED REGENERATION SYSTEM

MAINTENANCE MATERIALS

(Based on Full Time Operation)

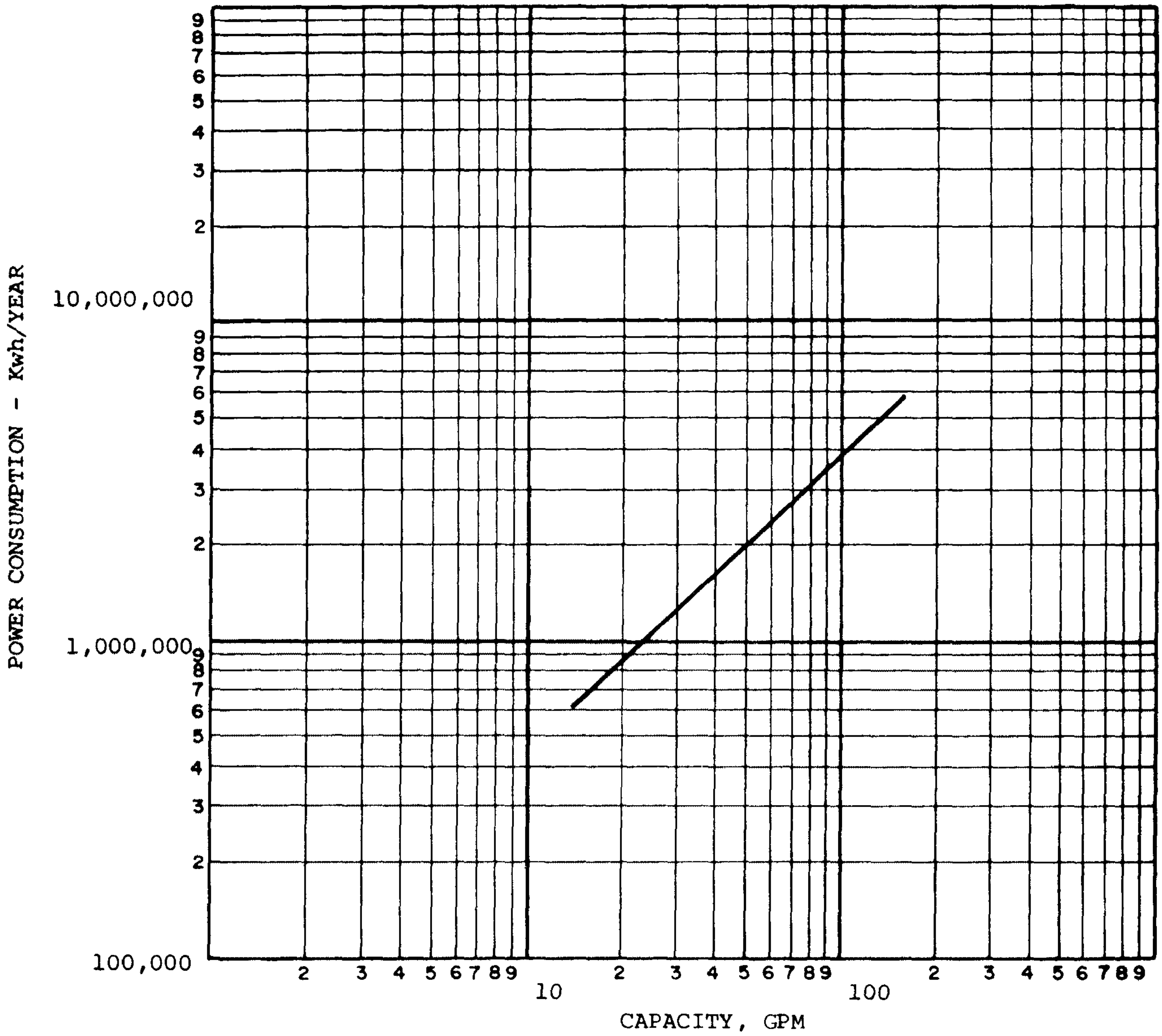
Curve 102



WET AIR REGENERATION SYSTEM

MAN HOUR REQUIREMENTS

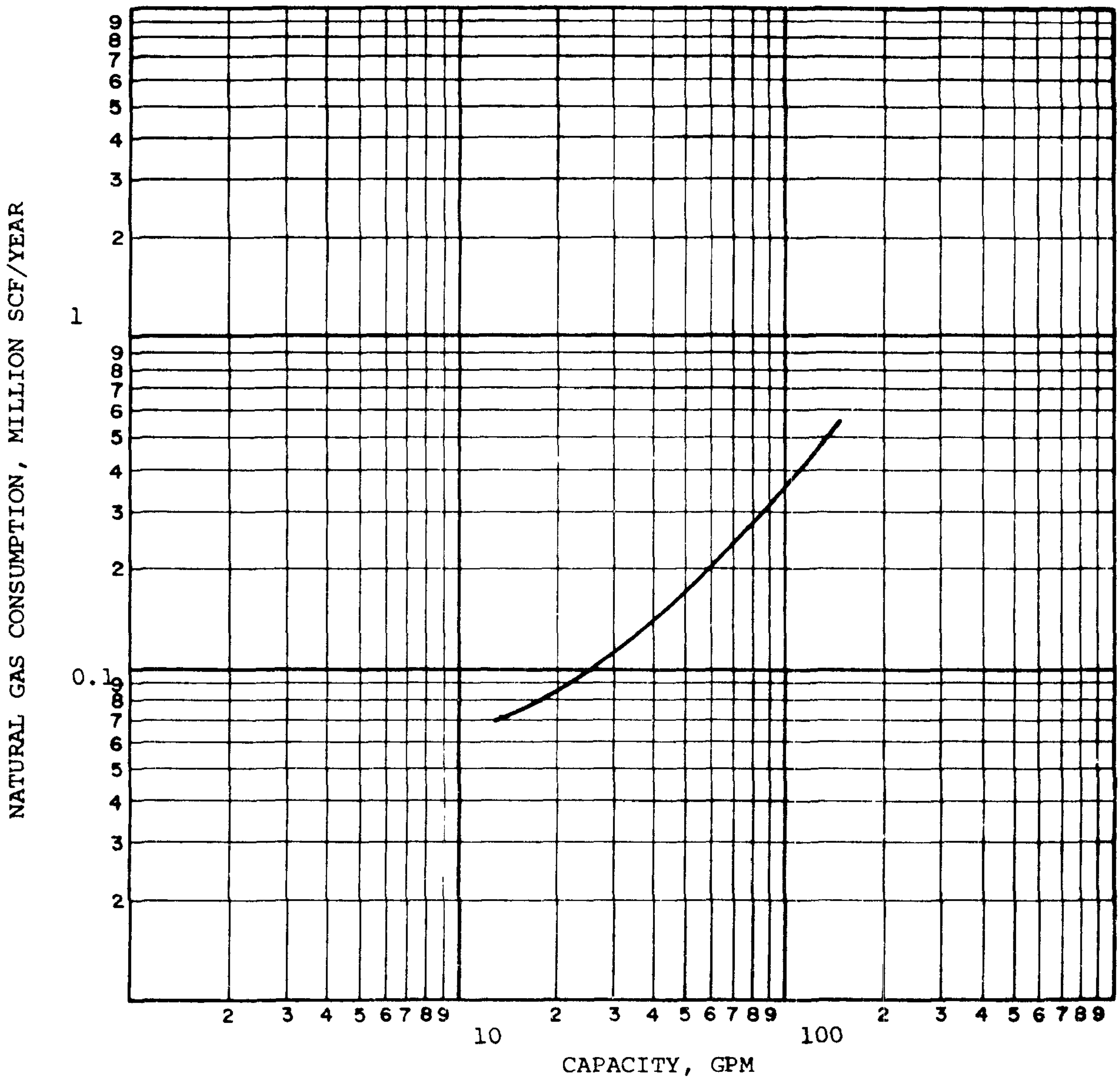
Curve 103



WET AIR REGENERATION SYSTEM

POWER REQUIREMENTS

Curve 104

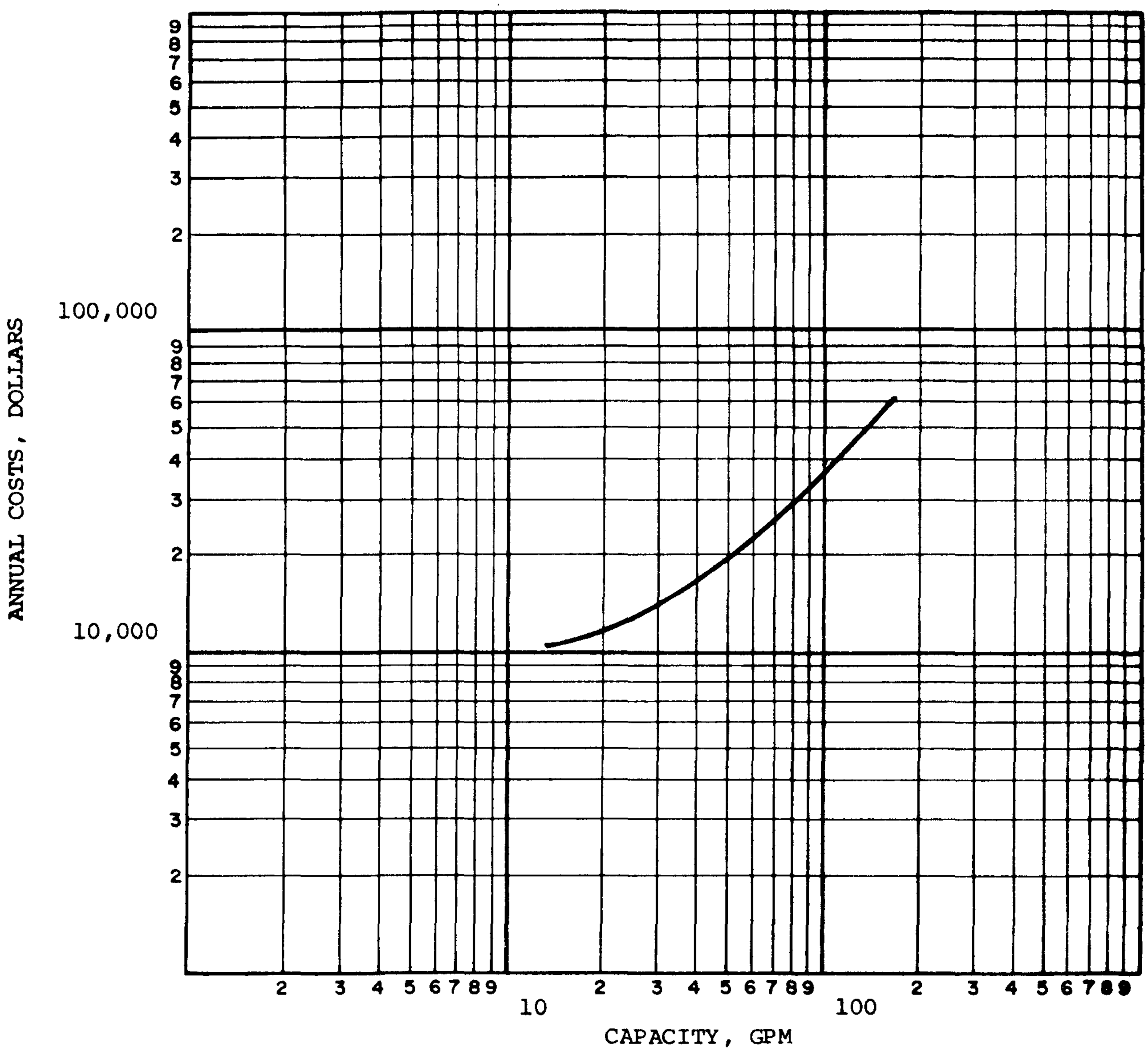


WET AIR REGENERATION SYSTEM

FUEL REQUIREMENTS

(Based on sludge characteristics shown in Table 101)

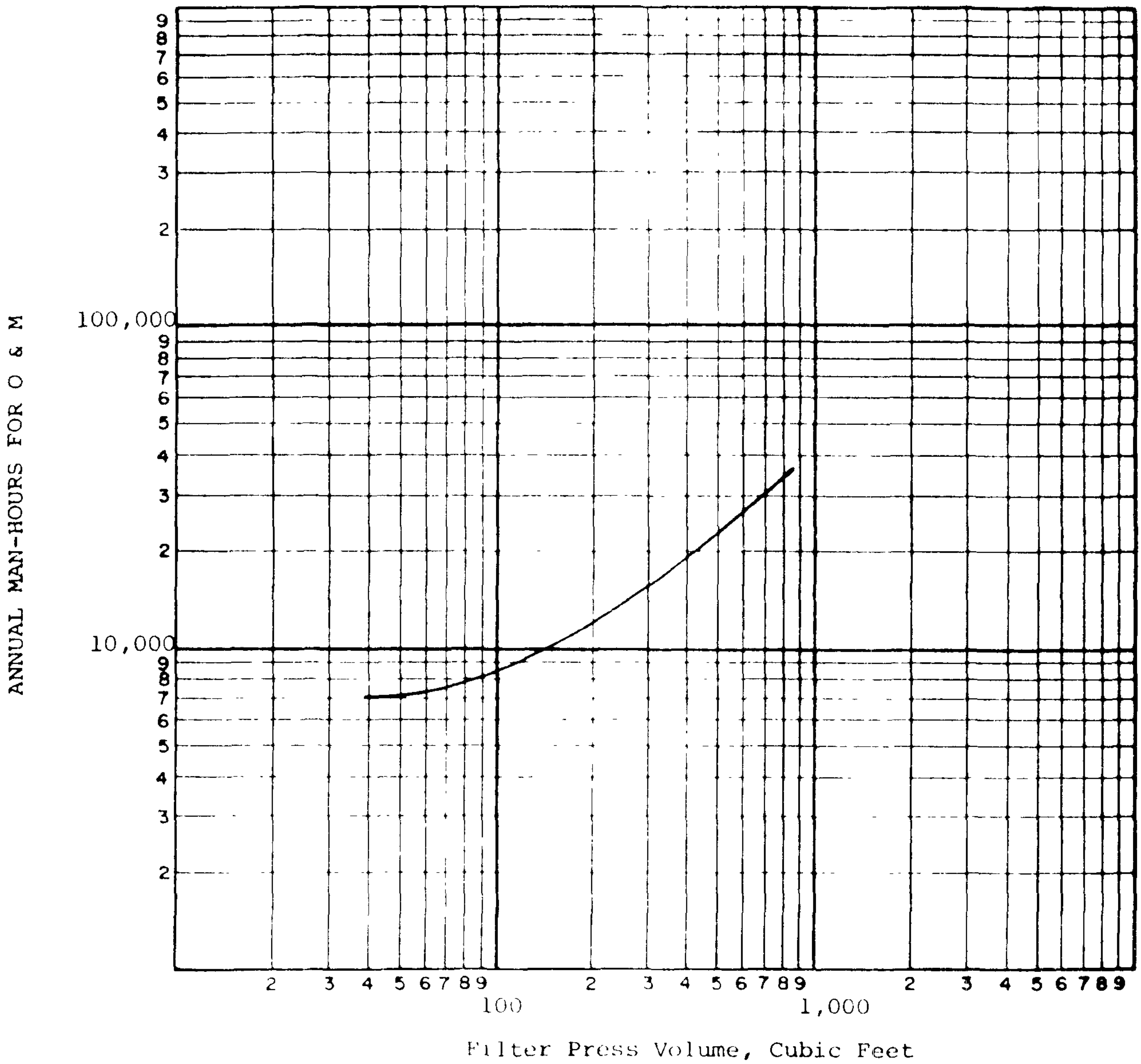
Curve 105



WET AIR REGENERATION SYSTEM

MAINTENANCE MATERIAL COSTS

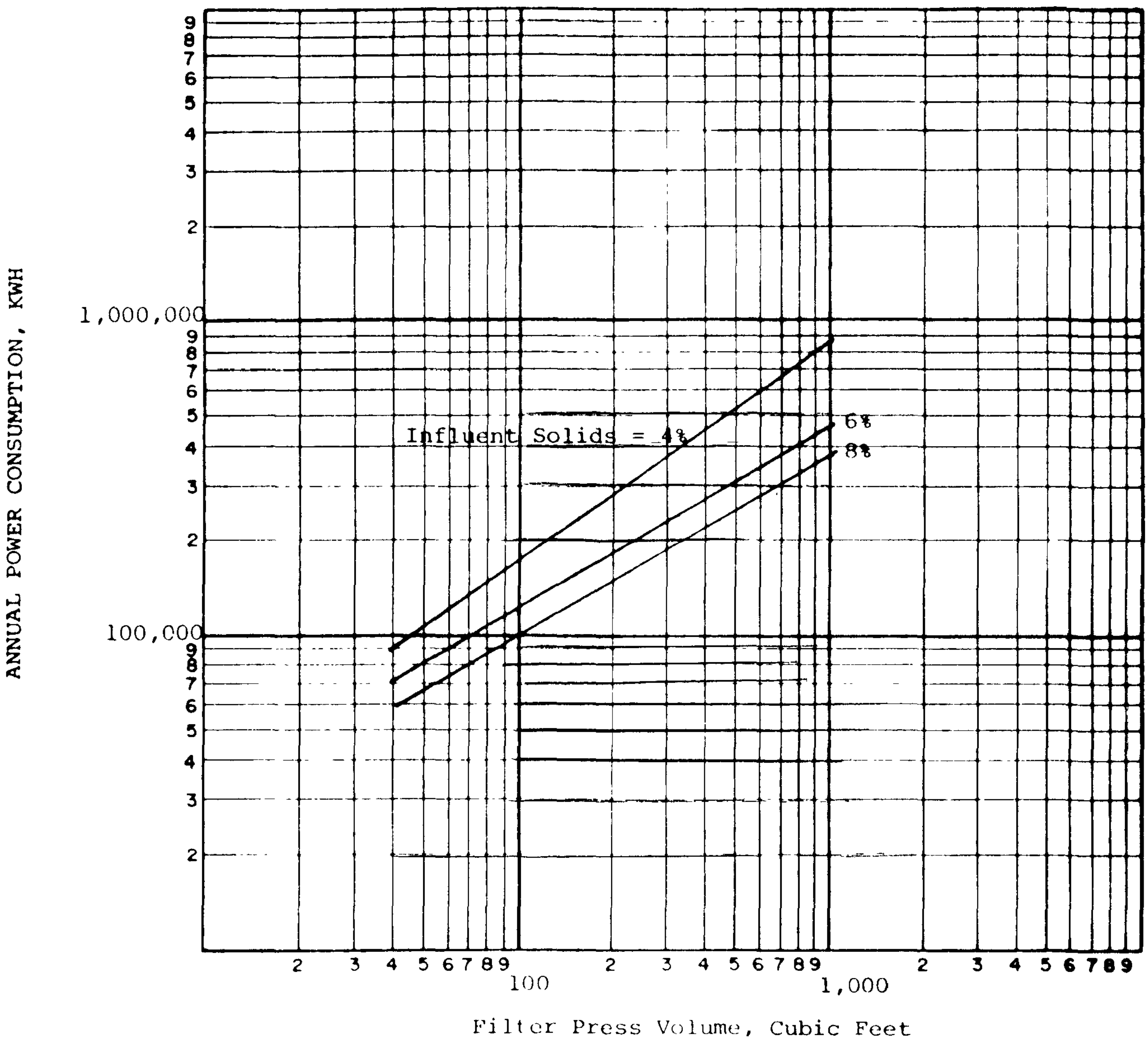
Curve 106



PRESSURE FILTRATION, LABOR
(BASED ON CONTINUOUS, 7 DAY/WEEK OPERATION, 2 HR CYCLE)

MAN-HOUR REQUIREMENTS

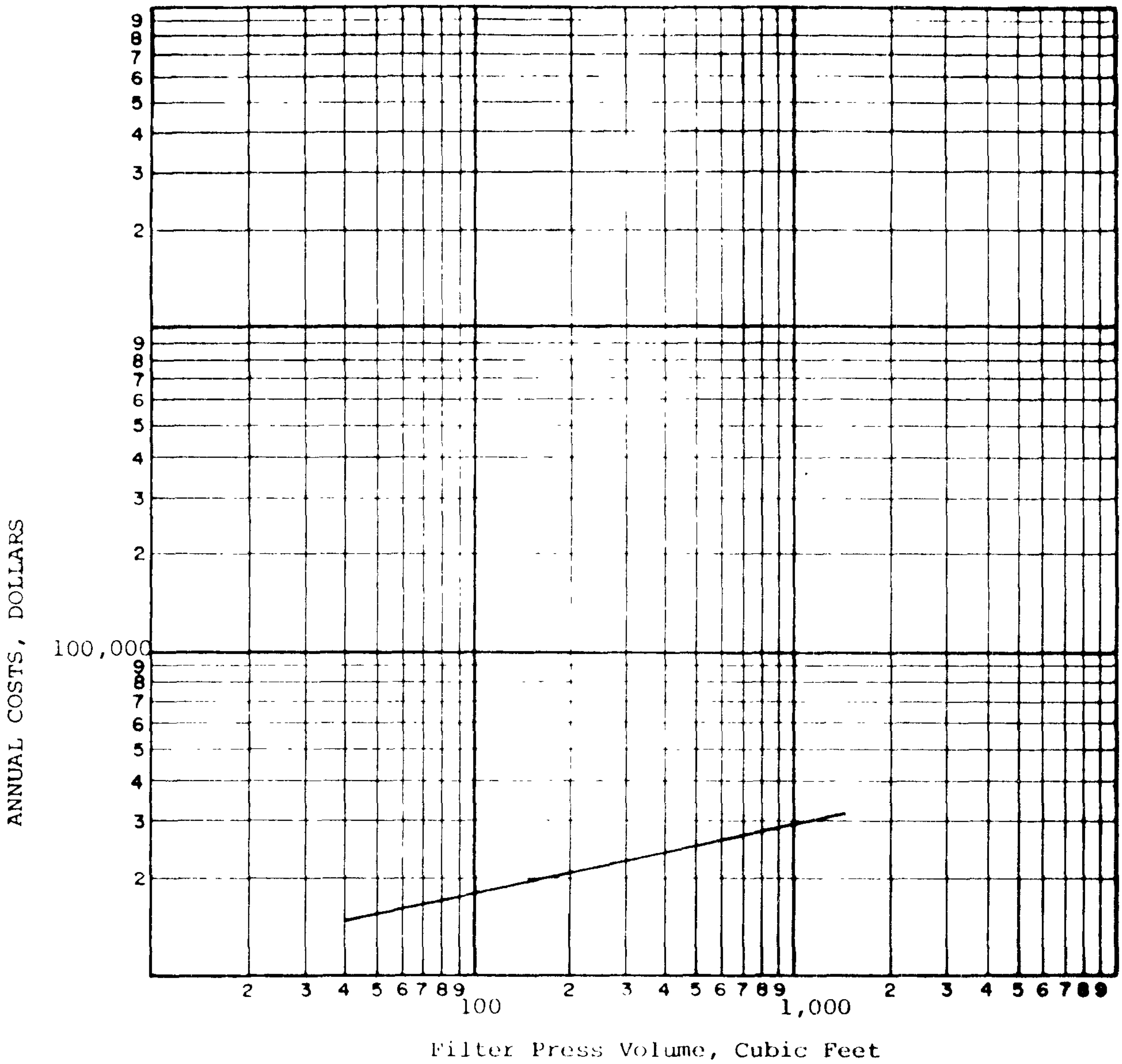
Curve 107



PRESSURE FILTRATION, POWER
(BASED ON CONTINUOUS, 7 DAY/WEEK OPERATION, 2 HR CYCLE)

POWER REQUIREMENTS

Curve 108



PRESSURE FILTRATION
(BASED ON CONTINUOUS, 7 DAY/WEEK OPERATION, 2 HR CYCLE)

MAINTENANCE MATERIAL COSTS

Curve 109

CHARACTERISTICS OF COMMERCIALLY AVAILABLE POWDERED ACTIVATED CARBONS

	ICI United States				Westvaco		
Typical Properties	Hydrodarco H	Hydrodarco C	Darco S-51	Darco KB	Nuchar S-A	Nuchar S-N	Filtchar
Surface Area, m^2/gm	475	550	650	1500	1577	-	-
pH	10.5	10.5	5.0	5.0	3.5-5.0	6.0-8.0	-
Molasses Number	40	95	-	-	170 Min	170 Min	-
Phenol Number	-	-	-	-	-	-	18-24
Iodine Number	-	-	-	-	-	-	-
Pore Volume, cc/gm	-	-	1.0	1.5	1.43	-	-
Particle Size, % Thru 100	-	-	98	99	95 Min	95 Min	99 Min
% Thru 200	-	-	-	-	80 Min	80 Min	97 Min
% Thru 325	70	70	70	70	70 Min	70 Min	90 Min
Bulk Density, gm/cc	0.70	0.70	0.51	0.45	0.34-0.40	0.34-0.40	0.42-0.50
Ash, %	-	-	-	3	-	-	7 Max
Moisture, %	-	-	12 Max	33 Max	-	-	5 Max
Bulk Cost, ¢/lb	21	24	30	56	31	-	-

(Cont'd.)

	Calgon		Amoco		
Typical Properties	Filtrasorb WG	GM Pulverized Carbon	FX-21	PX-23	PX-24M
Surface Area, m^2/gm	900-1000	700-800	2800-3300	3000-3300	1300-1400
pH	-	-	7-9	4-6	-
Molasses Number	-	-	-	200-300	-
Phenol Number	14-20	-	13-16	11-13	8-12
Iodine Number	900-1100	700 Min	2800-3600	3200-3500	1900-2100
Pore Volume, cc/gm	-	-	1.4-2.0	1.8-2.2	0.64-0.70
Particle Size, % Thru 100	99	-	90-99	95-99	97-99
% Thru 200	98	-	70-85	85-95	88-92
% Thru 325	90	65-85	55-70	75-85	78-88
Bulk Density, gm/cc	0.45-0.51	-	0.27-0.32	0.22-0.26	0.61-0.64
Ash, %	-	14 Max	2 Max	2.5 Max	-
Moisture, %	2 Max	2 Max	-	-	-
Bulk Cost, C/lb	40-44	30-34	-	-	-

(Cont'd.)

Typical Properties	Norit A	Norit FQA	Norit F
Surface Area, m^2/gm	700-800	650-750	650-700
pH	8.5-10.0	8.5-10.0	8.5-10.0
Molasses Number	-	-	-
Phenol Number	-	-	-
Iodine Number	800 Avg	740 Avg	700 Avg
Pore Volume, cc/gm	-	-	-
Particle Size, % Thru 100	-	-	-
% Thru 200	-	-	-
% Thru 325	80-85 (Est.)	80-85 (Est.)	80-85 (Est.)
Bulk Density, gm/cc	0.22-0.40	0.22-0.40	0.22-0.40
Ash, %	5-10	5-10	5-10
Moisture, %	15 Max	15 Max	15 Max
Bulk Cost, ¢/lb	28	24	22

TABLE 132

CONVERSION FACTORS FOR UNITS EMPLOYED

English	SI	SI	English
BTU	= 1.055 kJ	°C→1.8 (°C) + 32	= °F
	= 0.252 kg-cal	Cm	= 0.3937 in
BTU/ft^3	= 37.68 kJ/m^3	dm^3/sec	= 15.85 gpm
	= 9 kg-cal/m^3	$dm^3/sec/m^2$	= 0.0245 gpm/ft^2
BTU/hr/MGD	= .278 J/hr/m^3/day	g	= .002205 lb
BTU/lb	= 2.321 kJ/kg	g/day/m^2	= .002205 lb/ft^2/day
	= 0.555 kg-cal/kg	g/hr/m^2	= .002205 lb/ft^2/hr
°F→0.555 (°F-32)	= °C	g/l	= 1000 ppm
ft	= 0.3048 m	g/m^3	= 8.333 lb/MG
ft^2	= 0.0929 m^2	J/hr/m^3/day	= 3.5971 BTU/hr/MGD
ft^3	= .028 m^3	kg	= 2.205 lb
ft^3/hr	= .028 m^3/hr	kg-cal	= 3.968 BTU
ft/sec	= 0.3048 m/sec	kg-cal/Kg	= 1.80 BTU/lb
gallon	= 3.785 l	kg-cal/m^3	= .111 BTU/ft^3
gpd	= .003785 m^3/day	kg/day	= 2.205 lb/day
gpd/ft^2	= .0408 m^3/day/m^2	kg/kWh	= 2.205 lb/kWh
gpm	= .0631 dm^3/sec	kg/MJ	= 5.91 lb/hp-hr
	= .0631 l/sec	kJ	= .9478 BTU
gpm/ft^2	= 40.7 dm^3/sec/m^2	kJ/kg	= .0004308
	= 40.7 l/min/m^2	kJ/m^3	= .0265 BTU/ft^3
hp-hr	= 2.684 MJ	kWh	= 1.341 hp-hr
in	= 2.54 cm	l/min/m^2	= .0245 gpm/ft^2
lb	= .454 kg	l/sec	= 15.85 gpm
lb/day	= .454 kg/day	m	= 3.28 ft
lb/ft^2/day	= 4.880 g/day/m^2	m^2	= 10.76 ft^2
lb/ft^2/hr	= 4.880 g/hr/m^2	m^3	= 35.314 ft^3
lb/hp-hr	= 0.1692 kg/MJ	m^3/day	= 264.2 gpd
lb/kWh	= .454 kg/kWh	m^3/day/m^2	= 24.51 gpd/ft^2
lb/MG	= 0.92 g/m^3	m^3/hr	= 35.314 ft^3/hr
MG	= 3,785 m^3	m/sec	= 3.28 ft/sec (fps)
MGD	= 3,785 m^3/day	mg/l	= ppm (approximate)
ppm	= mg/l (approximate)	mg/l/hr	= ppm/hr (approximate)
psi	= 0.006895 N/mm^2	MJ	= 0.372 hp-hr
tons/day	= 907 kg/day	N/mm^2	= 145.03 psi

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

Project Officer: James J. Westrick (513-684-7652)

16. ABSTRACT Powdered activated carbon has been the subject of several developmental efforts directed towards producing improved methods for treating municipal wastewaters. Granular activated carbon has proven itself as an effective means of reducing dissolved organic contaminant levels, but is plagued with specific operational problems which can be avoided with powdered carbon. The work reported herein was aimed at putting powdered activated carbon (PAC) treatment in proper perspective relative to competing technology. All work with PAC and PAC regeneration was reviewed and representative process approaches selected for comparison with granular activated carbon. While no one PAC approach is clearly superior from a performance standpoint, biophysical processes are attractive because they can be incorporated into existing biological plants. Comparison of capital and operating costs were made for plants with throughput rates of 1, 5, 10, 25, and 50 MGD. Cost relations were generated in curvilinear relations to allow interpolation. Based on these estimates, it was determined that independent physical-chemical PAC systems are not economically competitive with other modes of treatment. PAC may offer advantages for specific cases where highly variant flows are experienced such as plant receiving flows of a seasonal nature or areas with combined storm sewer systems A sensitivity analysis was also conducted to determine where improvements could be made to make PAC competitive. Lower carbon doses and/or inexpensive throwaway carbon would be needed to successfully challenge the other systems evaluated.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Activated carbon Activated sludge process Cost comparison Economic analysis Estimates Powder (particles) Regeneration (engineering) Sewage treatment	Powdered activated carbon processes Municipal wastewater Granular activated carbon processes Physcial-chemical treatment	13B

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