GUIDEBOOK TO THE APPLICABILITY OF FLUE GAS DESULFURIZATION FOR INDUSTRIAL COAL-FIRED BOILERS

Submitted to:

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EXECUTIVE SUMMARY

A. Scope and Objectives

One important element of this nation's energy policy is to increase reliance on coal instead of scarce domestic natural gas and oil supplies or imported oil. A sector with major future potential for coal use is industrial energy use since utilities are already heavily reliant on coal and are planning to increase their reliance on coal in the future.[1/]

Efforts to encourage the industrial sector to place greater reliance on coal in fuel burning installations must also consider methods of insuring that increased coal utilization is compatible with the protection of the environment. In comparison with oil or natural gas, coal combustion tends to generate higher emissions of sulfur oxide and particulates. Solid waste disposal problems associated with coal use are also much greater. One means of reducing sulfur and particulate emissions to acceptable levels is through the application of flue gas desulfurization (FGD) equipment. These devices, installed near the fuel combustor, scrub the flue gases resulting from combustion to remove sulfur and fly ash.

The overall purpose of this report is to serve as a guide to the perspective industrial user of FGD equipment on coal-fired boilers by providng an evaluation of operating experience with FGD systems on industrial boilers and by providing comparisons of the general types of FGD equipment available. Specifically, this report:

[1/] See "The Natural Energy Plan," Executive Office of The President, Energy Policy and Planning; April 29, 1977.

- Completes the survey of FGD installations identified in an earlier study, including a review of operating experience to date.[1/]

- Presents data on the capital and operating costs of the major types of FGD systems currently available.

- Provides cost estimates for typical industry installations (heating plants or facilities generating process steam of various sizes and configurations).

- Reviews and analyzes industries which are major energy consumers for the applicability of alkaline waste streams as FGD reagents. Preliminary cost analysis indicates that if it is possible for an industry to use a production process waste stream as the scrubbing reagent, there are very significant cost savings (50 percent or greater) over other types of FGD systems.

The report is not intended to serve as complete design manual for FGD, but to assist industry in determining whether or not FGD equipment is a viable alternative in comparison to alternate means of complying with environmental requirements.

[1/] "Survey of the Application of Flue Gas Desulfurization Technology in the Industrial Sector," prepared by Energy and Environmental Analysis under Contract #CO-05-60469, Task #13, for the Federal Energy Administration, December 22, 1976.

B. Description of Alternative FGD Systems

The following four generic types of FGD systems were identified in the study:

- Self-Contained, solid waste;
- Self-Contained, liquid waste (with chemical addition);
- Self-Contained, liquid waste (without chemical addition); and
- Industrial process waste stream systems.

Table E-1 describes the characteristics of each generic system. These systems differ in cost and applicability to varying industrial facilities. For example, self-contained, liquid waste systems with no chemical addition are used primarily for particulate removal since without the addition of basic chemical reagents the sulfur removal capability is relatively low. The process waste stream FGD can obviously be applied only where an adequate flow and quality waste stream normally generated by the industrial production process (i.e., pulping) is available.

C. Current Application and Operating Experience With Flue Gas Desulfurization on Industrial Coal-Fired Boilers

The survey identified FGD systems on 94 coal-fired boilers at 46 industrial installations. The systems were installed on units ranging from 2 to 65 megawatt equivalent capacity. The food processing, paper, chemical and petroleum sectors accounted for 52 percent of the applications, although FGD was also applied in a wide variety of other industries.

All four generic FGD systems were being applied in a significant number of installations. Existing applications do reflect an overwhelming preference for sodium-based FGD systems rather than the lime/limestone based systems predominantly applied on the larger electric utility boilers.

TABLE E-1

GENERAL CATEGORIES OF INDUSTRIAL FGD SYSTEMS

FGD System Types	Source of Chemical Reagent	Type of Waste	Disposal of Waste
Self-contained, solid waste FGD systems.	Chemicals are purchased.	Solid waste (untreated sludge of approximately 50 to 60 percent solid consistency).	Solid waste is sent to a disposal (i.e., landfill) area.
Self-contained, liquid waste (chemical addition) FGD systems	Chemicals are purchased.	Liquid waste contains soluble compounds, i.e., sulfites, sulfates, and fly ash.	Liquid waste can be processed in a waste treatment plant or disposed of in a sewer system.
Self-contained, liquid waste (no chemical addition)	No chemicals utilized.	Liquid waste contains sulfur dioxide and fly ash.	Liquid waste processed in a waste treatment plant.
Waste stream FGD systems	Process waste streams contain scrubbing chemicals.	Liquid wastes contain soluble compounds, i.e., sulfites, sulfates, and fly ash, or solid waste of similar consistency to that of self-contained, solid waste FGD systems.	Liquid waste can be processed in a waste treatment plant or disposed of in a sewer system. Solid waste may be disposed of as landfill.

The vendors offering FGD systems for sale to the industrial market are generally not the same vendors who comprise significant market shares in the electric utility markets.

Operating experience in coal-fired industrial boilers is not extensive ... with few facilities having longer than one year of actual operating experience.

For those installations with at least one year of operating experience:

- Sulfur dioxide removal--up to 95%, with removal rates as low as 30-45% for systems which do not add chemicals.
- Fly ash removal--94-99%.
- System availability--90-99%.

Specific problems encountered at individual sites include material erosion and corrosion, lack of qualified operating personnel and disposal of solid and liquid waste materials. Waste disposal is an issue at all sites. Solid waste is being ponded or landfilled and liquid wastes sent to wastewater treatment plants or disposed of directly.

D. Cost Estimates

Table E-2 presents estimates of the capital, operating and total annual costs (annualized capital and operating costs) of alternative FGD systems for industrial facilities of various sizes and operating hours.[1/]

The most striking comparison is the relatively low cost of the waste stream FGD system. Except for boilers with operating rates below 2,000 hours, the annual cost of waste stream FGD systems is $2.30-$8.00 per ton of coal thruput. This system cost is lower because of the savings in chemical costs of capital equipment. However, application of waste stream FGD systems will be limited by the requirements for appropriate production process waste streams.

For facilities where such production waste streams are not available (including essentially all heating plant facilities where process steam requirements are low), FGD costs range from $11-$13 per ton of coal.

The choice between self-contained, solid waste and self-contained, liquid waste FGD systems is a function of boiler size and operating hours. Figure E-1 illustrates cost advantages of the two FGD systems at varying rates of capacity utilization for a 25 MW boiler. For facilities operating less than 4500 hours per year, the self-contained, liquid waste system appears considerably less expensive because of its lower capital cost. At very high operating rates, the self-contained solid waste system is more competitive because of its lower operating costs.

1/ All comparisons assume 90 percent sulfur dioxide removal efficiency. The self-contained liquid waste (no chemical addition) FGD system is not shown since it cannot achieve a high degree of sulfur removal.

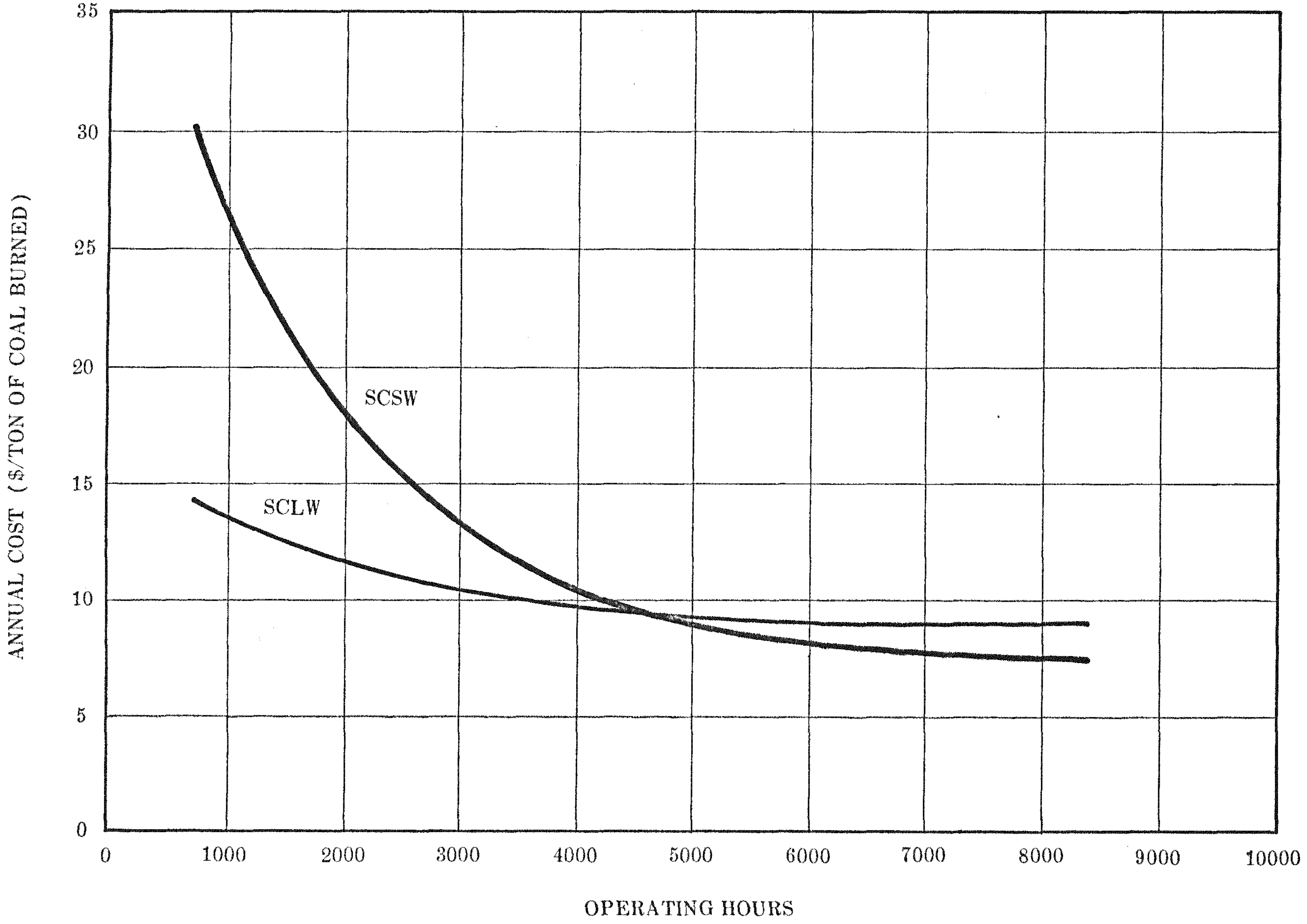
TABLE E-2

CAPITAL, OPERATING, AND ANNUAL COSTS OF SELECTED INDUSTRIAL FGD SYSTEMS

	FGD System Type								
	Self-Contained Solid Waste System, FGD System			Self-Contained Liquid Waste System, FGD System			Waste Stream FGD System		
Boiler Size/ Operating Hours (MW Equivalent)	Capital Cost (10^3\$)	Operating Cost (10^3\$)	Annual Cost (\$/ton of coal)	Capital Cost (10^3\$)	Operating Cost (10^3\$)	Annual Cost (\$/ton of coal)	Capital Cost (10^3\$)	Operating Cost (10^3\$)	Annual Cost (\$/ton of coal)
10 MW	1,000			314.0			304.0		
8400		298.5	9.80		379.0	9.85		90.0	2.95
6400		238.0	10.80		294.5	10.13		71.0	3.40
4000		157.5	13.50		182.5	10.90		45.5	4.70
1000		62.0	34.90		50.5	16.92		15.5	14.75
25 MW	1,900			569.0			549.0		
8400		594.0	7.70		895.5	9.14		180.0	2.30
6400		472.0	8.45		695.5	9.34		141.5	2.60
4000		312.5	10.50		431.0	9.89		90.0	3.30
1000		120.5	26.75		115.0	14.22		29.0	9.12
40 MW	3,000			794.0			768.0		
8400		940.5	7.65		1431.5	9.10		298.0	2.30
6400		752.6	8.40		1111.5	9.20		234.0	2.50
4000		498.5	10.45		688.0	9.70		148.0	3.10
1000		191.5	26.45		180.5	13.50		45.5	7.85

FIGURE E-1

COMPARISON OF ANNUAL COST/TON OF COAL VS. OPERATING HOURS



The sulfur removal required to satisfy applicable regulations is also a critical factor affecting the comparative costs of alternative FGD systems. Figure E-2 shows the cost comparison for 90 percent and 70 percent sulfur removal. At the lower sulfur removal the self-contained, liquid waste system appears more competitive for operating rates below 7,000 hours. The self-contained, liquid waste system becomes more cost effective as sulfur removal requirements drop since chemicals are a larger percentage of total costs for liquid rather than solid waste FGD systems.

These comparisons are based on generic cost factors. Plant specific conditions can result in significantly different costs. For example, costs will vary depending on:

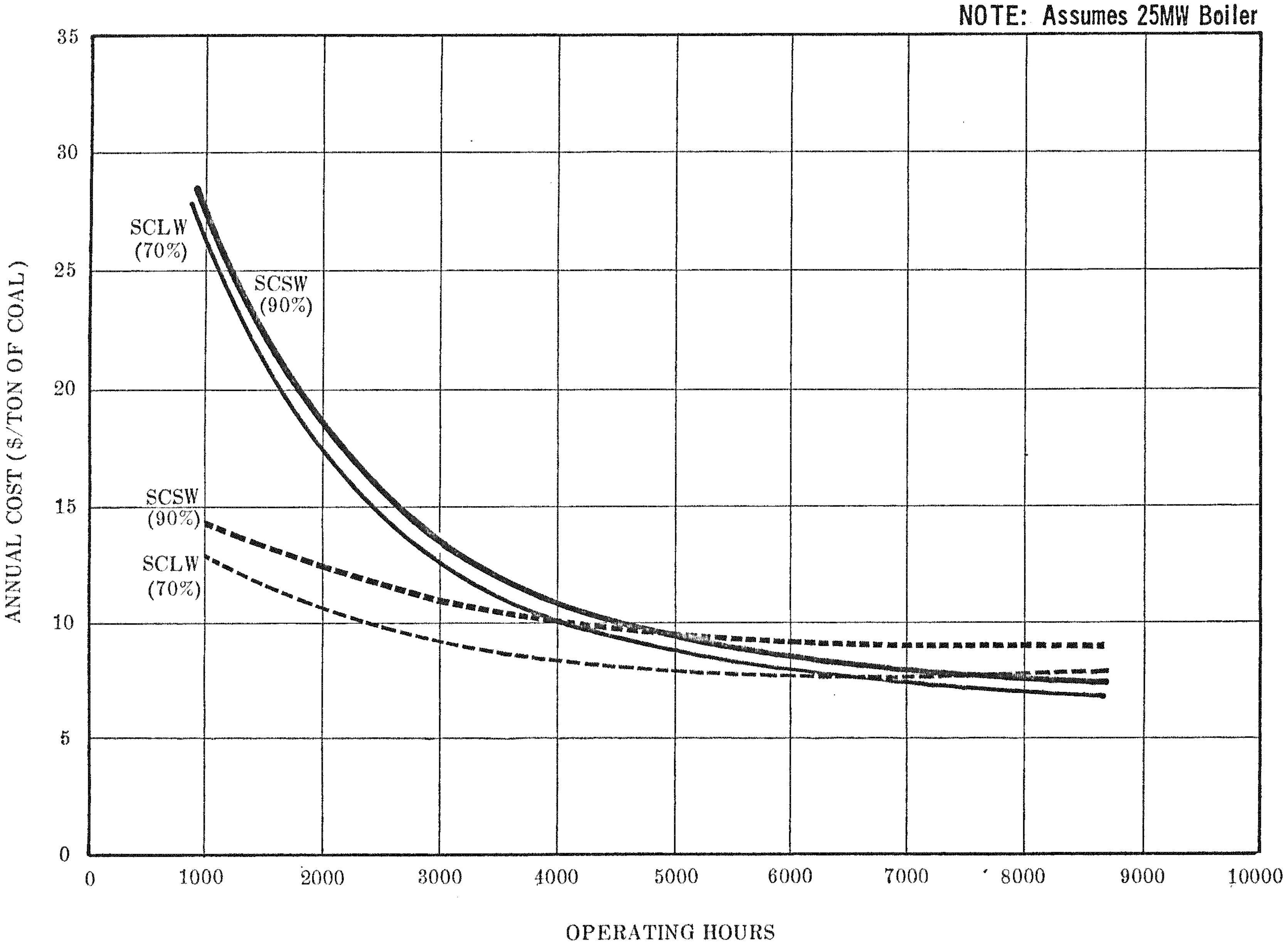
- particulate control requirements;
- available space and choice of waste disposal options;
- the necessity to treat process waste streams beyond existing wastewater treatment facilities;
- the need to pretreat production process waste streams for waste stream FGD systems to control environmental problems (hydrogen sulfide);
- regional variations in operating costs.

E. Applicability of Process Waste Streams in Industrial FGD Systems

Since a signficant savings in costs can be realized if a waste stream from the plant production process can be used as the chemical source for the FGD system, the primary characteristics which would provide a waste stream suitable for use are: waste flow volume, pH, alkalinity, and presence of chemical constituents

FIGURE E-2

EFFECT OF SO_2 REMOVAL EFFICIENCY ON COST OF FGD SYSTEMS



such as sodium, calcium, or ammonia. The most important of these constituents is the alkalinity. As alkalinity increases the required flow rate (for a fixed sulfur removal requirement) decreases greatly.

Based on the above criteria a number of industries were reviewed to determine their ability to generate process wastes for FGD systems. The criteria used to evaluate these industries were; the magnitude of energy use in the industry, the constituents and nature of the waste flow and the amount of information available on the production processes. Based on this review three industries were selected for detailed analysis. The industries were:

- Iron and Steel - the only process in the iron and steel industry which shows potential in an FGD system is the production of by-product coke. Effluent from this process averages about 175 gal/ton and is very high in ammonia. Both flow and ammonia levels are high enough to accomplish substantial SO_2 removal.
- Petroleum Refining - Waste streams from hydroprocessing activities such as catalytic cracking appear to have potential in an FGD system. This "sour" or "foul" water is extremely high in ammonia and sulfides although the flow is relatively small. The ammonia and sulfide levels are extremely variable from refinery to refinery and are dependent on the type of processing and characteristics of the crude used.
- Paper and Pulp - Several processes within the paper and pulp industry have potential for use of FGD processes. Alkaline waste streams from Deinking plants and Kraft Pulp mills are currently being used in FGD systems at some plants.

Kraft mills and sulfite mills have the potential to use an FGD system to make chemicals used in the pulping process. The ability to use the FGD system to produce these chemicals is dependent on the makeup chemical (both as to amount and type) required at each plant.

Potential problems exist with the use of these waste streams. Some of the problems are:

- In the waste streams from both the iron and steel and the refinery operations H_2S may pose a problem. This problem is much more significant in the refinery streams than the coke oven waste streams.
- In the paper industry water pollution control re-requirements may eliminate several of the alkaline waste streams from new pulp plants.

Other processes considered in the study also showed potential for use of a waste stream, but were in small industries unlikely to use coal or where site-specific where the process could be either basic or acidic depending on the particular product being produced. In these cases a site-specific analysis would be required to determine whether the production waste streams are appropriate.

SECTION I

INTRODUCTION

A. Background

One of the nation's primary goals is to decrease its dependence on residual fuel oil, especially imported fuel oil, and natural gas used by utilities and industrial facilities. The Federal Energy Administration (FEA) is approaching the problem on several fronts including: the encouragement of voluntary conversion to coal in existing boilers with pricing policies that reflect the premium value of scarce fuels, the prohibition of the oil and natural gas combustion in some utility and industrial boilers, and requiring new utility and industrial boilers in their early planning stages to install the capability to burn coal.

Efforts to encourage the private sector to place greater reliance on coal in fuel burning installations must also consider methods of insuring that increased coal utilization is compatible with the protection of the environment. In comparison with oil or natural gas, coal combustion tends to generate higher emissions of sulfur oxide and particulates. Solid waste disposal problems associated with coal use are also much greater. One means of reducing sulfur and particulate emissions to acceptable levels is through the application of flue gas desulfurization (FGD) equipment. These devices, installed near the fuel combustor, scrub the flue gases resulting from combustion to remove sulfur and fly ash.

B. Purpose

In a recent study [1/], a rapid survey was conducted to determine the extent to which FGD has been applied in the industrial sector. The report identified over thiry boilers controlled with FGD systems. The previous study also attempted to determine the approximate costs of FGD systems and the factors influencing the choice of FGD systems compared to alternate pollution control strategies.

The overall purpose of this report is to serve as a guide to the prospective industrial user of FGD equipment by providing an evaluation of operating experience with FGD systems on industrial boilers and by providing comparisons of the general types of FGD equipment available. Specifically, this report:

- Completes and further refines the survey of FGD installations identified in the earlier study. All major vendors of FGD equipment and users of FGD systems were surveyed to determine the operating characteristics of each system.
- Reviews and analyzes industries which are major energy consumers for the applicability of alkaline waste streams as FGD reagents. Preliminary cost analysis indicates that if it is possible for an industry to use a production process waste stream as the scrubbing reagent, there are very significant cost savings (50% or greater) over other types of FGD systems. Qualities of the waste stream such as flow, pH, and alkalinity have to be considered in evaluating the usefulness of each waste stream as a scrubbing reagent.

1/ "Survey of the Application of Flue Gas Desulfurization Technology in the Industrial Sector," prepared by Energy and Environmental Analysis under Contract #CO-05-60469, Task #13, for the Federal Energy Administration, December 22, 1976.

- Presents data on the capital and operating costs of the major types of FGD systems currently available.

- Provides cost estimates for typical industry installations (heating plants or facilities generating process steam of various sizes and configurations).

- The report is not intended to serve as complete design manual for FGD, but to assist industry in determining whether or not FGD equipment is a viable alternative in comparison to alternate means of complying with environmental requirements.

C. Report Organization

The report is organized into overview sections describing the technology, operating experience and current applications, and the cost components of FGD systems. Supporting each major section is an appendix presenting more detailed technical information for interested readers. Specifically, the report is organized as follows:

- SECTION II is a discussion of the methodology used in preparing the report including a discussion of the types of data collected in the course of the study.

- SECTION III presents a brief overview of the various types of FGD systems used on industrial boilers and the general advantages and disadvantages of each system. Appendix A provides a more detailed description of each system type showing the process chemistry of each system and a process flow diagram with general system layouts.

- SECTION IV contains a short discussion of the degree to which FGD is being used on coal-fired industrial boilers and summary statistics on operating experience. Appendix B contains backup material including type and location of each system identified in the course of this study, as well as trip reports for several operating installations.

- SECTION V is an investigation into the possible use of alkaline waste streams as possible scrubbing reagents in FGD systems. As discussed earlier, if alkaline waste streams are suitable for use in FGD systems in certain industries, the cost of sulfur control can be markedly reduced. The discussion highlights those industries which appear to generate such alkaline waste streams.

- SECTION VI presents the elements of capital and operating costs which determine the total cost of FGD systems. Each element is discussed as to the function of each element in the process; and the importance in the overall capital and operating costs is outlined. Appendix C illustrates the cost algorithms used to determine each of these capital elements. All of the data in Appendix C is equipment purchase cost and must be adjusted for installation, engineering, site preparation, etc. Appendix D shows the operating cost factors used in the report.

- SECTION VII of the report applies the cost data in Appendix C to several case examples. These examples are based on typical industrial coal-fired boiler applications. The purpose of the case examples is to demonstrate the application of the data developed in the report and to show the effect of changes in operating parameters on the costs of different FGD systems.

D. Study Limitations

The primary limitation in any study presenting generic costs is that site-specific variables can have significant impact on the type of FGD system employed and the cost of any FGD system. For example, site factors can cause the installed cost of the FGD system to increase by a factor of 50 to 60 percent or more if the system has to be installed with severe space constraints.

The characteristics of individual plants will also significantly affect the ability of a plant to use a waste stream as the FGD reagent. The particular production process at the plant will influence the character and usefulness of any waste stream. The factors which influence the usefulness can be qualitatively identified, but the significance of each of the factors can be assessed only at the individual plant level.

SECTION II

METHODOLOGY

This study was conducted in four stages, each of which is essentially independent of the others.

- Completion of a survey of FGD systems installed on industrial coal-fired boilers;
- Evaluation of effluent streams from major industrial categories;
- Development of cost data and factors influencing costs of industrial FGD systems; and
- Development of all information into a series of case examples which can be used to estimate the costs and variations in cost between various FGD systems.

A similar procedure was used to investigate all four areas of study. This methodology can be viewed as basically a four-step process. First, literature searches were conducted to gather available data. This data was supplemented with communication with FGD vendors and industry personnel to gather additional details. Second, this data was analyzed for trends in FGD installations or applications, as well as those factors which appeared to account for reported differences in FGD cost, application, or effluent constituents. Third, the data collected was analyzed to draw conclusions on the applicability and cost of FGD systems in various types of applications. Finally, the conclusions on the factors affecting FGD use and cost were reviewed with vendors and industrial users to determine the appropriateness of the conclusions and the relative importance of various FGD variables.

A. Data Collection

Literature searches were conducted and FGD vendors were contacted to determine to what extent FGD systems are being applied, what factors would be required to make an alkaline waste suitable for use in an FGD system, and what elements determine the cost of FGD systems.

Data collected on the FGD system application included:

- size and number of industrial boiler(s) fitted with FGD equipment;
- location and type of industry using the FGD system;
- type of FGD system employed; and
- general operating characteristics of each FGD system.

Data collected on the waste characteristics of industries and the waste characteristics required for FGD systems included:

- flow of waste product and consistency of flow;
- the pH of the waste stream;
- the alkalinity of the flow;
- the presence of chemical compounds which would react with SO_2; and
- the types of problems such as fouling or undesirable compounds which might be expected from the operation of the FGD system.

Data collected on the cost of FGD systems included:

- type and size of probable pieces of equipment included in an FGD system;
- materials of construction for the system;
- factors influencing the choice of system components and the factors affecting the cost of each component;
- approximate variability of total installed cost for specific sites; and
- requirements for power, chemicals, water and maintenance required for various system types.

Data collected for development of case examples included:

- distribution by size and number of boiler plants likely to be candidates for FGD use;
- range of operating hours and load factors associated with plants likely to use FGD; and
- types of industries where a combination of boiler size and process made the use of process waste streams as a scrubbing reagent a viable alternative.

From these data general characteristics of industrial systems were apparent, enabling the selection of specific system types and industrial types for detailed analysis.

B. Selection of System Types and Industries for Analysis

Each of the FGD systems and industries identified in the preceeding task was screened to determine which system configurations and industries were to be examined in greater detail. The major criteria used in selecting the system configuration for cost analysis were:

- FGD system type--Each of the three major FGD types, i.e., self-contained, solid waste; self-contained, liquid waste, and waste stream systems had sufficient overall potential for application in various configurations.
- FGD System Components--Each of the FGD systems currently operating on industrial boilers was examined to determine the common system components and those components specific to individual facilities.
- Additional Components--A range of alternative system components was established for solids and sludge disposal.
- Installation Factors--Existing FGD installations were reviewed to determine which factors led to atypical installation costs and how these factors could be quantified.

The major criteria for selecting industries for detailed analysis were:

- Waste Stream Characteristics--The data collected on the chemical characteristics of waste streams was used to screen the initial list of industries.
- Process Similarities--Data on waste stream production was reviewed to determine the degree to which the basic process producing the waste stream was used throughout the industry.
- Industry Size--The current and potential energy use in the industry was reviewed to focus on those indsutries which have a potential for significant coal consumption.

Based on these selection criteria, the most representative system designs and industries were chosen.

C. Data Analysis and Report Preparation

Based on the data collected and reviewed in the previous steps, the systems selected for evaluation were costed in detail. The basic steps in the costing procedure was to develop component costs and aggregate these costs into a total system cost. These costs were compared with costs reported during the survey of FGD installation and differences were analyzed to determine if site specific factors were the reason for the difference. The costs were also reviewed with vendors of FGD equipment to better focus on actual field costs. Differences in costs between those computed and quoted by the vendors were reviewed to determine reasons for differences and what component accounted for the differences.

Data on the effluent stream from industrial plants was developed in a similar fashion. The results from the data collection and screening efforts were developed so as to establish the likely characterisitcs of the effluent systems and the usefulness of the effluent stream in an FGD system. Data collected was reviewed with FGD vendors and industry representatives to determine applicability and potential problems with the use of a process waste stream in an FGD system.

SECTION III

TECHNOLOGY DESCRIPTION

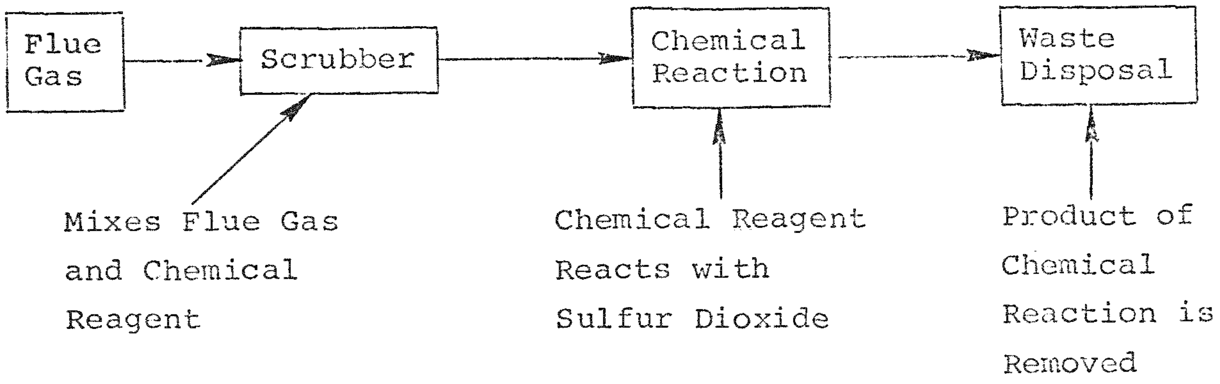
A. Introduction

FGD is a method to reduce stack gas sulfur dioxide emissions from the combustion of fuel. FGD systems can be conceptually viewed as having three components - a scrubber, chemical reaction(s), and a waste disposal system as diagramed in Figure 3-1. The purpose of the scrubber portion of the FGD system is to mix the flue gas and the scrubbing reagent so that the desired chemical reactions can occur. Once the chemical reaction has taken place, the resulting waste product is disposed of in some manner.

The purpose of this section is to briefly describe the key features of the various types of FGD systems identified in the course of this study. The following four types of FGD systems were considered: self-contained, solid waste systems (SCSW); self-contained liquid waste systems (SCLW), with and without the addition of reagent chemicals; and waste stream (WS) system. These systems differ in their source of chemicals and in the nature of the FGD system wastes. Table III-1 summarizes the difference between the various system types. Appendix A describes in detail the type and layouts of FGD systems currently used on industrial coal-fired boilers. The appendix describes technical features of the various FGD system types and discusses the chemical reactions designed to remove SO_2 and illustrates the layout of the main pieces of equipment. This section briefly describes the key features of each type of FGD system and compares the relative advantages and disadvantages of each system in relation to other types of FGD systems. Section IV of this report and Appendix C describe the application of this equipment in the industrial sector.

FIGURE 3-1

FGD SYSTEMS COMPONENTS[a]



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[a] FGD systems pertain to those systems reviewed in this report.

TABLE III-1

GENERAL CATEGORIES OF INDUSTRIAL FGD SYSTEMS

FGD System Types	Source of Chemical Reagent	Type of Waste	Disposal of Waste
Self-contained, solid waste FGD systems.	Chemicals are purchased.	Solid waste (untreated sludge of approximately 50 to 60 percent solid consistency).	Solid waste is sent to a disposal (i.e., landfill) area.
Self-contained, liquid waste (chemical addition) FGD systems	Chemicals are purchased.	Liquid waste contains soluble compounds, i.e., sulfites, sulfates, and fly ash.	Liquid waste can be processed in a waste treatment plant or disposed of in a sewer system.
Self-contained, liquid waste (no chemical addition)	No chemicals utilized.	Liquid waste contains sulfur dioxide and fly ash.	Liquid waste processed in a waste treatment plant.
Waste stream FGD systems	Process waste streams contain scrubbing chemicals.	Liquid wastes contain soluble compounds, i.e., sulfites, sulfates, and fly ash, or solid waste of similar consistency to that of self-contained, solid waste FGD systems.	Liquid waste can be processed in a waste treatment plant or disposed of in a sewer system. Solid waste may be disposed of as landfill.

B. Self-Contained, Solid Waste FGD Systems (SCSW)

The SCSW FGD system removes sulfur dioxide from flue gas and produces a solid waste containing system reaction products. The system may be quite elaborate in design incorporating a scrubbing, recycle and regeneration system, or be simpler in design incorporating only a scrubber module and waste disposal system. The chemical scrubbing reagent may be lime or a sodium compound, or any other chemical capable of reacting with sulfur dioxide, i.e., ammonia. All of the facilities investigated in this study used or planned to use either a sodium or lime compound as the scrubbing agent.

The primary advantages of this type of FGD system are its applicability to any type of industrial application and a high degree of SO_2 removal. The disadvantages of this type of system are the high capital costs relative to other types of FGD systems, and the requirements to dispose of significant quantities of solid waste. Disposal of this waste material (four to six pounds per pound of SO_2 removed) may pose difficulties in many localities.

C. Self-Contained, Liquid Waste (Chemical Addition) (SCLW) FGD Systems

A scrubbing system that uses a chemical base (i.e., ammonia, sodium) as the scrubbing agent and does not recycle the chemical for further use can be considered a SCLW (chemical addition) FGD system. In the SCLW (chemical addition) FGD system, the bleed stream from the scrubber is discarded as a liquid waste product. In order to prevent water pollution problems, some processing of the waste stream may be needed before release in to a receiving stream.

The chemical utilized in a SCLW (chemical addition) FGD system may be ammonia, sodium hydroxide, sodium carbonate, or any number of other scrubbing agents. All of the facilities investigated in this study use or plan to use a sodium-based re-agent. The efficiency of sulfur dioxide removal is primarily dependent on the amount of chemical used.

The primary advantages of this type of system are its wide applicability to all types of industrial boilers, low capital cost relative to the SCSW system and a potentially high degree of SO_2 removal. Disadvantages of the SCLW system are a high operating cost due to the use of more expensive chemicals such as sodium carbonate or sodium hydroxide and the need to dispose of a liquid waste stream high in dissolved solids. The disposal of this waste stream may pose porblems unless existing waste water treatment facilities at the plant can handle the increased water flow.

D. Self-Contained, Liquid Waste (No Chemical Addition) FGD Systems (SCLWNC)

This FGD system is analogous to the SCLW (chemical addition) system except chemicals are not added to the scrubbing liquid. The scrubbing liquid, i.e., water, usually passes once through the scrubber unit and exits to a waste water treatment plant or settling pond. The SCLW (no chemical addition) FGD system can be converted to a more efficient FGD system, i.e., greater sulfur dioxide removal efficiency, by the addition of a basic chemical, i.e., lime or caustic to the scrubbing liquid. The primary purpose of this type of FGD system is to collect particulate matter, i.e., fly ash, but as a result of sulfur dioxide absorption in the scrubbing liquid, sulfur dioxide is also removed from the flue gas.

The advantages of this type of system are its low capital and operating cost relative to other FGD systems and its applicability to any industrial boiler. Its disadvantages are a low SO_2 removal efficiency (30-40 percent), very high water consumption and the need to treat an acidic waste stream. This type of FGD system may not be suitable as an FGD sulfur removal system (depending on the coal used and the stringency of applicable regulations) and is generally used to remove particulate matter with SO_2 control only as an incidental benefit.

E. Waste Stream (WS) FGD Systems

Waste stream FGD systems are similar to SCLW systems except that the source of alkaline chemical is from a processing operation within the facility. For example, plants manufacturing soda ash have a liquid waste stream containing high levels of this compound which can be used as an FGD reagent. After reaction in the scrubber unit of the FGD system the waste stream may be ponded or disposed in the general plant facility.

This type of FGD system has the lowest capital and operating costs of any FGD system since no purchased chemicals are required.

The disadvantages of the WS FGD are its limited applicability due to the requirement for a suitable waste stream.

SECTION IV

INDUSTRIAL SCALE FLUE GAS DESULFURIZATION SYSTEMS IN USE

A. Introduction

This section reports the status of FGD systems currently installed on industrial coal-fired boilers. [1] This section describes the overall operating characteristics of industrial FGD systems and characterizes them by the type of FGD process employed. In addition, trends observed in the application of industrial FGD sytems are described in terms of the number of facilities, number of boilers, and industrial sector application.

B. Survey of Industrial FGD Systems

A survey was conducted to determine the types and manufacturers of industrial FGD systems. Based on published reports, potential manufacturers were identified. Data were then collected [2] on approximately eighty of these scrubber vendors to determine the types of industrial FGD systems available.

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[1] FGD systems are currently being used on other types of installations, such as secondary smelters, ore roasters, and pulp mill recovery boilers. These systems were not considered in this report.

[2] Information compiled from literature searches and telephone conversations.

Appendix C describes each of the industrial FGD installations uncovered in this survey by system type, company name and location, number and size of boiler unit, scrubber vendor, and FGD operational characteristics. In addition, trip reports for seven FGD installations--American Thread, Great Southern Paper, Cannon Textile, Caterpillar Tractor, Firestone, Rickenbacker, and Nejoosa-Edwards Paper--describing the operational characteristics and problems of each FGD system are contained in the appendix.

Altogether, the survey revealed ninety-four coal-fired boilers in forty-six installations ranging from two to sixty-five megawatt equivalent. 1/ Table 1 summarizes the results of the survey by characterizing the number of FGD installations by FGD system type and industrial sector. Of the forty-six FGD systems located, approximately 30 percent were SCSW units, 30 percent were SCLW units, 24 percent were WS units, and 15 percent were SCLWNC units. Approximately 37 percent of these units were general industrial 2/ applications. The remaining units are operating in the food processing (22 percent), paper/pulp (17 percent), chemical and petroleum (13 percent), textile (7 percent), steel (2 percent), and mining (2 percent) industries. The majority of the SCSW systems are located in several manufacturing sectors. 2/ The SCLW systems are not only largely employed by equipment manufacturing sectors, but also appear to a large extent in the paper/pulp industry. The SCLWNC systems operate only at food processing locations. WS FGD systems are spread widely across the textile, paper/pulp, and chemical and petroleum sectors, in addition to food processing and general industry applications.

1/ Industrial boilers are generally rated in terms of thousand pounds per hour steam, whereas utility boilers are rated by megawatt. For convenience, industrial boiler capacity is stated in megawatt equivalent units, assuming 10,000 pounds per hour steam is equivalent to 1.0 megawatt.

2/ Equipment manufacturing, construction.

TABLE IV-1

SUMMARY OF INDUSTRY FGD SYSTEM SURVEY
NUMBER OF SYSTEMS BY INDUSTRIAL SECTOR

	NUMBER OF INSTALLATIONS				
	FGD SYSTEM TYPE				
Industrial Sector	SCSW	SCLW	SCLWNC	WS	TOTALS
General	10	6		1	17
Steel	1				1
Chemical and Petroleum	3			3	6
Paper/Pulp		5		3	8
Food Processing		2	7	1	10
Textile				3	3
Mining		1			1
Total	14	14	7	11	46

Table IV-2 outlines the number and size of the industrial boilers controlled by FGD system type. The SCLW FGD system is presently in use at approximately 46 percent of the industrial boilers surveyed. The other three FGD systems each account for 15 to 20 percent of the remaining installations. The survey uncovered FGD systems controlling boilers that ranged in size from 2 to 65 megawatts--the full range of industrial boiler sizes.

Based on information compiled for this report, several features of industrial FGD systems can be established. First, there appears to be a preference for using a sodium-based scrubbing liquid as opposed to the utility system use of lime/limestone.[1/]

Second, the types of FGD systems supplied and vendors supplying them tend to be different than those of the utility FGD market. Third, the use of a process waste stream as the scrubbing liquid appears to represent a viable FGD system with present and potential application in many industrial sectors. This is probably due to the lack of a chemical requirement of the system, the lower capital cost of the system compared to corresponding self-contained units, and potential applications to small scale industrial boiler installations.

C. Operational Characteristics of FGD Systems

When contacting the FGD system vendors and operators of FGD installations, operational experience and performance data were major topics of discussion. For the most part, vendor and/or operators were willing to discuss the operational characteristics of each FGD system. Since the FGD systems investigated in the study have only been in operation one or two years, long-terms operational experience is nonexistent.

[1/] It should be emphasized that this statement is not a technical finding but is intended only to portray the apparent preferences of industrial users of FGD equipment.

TABLE IV-2

SUMMARY OF INDUSTRIAL FGD SYSTEM SURVEY - NUMBER AND SIZE OF BOILER UNITS BY SYSTEM TYPE

FGD SYSTEM TYPE	NUMBER OF BOILER UNITS CONTROLLED	BOILER SIZE RANGE MW EQUIVALENT
SCSW	43	2-35
SCLW	20	6-50
SCLWNC	14	5.5-15
WS	17	3-65
TOTAL	94	

Table IV-3 compares the four types of industrial FGD systems investigated in this study in terms of sulfur dioxide removal efficiency, flyash removal efficiency, and system availability. The sulfur dioxide removal efficiency for the SCSW and SCLW FGD systems is higher than for WS and FGD systems. This is primarily due to the higher concentrations of basic chemicals utilized in the scrubbing liquid of the first two. The fly ash removal efficiences and system availability of all four FGD system types are all in the same approximate percentage range. It should be noted that (1) fly ash removal efficiency is dependent on the type of scrubber employed in the FGD system, and (2) an FGD system incorporating many interdependent process operations is more likely to be less available than a simple FGD system.

The operating characteristics of each industrial FGD system are described below in detail:

1. <u>SCSW FGD Systems</u> - The SCSW FGD systems reviewed in this report were operating without significant difficulties. However, a number of operating problems have been reported by installation personnel. Among these were material corrosion, availability of qualified operating personnel, and waste disposal. These problems were not common to all installations, but were site-specific at a number of reviewed installations. It appears that as each of these installation gains valuable operation time, the majority of these problems were eliminated. However, solid waste disposal remains a major concern of several operators at the present time. Sulfur dioxide removal efficiency 1/ for this FGD system varies between 90 and 95 percent depending on the type of FGD component employed at a given installation.

1/ Based on information supplied by the FGD installation personnel contacted.

TABLE IV-3

ACTUAL OPERATING EXPERIENCE OF INDUSTRIAL FGD SYSTEMS SURVEYED [1]

● Sulfur Dioxide Removal	SCSW	-85-95%
	SCLW	-85-95+%
	SCLWNC	-30-45%
	WS	-70-95%
● Fly Ash Removal	SCSW	-95-99%
	SCLW	-95+%
	SCLWNC	-95+%
	WS	-94-99%
● System Availability [2]	SCSW	-90-95%
	SCLW	-95-99+%
	SCLWNC	-95-99+%
	WS	-95+%

1/ Data only for FGD systems with one year or more operational experience.

2/ Availability is defined as the percentage of scrubber operating hours to boiler operating hours.

There appears to be a preference for the use of a sodium-based scrubbing liquid as opposed to the utility system use of a lime/limestone scrubbing liquid for SCSW FGD systems. This preference appears to be based on a concern that: (1) lime/limestone systems may scale whereas sodium systems will not; (2) the untreated sludge from a sodium self-contained system is superior to the untreated lime/limestone sludge; and (3) sodium systems seem to be more tolerant of changing boiler load conditions. Based on early experience with lime/limestone utility FGD systems, there was a concern that calcium compounds from process liquor streams may scale on the surfaces of or cause plugging in the scrubbing components of the system. As a result, many prefer sodium scrubbing systems using a clear solution rather than a lime/limestone slurry, thus eliminating potential plugging or scaling problems. Since the sludge from a sodium system has a higher solids consistency and different crystaline structure than that from a limestone system prior to primary treatment, it is preferred material from a handling and/or disposal point of view. However, the sludge from both systems, after treatment, possesses approximately the same solid consistencies. Sodium systems are thought to be more tolerant than a lime/limestone FGD system of changing boiler load conditions due to the buffered capacity of the sulfite-bisulfite system. When the sodium scrubbing system is operating in the pH range of 6 to 7 units, a highly buffered system exists which can adapt rapidly to variable flue gas conditions. A lime/limestone system is not as highly buffered as a sodium FGD system and is more sensitive to change in flue gas load conditions.

2. <u>SCLW FGD Systems</u> - The SCLW FGD system involves the addition of a caustic agent to a scrubbing liquid dependent on its buffer level. The SCLW FGD systems reviewed in this study all used a sodium based chemical to the scrubbing liquid. Several general problems have been expressed by the installation operators. Among these are corrosion and erosion of the scrubbing system, which can be eliminated,

for the most part, with proper system pH control. In addition, since the scrubbing chemical is not recycled, it constitutes a significant system material loss especially where a high sulfur dioxide (85 percent higher) removal efficiency [1] is required.

3. SCLWNC FGD Systems - Overall, the SCLWNC FGD systems, according to operating personnel at various facilities reviewed, have been operating well. One major problem that may occur, though, is corrosion or erosion of scrubber components. As the scrubbing liquid collects more sulfur dioxide, its pH level decreases to increasing acidic levels. If the scrubbing liquid pH drops below 4-5, scrubbing and piping system components will erode or corrode. The scrubber and piping system may be lined with non-corrosive material, i.e., PVC or figerglass to avoid this type of damage. Sulfur dioxide removal efficiency is usually between 30 and 45 percent depending on the recycling characteristics of the scrubber and the incoming pH of the scrubbing liquid.

4. WS FGD Systems - The operation of FGD units using conventional scrubbing equipment and a process waste stream as its scrubbing liquid appears to be a viable FGD design. Installations in the pulp and paper, textile, chemical, and food processing industries are presently using waste streams as scrubbing liquid. Operational problems encountered by contacted FGD installation personnel have included waste stream disposal, fabrication, poor liquid distribution, mechanical failure, and low sulfur dioxide collection efficiency. The majority of these problems have been alleviated with increased operating experience and altered system design. A 75 to 90 percent removal efficiency for sulfur dioxide from flue gas is possible, depending on the basic properties of the scrubbing agent in the waste stream and the amount of make-up chemical used.

1/ Sulfur dioxide removal efficiency is dependent on the amount of scrubbing chemical used.

SECTION V

USE OF PROCESS WASTE STREAMS IN INDUSTRIAL FGD SYSTEMS

A. Introduction

A previous study conducted by EEA illustrated some advantages of using process waste as scrubber reagents in industrial FGD systems. [1/] Several industries were identified as having suitable waste stream characteristics; these examples demonstrated that utilizing process waste as FGD reagents could result in major cost savings over the use of more sophisticated FGD systems or, in many cases, low sulfur oil or coal. [2/]

This section expands on previous work: it further analyzes potential FGD use of process wastes in several industries and presents a framework for determining waste stream suitability for FGD systems. The analysis focuses on the average waste characteristics of several representative industries. First, characteristics necessary for a suitable scrubbing reagent are presented; next, the factors that complicate waste stream

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[1/] "Survey of the Application of Flue Gas Desulfurization Technology in the Industrial Sector," prepared by Energy & Environmental Analysis under Contract #CO-05-60469, Task 13, for the Federal Energy Administration, December 22, 1976.

[2/] Ibid., p. 63.

suitability are discussed; finally, a screening criteria is developed and several industrial examples are analyzed. It should be noted that this present study does not unequivocally determine the suitability of a particular process waste for FGD applications detailed empirical data on waste stream characteristics are required for such determination. However, based on information drawn from EPA "Effluent Guidelines" documents and industry representatives, potential suitability of several industrial waste streams has been assessed.

B. Waste Stream Requirements

The many characteristics of an industrial waste stream all contribute to its suitability as an FGD scrubbing reagent. A principle requirement, however, is that the waste stream have a sufficient level of alkalinity. Alkalinity denotes the capacity of water to neutralize acids, which is an important factor in the scrubbing of SO_2. The scrubbing of gaseous SO_2 by an aqueous solvent involves a series of acid-base equilibrium reactions. SO_2 dissolved in water forms an acidic solution; a high alkaline content in the scrubber solution shifts the acid-base equilibria in favor of greater SO_2 solvation and, hence, greater SO_2 removal.

The chemical compounds possibly present in a waste stream that contribute to alkalinity include the hydroxide ion (OH^-); carbonate and bicarbonate ion (CO_3^{2-} and HCO_3^-); ammonia (NH_3); sulfite and bisulfite ions (SO_3^{2-} and HSO_3^-); and conjugate bases of phosphonic, silicic, boric, and organic acids.3/ These compounds aid in the solution of gaseous SO_2 and serve as effective scrubber reagents.

3/ With regard to sulfite and bisulfite ion, only sulfite ion will aid in removal of SO_2.

The alkaline nature of water (the relative amounts present of the above compounds) is determined from the alkalinity measurement and partly from pH measurement. Alkalinity is a capacity factor and is the preferred measurement for determining SO_2 scrubbing capacity. On the other hand, pH is an intensity factor, denoting only the amount of free hydroxide ions present in solution at any given time. While pH rarely accurately describes the scrubbing capacity of a solution, it should at least corroborate the alkalinity measurement, i.e., high alkalinity should be accompanied by an above-neutral pH. The following series of figures and tables should help illustrate the required properties of scrubbing liquors.

Table V-1 describes the relationship between the alkalinity measurement and the scrubbing capability of a solution. Table V-1 also presents example calculations using ammonia and base anions of sodium salts. When ammonia data is used, care must be taken to ascertain that only ammonia (NH_3) concentration, and not the ammonium ion (NH_4^+) concentration (which has no scrubbing capability) is given. The latter example Table V-1 illustrates calculation of scrubbing capacity when sodium ion concentration from dissolved sodium salts having conjugate base anions is known. Such calculations are common for so-called "sodium scrubber" systems, although such termination is a misnomer since sodium does not actually participate in the scrubbing reactions--only the basic anions do.

In practical applications, scrubbing capability of a waste stream is a function of both the alkalinity concentration and the amount of waste water flow available. The amount of water which can be put into a scrubber is limited by the scrubber design. In this analysis, we assume a maximum liquid-to-gas ratio (L/G) of approximately 25 gallons per thousand actual

TABLE V-1

ASSUMED CHEMISTRY OF WASTE STREAM FGD SYSTEMS

1) If Total Alkalinity is Known Alkalinity is expressed as equivalent weights of C_aCO_3 (50 x 10^3 mg). Assume 1 mole B^- is equal to 50 x 10^3 mg. Then

$$SO_2 + H_2O + B^- \leftrightarrows HB + HSO_3^-$$

Thus 1 mole B^- is capable of bringing into solution 1 mole of SO_2

2) If Ammonia Concentration is Known
1 mole of ammonia equals 17 x 10^3 mg.
For each mole of ammonia

$$SO_2 + H_2O + NH_3 \leftrightarrows NH_4^+ + HSO_3^-$$

Thus 1 mole of NH_3 is capable of bringing into solution 1 mole of SO_2

3) If Sodium Concentration is Known
Assume N_a^+ in solution is contributed by N_aOH and/or $N_{a2}CO_3$.

$$SO_2 + H_2O + N_aOH \leftrightarrows HSO_3^- + H_2O + N_a^+$$

$$2\ SO_2 + H_2O + N_{a2}CO_3 \leftrightarrows 2HSO_3^- + CO_2\uparrow + 2\ N_a^+$$

Then, under these circumstances, 1 mole of N_a^+ in solution is equivalent to the capacity for removing 1 mole SO_2

cubic feet (acf) of gas. (This limit is placed on the scrubber so as not to interfere with its particulate collection efficiency.) Based on this limiting factor, a waste stream having low alkalinity but high flow rates may not be suitable for use in a particular FGD design.

Figure V-1 shows the relationship between alkalinity and flow for an FGD system designed to remove 80 percent of the flue-gas SO_2 from a 25 MW boiler burning either 3 or 1.5 percent sulfur coal. It is assumed that the scrubber in Figure V-1 operates at an L/G ratio of 20 gallons per 1,000 acf. The results shown in Figure V-1 are based on total alkalinity consumption while maintaining a pH of 5.0 to 5.5 in the scrubber recirculation tank. As depicted in the figure, an approximate alkalinity of 1,500 ppm would require a flow of 1,150 gpm to satisfy the design criteria of the FGD system.

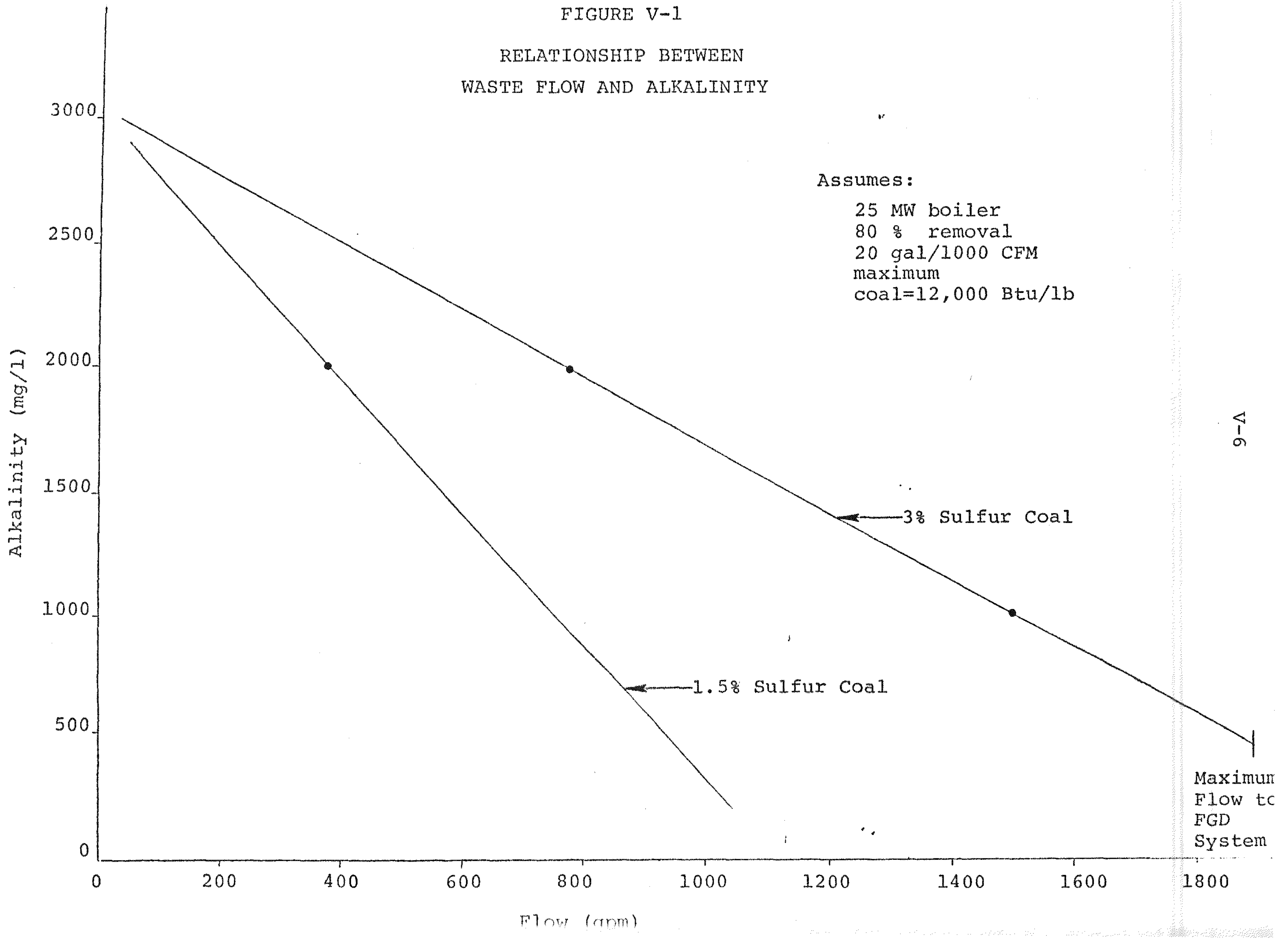
Finally, the desired degree of SO_2 removal may be shown as a function of both alkalinity and flow. Figure V-2 illustrates the variation between waste stream flow and SO_2 removal efficiency for these different alkalinity parameters. Values depicted in Figure V-2 are based on operation of a 25 MW boiler burning 3 percent sulfur coal. According to the figure, if the waste stream flow was 400 gpm and the desired sulfur removal 50 percent, required alkalinity would be on the order of 2,000 ppm or greater.

C. Complicating Factors Affecting Waste Stream Suitability

The presence of high alkalinity in a waste stream does not singularly determine its suitability for use in an FGD system. Other properties or situations can limit use of the

FIGURE V-1

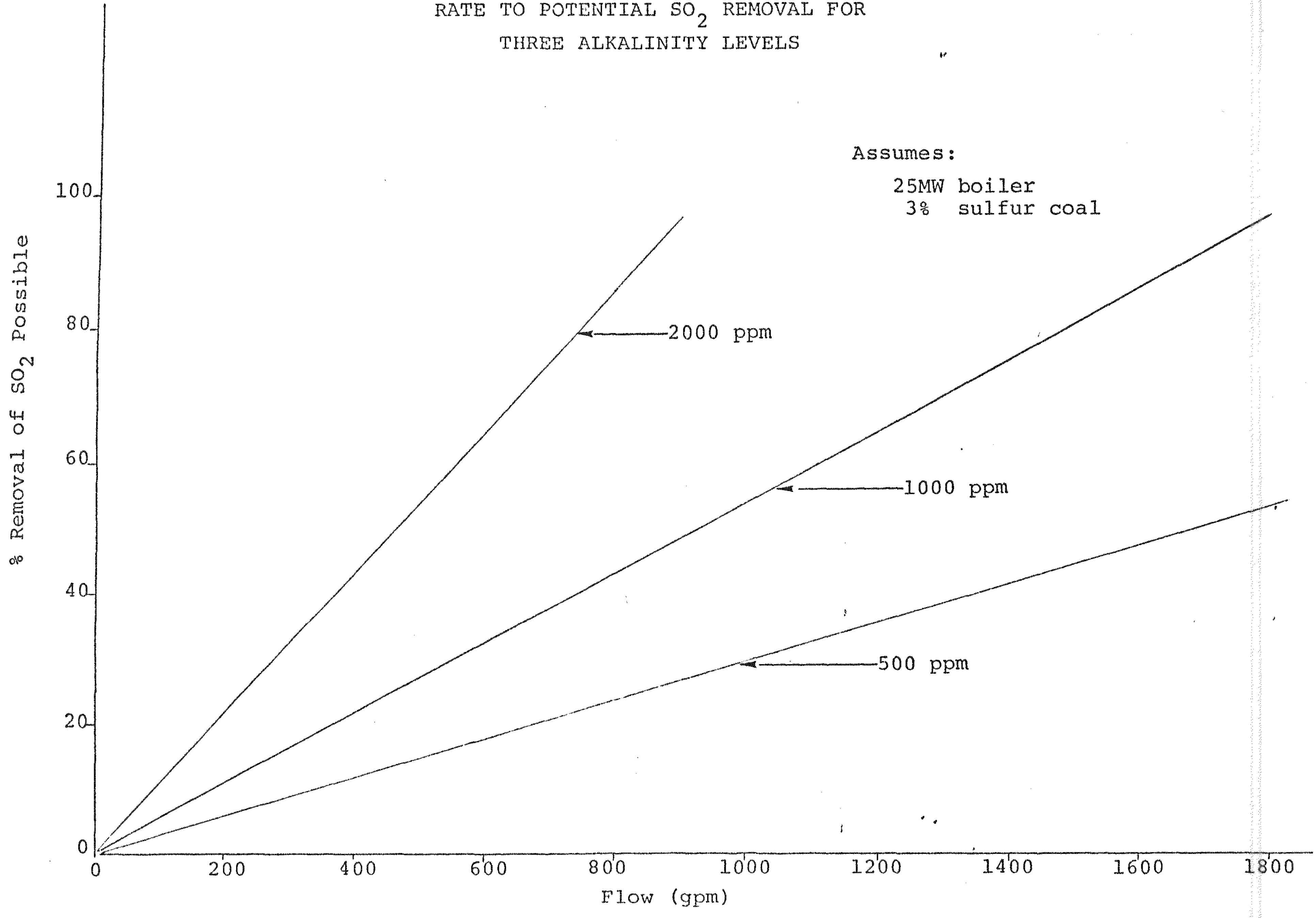
RELATIONSHIP BETWEEN
WASTE FLOW AND ALKALINITY



Assumes:
25 MW boiler
80 % removal
20 gal/1000 CFM
maximum
coal=12,000 Btu/lb

FIGURE V-2

RELATIONSHIP OF WASTE FLOW RATE TO POTENTIAL SO_2 REMOVAL FOR THREE ALKALINITY LEVELS



Assumes:
25MW boiler
3% sulfur coal

waste stream or increase the cost of the FGD system. Some of the problems possibly interfering with use of an alkaline waste stream as a scrubbing liquor include the following:

- Presence of Undesirable Compounds. Some process wastes may include other constituents such as dissolved sulfides. While dissolved sulfides could serve as effective scrubbing reagents, such use could result in H_2S emissions to the atmosphere. Consequently, sulfides would have to be removed from the waste stream, resulting in expenditures which could prove economically prohibitive for waste stream FGD use.
- Existing Waste Stream Uses. In some industries the alkaline waste stream may be processed to recover the alkaline material for sale, or the alkaline stream may be blended with other acid streams (produced by the plant) to neutralize or treat the acid stream to an acceptable pH for discharge. Such use would render the waste stream unsuitable for FGD system application.
- Impacts of Future Water Pollution Control Requirements. Alkaline waste streams exist in many industries; however, future water pollution control requirements may either result in process modification to reduce alkalinity, or reduce discharge volume by increasing waste stream recirculation. Both possibilities would seem to reduce waste stream potential for FGD system use.

The above situations do not universally apply to any particular industry or process. They all vary between individual plants and must be uniquely considered when evaluating a particular plant or process. In the following

Sections, waste streams used in specific industries are discussed. This discussion highlights which, if any, of the above constraints have bearing on the particular process in question.

D. Industries Analyzed for Process Waste Use

1. Screening Criteria and Results

Within the context of this study over processes and subprocesses were analyzed in regard to their potential suitability as FGD scrubbing liquors. The characteristics used for evaluation were (1) the amount (flow) of liquid waste produced by the process; (2) the pH of the waste; (3) the alkalinity of the waste stream; and (4), if known, the chemical constituents of the waste stream. Ranking codes for these characteristics are shown in Table V-2.

Table V-3 lists the industries and processes evaluated for potential use in FGD systems. Criteria from Table V-2 were applied to these industries and an additional screening step was used which evaluated industry size and average energy use of plants within the industry. This step indicated whether the plants were large enough or used enough boiler capacity to warrant fuel-switching to coal.

The screening criteria applied to Table V-3 results in a significant reduction of waste stream candidates for FGD system use. From a practical viewpoint, only a limited subset of the industries analyzed have both an adequate waste stream and sufficient flow to justify further investigation. Furthermore, some industries--such as textiles--produce adequate waste streams only intermittently, depending on the specific product being made. Based on the analysis employed, therefore, three industries from Table V-3 were selected for further investigation: iron and steel; petroleum refining; and paper and pulp.

TABLE V-2

RANKING OF WASTE STREAM CHARACTERISTICS

Characteristic	0	1	2	3	4	5
Flow	Very Small; Not Adequate for scrubbing considering other constituents	Small; may be able to remove SO_2 from very small boiler (L5MW)	If entire stream is used, could scrub one small boiler (10MW)	If entire flow is used, could scrub 10-20 MW of capacity	Ability to scrub 20-50 MW	Ample flow for most normal boiler sizes (50 MW)
pH	<7	7 - 9	8 - 9	9 - 10	>10	>9
Alkalinity	<100 mg/l	100-200 mg/l	200-400 mg/l	400-600 mg/l	600-1000 mg/l	>1000 mg/l
Constituents	<100 mg/l	100-200 mg/l	200-400 mg/l	400-600 mg/l	600-1000 mg/l	>1000 mg/l
Potential*	No Potential	Very Limited	Limited	Moderate	Good Potential	Excellent or is currently being used.

*qualitative ranking only.

TABLE V-3

INDUSTRIES ANALYZED

		Characteristics				
Category	Industry	Flow	pH	Alkalinity	Constituents	Potential
Pressed Glass	Lamp Manufacturing	0	1	NA	2	1
	Blown Glass	0	3	NA	NA	1
Organic Chemicals	Acrylonitride	1	NA	3	3	2
	Diphenylamine	0	NA	NA	5	1
	Hexamethylenediomne	0	NA	NA	4	1
	Hexamethylenetetramine	0	NA	NA	2	1
	Fatty Acid	1	NA	NA	1	2
Nitrogen Fertilizer	Ammonia	2	NA	NA	3	3
	Urea	2	NA	NA	5	3
	Ammonium Nitrate	2	NA	NA	2	2
Ferrous Metals	Iron and Steel	5	3	NA	5	5
Metal Finishing	Anodizing	1	4*	NA	4*	1
	Coating	1	4*	NA	4*	1
	Plating	1	4*	NA	4*	1

* Alkaline Rinse Step
NA Not Available

Table V-3 (Cont'd)

Category	Industry	Flow	pH	Alkalinity	Constitutents	Potential
Soap and Detergent	Bath Kettle	1	5	5	NA	3
	Fatty Acid Neutralization	1	5	5	NA	3
	Spray Dried Detergent	1	4	4	NA	2
	Liquid Detergent	1	3	3	1	1
Alkalines and Chlorides	Potassium Hydroxide	5	4	2	5	5
	Sodium Ash	5	5	5	5	5
	Sodium Bicarbonate	5	4	4	4	4
Petroleum Refining		4	4	NA	5	4-5
Textiles*	Wool Scouring	0	2	1	1	0
	Wool Finishing	1	0	NA	NA	0
	Dry Processing	0	0	0	0	0
	Woven Fabric Finishing*	3	5	5	5	4
	Knit Fabric*	3	5	5	5	4
	Carpet Mills	0	0	0	0	0
	Yarn Finishing*	3	5	5	5	4
Paper and Pulp		5	5	3 - 5	NA	5

*Mercerizing Step

The following subsections present the results of further analysis on the above three industries.

2. Iron and Steel Industry

Table IV-4 shows the subprocesses within the Iron and Steel Industry which were analyzed for production of alkaline waste streams. Of these processes, only the production of coke via the by-product coke oven process appears to have a waste stream with potential application to FGD system use.

a. Process Description

By-product coke manufacturing can be divided into two steps: coke production and gas recovery. Coke production involves heating coal out of contact with air to drive off the volatile components in the coal. The remaining solid material is coke. Coke production uses water to cool the ovens and to quench and cool the coke when it comes out of the ovens. However, neither resultant effluent stream is a good scrubber medium.

Production of a potential scrubber medium waste occurs in the coke by-product recovery subprocess. The purpose of the coke by-product recovery subprocess is to recover valuable products in the waste gases. For example, much of the recovered coke gas is used to fire the coke ovens and other on-site processes. Coke gas recovery and processing involves a number of steps to cool, separate and isolate tars, gases, and oil. The most significant liquid wastes produced from coke plant by-product processes are ammonia liquor, final cooling water, and light oil recovery wastes.

Ammonia liquor results from the initial cooling of the volatile gases from the coke ovens. First the hot gases are withdrawn from the main gas stream and cooled by spraying

TABLE V-4

PROCESS IN IRON AND STEEL INDUSTRY

	Waste Characteristics*			
	Flow	pH	Alkalinity	Constituents
By-product Coke Oven	1	1	1	1
Sintering	1	1	0	0
Blast Furnace	1	0	0	0
BOF	1	0	0	0
Electric Arc	1	0	0	0
Continuous Casting	0	0	0	0
Vacuum Degassing	1	1	0	0

Key:

1 = potentially useable
0 = not adequate

the gases with a water called flushing liquor. This saturates the gases with water vapor and condenses tar. The tar and the flushing liquor condensate are then directed to a decantor tank. The remaining partially cooled gas is cooled further by indirect water application. This results in the condensation of flushing water liquor tas and coal-derived moisture which is then directed to the decanter tank holding the condensate from initial cooling. In the decanter tank ammonia liquor is decanted, the rest of the flushing liquor is recycled, and tar is drawn off and stored.

Final cooling water results from the final gas cooling step prior to the gas scrubbers. In this step, water is sprayed on the gases to dissolve soluble constituents in the gas and flush out napthalene. If not recirculated and cooled properly, this cooling water can be the largest source of contaminated waste water from coking.

Light oil recovery involves first scrubbing the gas stream with an absorbent known as wash oil. The wash oil removes all light oils from the gas rendering the gas usable as a fuel for the coke ovens. Light oils are stripped from the wash oil by steam distillation. The vapors leaving the wash oil are then condensed to light oil and water. (This water, separated from the oil in a decanter operation, is another major source of wastewater.)

b. Waste Stream Characteristics and Suitability

Recovered ammonia from the above processes is the primary constitutent having potential FGD scrubbing application. The volume of ammonia and flushing liquor produced varies from 24 to 127 gal/ton of coke depending on the type of ammonia recovery operation used. Final gas cooling produces a highly contaminated wastewater. Frequently this water is recirculated. The discharge volume ranges from 10 to 20 gal/ton. Light oil recovery wastewater constitutes the bulk of water discharged from by-product coke operations. Flows vary from 500 to 1500 gal/ton for once through operations and from 30 to 50 gal/ton for recycling plants. The primary effluents from light oil recovery are phenols, cyanide, oil and ammonia.

While no accurate estimates have been made for flow rates of each of the processes within the coke oven, overall flow and constituent analyses are shown in Table V-5. Based on the ammonia/SO_2 reaction shown on Table V-1, each gallon of effluent from the coke ovens can remove (assuming complete reaction) 0.064 pounds of SO_2 or, similarly, the production of one ton of coke provides sufficient wastewater to remove 11.2 pounds of SO_2. Figure V-3 summarizes the relationship between coke production and boiler size assuming an 80 percent SO_2 removal.

c. Potential Complications

No special problems in regard to the use of the coke oven effluent as the reagent in an FGD system were raised by industry representatives contacted. In fact, it was reported that Nippon Steel Company is using coke oven water to remove SO_2 from sinter plant flue gases. However, the normal site-specific problems regarding the location of coke ovens relative to the boiler house must be considered. In many steel plants, this may pose a problem since the facilities may be far apart. However, the cost of piping the relatively small amounts of required water such distances appears low.

Based on limited discussions with industry personnel, the effluent (bleed off) from the FGD system would not pose any problems to the overall plant wastewater treatment system.

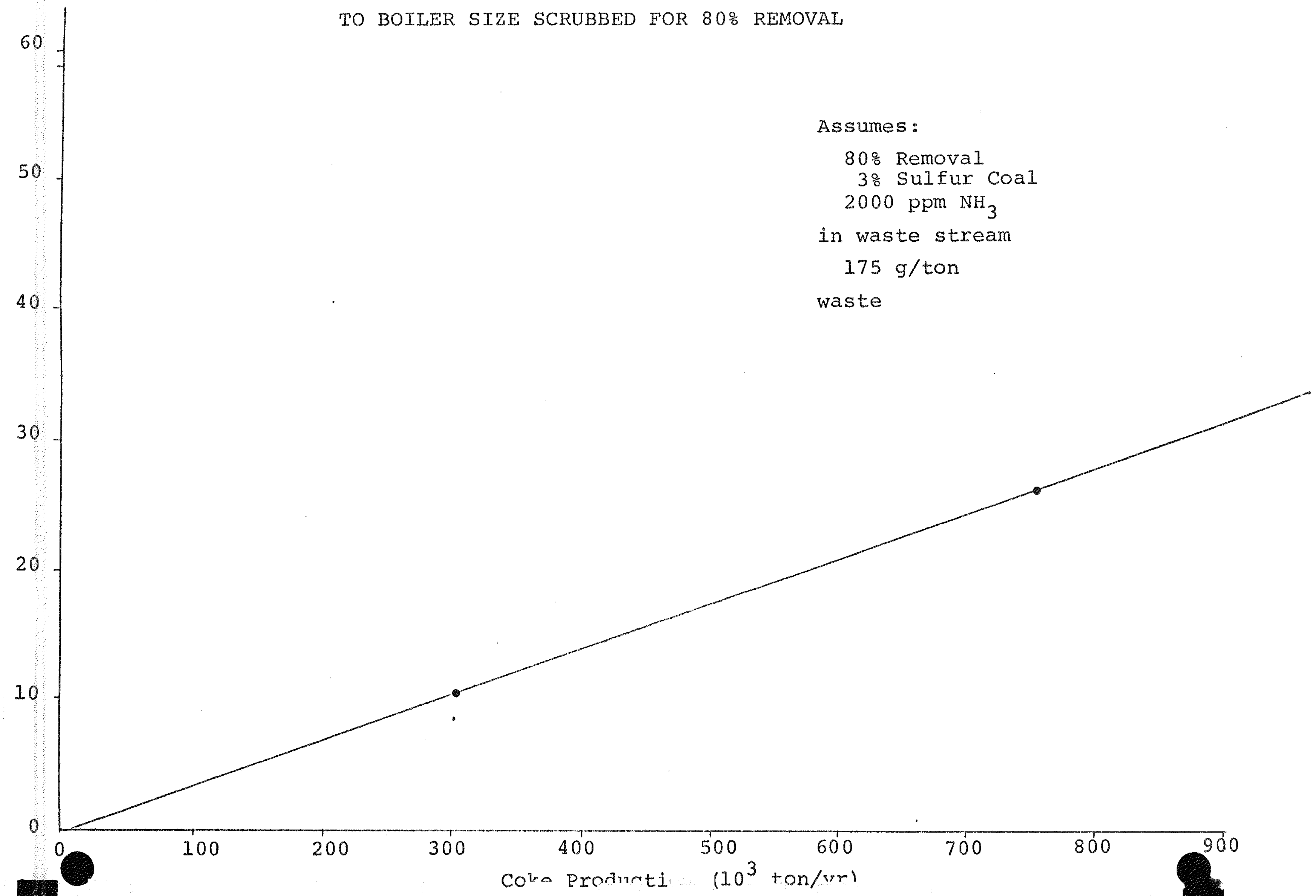
TABLE V-5

EFFLUENT FROM BY-PRODUCT COKE OVENS

Effluent Constituents Parameters - units	Raw Waste Load
Flow, gal/ton	175
Ammonia, mg/l	2,000
Phenol, mg/l	360
Cyanide, mg/l	200
BOD_5, mg/l	1,200
Sulfide, mg/l	400
Oil and Grease, mg/l	120
Suspended solids, mg/l	90
pH	6-9

FIGURE V-3

RELATIONSHIP OF COKE PRODUCTION
TO BOILER SIZE SCRUBBED FOR 80% REMOVAL



Assumes:
80% Removal
3% Sulfur Coal
2000 ppm NH_3
in waste stream
175 g/ton
waste

The additional fly ash and ammonium salts will cause an increase in solid waste disposal costs but this should not be significant when compared with current disposal levels.

The primary drawback to coke oven wastewater use in FGD systems is the presence of sulfides in the wastewaters. Sulfides are formed from the sulfur present in the raw coal. The sulfides in the wastewater system are present in solution probably as a combination of both ammonium sulfide compounds and other sulfides such as carbonyl sulfide, etc. The ammonium sulfide compounds are unstable at higher temperatures and disassociate to form soluble H_2S. This sulfide could volatize when the waste is used in an FGD system, presenting H_2S emission problems.

As shown in Table V-5 the average amount of sulfide in the water is 200 mg/l. A 40 MW equivalent boiler house requires about 650 gpm of coke oven wastewater. Although it cannot be determined how much H_2S might be released, a maximum can be estimated. Thus, for the 40 MW equivalent plant, the maximum H_2S emission rate would be about 10 grams/sec.

The odor threshold for H_2S has been reported at about 45 $\mu g/m^3$. Based on modelling results from industrial boilers1/ it is unlikely that even the highest possible emission rate would cause an odor problem. However, any precise estimate is not possible due to the site-specific variables involved. Some of these variables are (1) the sulfur content of the raw coal used in the coking process; (2) the size of the boilers to be scrubbed; and (3) the stack height of the boilers. If the sulfide concentrations appear prohibitively high, two options

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1/ "An Investigation of the Best Systems of Emission Reduction for Sulfur Compounds from Crude Oil Natural Gas Field Processing Plants", U. S. EPA, January 1977.

exist. First, it is technically feasible to remove the H_2S from the waste stream. The recovered H_2S would then be sent to a sulfur recovery plant. This type of process is carried out at one or two facilities where the ammonia content of some of the waste is used for the production of ammonium nitrate fertilizer. (For example, U. S. Steel at Donova, Penn., is producing more than 100,000 tons/year of ammonium nitrate.) The prime drawback to this type of system is high cost. Another alternative is to treat the waste stream with alkaline compounds, such as caustic soda or soda ash. The operating costs of this type of system would be higher than a simple waste stream system, but considerably lower than a self-contained liquid waste system.

d. Summary

Overall, the wastewater from by-product coke ovens appears to be a useful reagent for use in an FGD system due to the very high ammonia content of this waste. A potential difficulty is the presence of sulfides in the waste water which may result in the emission of H_2S from the boilers. The amount of H_2S potentially emitted cannot be generalized, but is not generally expected to be significant. If individual site factors could lead to unacceptable emissions of H_2S, then the volume of waste water used could be treated with chemicals such as soda ash or caustic soda.

3. Petroleum Refining

a. Process Description

Table V-6 shows the subprocesses within the petroleum industry which were analyzed for production of alkaline waste streams. Within these processes, there exist almost an unlimited number of process combinations that produce a particular product mix. The major processes shown in Table V-6 are

TABLE V-6

QUALITATIVE EVALUATION OF WASTEWATER FLOW AND CAHRACTERISTICS BY FUNDAMENTAL REFINERY PROCESSES

Production Processes	Flow	pH	Ammonia	Alkalinity
Crude Oil and Product Storage	XX	0	0	
Crude Desalting	XX	X	XX	X
Crude Distillation	XXX	X	XXX	X
Thermal Cracking	X	XX	X	XX
Catalytic Cracking	XXX	XXX	XXX	XXX
Hydrocracking	X		XX	
Polymerization	X	X	X	0
Alkylation	XX	XX	X	0
Isomerization	X			
Reforming	X	0	X	0
Solvent Refining	X	X		X
Asphalt Blowing	XXX			
Dewaxing	X			
Hydrotreating	X	XX	XX	X
Drying and Sweetening	XXX	XX	X	X

XXX - Major Contribution XX - Moderate Contribution X - Minor Contribution
0 - No Problem -- No Data

crude oil and product storage, crude desalting, crude distillation, thermal cracking, catalytic cracking, hydrocracking, polymerization, alkylation, isomerization, reforming, solvent refining, asphalt blowing, dewaxing, hydrotreating, and drying and sweetening.

Crude oil and product storage involves storing crude oil and finished or intermediate products in large tanks. Waste water results from the settling and separation of waters from the oil and includes ballast water from oil tankerships. Crude desalting involves an emulsifier and settling process. Crude oil is waterwashed in the presence of chemicals, then followed by a water/oil separation step, the water removing the salts. Crude oil distillation or fractionation is the basic refining process by which crude oil is separated into intermediate fractions of specific boiling ranges. A number of distillation processes are employed (prefractionation, atmospheric distillating topping or vacuum fractionation) but the general distillation process involves vaporizing crude oil in atmospheric towers. This results in various products based on boiling point.

Thermal cracking involves degrading by heat in the absence of a catalyst the molecules of heavy gas oil fractions (obtained from the distillation process) into lower molecular weight fractions to obtain domestic heating oil, catalytic cracking stock, etc. Catalytic cracking also breaks down heavy fractions into lower molecular weight fractions, particularly, high octane gasoline stocks. The overall catalytic process involves four steps: thermal decomposition, primary catalytic reactions at the catalytic surface, secondary catalytic reactions between primary products, and the removal of polymerizable products from further reaction by absorption into the surface of the catalyst as coke. A final thermochemical process is hydrocracking. Hydrocracking is similar to catalytic cracking except that catalytic cracking occurs in the presence of hydrogen.

There are two types of hydrocarbon rebuilding process, polymerization and alkylation. Polymerization converts olefin feedstocks into higher octane polymer units through the use of catalysts. Alkylation involves the reaction of a paraffin and an olefin in the presence of sulfuric acid catalyst to produce a high octane alkylate stream. After passing through the catalyst reactor and separator, the hydrocarbon stream exits through a caustic water wash, neutralizing the stream as it passes.

There are two types of hydrocarbon rearrangement processes: isomerization and reforming. Isomerization involves first fractionating desulfurized light gasoline into isoparaffins and normal paraffins. Normal paraffins are then heated, compressed, and passed through a catalytic hydrogenation reactor which converts the normal paraffin into its high octane isomer. After this step, the hydrogen is separated and the high octane isomer is stabilized. Reforming converts low octane naptha and heavy gasoline to a high octane gasoline blend via a series of catalytic reactions and decomposition processes. Prior to entrance into the reaction chamber, the process involves hydroheating the feedstock for the removal of sulfur and nitrogen.

Solvent refining includes a wide spectrum of processes to separate desirable from undesirable feedstocks. These processes include solvent deasphalting, solvent dewaxing, tube oil solvent dewaxing, aromatic extraction, and bulactine extraction. All processes depend on the differential solubilities of the feedstock constituents. Each process involves three steps: counter current extraction, separating the solvent and product by heating and fractionalization, and solvent recovery.

Hydrotreating is another process to separate undesirable constituents of a feedstock from desirable constituents. As previously mentioned, hydrotreating removes sulfur and nitrogen compounds, odor, color and gum-forming materials by catalytic action in the presence of hydrogen. A feedstock is mixed with hydrogen, heated, and charged to a catalytic reaction. The reaction products are cooled; and the hydrogen, impurities and product are separated.

In asphalt production, asphalt feedstock (flux) is contracted with hot air (203°C to 280°C) to obtain a desirable asphalt product. No catalyst is employed in this process.

Drying and sweetening is a relatively broad process category. Each is used to remove sulfur compounds, water, and other impurities from gasoline, etc. Sweetening pertains to the removal of hydrogen sulfide and mercaptans by oxidation or destruction with caustic. Drying is accomplished by salt filter or absorptive clay beds.

Of the processes considered, those processes which produce a "sour" or "foul" water are potential sources of alkaline waster possibly suitable as scrubbing liquors. The processes which are sources of sour water are catalytic cracking, crude distillation, hydrotreating, and hydrocracking. In addition, crude oil drying and sweetening operations can produce a caustic waste stream with good potential for use in an FGD system.

b. Waste Stream Characteristics and Suitability.

Sour water--a potential SO_2 scrubbing reagent--predominantly originates from the steam used to separate hydrocarbon components. This steam is condensed and the bleed-off from these accumulations is very high in sulfides and ammonia. The characteristics and volume of this sour water vary considerably depending on the refinery type (refineries with more catalytic cracking and hydrotreating have higher flow volumes) and type of cracking process (high nitrogen crudes will give higher ammonia levels). Ammonia is the primary constituent affording "sour" waste streams scrubbing capability. In general, West Coast refineries tend to produce much higher ammonia levels than East Coast refineries due to the type of crude processed. Reported ammonia concentrations at West Coast operations range from 1000 to more than 12,000 mg/l; and reported sulfide levels range from 500 to more than 12,000 mg/l. The volumes of sour water generally will range from one to three gpm/1000 bbl of capacity (i.e., a 100,000 bbl/day refinery will have a sour water stream of 100 to 300 gpm. Figure V-4 shows the relationship between flow and potential SO_2 removal at various ammonia contents. In this figure it is assumed that a 40 MW boiler is controlled by the FGD system.

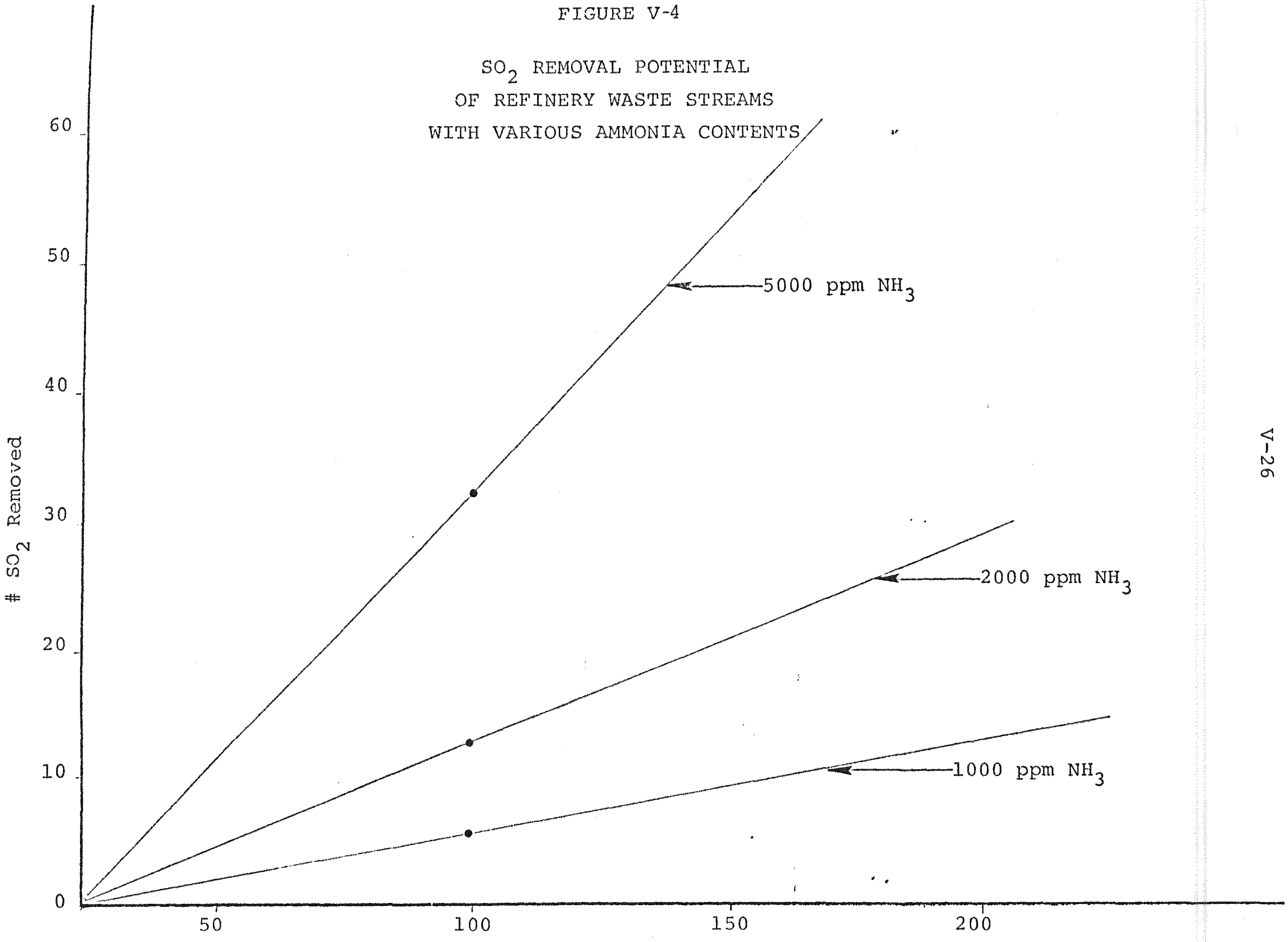
In addition to those processes which produce sour water, some types of drying and sweetening processes use a caustic wash. The particular process and the volume and characteristics of the discharge vary greatly from refinery to refinery and some refineries may not use any type of caustic wash. If a caustic wash is used it should provide a good source of reagent for an FGD system.

c. Potential Complications

While the ammonia content of the sour water is always very high and potentially usable in an FGD system, the corresponding high levels of sulfides present can cause problems. As in the case of the waste stream from by-product coke

FIGURE V-4

SO$_2$ REMOVAL POTENTIAL
OF REFINERY WASTE STREAMS
WITH VARIOUS AMMONIA CONTENTS



ovens, the sulfides in the water may be released into the atmosphere. However, due to the much higher levels of sulfides present in the refinery sour water, the problem becomes more significant.

The best method of alleviating potential H_2S emissions is to remove the sulfides from the wastewater while not affecting the ammonia levels. Exxon Corporation is developing such a system but the process is in early stages and no details are available. On the other hand, Chevron Corporation has developed a process for selectively removing H_2S and ammonia. The primary emphasis of the Chevron process is the production of a pure ammonia stream which can be processed into aqueous or anhydrous ammonia for sale. This process is currently used to produce salable ammonia; thus, the waste stream involved is unavailable for use in an FGD system. Nevertheless, the Chevron recovery system has application to other processes.

The basic Chevron process involves a two column separation of sulfides and ammonia. The process can be adapted for use in an FGD system. The first column in the separation process removes (according to Chevron) 80 to 85 percent of the H_2S. Depending on the sulfide concentration of the incoming sour water, the first column may be used to reduce sulfides to acceptable levels. However, if very high levels of sulfides are present, the full system may be required. The capital cost of the Chevron system has been estimated at between 1.5 and 1.75 million dollars for a two column system, capable of handling 100 gpm of sour water. If only one column was required, the cost would fall between 0.75 and 1 million dollars. Utility costs for both systems are reported as very small.

Even though the capital costs of the Chevron-type system are quite high, it likely represents capital cost savings over a self-contained, solid waste system. For example (as discussed in the next section) the capital cost for a self-contained, solid waste FGD system for a 40 MW boiler runs between 2.5 and 3.0 million dollars; conversely, the cost of the waste stream scrubber for a similar boiler is about 0.6 to 0.7 million dollars. If the cost of the sour water treatment systems are added to the cost of the waste stream, the total system would cost approximately 2.1 to 2.5 million dollars. These costs are estimated assuming that the entire cost of the sour water treatment system is attributed to the FGD system. Such would be the case at an existing refinery where the current sour water treatment system is adequate. At an expanded facility, where the sour water treatment must be upgraded, it would be necessary to install additional sour water treatment facilities. In such situations, the capital cost of the FGD system would be reduced by the amount of capital required for the standard type of sour water treatment.

d. Summary

The ammonia levels of sour water produced in some refinery operations are very high. However, very high levels of sulfides also accompany this waste water and potentially H_2S could be released if the water were used in the FGD system without clean-up. While it is technologically possible to remove H_2S from the waste stream, the cost of this type of treatment is relatively high at existing installations. However, costs are considerably lower for expanded facilities. Other alkaline water streams may exist in the refinery; yet, the quality and amount of reagent vary from refinery to refinery and cannot be generalized.

4. Pulp and Paper

Like the previous industries, the pulp and paper industry consists of many major processes as well as subprocesses within each group. In addition, the pulp portion of the industry is unique in that several processes use chemicals in the pulping process which potentially can be produced in the FGD system. The major paper and pulping processes evaluated were the following:

a. bleached and unbleached Kraft;
b. groundwood;
c. sulfite;
d. soda;
e. deink;
f. non-integrated paper mills;
g. neutral, sulfite, semi-chemical (NSSC); and
h. paperboard.

Table V-7 shows the subprocesses evaluated and those which have potential FGD system use. The following subsections discuss each of the key applicable processes in some detail, primarily focussing on process description, waste stream characterisitcs and suitability, and potential complications. (A slight modification of the outline occurs in this section in that subheadings are not used to indicate the above three focus areas.) Based on available information, subprocesses which appear to have potential FGD system use are the Kraft, Deink, and NSSC mills processes.

a. Kraft Process

In the Kraft (sulfate) process, wood chips are cooked at elevated temperatures and pressured with a solution of sodium sulfide and sodium hydroxide (white liquor). The spent cooking liquor (black liquor) is later separated from cellulose

TABLE V-7

SUBPROCESS EVALUATED IN PULP AND PAPER INDUSTRY

		Characteristics		
Process	Subset	Flow	pH	Alkalinity
Kraft				
	Pulp Washing	1	1	1
	Bleaching	1	1	1
	Recaustizing	1	1	1
Sulfite		1	0	0
Groundwood		1	0	0
Deink		1	1	1
Paper Mills		1	0	0
NSSC				
	Pulp	1	0	0
	Bleach Plant	1	0	0
Paper Board		1	0	0

1 = Possible

0 = Not Adequate

fiber, and the fiber is then washed and bleached to produce the desired product. The spent cooking liquor is regenerated and reused.

The Kraft subprocesses which show the maximum potential use for FGD systems are the pulp-washing water and the caustic-bleed stream from the bleach plant (if the pulp is bleached).

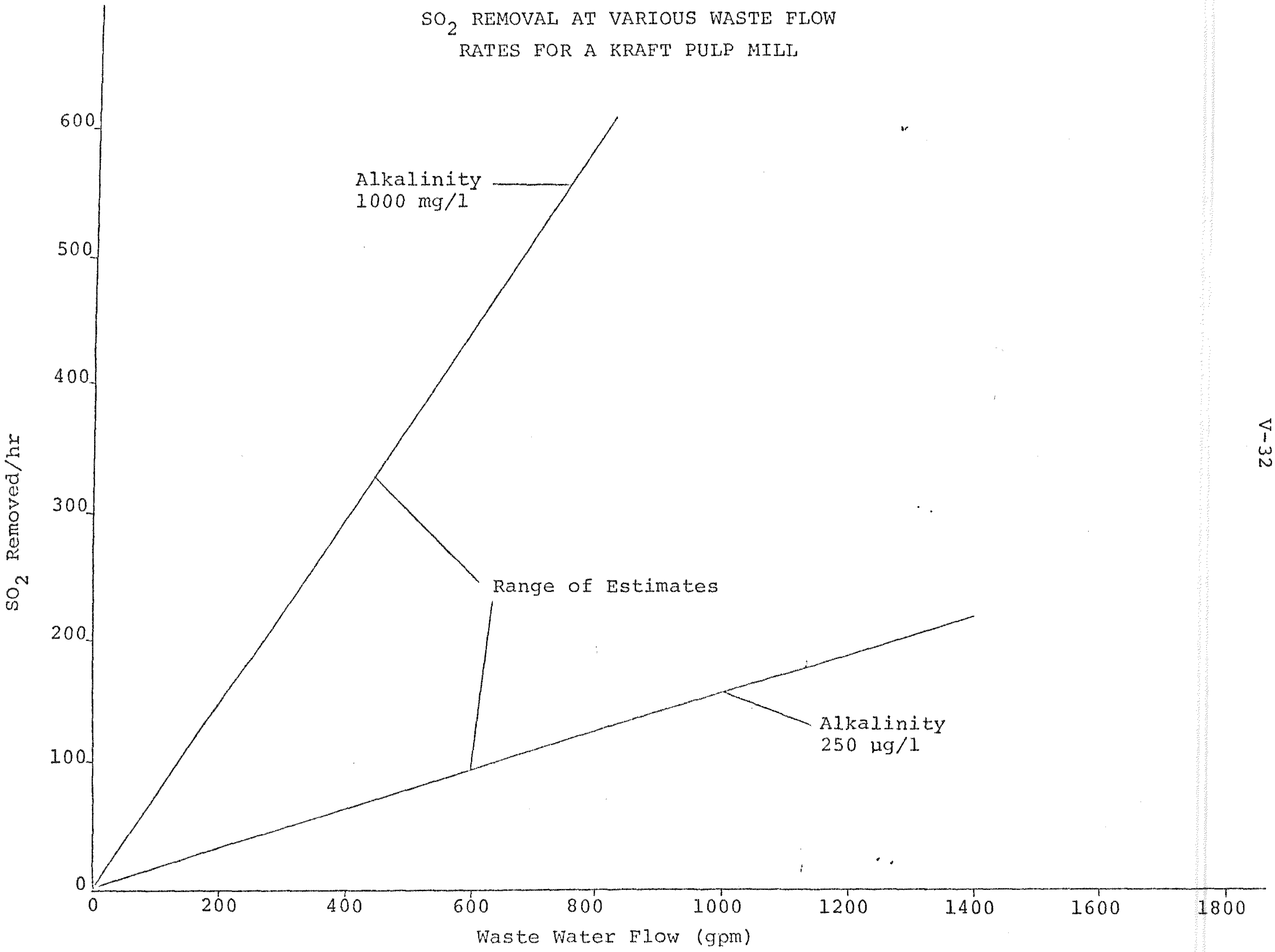
The pulp-washing processes is characterized by a high pH (9 to 12) and alkalinity (estimated between 250 and 1,000 ppm) and high water (6,000 gal/ton). This wash water is currently used as a scrubbing reagent in several mills. Figure V-5 shows the relationship between SO_2 removal and required flow rate. Figure V-6 shows the amount of waste flow required for various removal efficiencies and two types of coal.

The caustic bleed from the bleach plant is also useful in FGD systems. Typical pulp mill bleach plants utilize a series of caxstic and acid bleaches and a portion of these caustic streams may be withdrawn for use in the FGD system. The caustic flow from the bleach plant is high (8,000 gal/ton), with a high pH (10.2-12) and high alkalinity.

A third potential source of FGD reagent from a Kraft Pulping operation is the deionization rinse water. Pulp operations tend to have relatively large amounts of bark- and black liquor-fired boiler capacity in addition to coal-fired capacity. Water treatment for boiler feed water may involve the use of a strong base ion exchange system. The regeneration water from this process is very alkaline and is currently used as the FGD reagent in one large mill. Depending on the size of the mill and the type of treatment process, deionized rinse water may have sufficient volume to serve alone or supplement other chemicals used in the FGD system.

FIGURE V-5

SO_2 REMOVAL AT VARIOUS WASTE FLOW RATES FOR A KRAFT PULP MILL



In general, none of the industry representatives contacted forsaw any particular problems in the use of Kraft pulp mill waste streams in FGD systems assuming current operating practices. The only drawback mentioned was the potential foaming of the wash water and perhaps the formation of an organic scale. Experience at current installations indicates that pH control in the system or the use of foam breakers can overcome such problems. The foaming potential and the type of solution is a function of the specific mill. However, two mill-specific factors could cause problems in this application. First, the overall pH of all wastewater discharged from the mill must fall in the range of six to nine. In some mills, acidic wastes form a considerable volume of the total effluent and the alkaline wastes are used to raise the pH; thus, it is possible that the withdrawal of alkaline materials will adversely affect the pH balance of the mill. Secondly, processes which produce an effluent from the pulp washing stages contribute heavily to water pollution problems at Kraft mills. Future EPA water pollution control requirements may prohibit this technique in place of newer techniques which have little if any discharge. For some newer mills, this revised process is already in use. Consequently, if the discharge of alkaline waste is eliminated, so will the potential FGD application.

A potential beneficial characteristic of FGD scrubber systems are the useful by-products resulting from the scrubbing reactions. Since the Kraft process utilizes sodium-based chemicals in the production, it is possible to utilize the FGD system in producing these chemicals. The primary chemical added to the Kraft process is sodium sulfate, a possible FGD by-product. The scrubber can be used to add chemicals to the pulping process in one of two ways. In one method, the weak black liquor stream can be used as the scrubbing liquor. Under this system, the scrubber increases concentration (sulfur compound) in the black liquor stream.

The alternative method is to use caustic soda or soda ash as the scrubbing solution. In this system, the sodium sulfute and fly ash bleed-off would be treated in a vacuum filter to remove particulates, and the sodium sulfite then oxidized to sodium sulfate. The sodium sulfate solution can be used as a liquid or the water evaporated; and the sodium sulfate crystallized and used for chemical makeup. The primary difficulty in using an FGD system to produce chemicals lies in mill demand for chemicals. Normal Kraft mill sulfidity (ratio of sodium to sulfur) is about 20 percent. Previously, more sulfur than sodium was lost in the pulping process and makeup chemical requirements were in the range of one-to-one sulfur-to-sodium, and relatively large amounts of chemicals were required. However, environmental control requirements (especially odor) and economic considerations have greatly reduced the need for chemical makeup and, especially, for sulfur compound makeup. It is quite possible that using FGD systems to generate chemicals would produce more sodium sulfate than needed by the mill. Depending on the cost of sodium sulfate and the mill location, it may be possible to sell sodium sulfate to nearby Kraft mills. However, the possible alternatives--either using or selling chemicals--will depend on the individual mill.

b. Neutral Sulfite Semi-Chemical (NSSC) and Sulfite Process

In the NSSC Process, the wood chips are cooked in a neutral mixture of sodium sulfite and carbonates. In the sulfite process, the wood chips are cooked in an acidic medium, such as sodium or ammonium bisulfite. Waste liquor is not recovered as efficiently as in the Kraft process, and makeup chemical requirements are thus greater. The potential for FGD use in this subprocess lies in the ability of the FGD system to produce the sulfite chemical. Sodium sulfite would be produced by removing fly ash from the bleed stream of the scrubber, and could be later used in the process. Several mills burn sulfur to produce an SO_2 stream which is scrubbed with sodium compounds or ammonia to produce the useful sulfite. At least one mill is using a high sulfur fuel oil with an FGD system to produce cooking chemicals. In other mills, FGD systems on process emission points other than the power boilers may provide sufficient chemical recovery.

As in the case of the Kraft process, the choice of FGD to produce pulping liquids can only be made on a mill-by-mill basis after considering the makeup chemical requirements of the mill.

c. Deink Plants

In the Deink process, the basic raw materials is waste paper as opposed to wood chips. The washing and cleaning operations are quite alkaline (-H 40.5, alkalinity 1,000 mg/l) and the wastewater flow is high. One deink plant in New York is currently using this waste stream to scrub a coal-fired boiler. There does not appear to be any particular problem in this type of application.

d. Summary

Many processes within the pulp and paper industry have good potential for FGD system use. However, differing processes and other environmental control requirements may influence the ability of any particular mill to use these waste streams.

Several of the paper and pulp processes also have the potential to produce useful chemicals by using an FGD system. The usefulness of this type of system is dependent on the make-up chemical requirements of the particular plant and anticipated utilization rates of the FGD system.

SECTION VI

COST ELEMENTS OF INDUSTRIAL FLUE GAS DESULFURIZATION SYSTEMS

A. Introduction

The purpose of this section is to identify elements of cost industrial FGD systems. The system components contributing to the capital and operating costs of industrial FGD systems are described first. In addition, variables influencing these component costs, economy of scale factors, and component costs of industrial FGD systems are considered. While the relative importance of various elements in total system costs are presented here, cost estimates are discussed in Section VII.

The capital cost parameters presented in this section are described by FGD system type. The self-contained, solid waste FGD system capital costs are presented separately from the self-contained, liquid waste and waste stream FGD systems. This is due to the variable component equipment and costs between these system types. The operating costs are presented on a unit basis independent of FGD system type.

The capital, operating, and annual costs parameters presented in this section are not meant to be inclusive of all those encountered in industrial FGD systems. However, they do represent the major cost parameters of the industrial FGD systems reviewed in this study; even though, in application, the specific design and operating of these components may vary between systems.

Cost factors are presented for individual items of equipment to the extent possible. This was done to enable the prospective user of this report to select those types of equipment most suitable for his specific installation.

B. Capital Cost Components for Self-Contained, Solid Waste Systems

Appendix C shows the total estimated capital cost of a SCSW FGD system. Costs shown in Appendix C are based on a combination of vendor quotations from the major vendors of SCSW FGD systems and costs of actual installations. Costs are presentative of new or easily retrofittable situations. Costs include an estimate of site preparation and offsite utilities costs as well as the turnkey cost for the FGD systems. Sludge disposal is treated as an operating cost and discussed in the next section.

It was not possible to break down the costs of the SCSW system into component costs due to the diversity of systems offered by different vendors. For example, as shown in Appendix A, the major component in the Research-Cottrell Bahco FGD is the scrubber, separator, and recycle system which are contained in one module. It was not possible to cost these items individually. In contrast in the FMC double alkali system the scrubber and separator constitute a relatively small portion of the total cost with the chemical regeneration system contributing a more significant portion of the cost. In spite of the differences in the costs of individual pieces of equipment the total installed equipment cost of the various systems (based on installations and vendor quotes) are very close. Differences in the costs of the systems could occur at specific sites depending on the installation characteristics of each plant such as available space.

C. Self-Contained, Liquid Waste and Waste Stream Systems

1. Capital Costs

The SCLW and WS FGD systems reviewed in this study incorporate similar design features. The major difference between these systems is the source of scrubbing chemical. As a result, the FGD chemical processing and handling equipment may vary, to an extent, between system types. For example, the self-contained, liquid waste FGD system would likely incorporate a chemical mix tank whereas a waste stream FGD system usually feeds directly into the scrubber recycle tank, thus bypassing the need for a chemical mix tank. Figures 6-1 and 6-2 show the assumed layouts of the SCLW and WS.

The principal components contributing to the capital cost are the mechanical collectors, scrubber and separator, fan including radial blade, damper, and direct drive coupling or V-belt pumps, starters, motors, ducting and piping, screw conveyors, tanks, waste removal units, stacks, and indirect costs. Additional FGD capital cost components may exist for a given system. However, the cost components reviewed below are considered to be the major system components comprising the industrial FGD installations reviewed in this study. Appendix C contains the capital cost curves and the pricing procedures for these components. Costs in Appendix C are based on published literature and were compared with vendor estimates and cost of systems surveyed in this study.

a. Mechanical Collectors

The capital cost of a mechanical collector is dependent on its type, materials of construction, capacity, and pressure drop. A single unit mechanical collector equipped with a hopper, scroll outlet, and supports was assumed in this analysis. Both the design of the self-contained, liquid waste and wastestream FGD system assumes the placement of a mechanical collector before the scrubber to collect fly ash from the flue gas.

FIGURE 6-1

PROCESS FLOW DIAGRAM REPRESENTATIVE OF A
SELF-CONTAINED, LIQUID WASTE (CHEMICAL ADDITION) FGD SYSTEM

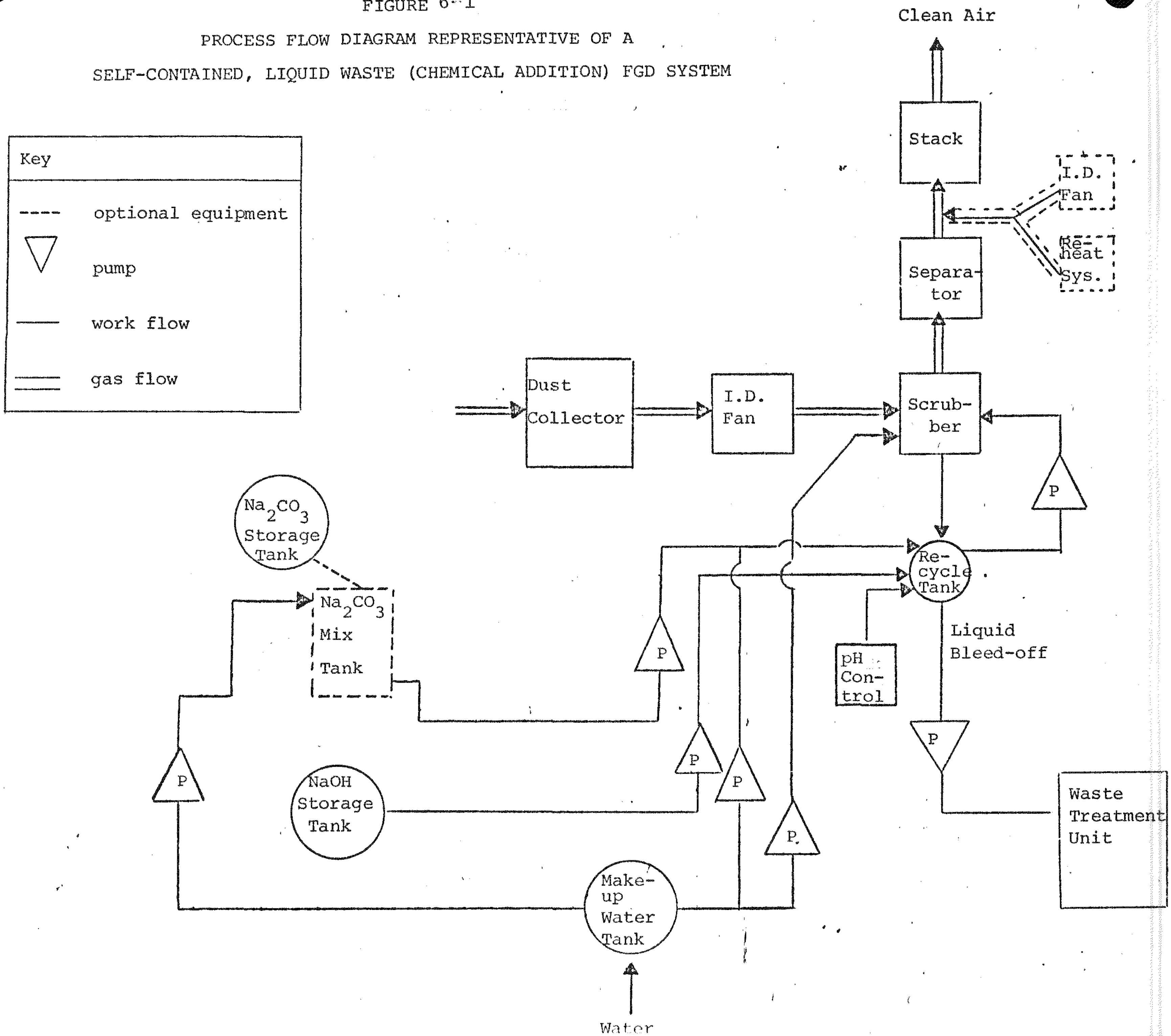
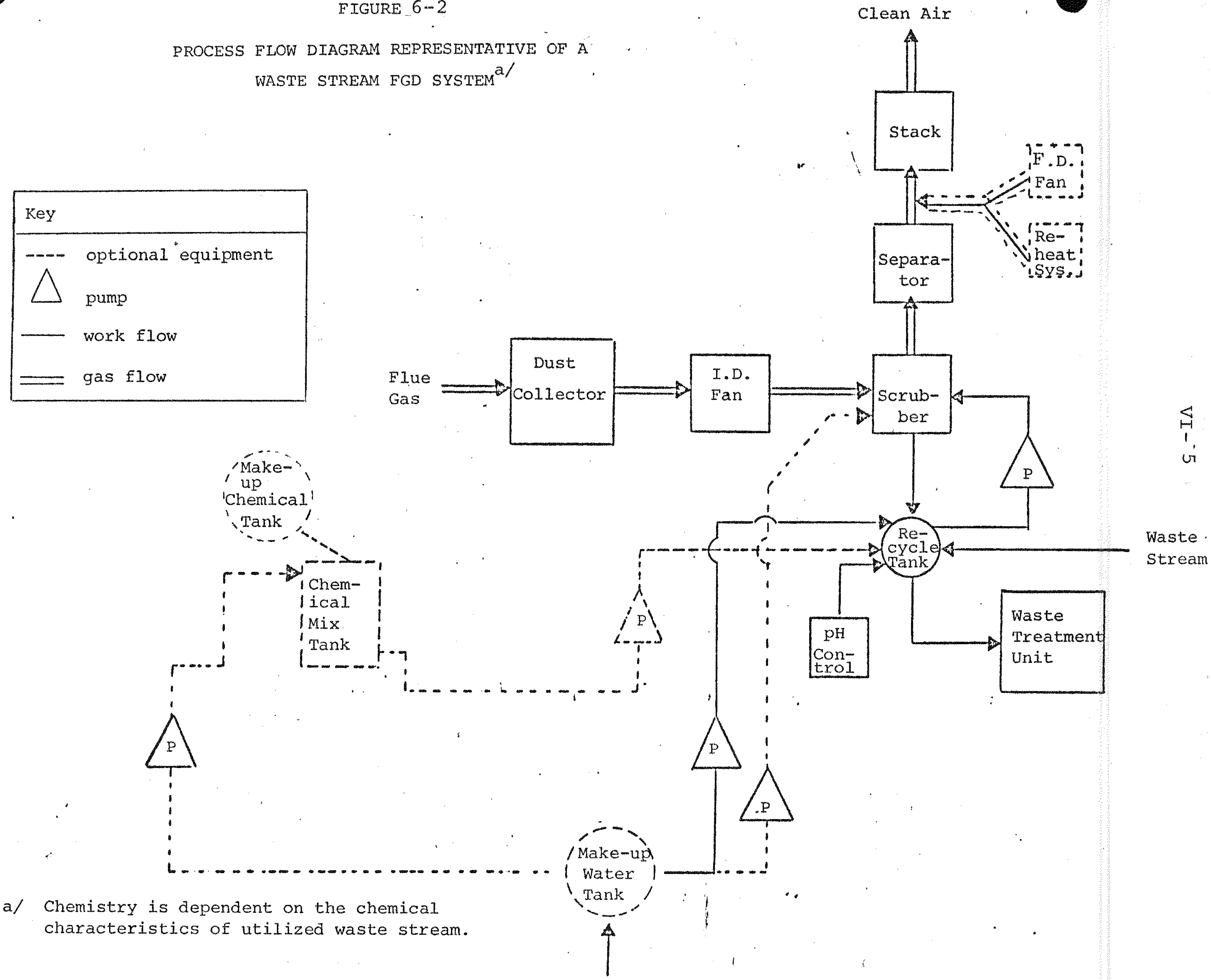


FIGURE 6-2

PROCESS FLOW DIAGRAM REPRESENTATIVE OF A WASTE STREAM FGD SYSTEM[a/]



[a/] Chemistry is dependent on the chemical characteristics of utilized waste stream.

b. Scrubber and Separator

The scrubber and separator are the main functional components of a FGD system. A high-energy variable throat venturi scrubber and cyclonic separator were assumed to be functional unit design in this analysis. Other scrubber types such as plate or spray tower are employed on industrial FGD systems. However, the venturi was chosen as the example because, based on installations reviewed in this study, it was the most common where control of both particulate and sulfur dioxide was required. The capital cost of a scrubber and separator is dependent on its volumetric flow rate, operating pressure, and construction materials. As the gas flow rate increases, the size of the scrubber, elbow, and separator increases, as do the capital costs. The scrubber and separator outside plate thickness is a function of system operating pressure and shell diameter. As the columetric flow rate and/or pressure drop across the venturi inlet increases, the wall thickness increases. Construction materials can vary from rubber or fiberglass lined carbon steel or stainless steel, depending on system design characteristics. Both increased plate thickness and less corrosive construction materials increase the scrubber and separator component cost. Both the self-contained, liquid waste and waste stream FGD systems are assumed to operate a venturi scrubber and cyclonic separator.

c. Fan

Radial tip fans are predominantly used in high energy venturi scrubber applications becuase of their ability to operate at high pressures and temperature, and in abrasive gas streams. The primary function of the fan is to move the flue gas through the pollution control equipment and out the stack. The cost of radial blade fans increases as a function of volumetric flow rate and/or fan static pressure. Construction may be of various materials including carbon and stainless steel, and may incorporate special linings for abrasive operating conditions. Fan blades constructed of less corrosive materials significantly increase their capital cost.

Additional equipment needed to operate a fan includes an outlet damper, direct drive coupling or V-belt, motor (drop-proof), and starter (magnetic with circuit breakers). The cost of an outlet damper is a function of gas flow and pressure drop. The capital cost of V-belts are a function of motor brake horsepower and fan RPM.

d. Pumps

Pumps are responsible for the movement of liquid throughout the FGD system. Specific pump applications would be in the areas of water recycle, water and chemical make-up for losses occurring in the system, and as a means to remove liquid waste from the system. Both self-contained, liquid waste and wastestream FGD systems utilize pumps in similar applications, except in the area of make-up water and chemicals due to the inherent design of each system.

e. Motors and Starters

Motors and starters are installed on all pumps and fan displacements, as well as on the majority of mechanically operated equipment, i.e., screw conveyors, mixers, etc. The type of motor may be drip-proof, explosion proof, or enclosed fan cooled. The magnetic starter may be explosion proof with or without circuit breaks. Pumps and motor are installed in both the self-contained, liquid waste, and waste stream FGD systems.

The capital cost of motors is dependent on motor size measured in brake horsepower and motor RPM. The major capital cost variable for magnetic starters is the adjacent motor brake horsepower rating.

f. Ducting and Piping

Ducting and piping is the means for transporting gas and liquid, respectively, through a FGD system. The capital cost of ducting is dependent on the construction material, shell diameter, and plate thickness. The capital cost of piping is also dependent on construction material, shell diameter, and pipe thickness. The WS FGD system will usually incorporate more piping than the SCLW FGD system. This is due to the transport of the wastestream from its source to the scrubber. The two FGD systems employ approximately the same amount of ducting.

g. Screw Conveyors

The Capital cost of screw conveyors is dependent on the conveyor diameter and length. The cost of the conveyor through, screw, drive, fittings, and motor may also be considered when estimating the capital cost of the unit. The WS FGD system employs fewer conveyor systems than SCLW FGD systems. This is primarily a result of the liquid character of the waste stream system's chemical source.

h. Tanks

The capital cost of a tank is dependent on the capacity and type of tank. FGD systems have need for recycle, mixing, settling, and holding tanks. The waste stream FGD system will incorporate approximately the same or more tankage than a self-contained liquid waste system. Even though the waste stream FGD system does not use a dry chemical storage tank, the system design may still have to include a supplementary chemical mix tank and probably larger recycle and waste stream holding tank, depending on the waste stream chemical characteristics.

i. Waste Treatment Units

Any liquid overflow from the FGD system must be treated before it can be discharged into a sewer system, river, or, possibly, the plant wastewater treatment facility. The type of equipment assumed in this report is capable of fly ash removal only. It is assumed that if further treatment, such as aeration or dissolved solids removal or chemical treatment is needed, it will be carried out at the main wastewater treatment plant.

The capital cost of scrubber effluent treatment and disposal depends on a number of factors including: (1) the type and degree of treatment required; (2) the size of the treatment units; (3) the corrosivity of the effluent; (4) the method of disposal for the liquid and/or solid; and (5) the need and availability of land and manpower. The waste treatment unit operations considered in this analysis are: (1) aerated lagoons and equalization basins; (2) neutralization facilities; (3) oil separators; (4) primary clarifier; (5) lagoons; and (6) vacuum filtration. The sequence of application of waste water unit operations for both the self-contained, liquid waste, and waste stream FGD system assumed in this report is as follows: disposal of scrubber wastes: (1) in the plant's wastewater treatment facility; (2) by ponding; (3) in a settling tank to be disposed of through: a) the plant's wastewater treatment facility and/or, b) the city sewer system; (4) clarifier; (5) thickener; and (6) vacuum filter.

j. Stacks

The obvious function of the stack is to allow the release of gaseous effluents at some point above the ground. The cost of the stack is a function of stack diameter, height, wall thickness, and materials of construction. A steel insulated stack was assumed for all systems.

k. Summary

Table IV-1 shows the approximate percent of total capital cost due to the various components of the SCLW and WS FGD systems. In both cases, the scrubbing unit is the most expensive item of equipment while the importance of other pieces of equipment varies in each system type.

TABLE VI-1

CAPITAL COST BREAKDOWN OF TYPICAL INDUSTRIAL FGD SYSTEM [1/]

	SELF-CONTAINED, LIQUID WASTE FGD SYSTEM	WASTE STREAM FGD SYSTEM
CAPITAL COST COMPONENT	Percentage of Total System Capital Cost	Percentage of Total Capital Cost
Mechanical Collector--includes single unit collector, hopper, scroll outlet, and supports	8-9	8-9
Variable Throat Venturi Scrubber and Cyclonic Separator--stainless steel construction	34-38	35-39
Fan--includes radial tip blades, motor, starter, and direct coupling	4-11	4-11
Pumps--includes motors and starters	4-6	6-7
Ducting and Piping	7-8	7-8
Conveyor Systems	1-2	1-2
Tanks	7-8	5-7
Waste Treatment Units--includes settling tank and slurry pumps	2-3	N/A
Stack	1-2	2-3
Indirect Costs	23	23

[1/] Size of the FGD system varies from 10 to 40 megawatt equivalent.

2. Operating Costs

The operating cost of industrial FGD systems varies depending on the operating components and characteristics of each system. The operating cost components considered in this analysis include electrical power, chemicals, water, maintenance, manpower, and solid waste removal and disposal. These components and their relationship to the industrial FGD systems are discussed below in greater detail. Appendix D contains data on the variation in costs for various systems and variation in costs due to location.

a. Electric Power

Electrical power is used by an FGD system to move air and liquids through the system. Power consumption is dependent upon the number of electrical-powered units incorporated in the FGD design and varies with system type. The major power utilizers of an FGD system are motors and starters. These units are operated in the majority of functional components of an FGD system, including the mechanical collector, scrubber, conveyor system, various pumps, and wastewater treatment units.

A self-contained, solid waste FGD system, due to its more complex design, has a greater power consumption than either the self-contained, liquid waste or waste stream FGD systems. The waste stream FGD system may require more electrical power than an equivalent self-contained, liquid waste FGD system, if the waste stream is large in volume, thus, requiring more pump horsepower and wastewater treatment capacity.

Power requirements vary also by type of scrubber selected and amount of particulate control required. The verturi scrubber selected as the example for this study has singificantly higher power requirements than other scrubber types, but will remove both particulates and sulfur. If very high particulate control is required, then power requirements will also be high.

b. Chemical Costs

The purpose of the chemical in an industrial FGD system is to react with flue gas sulfur dioxide. The amount of chemical utilized by an industrial FGD system is dependent upon the system's sulfur dioxide removal efficiency, type of chemical reagent, pH balance, and chemical recycle and recovery systems. The waste stream FGD system, depending on the chemical composition and volume of waste stream, should utilize the least amount of chemical additive among equivalent industrial FGD systems. However, the chemical content of the waste stream, if otherwise recoverable may be considered as a system chemical cost.

Chemical costs are mainly a function of the amount of SO_2 removed from the system. In well-designed FGD systems, the chemical requirements are very close to stoichiometric (that is, the theoretical requirements), and as such, the amount of chemical will vary linearly with the amount of SO_2 removed. The cost of chemicals, therefore, is a function of both the removal rate desired and the type of chemical used.

c. Water Use

The amount of water an industrial FGD system utilizes is dependent on the system's design, evaporation losses, make-up chemical consumption, and wastewater treatment capability. The SCSW FGD system utilizes a small amount of water 1/ and will require only the amount of water lost in evaporation and the water lost in the solid waste. However, the waste stream FGD system has the smallest potential water operating

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1/ Based on communcation with FGD vendors.

cost and demand of the reviewed industrial FGD systems due to its utilization of a process waste stream and the probability that this waste stream will supply all of the water needed in the system. Of course, waste added onto such a system depends upon the chemical characteristics, volumentric flow rate, and fluid base of the waste stream; and the assumption that the water used by the FGD system can be returned to the normal wastewater treatment plant.

d. Maintenance

Maintenance is defined as the general up-keep of a system and replacement of routine components. The amount of maintenance required by an FGD system depends on a number of factors, including equipment complexity and age, and the corrosion/erosion prevention factor designed into the equipment. The SCSW FGD would have a higher maintenance factor (approximately three percent of the system's capital cost) among comparable industrial FGD systems. This is due to the greater amount of mechanical equipment and higher complexity factor inherent in the system. Equivalent SCLW and waste stream FGD systems would have approximately the same maintenance cost (approximately one to two percent of the system's capital cost) due to similar equipment design and function.

e. Manpower

Personnel are required to perform routine tests and maintain an FGD system. The factors affecting the amount of manpower required by an FGD system is the quality of manpower, amount of system automation, and the operating condition and characteristics of the equipment. The manpower requirement for a SCSW FGD system is assumed to be approximately 0.5 to 1.0 men/shift depending on system size, whereas the manpower requirement for the SCLW, and waste stream FGD systems is assumed to be approximately 0.25 men/shift. SCSW FGD system has higher manpower requirements than an equivalent SCLW or waste stream FGD system primarily because of the operation and up-keep of a larger amount of FGD equipment and control devices of higher complexity.

f. Solid Waste Removal and Disposal

The amount of solids generated by an industrial FGD system is dependent on a number of factors including the fly ash content of the fuel, geographical location, particulate and sulfur dioxide collection efficiency of the unit, chemical regeneration capacity of the system, and the need for a wastewater treatment unit. The SCSW systems, since they produce a sludge waste product, incur larger solid removal and disposal costs than an equivalent WS FGD system. Disposal of the liquid waste from a SCLW and WS FGD system was assumed to occur by piping the liquid to the plant's wastewater treatment facility. This cost of disposal was not included in the FGD cost analysis for the self-contained, liquid waste, or WS FGD systems. A WS FGD system <u>may</u> utilize a lime-based waste stream, therefore, producing a sludge waste product. However, the WS FGD systems uncovered in this study were all sodium-based.

SECTION VII

FLUE GAS DESULFURIZATION COST ESTIMATES

A. Introduction

The purpose of this section is to use a series of case examples to indicate the factors which influence the cost and applicability of various types of FGD systems. The factors which will be considered in the examples are unit capacity, operating hours, FGD type, and removal efficiency. The costs presented in this section are generic in nature and may not be applicable to specific plants, but will serve to provide approximate costs to allow a user to determine whether any FGD system merits detailed consideration and which type of system is likely to be the most cost-effective for a class of industrial facilities.

B. Case Examples

The case examples chosen in this analysis are representative of the industrial boilers using FGD and of the population of industrial coal-fired boilers in general. The three systems chosen for analysis are intended to span the sizes of coal-fired boilers used in industrial installations. The sizes chosen were:

- A 10 MW equivalent boiler (100 million Btu/hour heat input) as representative of smaller coal-fired boilers.
- A 25 MW equivalent boiler (250 million Btu/hour heat input) as representative of larger size boilers and also of the smallest boiler subject to EPA's New Source Performance Standards.

- A 40 MW equivalent boiler (400 million Btu/hour heat input) as representative of large industrial boilers such as would be used for process heat requirements in the petroleum or paper industries.
- Two 20 MW equivalent boilers (each 200 million Btu/hour heat input) as representative of multiple boiler installations.

Assumptions concerning the design and operation of the FGD systems were made so that the cost of each case example would be calculated. Table VII-1 lists the design assumptions for each major FGD system component. The assumptions were based on basic engineering principles and practices.

Additional assumptions were made throughput the analysis, i.e., type of construction material, pumps type, etc. However, reference to these equipment and operational assumptions, plus the pricing sectors used in costing each system, have already been stated elsewhere in the text, i.e., Chapter VI and Appendices and will not be repeated.

The assumptions used to calculate the cost of each FGD case examples are intended to characterize each system into specific components amenable to a costing procedure. The cost estimates do not encompass all the cost components that would comprise a FGD turnkey construction job, i.e., overhead charge, site preparation, etc. However, the analysis was comprehensive and did incorporate all FGD component costs that were involved in the industrial installations reviewed in this study.

Basic assumptions were also made concerning the parameters affecting operating cost. Table VII-2 lists the demands for chemicals, electric power, etc., for each of the systems.

FGD SYSTEM DESIGN ASSUMPTIONS

TABLE VII-1

FGD SYSTEM COMPONENT	DESIGN ASSUMPTION
Boiler	Boilers with a steam-firing rate of 10 and 20 megawatts equivalent are spreader stoker fired.
	Boilers with a steam-firing rate of 25 and 40 megawatts equivalent are net bottom, pulverized coal-fired. 30 percent excess air 80 percent efficient Air preheater Flue gas at 350° F Emission factors: Particulates - 13 x (percent ash content)=lb/ton coal burned; Sulfur Oxides - 38 x (percent sulfur content)=lb/ton coal burned. a/
Mechanical Collector	Particulate collection efficiency of 70 percent; 10,20, 25 megawatts equivalent system have a 4 inch W.G. pressure drop mechanical collector; 40 megawatts equivalent system has a 6 inch W.C. pressure drop mechanical collector; inlet flue gas temperature = 350° F.
Scrubber	Inlet flue gas temperature = 315° F Inlet flue gas moisture = 12 percent Outlet flue gas temperature = 140° F (saturated) Scrubber pressure drop is 15 inches W.C. total Sulfur dioxide removal efficiency of 90 percent Particulate removal efficiency of 95 percent Scrubbing liquid is recycled caustic water Liquid to gas ratio is 20 gallons per 1,000 ACFM Make-up water required: Evaporation--approximately 4 percent of scrubber liquid input Bleed--approximately 5 percent of recycle liquid 1/4 inch 316-stainless steel construction

FGD SYSTEM DESIGN ASSUMPTIONS

TABLE VII-1 (Continued)

FGD SYSTEM COMPONENT	DESIGN ASSUMPTION
Waste Treatment Unit	Settling tank with 1.8 hours retention time The liquid waste from the self-contained, liquid waste, and waste stream FGD systems is treated in the installations on-site wastewater treatment facility.
Ducting	20 feet straight, 5 feet elbow between the boiler and mechanical collection 20 feet straight, 5 feet elbow between the boiler and mechanical collection Design volumetric flow rate = 3,500 fpm
Fuel-Fired	Bituminous coal sulfur content - 3 percent ash content - 11.5 percent received heat value - 12,000 Btu/lb coal
Stack	50 foot stack for each scrubber installation
General	Loss of air through system is negligible Loss of heat in ducts is negligible Carbon steel construction, unless otherwise specified, 1,000 Btu/lb steam-produced No reheat system, I.D. fan

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a/ Compilation of Air Pollutant Emission Factors-Second Edition; Environmental Protection Agency, AP-42, April 1973.

TABLE VII-2

ASSUMED OPERATING DEMANDS FOR VARIOUS FGD SYSTEMS

SIZE SYSTEM	ELECTRICITY (Kw)	CHEMICALS[1/] (Tons/hr)	WATER (gpm)	MANPOWER (Men/Shift)	SOLID WASTE (Tons/Hour)
10 MW					
SCSW	165	0.23	29	0.5	
SCLW	143	0.44	41	0.25	0.14
WS[2/]	150	0	0	0.25	0.14
25 MW					
SCSW	400	0.58	73	0.75	
SCLW	345	1.10	100	0.25	0.35
WS	350	0	0	.25	.35
40 MW					
SCSW	693	0.92	117	1.0	
SCLW	603	1.74	164	0.25	0.56
WS	620	0	0	0.25	0.56

1/ Lime is used by SCSW and soda ash by the SCLW system.

2/ Assumed 1,000 ppm alkalinity.

C. Cost of FGD Case Examples

The capital, operating, and annual costs of these different types of systems (SCSW FGD system, SLSC FGD system, and WS FGD system) were determined for four different sized systems (one-10 megawatt equivalent FGD system; two-20 megawatt equivalent FGD systems; one-25 megawatt equivalent FGD system; and one-40 megawatt equivalent FGD system). Costs for a SCSW system for the two-20 MW equivalent systems were not computed due to a lack of data on existing installations. However, an evaluation of the basic design of the SCSW system in use would suggest that the cost of this system would be very close to the cost of the 40 MW equivalent system.

1. Capital Costs

The capital cost component breakdown was determined for a 10, (2) 20, 25, and 40 megawatt equivalent SCLW liquid waste, and WS FGD systems, as seen in Tables VII-3 and VII-4, respectively. The major capital cost components considered were the mechanical collector, venturi scrubber and cyclonic separator, fan, pumps, ducting and piping, conveyor systems, tanks, waste treatment units, stack, and indirect costs. The capital cost of a system component was assumed to be its initial unit cost plus an installation cost of 2.0 times the initial cost.

Table VII-5 shows the estimated capital cost of the SCSW system. A capital cost breakdown of this system was not attempted due to large differences in the relative importance of components in the FGD systems offered by different vendors.

Figure VII-1a shows a comparison of the capital cost for all three FGD systems when applied to a single boiler. As would be expected, the capital cost of the SCSW FGD system is significantly higher (from $50 to $66/KW) than either the SCLW or WS FGD system. The SCLW and WS FGD system are very close in capital cost. The WS system is somewhat lower due to the lack of chemical storage and mix tanks. This cost is offset somewhat by the increased costs due to pumps in the WS system.

Table VII-3

CAPITAL COST COMPONENT BREAKDOWN OF A 10, (2) 20, 25, and 40 MEGAWATT EQUIVALENT SCLW FGD SYSTEM

CAPITAL COST COMPONENT	FGD System Number ( ) and Size			
	(1) 10 Megawatt Equivalent	(2) 20 Megawatt Equivalent	(1) 25 Megawatt Equivalent	(1) 40 Megawatt Equivalent
	Approximate Capital Cost[a/] - $\$ \times 10^3$			
Mechanical Collector - includes single unit collector, hopper, siroll outlet, and supports	25.0	82.0	49.0	710.0
Variable-Throat Venturi Scrubber and Cyclonic Separator-Stainless Steel Construction	119.0	366.0	205.0	266.0
Fan - includes radial hip fan blade, motor, starter, and direct coupling	13.0	79.0	50.0	87.0
Pump - includes motor and starter	17.0	33.0	22.0	29.0
Ducting and Piping	24.0	73.0	42.0	65.0
Conveyor System	5.0	8.0	5.0	5.0
Tanks	23.0	63.0	43.0	63.0
Waste Treatment Unit - includes settling tank and slurry pump	8.0	14.0	11.0	14.0
Stack	7.0	19.0	10.0	10.0
Installed Cost	241.0	737.0	437.0	610.0
Indirect Cost	73.0	222.0	132.0	184.0
TOTAL	314.0	959.0	569.0	794.0
$/KW	31.4	24.0	22.8	19.9

[a/] Capital costs include installation

Table VII -

CAPITAL COST COMPONENT BREAKDOWN OF A 10, (2) 20, 25, and 40 MEGAWATT EQUIVALENT FGD SYSTEM

CAPITAL COST COMPONENT [a]	FGD System WS Number ( ) and Size			
	(1) 10 Megawatt Equivalent	(2) 20 Megawatt Equivalent	(1) 25 Megawatt Equivalent	(1) 40 Megawatt Equivalent
	Approximate Capital Cost[b] - $\$ \times 10^3$			
Mechanical Collector - includes single unit collector, hopper, siroll outlet, and supports	25.0	82.0	49.0	71.0
Variable-Throat Venturi Scrubber and Cyclonic Separator-Stainless Steel Construction	119.0	366.0	205.0	266.0
Fan - includes radial hip fan blade, motor, starter, and direct coupling	130.0	79.0	50.0	87.0
Pump - includes motor and starter	23.0	51.0	31.0	47.0
Ducting and Piping	24.0	73.0	42.0	65.0
Conveyor System	5.0	8.0	5.0	5.0
Tanks	18.0	40.0	30.0	40.0
Stack	7.0	19.0	10.0	10.0
Installed Cost	234.0	718.0	422.0	591.0
Indirect Cost	70.0	215.0	127.0	177.0
TOTAL	304.0	933.0	549.0	768.0
$/KW	30.4	23.3	22.0	19.2

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[a] A wastewater treatment unit was not costed for the system. It is assumed that the wastestream will be treated in the installation's on-site wastewater treatment facility.

[b] Capital costs include installation.

FIGURE VII-1a

COMPARISON OF CAPITAL COST ($/KW) FOR SCSW, SCLW, AND WS FGD SYSTEMS

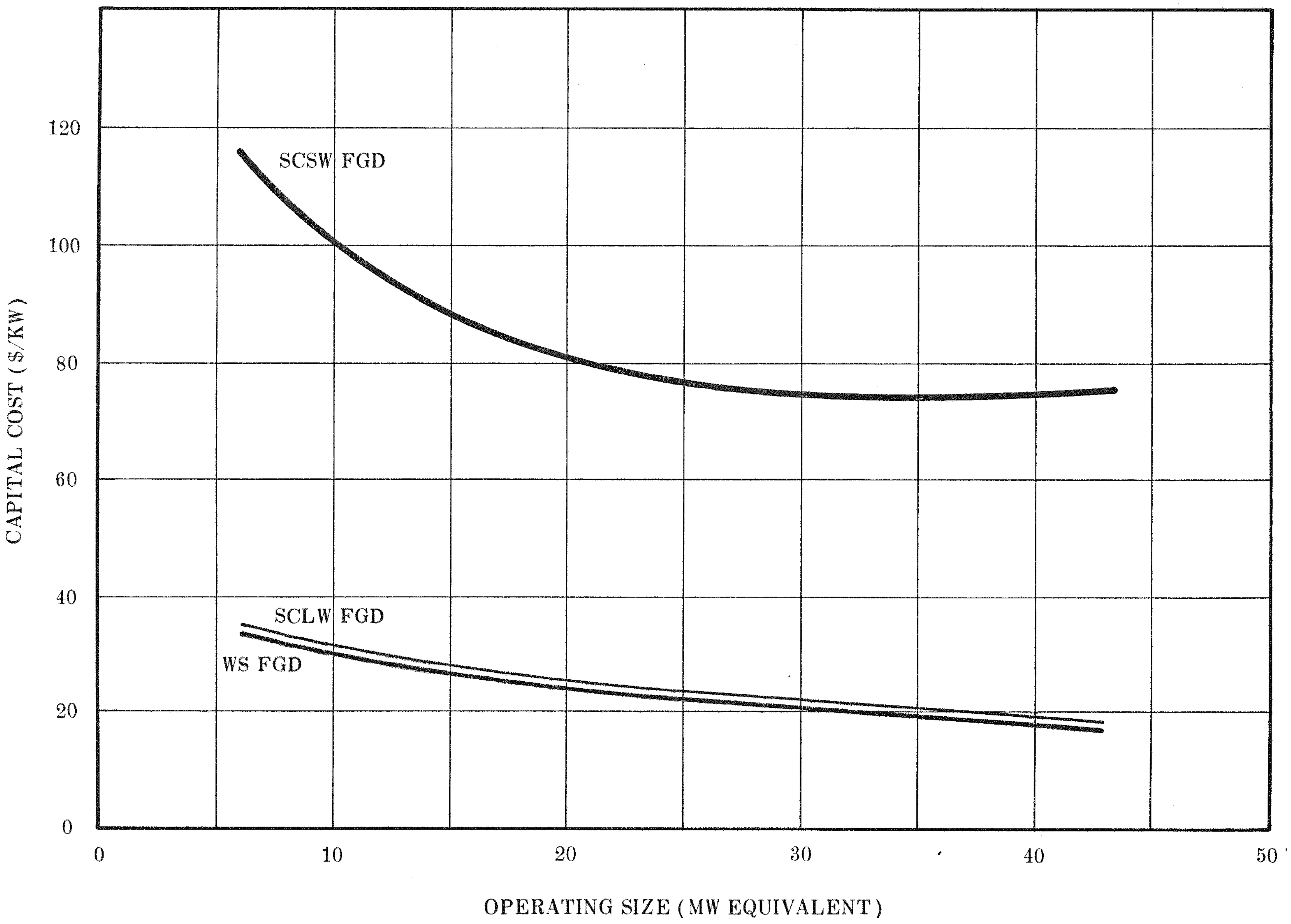

TABLE VII-5

APPROXIMATE CAPITAL COST OF SCSW FGD SYSTEMS

SIZE	CAPITAL COST (10^3 \$)	CAPITAL COST (\$/KW)
10 MW Equivalent	1,000	100
25 MW Equivalent	1,900	76
40 MW Equivalent	3,000	75

The SCSW system shows greater economies of scale than the SCLW or WS FGD system. This is due to the greater amount of capital intensive equipment in the SCSW FGD system versus the other systems.

2. Operating Costs

Table VII-6 shows the operating cost of the various types of FGD systems. The costs shown on Table VII-6 are expressed as the cost per hour of operation and vary linearly with the hours of operation. The exception to this is the assumed cost for maintenance which is expressed as a percentage of overall capital cost and is independent of hours of operation.

3. Annual Costs

Annual costs are a combination of operating costs and the annualized cost of the capital equipment associated with the FGD equipment. In this study the annual cost of each FGD system is assumed to be the equivalent of an investment in profit making equipment which would provide an after tax rate of return of 15 percent. A discount cash flow type of analysis was used. Other methods of financial analysis which treat capital and operating costs differently could provide a different estimate of annual cost. Table VII-7 shows the financial parameters assumed.

Table VII-8 shows the annual cost of the industrial FGD systems selected in this analysis. Several observations can be made about the data in Table VII-8.

- As would be expected, the cost of all FGD systems varies considerably with the hours of operation. If applicable, the WS FGD is the choice for any hours of operation. Its operation is probably limited to units producing steam for process use.

TABLE VII-6

APPROXIMATE OPERATING COST FOR INDUSTRIAL FGD SYSTEMS ($/hour)

Size/System	Electricity	Chemical	Water	Maintenance[a]	Manpower	Solid Waste Disposal	Total
10 MW Equivalent							
SCSW	6.60	9.20	0.64	30,000	$ 6.75	8.76	31.95
SCLW	5.72	34.00	0.90	6,280	3.40	0.42	44.44
WS	6.00	0	0	6,100	3.40	0.42	9.82
25 MW Equivalent							
SCSW	16.00	23.25	1.60	57,000	10.00	13.0	63.85
SCLW	13.80	85.00	2.25	11,380	3.40	1.05	105.50
WS	14.00		0	11,380	3.40	1.05	18.45
40 MW Equivalent							
SCSW	27.70	36.80	2.56	90,000	13.50	21.0	101.6
SCLW	24.10	136.00	3.60	15,360	3.40	1.68	168.79
WS	24.80	0	0	15,800	3.40	1.68	29.88
2-20 MW Equivalent							
SCSW	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
SCLW	23.80	136.00	3.60	19,200	3.40	1.68	168.48
WS	24.50	0	0	18,700	3.40	1.68	29.58

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[a] Dollars per year; independent of hours of operation.

[b] Total dollars/hour excluding maintenance.

TABLE VII-7

FINANCIAL PARAMETERS ASSUMED IN ANNUAL COSTS OF INDUSTRIAL FGD SYSTEMS

- Debt Financing Assumed
- Loan Period = 10 years
- FGD System Life = 20 years
- Depreciable Life = 15 years
- Cost of Capital = 10%
- Straight Line Depreciation
- Tax Rate = 50%
- Discount Rate = 15%

TABLE VII-8

CAPITAL, OPERATING, AND ANNUAL COSTS OF SELECTED INDUSTRIAL FGD SYSTEMS

	FGD System Type								
	Self-Contained Solid Waste System, FGD System			Self-Contained Liquid Waste System, FGD System			Waste Stream FGD System		
Boiler Size/ Operating Hours (MW Equivalent)	Capital Cost ($10^3\$$)	Operating Cost ($10^3\$$)	Annual Cost (\$/ton of coal)	Capital Cost ($10^3\$$)	Operating Cost ($10^3\$$)	Annual Cost (\$/ton of coal)	Capital Cost ($10^3\$$)	Operating Cost ($10^3\$$)	Annual Cost (\$/ton of coal)
10 MW	1,000			314.0			304.0		
8400		298.5	9.80		379.0	9.85		90.0	2.95
6400		238.0	10.80		294.5	10.13		71.0	3.40
4000		157.5	13.50		182.5	10.90		45.5	4.70
1000		62.0	34.90		50.5	16.92		15.5	14.75
25 MW	1,900			569.0			549.0		
8400		594.0	7.70		895.5	9.14		180.0	2.30
6400		472.0	8.45		695.5	9.34		141.5	2.60
4000		312.5	10.50		431.0	9.89		90.0	3.30
1000		120.5	26.75		115.0	14.22		29.0	9.12
40 MW	3,000			794.0			768.0		
8400		940.5	7.65		1431.5	9.10		298.0	2.30
6400		752.6	8.40		1111.5	9.20		234.0	2.50
4000		498.5	10.45		688.0	9.70		148.0	3.10
1000		191.5	26.45		180.5	13.50		45.5	7.85

These units are characterized by high hours of operation (> 6400) and relatively stable loads. For heating plant type units with 2000-3000 hours of operation per year, the expected cost would be from $11 to $13 per ton of coal, depending on the size of the unit.

- As would also be expected if the WS FGD system is applicable to a particular plant, it offers a substantially lower cost than either the SCLW or the SCSW system for all boiler sizes and for all operating hours. The cost advantage of the WS FGD system is greatest in larger boilers and for high operating hours. This advantage is limited by the availability of suitable waste stream and the potentially limited SO_2 removal capabilities of many waste streams.

- The choice between the SCLW and SCSW systems is a function both of boiler size and operating hours. The SCLW system has a higher operating cost but lower capital cost then the SCSW system and SCSW. As the operating hours increase the relative importance of capital vs. operating hours changes and for high operating hours the SCSW system has a lower annual cost then the SCLW system. As can be seen from Table VII-8 the crossover point between the two systems falls somewhere between 4000 and 6400 hours per year of operation for the 25 and 40 MW equivalent systems and between 5400 and 8400 hours per year for the 10 MW equivalent system. This is shown graphically for the 25 MW system on Figure VII-1. As shown in this figure, the SCSW FGD system is more expensive than the SCLW system unitl about 4500 hours per year of operation. At this point, the higher capital cost of the SCSW system relative to the SCLW system is offset by the higher operating cost of the SCLW system. This would indicate that boilers used for space heating, or otherwise, which have a low load factor may well consider the simpler SCLW FGD for combined particulate and sulfur control.

The degree of sulfur removal required can affect the overall operating cost of the SCSW and SCLW FGD system. Figure VII-2 shows a comparison of the annual cost per ton of coal for 90 and 70 percent SO_2 control with a SCSW FGD system and a SCLW system on a 25 MW equivalent boiler. It can be seen that a 20 percent reduction has little effect ($\approx$ 50¢/ton of coal) on the annual cost of a SCSW FGD system. This is due to the relatively small significance of chemical costs in the SCSW system (see Figure VII-1) relative to other operating and capital costs. The situation is different in regard to the SCLW system where operating costs and chemical costs in particular represent a major component of total annual costs. As can be seen from Figure VII-2, the 20 percent reduction in SO_2 removal requirements results in approximately $2/ton of coal savings.

The change in SO_2 removal requirements alters the point at which the cost of the SCSW FGD system equals the cost of the SCLW system. The 20 percent reduction changes the equal cost point from about

IGU VII

COMPARISON OF ANNUAL COST/TON OF COAL VS. OPERATING HOURS

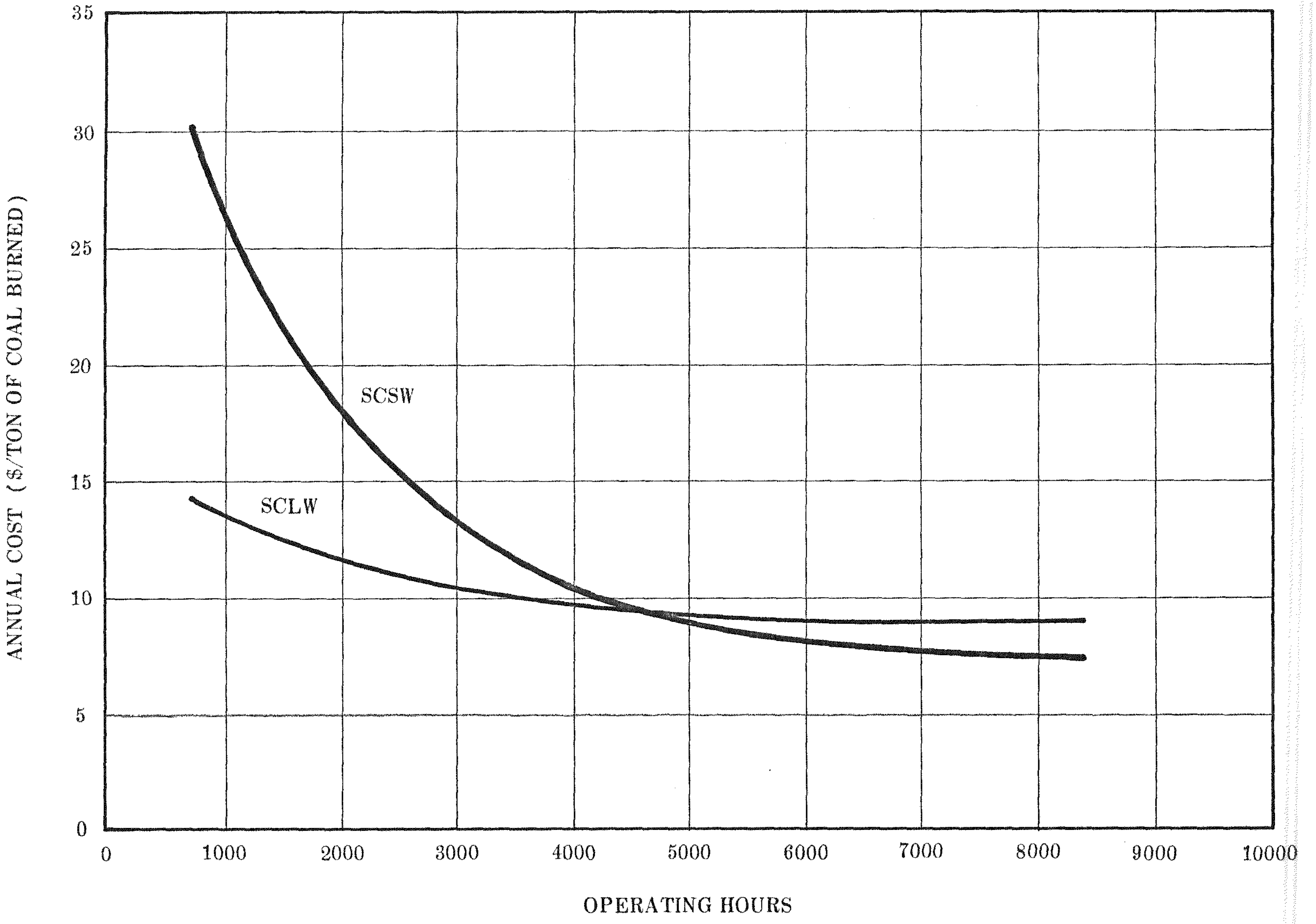
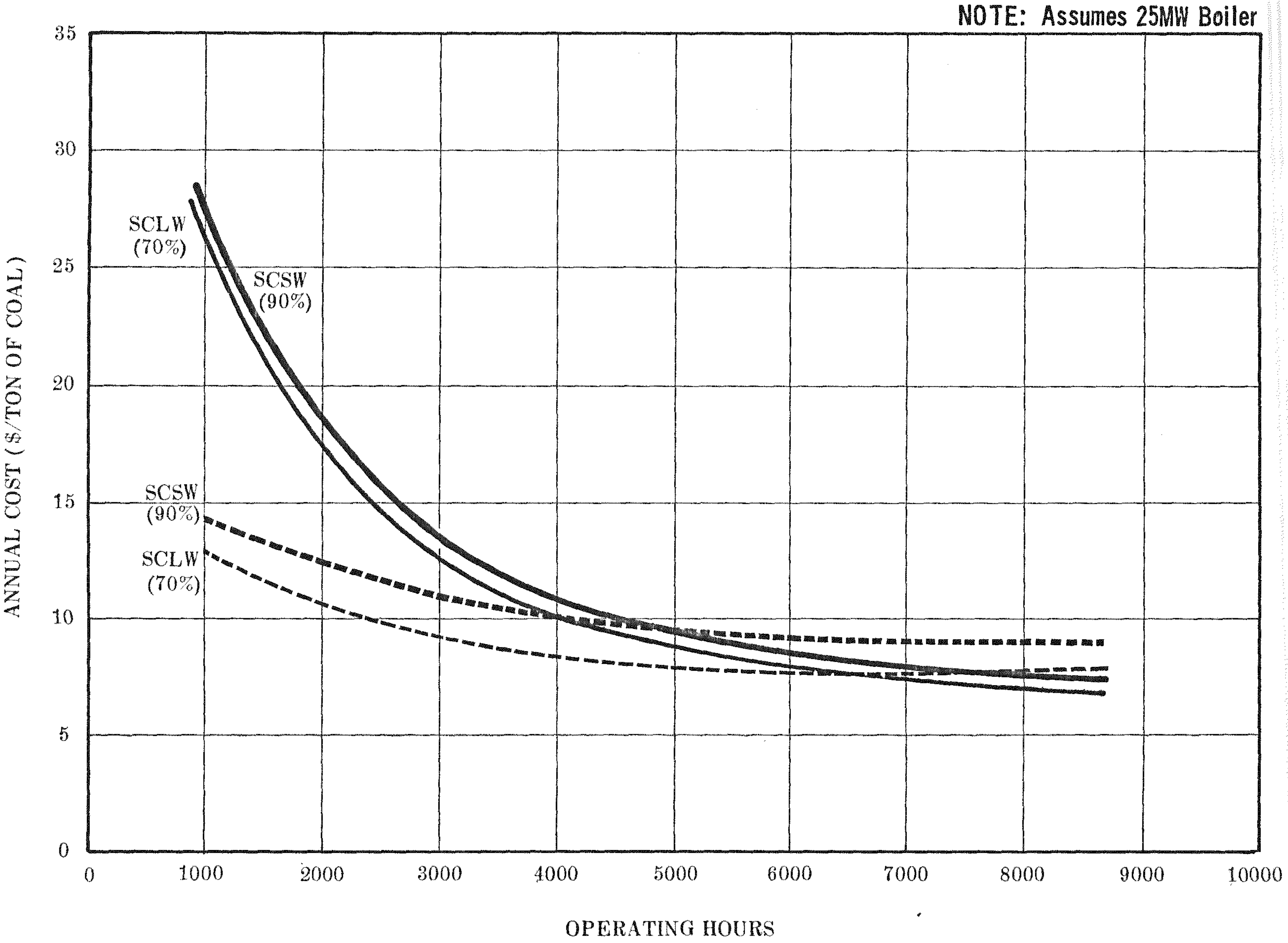


FIGURE VII-2

EFFECT OF SO_2 REMOVAL EFFICIENCY ON COST OF FGD SYSTEMS



4400 hours per year up to almost 8000 hours per year for a 25MW equivalent boiler. This would indicate that where less stringent SO_2 control is required, a SCLW system may be less expensive than a SCSW system for almost all applications.

4. Factors Affecting FGD Costs

All of the costs shown in the proceeding sections can be changed due to specific site situations. Some of the factors which could cause a change in the capital cost are:

- Changes in particulate control requirements could change the pressure drop across the scrubber. This, in turn, can modify the size and cost of fans, motors, and the scrubber (due to increased wall thickness). The cost of these components can easily increase twofold. Of course, reduced particulate requirements can also reduce the cost of each component.

- Available space and choice of sludge disposal options can affect capital costs. Cost increases up to 50-60 percent might be expected if space is at a premium.

- The case examples assume that the overflow from the SCLW and WS FGD systems are handled in the plant wastewater treatment plant with only particulate removal costs attributable to the FGD system. If adequate wastewater treatment is not available, costs for these systems would increase considerably depending on specific requirements. Determination of costs for wastewater treatment was beyond the scope of this report.

- The case examples for the WS FGD system assume that no pretreatment of the waste stream is needed prior to its use in the FGD system. As discussed in Section V, some waste streams could contain significant amounts of contaminents such as H_2S. The removal of these contaminents could significantly increase the costs of the WS FGD systems.

Some of the factors which can affect the operating cost are:

- A change in the requirements for particulate control will affect the amount of electricity required to operate fans, etc.
- The cost of each of the components making up operating cost vary significantly from region to region. Appendix D shows the observed variance in these costs.

APPENDIX A

INDUSTRIAL FGD TECHNOLOGY

This appendix describes the chemical and operational aspects of the following four types of industrial FGD systems: (1) self-contained, solid waste FGD systems, (2) self-contained, liquid waste (chemical addition) FGD systems, (3) self-contained, liquid waste (no chemical addition) and (4) waste stream FGD systems. The discussion of the self-contained, solid waste FGD systems focuses on specific systems offered by vendors. These vendor systems illustrate the general type of self-contained, solid waste FGD systems presently operating in industrial sectors. They are not the only self-contained, solid waste FGD systems offered or effective if applied. The discussion of the self-contained, liquid waste (chemical and no chemical addition) and waste stream FGD system is based on representative process flow diagrams and does not focus on specific vendor systems.

1. General FGD System Characteristics

Even though most FGD systems will remove both particulate matter, i.e., fly ash, and sulfur dioxide from a flue gas stream, some particulate removal equipment such as mechanical collectors often precedes the scrubbing units. The major reason for this placement strategy is to reduce the mechanical, i.e., pump fouling, fan failure, and operational problems, particulates would cause in the scrubbing system. In addition, many systems already have installed particulate control equipment prior to the installation of scrubbing equipment. In effect, the scrubbing equipment is used in conjunction with the particulate control equipment for additional control efficiency.

2. Self-contained, Solid Waste FGD Systems

Several representative self-contained, solid waste systems which have been applied to industrial coal-fired boilers are the Zurn[1/] dilute double alkali FGD process, FMC[2/] concentrated double alkali FGD process, and Research-Cottrell[3/] Bahco Lime FGD Process. These types of systems will remove both particulates and sulfur dioxide from a flue gas stream. These systems are described below in greater detail.

a. Zurn Dilute Double Alkali FGD System

The Zurn dilute double alkali FGD system is an aqueous alkali scrubbing process in which the absorption of sulfur dioxide and the formation of waste products occur in separate system components. Sulfur dioxide is first absorbed with water-soluble sodium hydroxide. Then the soluble alkali is regenerated with lime to precipitate insoluble calcium compounds. The double alkali system consists of three process phases as shown in Figure A-1. These process functions are gas scrubbing (Section A), chemical regeneration (Section B), and solids removal (Section C).

System Design

The function of the gas scrubbing section is to mix the flue gas containing sulfur dioxide with a dilute sodium hydroxide (NaOH) solution. This reacts with the sulfur dioxide (SO_2) in the flue gas and converts it to water soluble sulfur-containing compounds (sodium sulfite (Na_2SO_3), sodium bisulfite ($NaHSO_3$), and sodium sulfate (Na_2SO_4)). The mixing action in the scrubber (component #1 on Figure A-1) also removes a high percentage of particulate matter (fly ash) contained in the flue gas. The reactions that take place in the scrubbing section of the system are shown below:

1/ Zurn Industries, Inc., Birmingham, Alabama.

2/ FMC Corporation, Chicago, Illinois.

3/ Research-Cottrell, Bound Brook, New Jersey.

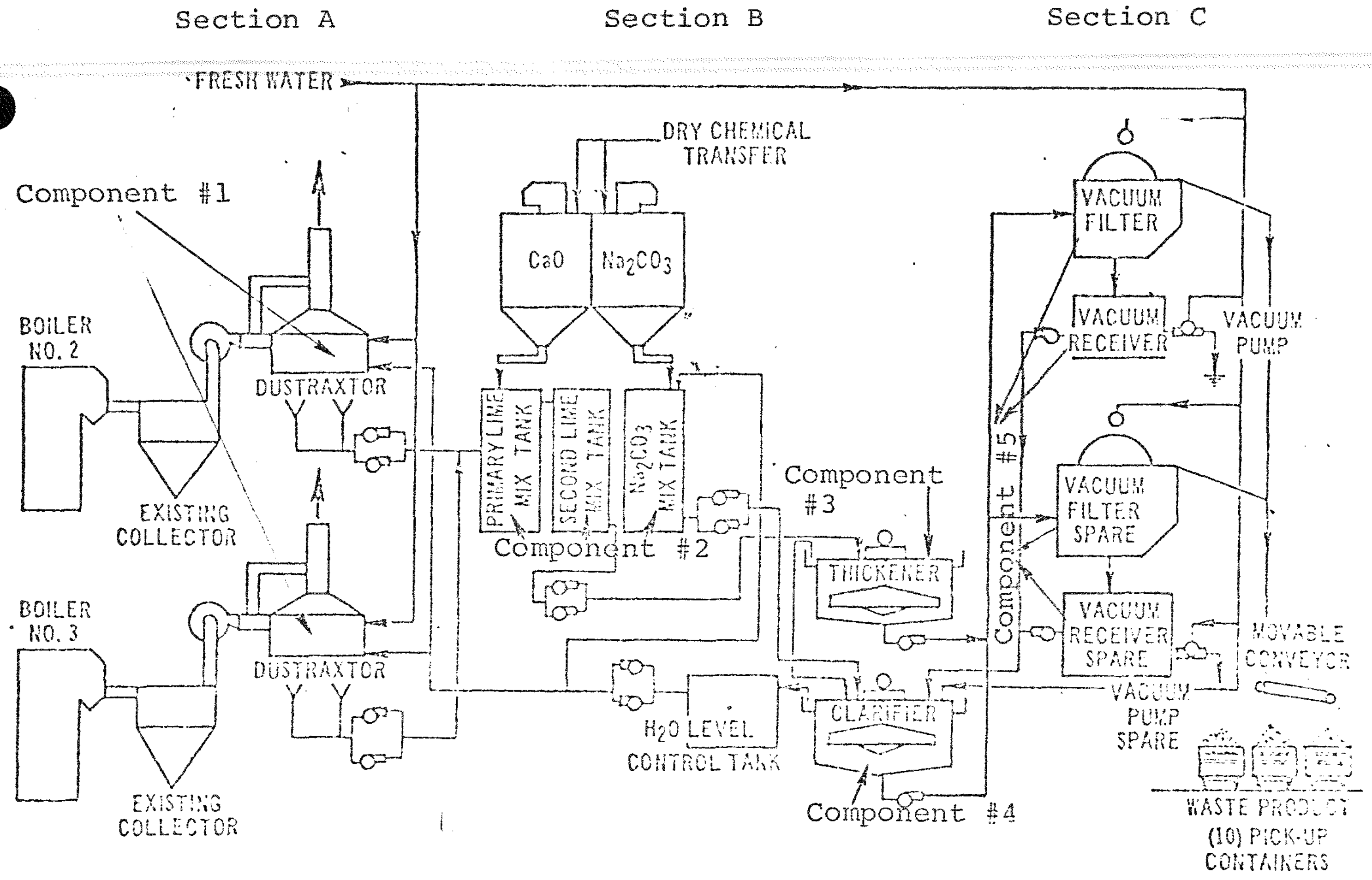


FIGURE A-1
ZURN DOUBLE ALKALI SYSTEM

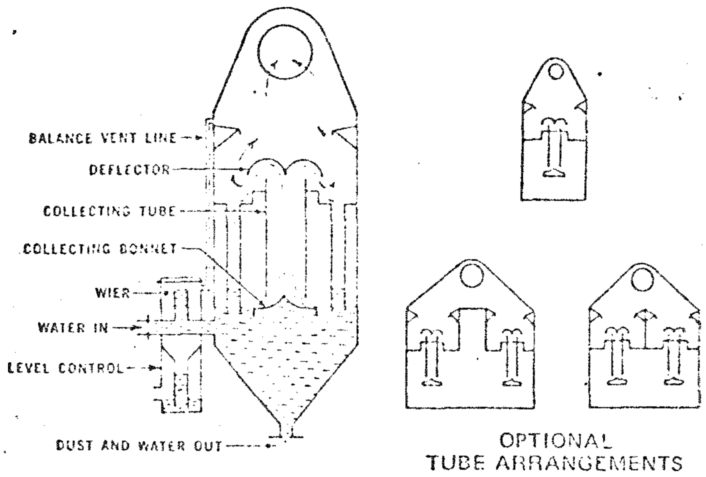


FIGURE A-2
ZURN "DUSTRAXTOR" SCRUBBER

$$2NaOH + SO_2 \longrightarrow Na_2SO_3 + H_2O$$

$$Na_2SO_3 + SO_2 + H_2O \longrightarrow 2NaHSO_2$$

$$2Na_2SO_3 + O_2 \longrightarrow 2Na_2SO_4.$$

The Zurn systems currently installed use an impingement and entrainment type of scrubber of their own design called a "dustraxtor". Figure A-2 illustrates its design. Specific site characteristics may lead to the use of another scrubber type.

The chemical regeneration section converts the spent scrubbing solution to a reusable form and separates the sulfur-containing solid compounds from the solution. In the mix tank (component #2 on Figure A-1), the calcium salts precipitate and are moved as a slurry. The reactions in the regeneration section are as follows:

$$NaHSO_3 + Ca(OH)_2 \longrightarrow NaOH + CaSO_3\downarrow + H_2O$$

$$Na_2SO_3 + Ca(OH)_2 \longrightarrow 2NaOH + CaSO_3\downarrow$$

$$Na_2SO_4 + Ca(OH)_2 \longrightarrow 2NaOH + CaSO_4\downarrow .$$

Sodium carbonate (Na_2CO_3) is added to the clarifier (component #4 on Figure A-1) to reduce further the concentration of calcium by the precipitation of calcium carbonate ($CaCO_3$). The further precipitation of calcium, as shown in the reaction below, is intended to reduce the likelihood of calcium salts precipitating in the scrubbing section:

$$Na_2CO_3 + Ca(OH)_2 \longrightarrow 2NaOH + CaCO_3.$$

After the solution has passed through the clarifier, the clarifier liquor (sodium hydroxide) is recycled to the scrubber for reuse.

The underflow slurry from the thickener and clarifier is pumped to the solids removal section of the process for dewatering.

Rotary drum vacuum filters (component #5 on Figure A-1) convert the slurry into an approximately 65-weight solid cake composed of calcium sulfite, calcium sulfate, calcium carbonate, sodium sulfite, sodium sulfate, and fly ash. Usable scrubbing solution contained in the underflow slurry (filtrate) is recycled. The filter cake is washed to remove as much soluble sodium compounds as possible and is disposed of, e.g., as landfill.

The Zurn dilute double alkali FGD system[1/] can remove fly ash and sulfur dioxide from flue gas with approximately 90[2/] and 95 percent efficiency, respectively; produce an untreated sludge with a greater solids consistency than a lime/limestone system; operate without scaling or plugging problems, due to the precipitation of calcium compounds in the scrubber system; and operate over a wide range of boiler operating conditions. The system does require process chemicals, i.e., lime, sodium hydroxide, input, but needs to circulate a large quantity of slurry due to its dilute OH ion concentration.

B. FMC Concentrated Double Alkali FGD System

FMC employes a concentrated sodium sulfite/bisulfite buffer solution to remove particulate matter and sulfur dioxide from flue gas. Slaked lime is added to the spent solution outside of the scrubbing system. A simplified flow sheet of the FMC Concentrated Double Alkali Process is shown in Figure A-3.

System Design

The flue gas enters the scrubber (component #1 on Figure A-3) where both particulates and sulfur dioxide are removed by contacting

---

[1/] Assuming a generic application, specific system applications may vary operating characteristics.

[2/] The Zurn high-energy venturi scrubber may be substituted for the medium energy "Dustraxtor" scrubber to increase the fly ash removed and efficiency of the system to 98-99 percent.

[3/] Hydroxide radical.

Overall System Reaction

$$Ca(OH)_2 + SO_2 \longrightarrow CaSO_3 \downarrow + 2H_2O$$

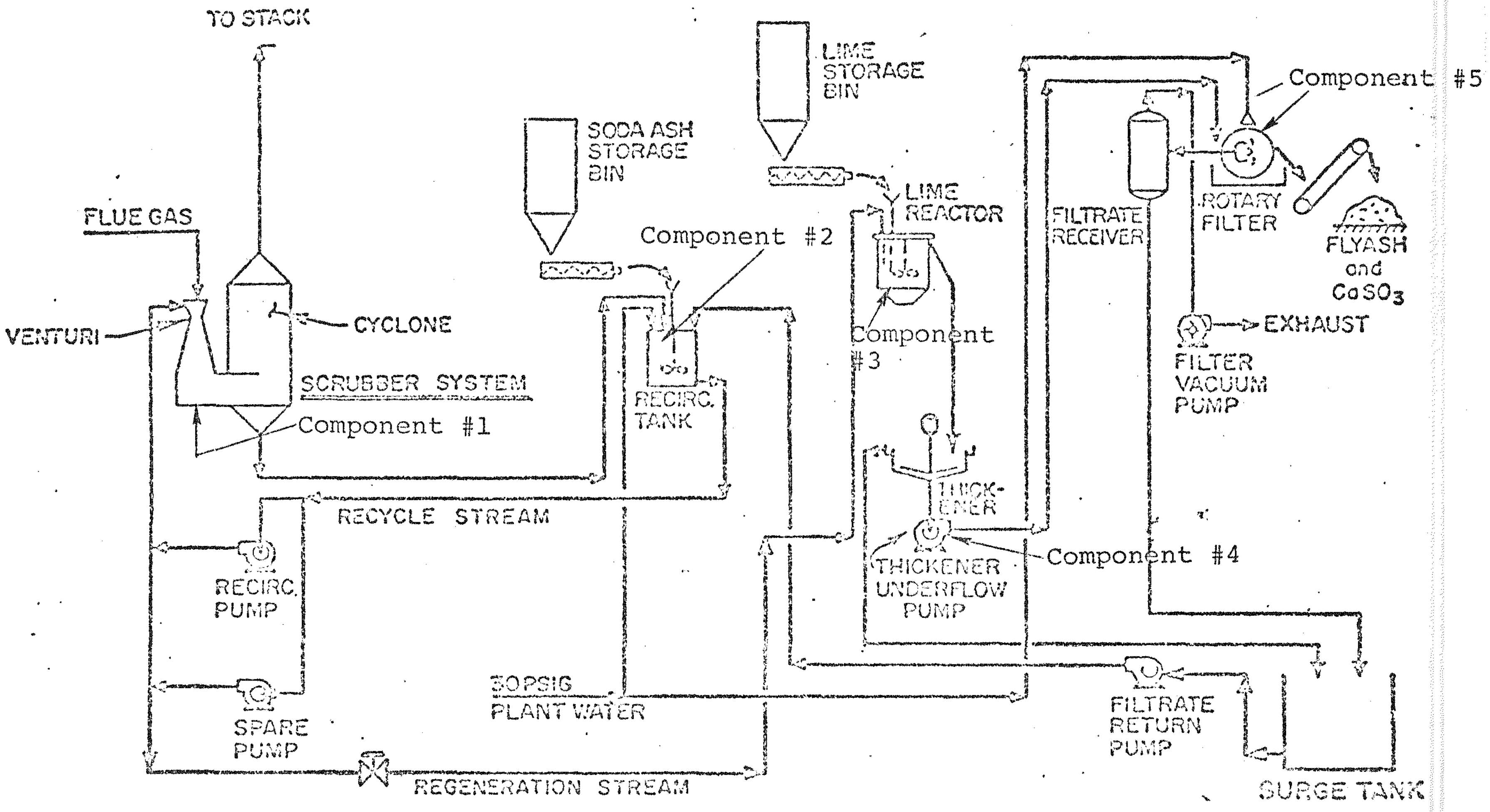


FIGURE A-3

FMC CONCENTRATED DOUBLE ALKALI FLUE GAS DESULFURIZATION SYSTEM a 20 weight percent solution of sodium sulfite (Na_2SO_3), sodium bisulfite ($NaHSO_3$), and sodium sulfate (Na_2SO_4). Sulfur reacts with sodium sulfite to form sodium bisulfite, and some sodium sulfite oxidizes to form sodium sulfate according to the following reactions:

$$Na_2SO_3 + SO_2 + H_2O \longrightarrow 2NaHSO_3$$

$$2Na_2SO_3 + O_2 \longrightarrow 2Na_2SO_4.$$

In the cyclone separator, water droplets separate from the flue gas and descend to the bottom of the tank. The flue gas exits through the top of the scrubber into a mesh-type mist eliminator and is sent to the stack. The spent slurry is pumped from the bottom of the scrubber to the recirculation tank (component #2 in Figure A-3). In the recirculation tank, sodium carbonate and water react to form sodium and sulfite radicals and sodium bisulfate according to the following reactions:

$$SO_2 + H_2O \rightleftharpoons H_2SO_3 \rightleftharpoons 2H^+ + SO_3^{=}$$

$$Na_2CO_3 + 2H^+ + SO_3^{=} \rightleftharpoons 2Na^+ + SO_3^{=} + H_2CO_3$$

$$H_2CO_3 \xrightarrow{\Delta} H_2O + CO_2$$

$$Na_2CO_3 + 2SO_2 + H_2O \longrightarrow 2NaHSO_3 + CO_2\uparrow.$$

A bleed stream is withdrawn from the scrubbing recirculation system at a rate exactly equivalent to the rate at which sulfur dioxide is being collected in the scrubber. This bleed stream is then reacted with calcium hydroxide ($Ca(OH)_2$) in a short retention time, agitated lime reactor vessel (component #3 in Figure A-3). The mixture of calcium sulfite ($CaSO_3$), sodium sulfite, sodium sulfate, and fly ash is transferred to the thickener (component #4 on Figure A-3). The thickener overflow contains sodium sulfite and sodium sulfate and is returned to the recirculation tank. The sodium sulfite is reused for absorption of sulfur dioxide. The thickener underflow is transferred to a rotary vacuum filter (component #5 on Figure A-3). The resultant filter cake is approximately 55-weight percent solid, composed of calcium sulfate, fly ash, sodium sulfite, and sodium sulfate, and may be disposed of as landfill or recycled into a process stream. The filter cake is washed, and the recovered salts are returned to the recirculation tank. The following reaction illustrates these process steps:

$$2NaHSO_3 + Ca(OH)_2 \longrightarrow Na_2SO_3 + CaSO_3 + 2H_2O.$$

The sulfite ion from the sodium sulfite precipitates from solution as insoluble calcium sulfite. Hydroxide ions generated by this reaction form sodium hydroxide which reacts immediately with the acidic sodium bisulfite to form sodium sulfite and water. Sodium carbonate is the makeup chemical for sodium losses.

A scrubbing unit which may be used in this FGD system is the dual throat variable flow venturi (Figure A-4). Another type of scrubber may be used depending on the demand of the FGD system. However, the chemistry of the system will remain the same regardless of scrubber type.

The FMC double alkali FGD system uses a strong ionic solution which limits the oxidation of sulfite to sulfate and does not allow calcium ions to return to the scrubber. The system[1/] can remove fly ash and sulfur dioxide from flue gas with approximately a 99 and 90 percent efficiency, respectively; produce an untreated sludge with a greater solids consistency than a lime/limestone system; operate over a wide range of boiler operating conditions; and operate without severe plugging or scaling problems, due to the solubility of the sodium scrubbing agent. The system does require chemical additives, i.e., lime, sodium carbonate, for operation.

[1/] Assumes a generic application. Specific system applications may vary operating characteristics.

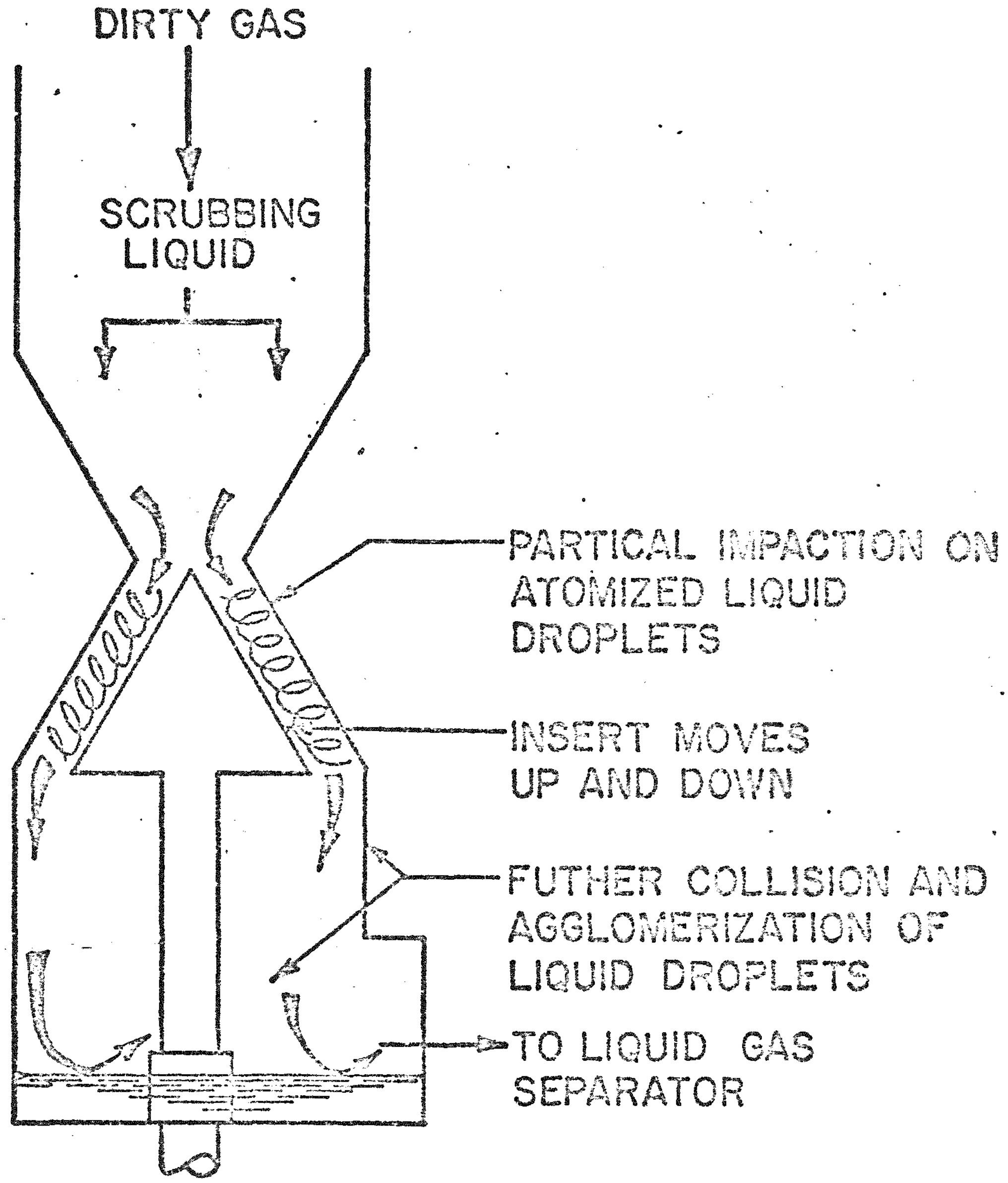


FIGURE A-4

FMC VARIABLE THROAT SCRUBBER

c. Research-Cottrell Bahco Lime FGD System

The Research-Cottrell Bahco lime process uses a lime slurry as the scrubbing reagent in two-stage venturi scrubber to remove both fly ash and sulfur dioxide from flue gas. Figure A-5 is an illustration of a Research-Cottrell Bahco unit.

System Design

Flue gas is introduced into the bottom stage of the scrubber . (component #1 on Figure A-5) where it contacts lime slurry to form calcium sulfite ($CaSO_3$) and calcium sulfate ($CaSO_4$). The reactions are listed below:

$$Ca(OH)_2 + S)_2 + H_2O \longrightarrow CaSO_3 \cdot 2H_2O$$

$$CaSO_3 \cdot 2H_2O + \tfrac{1}{2}O_2 \longrightarrow CaSO_4 \cdot 2H_2O$$

Above the first venturi scrubber, droplets are separated in an intertial collector while the gas continues to a second scrubber stage (component #2 on Figure A-5). A mist eliminator (component #3 on Figure A-5) above the second stage scrubber collects liquid droplets from the gas prior to exiting out the stack. Separated scrubbing liquid from both stages is returned to the impingement zone of the first stage scrubber. A fraction of the return stream is continuously withdrawn from a concentration regulator and fed to a thickener (component #4 on Figure A-5). Overflow is pumped to a lime-dissolving tank (component #5 on Figure A-5) to minimize make-up requirements and returned to the second stage scrubber impingement zone. The level in the first stage scrubber is regulated by controlling the level of the dissolving tank. The sludge stream leaving the thickener is disposed of in a pond[1/] (component #6 on Figure A-5).

[1/] The sludge leaving the thickener may be concentrated in a drum filter as an alternative to pond disposal.

OVERALL CHEMICAL REACTIONS:

$$Ca(OH_2) + SO_2 + H_2O \longrightarrow CaSO_3 \cdot 2H_2O$$

$$CaSO_3 \cdot 2H_2O + 1/2O_2 \longrightarrow CaSO_4 \cdot 2H_2O \text{ (Sludge)}$$

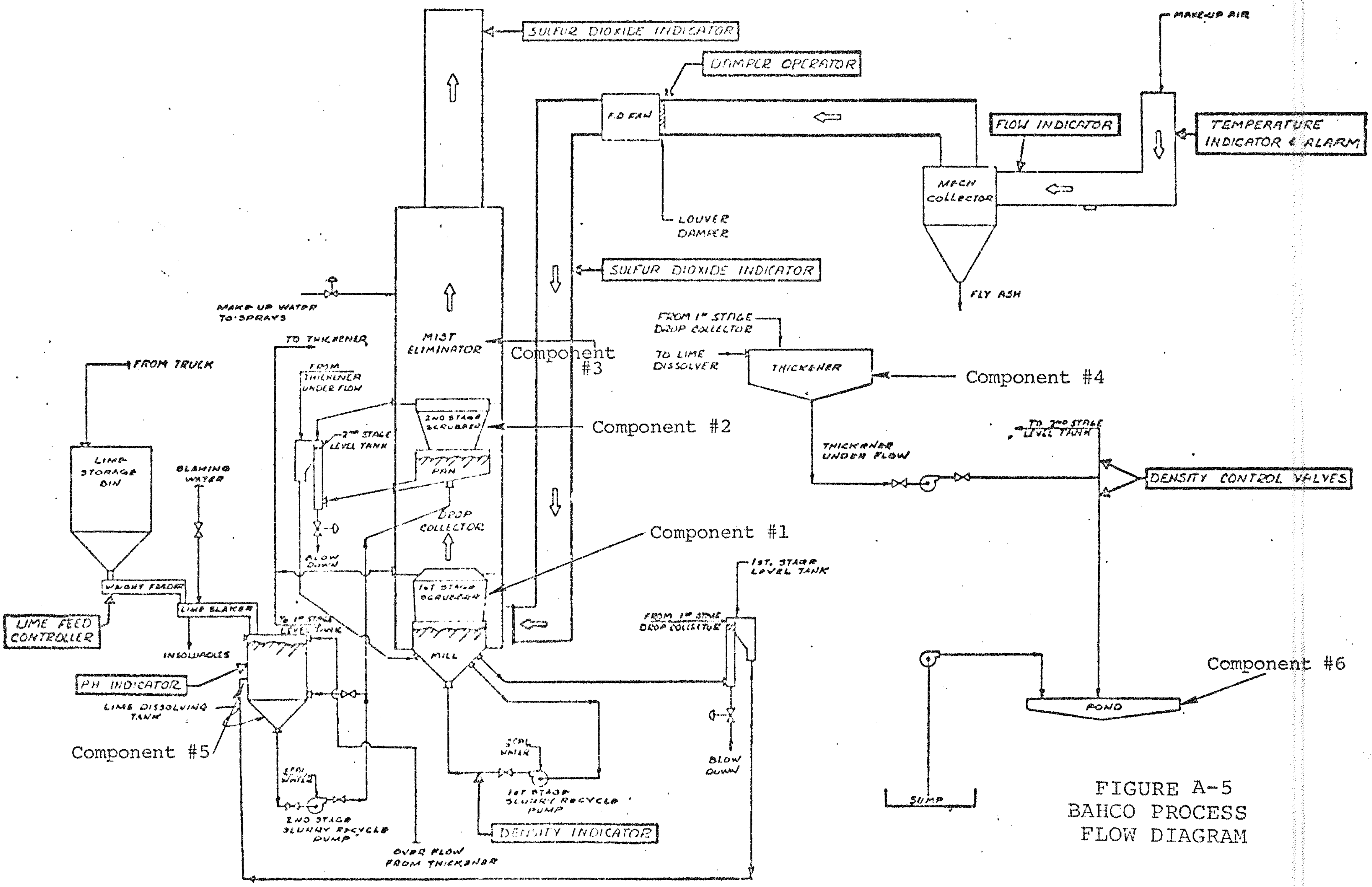


FIGURE A-5
BAHCO PROCESS
FLOW DIAGRAM

The scrubber incorporates many principles designed to prevent the normal tendency of lime or limestone to form calcium sulfate scale in the scrubber. Some of these features are: 1) the addition of make-up water that continuously wets the inside walls of the scrubber, and 2) the use of large-diameter flexible hose that initiates vibrations and motion in the slurry pump lines.

The Research-Cottrell Bahco lime process[1/] is a relatively simple FGD process[2/] that can simultaneously remove fly ash and sulfur dioxide from flue gas with an efficiency of approximately 90+ and 70 to 99 percent, respectively. The sulfur dioxide removal efficiency is dependent on the flue gas sulfur dioxide concentration and amount of scrubbing reagent used. The process can be operated over a wide range of boiler conditions, but does require chemical, i.e., lime addition, and due to the nature of the chemicals used, has potential for plugging and scaling of calcium sulfate precipitation in the scrubbing components. The sludge from the process is 50-weight percent solid composed of calcium sulfate, calcium sulfite, and fly ash.

d. Summary

The self-contained, solid waste FGD systems described in this section illustrate the technology of these units developed to date. All three systems - the Zurn dilute double alkali system, FMC concentrated double alkali system, and Research-Cottrell Bahco lime system - have been installed on industrial boilers and are operating as designed. These FGD systems were discussed in this section merely from a technological viewpoint, not to imply they are the only FGD processes in existence or presently in use.

[1/] Assuming a generic application. Specific system applications may vary operating characteristics.

[2/] The double alkali system has a chemical regeneration system inherent in its design which is not included in the design of the Research-Cottrell Bahco lime system.

Other FGD processes have been developed for industrial coal-fired boilers and are similar to those described above. The GM dilute double alkali system and API [1/] dilute double alkali system is similar in design to the Zurn dilute double alkali FGD system. The main difference between these two FGD systems is in the chemical regeneration and solid waste removal systems. In addition, several industrial FGD installations presently incorporate process designs similar to that of the Research-Cottrell Bahco lime FGD system. The differences between the systems mainly lies in the scrubber unit type and solids removal system.

3. Self-contained, Liquid Waste (Chemical Addition) FGD System

Figure A-6 illustrates the process flow diagram of a representative self-contained, liquid waste (chemical addition) FGD system. This system is similar in design to a double alkali (self-contained solid waste) FGD system. The main difference between these systems centers around the processing of the bleed stream drawn from the scrubbing solution. In a double alkali system, the bleed stream is processed to regenerate its chemical value; whereas, in a self-contained, liquid waste (chemical addition) system, the bleed stream is discarded as a waste product. For example, in a simple sodium scrubbing system, the bleed stream is neutralized and aerated (optional) to eliminate chemical oxygen demand and is then disposed of, i.e., by ponding, in a sewer system, etc. The gas scrubbing and dry chemical transfer sections of the two systems are approximately the same.

The type of scrubber used in a self-contained, liquid waste (chemical addition) FGD system may be any reasonable scrubbing design including plate, preformed spray, gas atomized spray, and impingement and entrainment scrubbers. The scrubbing agent may be any number of chemicals, including sodium

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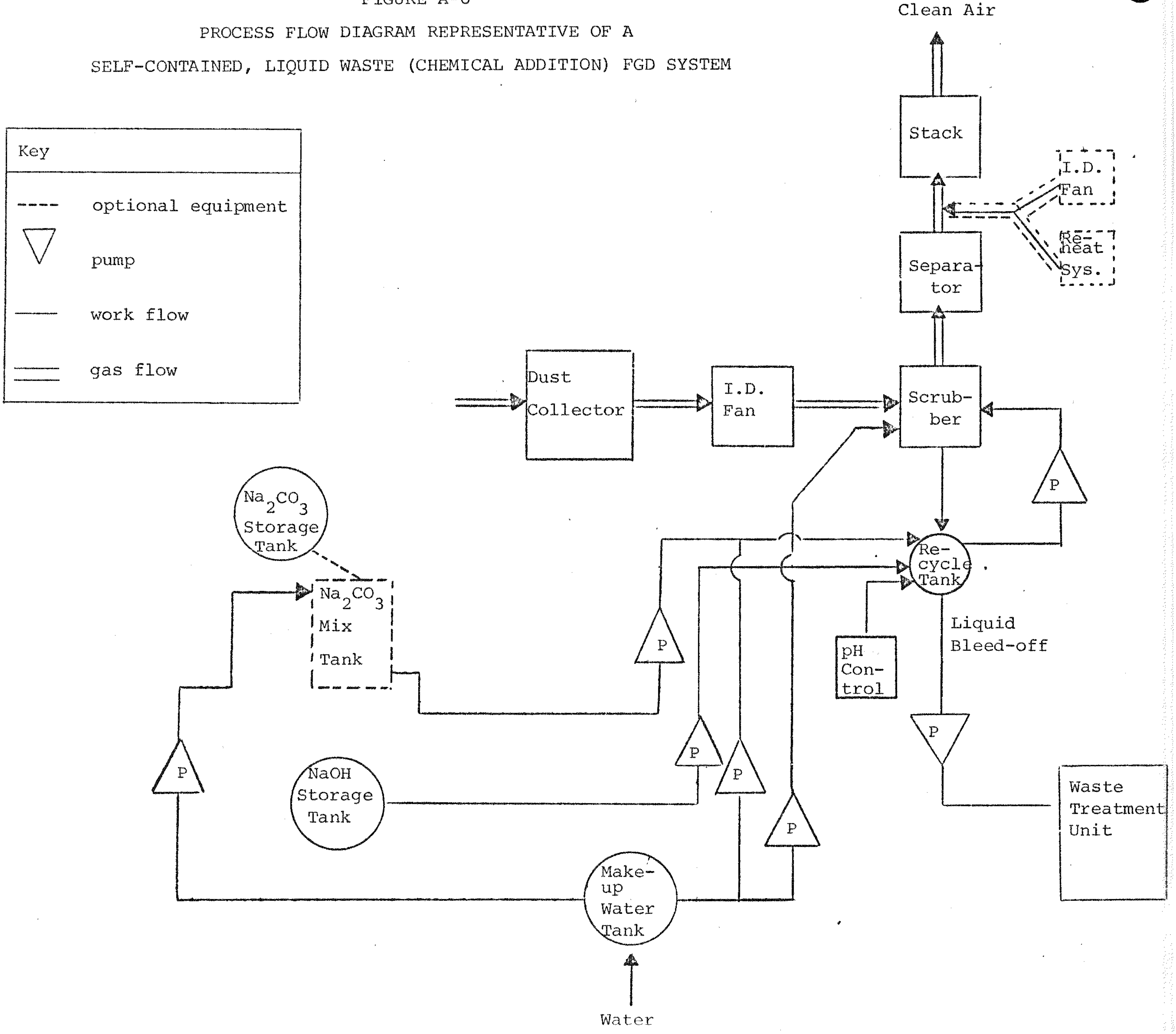
[1/] Air Pollution Industries, Inc., Englewood, N.J.

FIGURE A-6

PROCESS FLOW DIAGRAM REPRESENTATIVE OF A SELF-CONTAINED, LIQUID WASTE (CHEMICAL ADDITION) FGD SYSTEM



and ammonia compounds. All of the facilities investiated in this study use or plan to use a sodium-based scrubbing agent. The self-contained, liquid waste (chemical addition)[1/] FGD system can remove flue gas sulfur dioxide with an efficiency of 90+ percent, depending on the amount of scrubbing chemical used. However, the scrubber chemical is not recycled and may constitute a significant system material loss.

4. Self-contained, Liquid Waste (No Chemical Addition) FGD Systems

This FGD system is simple in design incorporating only a gas scrubbing and waste disposal system. Since chemicals are not added to the scrubbing liquid, i.e., water, to bolster its scrubbing capacity, a water make-up and recirculation system are not usually incorporated into the system design. The system may use any conventional type of scrubber including plate, preformed spray, gas atomized spray, impingement and entrainment scrubbers, or any other reasonable scrubber design. The scrubbing liquid usually passes once through the scrubber and exits to a wastewater treatment facility or settling pond. Sulfur dioxide removal efficiency is usually between 30 and 45 percent[2/] depending on the scrubber type and incoming pH of the scrubbing liquid.

5. Waste Stream FGD System

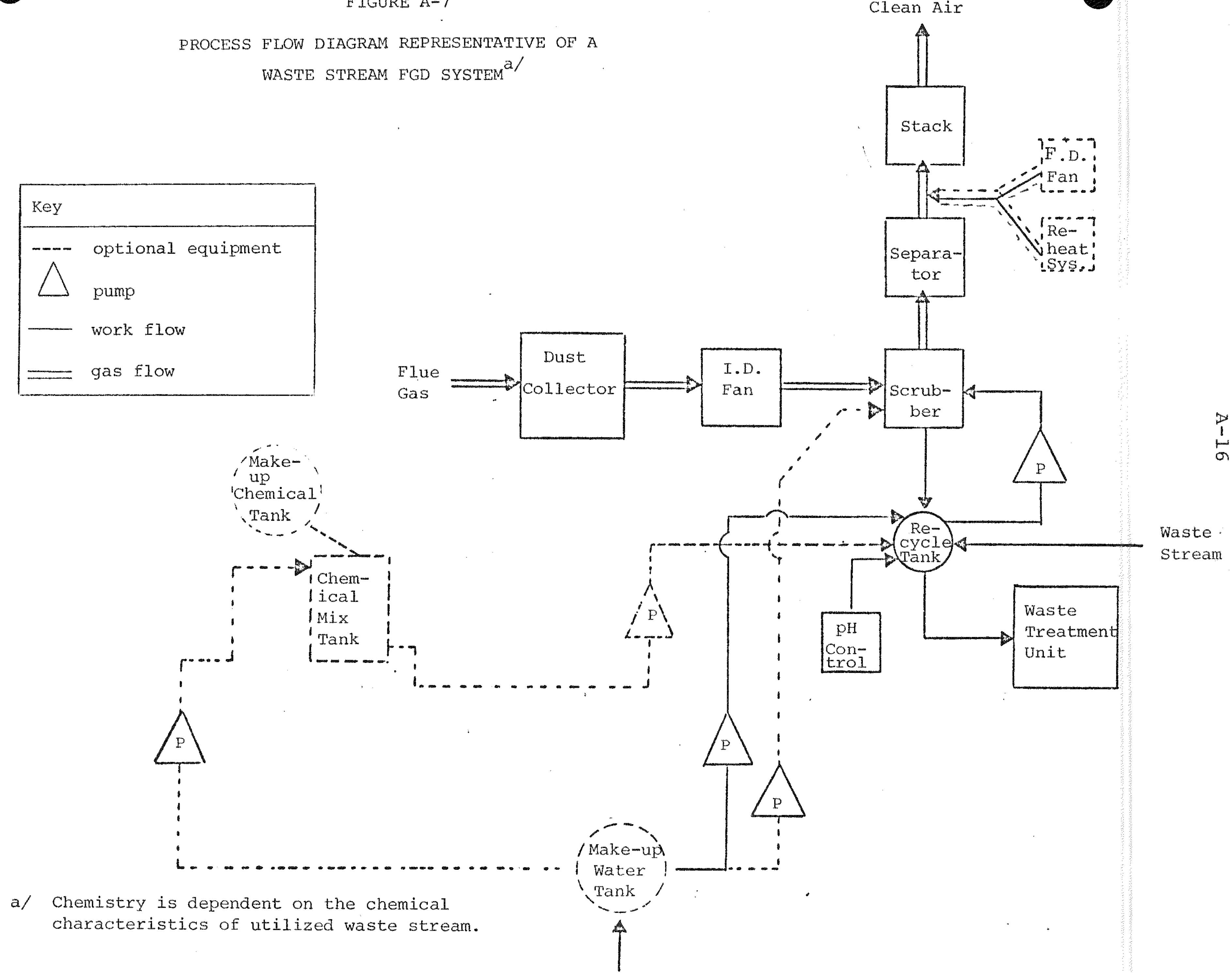
Figure A-7 illustrates a representative flow diagram of a waste stream FGD system. The scrubbing agent in the process waste stream may be a sodium or lime compound or any number of other chemicals, i.e., ammonia. After reaction in the scrubber unit, the waste stream may be recycled or treated as a waste product. The character (liquid or solid) of the waste produced is dependent on the chemical composition of the waste stream.

[1/] Based on the installations reviewed in this study.

[2/] *Ibid*.

FIGURE A-7

PROCESS FLOW DIAGRAM REPRESENTATIVE OF A WASTE STREAM FGD SYSTEM[a/]



a/ Chemistry is dependent on the chemical characteristics of utilized waste stream.

The use of a waste stream to scrub sulfur dioxide from flue gas is simply accomplished by using the basic chemical properties of the waste stream as the basis for the scrubbing liquid. Depending on the pH and alkalinity of the waste stream and its chemical composition, additional chemicals, i.e., sodium carbonate, sodium hydroxide, lime, limestone, may be added to the scrubbing liquid to increase its alkalinity. A 95 percent removal efficiency[1/] for sulfur dioxide is possible depending on the basic properties of the scrubbing agent in the waste stream and the amount of make-up chemical used. The type of scrubber used in a waste stream FGD system may be any conventional type including plate, preformed spray, gas atomized spray, impingement and entrainment scrubbers, or any other reasonable scrubber design.

1/ Based on the installations reviewed in this study.

APPENDIX B

INDUSTRIAL FGD SYSTEM APPLICATIONS

This appendix will review each industrial FGD system identified in this study and categorize them by type of system employed. In addition, detailed operational characteristics of those installations reviewed in detail or visited will be presented. Table B-1 lists the FGD systems that are operating at the present time and several which will be constructed in the near future on industrial coal-fired boilers. Also noted are the supplying manufacturers. The table is organized into four sections: (1) self-contained, solid waste FGD systems, (2) self-contained, liquid waste (chemical addition) FGD systems, (3) self-contained, liquid waste (no chemical addition) FGD systems, and (4) waste stream FGD systems. Some companies which were thought to manufacture scrubbers did not provide information. In addition, there may exist FGD manufacturers that were not identified in the survey. For these reasons, the scrubber installation information presented in Table B-1 may not be comprehensive.

The industrial installations that were investigated are listed and described in Table B-2. The three self-contained, solid waste FGD systems were selected because they represent two different types of technology. The Research-Cottrell Bahco FGD system utilizes lime as the scrubbing agent and is installed at Rickenbacker Air Force Base. The FMC double alkali system utilizes a sodium-based scrubbing liquid and is installed at Firestone and Caterpillar facilities. The three facilities utilizing a waste stream FGD system were chosen because of their unique operational characteristics. American Thread has a sodium-based mercerizing waste stream; Great Southern Paper uses a sodium-based deionizing water waste stream; and Canton Textile Mill utilizes a sodium-based dyeing waste stream. Nekoosa-Edwards Paper was chosen because the plant is presently operating a self-contained, liquid waste (chemical addition) FGD

TABLE B -1

FLUE GAS DESULFURIZATION (FGD) SYSTEMS OPERATING ON COAL-FIRED BOILERS*

FGD System Type	Company Name and Location	Number ( ) and Size-MW-equivalent of Boiler Unit(s)	Comments
Self-contained solid waste FGD system	Rickenbacker Air Force Base Columbus, OH	20[a/]	Research - Cottrell Bahco Unit - Lime used as caustic agent
	General Motors Chevrolet Plant Parma, OH	(2)10, (2)6	Koch scrubber, GM dilute double alkali system
	Firestone Pottstown, PA	(1)3.5	FMC concentrated double alkali system
	Caterpillar Tractor Corp. Mossville, IL	(1)16, (1)16[b/] 15[c/]	FMC concentrated double alkali system
	Mapleton, IL	85[d/]	FMC concentrated double alkali system under construction, regeneration system is designed for 8 boilers
	East Peoria, IL	(4)22	FMC concentrated double alkali system under construction
	Joliet, IL	18[e/]	Zurn dilute double alkali system
	NI	20[f/]	Zurn dilute double alkali system
	City of Buffalo Buffalo, NY	NI	W. W. Sly scrubber, lime addition to the scrubbing liquid
	ARMCO Steel Middletown, OH	(2)15	Koch scrubber, recycle with lime addition

TABLE B -1

(Continued)

FGD System Type	Company Name and Location	Number ( ) and Size-MW-equivalent of Boiler Unit(s)	Comments
Self-contained solid waste FGD systems	ARCO-Polymers Monaca, PA	(3)35	Davy Powergas system being designed to produce sulfur as a by-product
	Getty Oil NI	NI	Davy Powergas system being designed to produce sulfuric acid as a by-product
	American Metal Climax Golden, CO	(2)4	Zurn scrubber, lime addition to the scrubbing liquid
	Canton Drop Forging Company Canton, OH	(1)10	Meil scrubber, lime addition to the scrubbing liquid, in construction
Self-contained liquid waste FGD systems (chemical addition)	Nekoosa-Edwards Paper[h] Ashdown, AR	(1)50	API scrubber, sodium hydroxide addition to the scrubbing liquid
	Harris Mining NI	NI	W. W. Sly scrubber, sodium carbonate addition to the scrubbing liquid
	Nello L. Teer Construction	NI	W. W. Sly scrubber, sodium carbonate addition to the scrubbing liquid
	Sharman Paper Green Bay, WI	(1)28.5, (1)25	Koch scrubber, neutralize scrubber bleed-off with sodium hydroxide, in construction
	NCR-Appleton Roaring Springs, PA	(1)12.5	API scrubber under construction, may add caustic system to scrubber recirculation system

TABLE B -1

(Continued)

	Sheler Globe Norfolk, VA	NI	W.W. Sly scrubber, sodium hydroxide is added to the scrubbing liquid
Self-contained, liquid waste FGD systems (chemical addition)	Great Western Sugar Finley, OH Fremont, OH	NI	Koch/Great Western Sugar scrubber design, sodium hydroxide addition to the scrubbing liquid (Fremont installation under construction)
	International Paper Panama, FL	NI	FMC/International scrubber, sodium hydroxide addition to the scrubbing liquid
	Consolidated Paper Wisconsin Rapids, WI	2(10)	Riley scrubber, sodium hydroxide added to the scrubbing liquid
	General Motors Tanta Wanta, NY	3(34)	GM single alkali system, sodium hydroxided added to the scrubbing liquid
	GM Truck and Coach Pontiac, MI	1(15)	
	Delco-Marine Dayton, OH	2(6)	
	GM Assembly Plant St. Louis, MO	(1)8, (1)14	
Self-contained, liquid waste FGD systems (no chemical addition)	Great Western Sugar Scotts Bluff, NE	(2)15	Koch/Great Western Sugar scrubber design, once through system
	Garing, NE	(1)15, (1)5.5	
	Fort Morgan, CO	NI	
	Greeley, CO	NI	
	Longmont, CO	NI	
	Lebanon, CO	NI	
	Billings, MT	NI[h]	

TABLE B-1

(CONTINUED)

Waste Stream FGD Systems	Canton Textile Mill, Canton, GA	(1)6	FMC concentrated double-alkali scrubbing system using a sodium hydroxide and sodium sulfate waste stream as the scrubbing liquid
	American Thread Marion, NC	(2)4.5	W.W. Sly scrubbers, uses mercerizing waste stream (sodium hydroxide) as the scrubbing liquid
	Great Southern Paper Cedar Springs, GA	(2)50	API scrubber, uses deionization water (sodium hydroxide base) as the scrubbing liquid
	Nitac Paper Buffalo, NY	(1)7.0, (1)7.5	Carborundum scrubber, uses a sodium-based waste stream as the scrubber liquid
	Carborundum Abrasive Factory	(1)3	Carborundum scrubber, uses a sodium waste stream or lime from NITAC as the scrubbing liquid base
	Texas Gulf Granger, WY	(1)25	Swemco scrubber, uses a sodium carbonate waste stream from the crystallizer unit used as the scrubbing liquid
	Albemarle Paper Roanoke Rapids, NC	(1)50	API scrubber, will use deionization water and waste stream from the effluent clarifier (sodium hydroxide) as the scrubbing liquid, in construction
	FMC Soda Ash Plant Green Rivers, WY	(2)65	FMC scrubber, uses process end-stream sodium carbonate as the scrubbing liquid
	Regal Textile Trion, GA	(2)60	FMC scrubber, will use a mercerizing waste stream (sodium hydroxide) as the scrubbing liquid, in construction
	Keer-McGee Soda Ash Throna, CA	(2)65	FMC scrubber, uses process end-stream sodium carbonate as the scrubbing liquid
	White Satin Sugar, NI	NI	Century scrubber

TABLE B -1

(Continued)

*U.S.A. only NI - Information not available

a/ Seven boilers equivalent to 20 MW

b/ Stoker coal-fired steam boiler will become operational in February 1977

c/ Two boilers equivalent to 15 MW

d/ Eight boilers equivalent to 85 MW

e/ Two boilers equivalent to 18 MW

f/ Three boilers equivalent to 20 MW

g/ Design stage

h/ Designed as a self-contained, solid waste FGD system, now operating as a self-contained, liquid waste (chemical addition) FGD system

TABLE B-2

INDUSTRIAL FGD INSTALLATION DESCRIPTIONS

Installation	FGD System Type	Number ( ) and Size-MW equivalent of Boiler Unit(s)	Date Installed	Sulfur Dioxide Removal Efficiency	Fly Ash Removal Efficiency	Problems
American Thread Marion, NC	Waste stream	Stoker-Fired Boilers-(2)4.0	1973	90%	97%	None[a]
Great Southern Paper Cedar Springs, GA	Waste stream	Pulverized Coal Fired Boilers-(2)50	1975	88%	98%	Limited corrosion
Canton Textile Mill Canton, OH	Waste stream	Stoker-Fired Coal Boiler-(1)6	1975	76%	94-98%	PH probes malfunctioned; plugging due to material in scrubbing liquid; foaming in the scrubber pump; sulfuric acid mist generation
Caterpillar Tractor[b] Mossville, IL	Self-contained, solid waste	Stoker-Fired Boilers-4(47)[c]	1974,1975	90%	99%	Some erosion and mechanical problems
Firestone Pottstown, PA	Self-contained, solid waste	Pulverized Coal Fired Boilers (1)3.5[d]	1975	90%	NI	Minor pump problems due to system design
Rickenbacker Air Force Base[e] Columbia, OH	Self-contained, solid waste	Stoker-Fired Coal Boilers-(7)20[f]	1976	90+%[g]	95%	Pump problem shut down system for three weeks; fan and instrumentation problems
Nekoosa-Edwards Paper[h] Ashdown, AR	Self-contained, liquid waste (chemical addition)	Pulverized Coal Fired Boiler-(1)50	1976	90%	99%	Significant corrosion and erosion problems

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a/ Before sulfer dioxide removal was initiated, significant corrosion of scrubbing system was a problem; since corrected in 1974, no problems have been reported

b/ Company has systems from several vendors

c/ One 16 MW equivalent boiler will become operational in Februarv 1977

d/ Boiler was converted to coal from oil on October 4, 1976

e/ System in start-up phase.

f/ Seven boilers equivalent to 20 MW

g/ Design efficiency of 88 percent when burning 5 percent sulfur coal

h/ System was designed to recover chemicals; problems with system during start-up are continuing

NI - No Information Available.

system. The plant is using sodium hydroxide as its scrubbing agent. This plant does not appear to have a successful scrubber installation, but the reasons for the lack of success appear to be more related to plant characteristics that to FGD technology. A facility operating a self-contained, liquid waste (chemical addition) FGD system was not visited during this study due to its similarity to a self-contained, liquid waste (no chemical addition FGD system. These facilities are described in greater detail below.

1. American Thread Company

The American Thread plant near Marion, North Carolina, specializes in the dyeing and finishing of various types of industrial sewing threads and retail yarns. Spun thread and yarns manufactured at other American Thread plants are sent here, where they may be singed, mercerized, dyed, and finished for sale in package form desired by the customer. A very large portion of incoming cotton thread is mercerized, and dilute sodium hydroxide is used as one of the baths in the continuous mercerizer range.

Steam and heat for the plant are provided by two 4 megawatt equivalent coal-fired steam boilers and one megawatt equivalent stand-by oil burner. The two coal-fired boilers are the overfired stoker type. Coal for the boilers comes from Harlan County, Kentucky, and averages 0.9 percent sulfur with a received heating value of 13,400 Btu/lb. The scrubbing system consists of two W.W. Sly impingement-type scrubbers. Each scrubber is designed to handle approximately 30,000 ACFM at 400°F. The boilers are equipped with mechanical cyclone particulate collectors which precede the scrubber.

The scrubber was installed primarily to comply with the State of North Carolina particulate matter emission regulations. The issue of sulfur dioxide emissions did not enter the decision to install the scrubbers because the coal sulfur content was within the limits specified by the state. The calculated collection efficiencies for particulates and sulfur dioxide are 97 and 90 percent, respectively.

Upon startup in late 1973, it was noticed that the pH of the scrubbing solution composed of river water (pH of 6 to 7) dropped rapidly to approximately 2.0. This pH level cuased corrosion problems in the scrubber system. The sudden drop in pH indicated the system was collecting significant amounts of sulfur dioxide. The plant constructed a tie-in between a 7 percent waste caustic (sodium hydroxide) steam from the mercerizing process and the scrubber recirculation tank. A pH meter was installed to insure a pH of approximately 6.5 was maintained in the scrubber recirculation tank. All the piping in the scrubbing system was removed and replaced with PVC pipe.

After installation of the pH system, the plant has had very few operational problems. The only operational problem with the scrubber reported by plant personnel was its inability to operate as designed at low boiler rates. During startup and low load operations, there was a loss of boiler draft. As a solution, the plant operator opens an access door on the scrubbing during low load operations when additional flow through the scrubber is needed, and closes the door during full load operation. Other than this, the plant engineer feels that the scrubber has performed as well as any other piece of mechanical equipment installed in the plant.

2. Great Southern Paper

The Great Southern Paper Pulp Mill in Cedar Springs, Georgia, has two 50 megawatt equivalent steam boilers, two 20 megawatt equivalent recovery furnaces, and one 30 megawatt equivalent recovery furnace. The fuel for the steam boilers may be coal, coal and bark, or oil and bark. The average sulfur content of the coal burned is 0.8 to 1.5 percent. Last year, fossil fuel utilization was 72 percent coal and 18 percent fuel oil. Design fossil fuel utilization is 95 percent coal and 5 percent fuel oil. Plant output varies between 2000 and 2200 tons of paper per day.

The scrubbing system consists of two Air Pollution Industries venturi scrubbers which are capable of collecting both sulfur dioxide and particulates. Western Precipitation multiclones are upstream of the scrubber to remove fly ash. The FGD systems on Boiler No. 1 and Boiler No. 2 were operational in August and October of 1975, respectively. The scrubbing liquid consists of river water, deionization wash water, and boiler blow-off water. Deionization water is generated an average of three times a day, and each regeneration contains approximately 1200 pounds of sodium hydroxide. The pH of the scrubbing liquid is usually maintained above 5 units. If the deionization water system fails, a 50 percent sodium hydroxide solution is added to the scrubbing liquid manually to maintain the design pH level. Presently, Great Southern Paper is installing a pH control system to automatically monitor and regulate the scrubbing liquid pH by caustic addition or varying the deionization water make-up rate. Scrubber bleed-off liquid is piped to an ash pond. The FGD system is designed for a particulate removal efficiency of approximately 98 percent. A design sulfur dioxide removal efficiency of approximately 88 percent could be achieved when the pH system is operating.

Initial operational problems with the system included corrosion of the water lines and recycle pipes to the venturi, erosion of the rubber linings on several valves, and packing failures in the recycle pumps. Another potential problem area appears to be ash disposal. Great Southern Paper is considering alternative methods of ash disposal to its present system of pond disposal.

3. Canton Textile Mills[1/]

Canton Textile Mills in Canton, Georgia, has a coal-fired steam boiler rated at 6 megawatt equivalent, which is normally used during periods of interrupted natural gas service. The boiler is a Combustion Engineering C-E vertical unit equipped with a cyclonic dust collector. The dust collector captures approximately 75 to 100 pounds of fly ash per hour. The typical coal burned has a sulfur content of 0.8 percent and a received heat value of 13,600 Btu per pound coal.

A full-scale demonstration flue gas desulfurization system was installed to neutralize caustic wastewaters in July of 1975. This project was part of a bench scale investigation by the Environmental Protection Agency and Canton Mills of color removal from indigo and sulfur dyeing wastewaters from a denim textile mill. The scrubbing system was also installed to be in compliance with New Source Performance Standards and has the capability of providing reductions in particulate and sulfur dioxide emissions to meet more stringent standards that may be adopted in the future.

The FGD system consists of an FMC medium energy, venturi-type scrubber and is based on a concentrated double alkali scrubbing process. Caustic dyeing wastewater containing sodium hydroxide and sodium sulfate with a pH of approximately 11 to 12 units is the scrubbing liquid. The scrubbing liquid is injected into the flue gas stream through spray nozzles ahead of the venturi throat. The incorporation of spray pipe liquid injection was initiated due to the presence of cotton fibers in the wastewater scrubbing liquid. The scrubbing liquid passes through the scrubber and is then treated with lime or limestone in the chemical regeneration section of the

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1/ Information supplied from communication with Mr. Kranston Gray at Canton Mills, Canton, Georgia, September 16, 1976, and the following publication: "Treatment of Denim Textile Mill Wastewater: Neutralization and Color Removal", Environmental Protection Agency, EPA Publication No. EPA-600/2-76-139, Research Triangle Park, N.C., May 1976.

system. Upon removal of the insoluble compounds resulting from the regeneration process, the wastewater is collected in an equalization basin. Depending on the desired degree of neutralization, the wastewater is then recycled to the scrubber or pumped to the wastewater treatment facility.

Several operational problems were encountered upon initial startup. A severe plugging problem was encountered in several pumps due to the presence of cotton fibers in the wastewater. A solution to this problem being investigated is the possible use of a mechanically-cleaned screen prior to the scrubbing system. Surface-active agents in the dyeing wastewaters which produce foaming in the scrubber pump, fouling of the pH probes, and sulfur and mist generation are other problem areas that are presently being investigated.

The full-scale scrubber installation has successfully demonstrated the ability to achieve a particulate removal efficiency of 94 to 98 percent in combination with the mechanical cyclone unit. A sulfur dioxide removal efficiency as high as 76 percent is achievable while reducing the scrubber liquid pH to a level of 4.5 to 5.0. By utilizing a sulfur dioxide removal rate of 29 percent, it is possible to produce a neutralized dyestream having a pH of approximately 7.2 units. The full-scale scrubber capacity to remove sulfur dioxide from the boiler flue gas was found to be a function of the scrubbing liquid's pH and also, indirectly, a function of alkalinity. Neutralization of the wastewaters by flue gas scrubbing was shown to improve the efficiency of the subsequent biological wastewater treatment system by producing a more favorable influent pH and alkalinity level.

4. Caterpillar Tractor Corporation

The Caterpillar Tractor plant in Mossvile, Illinois, manufactures engines for the Caterpillar Corporation. The FGD unit is installed on the main heating plant of the installation. The scrubbers are designed to handle a total of approximately 47 megawatt equivalent from four boilers burning 2.5 to 3 percent sulfur coal. Boilers No. 1 and 2 are older, stoker-fired steam boilers with a total rated capacity of approximate 15 megawatt equivalent. Boiler No. 3 is a standby gas-fired boiler which is not connected to the scrubbing system. Boiler No. 4 is a new stoker coal-fired steam boiler of approximately 16 megawatt equivalent capacity. Boiler No. 5, which is under construction, is also a stoker coal-fired steam boiler with a capacity of approximately 16 megawatt equivalent. This boiler will become operational in February of 1977.

The FGD system at the heating plant is an FMC concentrated double alkali scrubbing system. Each boiler (No. 1, 2, 3, and 4) has its own scrubbing unit, and all units feed to a common recycle and chemical regeneration system. The system layout was determined to a large extent by the space available in the boiler house. As a result, mechanical collectors were not installed to pre-clean the flue gas. In addition, the FGD system fans could not be located upstream of the scrubbing units. As a result, a reheat system was retrofitted to the boilers to prevent damage to the system fans by corrosive steam. The reheat system increases the exit temperature of the gases leaving the scrubber so that: (1) the normal steam plume from the scrubber will not be visible, and (2) potential corrosion in the downstream fan and stack will be reduced. The reheat system maintains the temperature of the released gas stream at approximately 175°F. A reheat system will not be installed on Boiler No. 5 because the mechanical collectors and fan will precede the scrubber.

The scrubbing systems on Boilers #2 and #4 began operation in October 1975. The scrubbing system on Boiler #1 became operational shortly afterwards. Since the chemical regeneration system and the recirculation system were designed to handle a full load from four boilers, some difficulties were encountered in running at a low load. Since the scrubber system on Boiler No. 1 has become operational, the recirculation system has been operating well. The sulfur dioxide and particulate removal efficiencies are reported to be approximately 90 and 99 percent, respectively.

Since the beginning of operation, the scrubbers have operated satisfactorily. Two major problems that have been corrected are: 1) the erosion of valves in the system piping, and 2) difficulty in maintaining the pumps. FMC feels these problems would not have occurred if mechanical collectors (to remove fly ash) were installed preceding the scrubber units.

The sludge disposal at the installation has, to date, not posed any significant problem. All sludge is removed from the plant by means of a conveyor system. It is then hauled by a commercial contractor for landfill purposes.

In addition to the scrubbing system at the Mossville plant, Caterpillar has contracted FMC to install scrubbers at two other facilities. At the Mapleton plant, FMC is supplying an FGD system capable of handling eight coal-fired steam boilers with a total rating of 85 megawatt equivalent. At the East Peoria plant, FMC has on order a scrubbing system for four 22 megawatt equivalent steam boilers. The regeneration systems at Mapleton and East Peoria are sized to handle the entire plant load.

5. Firestone Tire Company

The scrubber installation at the Firestone plant in Pottstown, Pennsylvania, is a demonstration scale plant designed to test the feasibility of FGD on industrial boilers. The scrubber system is the FMC version of the double alkali system. The plant is designed to handle approximately 10,000 ACFM or the equivalent of 3.5 megawatts. The boiler on which the scrubber is operating has a full load capacity of approximately 12 megawatt equivalent. The boiler was converted from burning a residual fuel oil with a sulfur content of 2.2 percent to a 2.5 to 3.0 percent sulfur coal in October 1976.

Since the installation at Firestone has recently converted to a coal-fired boiler, operational data for the coal system was not available. According to Firestone, the availability of the system will exceed 95 percent. In fact, Firestone plans, assuming the conversion to coal as the combustion fuel in October is successful, to install the same FGD system on all the plant's boilers.

The predominate reason for installing an FGD system at Firestone, as opposed to the other alternatives, is that the plant is located in an Air Quality Control Region with stringent sulfur regulations. The regulation which must be met by the plant is 0.86 pounds of sulfur dioxide per million Btu.

Firestone has established an experimental landfill operation for disposing approximately three tons per day of sludge. As a result of this landfill program, the State of Pennsylvania Department of Environmental Resources has granted a permit to Firestone allowing the continued disposal of this material. Firestone is also exploring alternative methods of sludge disposal including using it as a soil enrichment agent.

6. Rickenbacker Air Force Base

The purpose of this visit was to inspect the Research-Cottrell Bahco lime FGD unit installed on a heating plant at Rickenbacker Air Force Base in Columbus, Ohio. The heating plant consists of seven coal-fired steam boilers rated at a total of 20 megawatt equivalent. Research-Cottrell installed one large scrubber to handle the entire design gas flow of 55,000 SCFM from all boilers. The unit was designed solely to prevent the heating plant from violating applicable sulfur dioxide and particulate regulations.

The Research-Cottrell Bahco unit started operation in March of 1976. The system ran without malfunction for the first six weeks. At that time, the system was down for three weeks due to a pump lining failure followed by a delay in obtaining replacement parts. Two other problem areas were system instrumentation and a fan bearing failure.

The sulfur dioxide design efficiency of the scrubber is estimated to be approximately 88 percent when burning a 5 percent sulfur coal. Sulfur dioxide removal efficiency up to 97 percent has been demonstrated at Rickenbacker Air Force Base when 3 percent sulfur coal was burned. The scrubber is designed for 95 percent particulate control efficiency. Actual sulfur dioxide removal efficiency was tested to be 90 percent at a 1.0 stiochiometry and 95 percent at a 1.2 stoichiometry. The installation includes a mechanical collector in front of the scrubber fan. The reasons for this are two-fold: (1) to alleviate erosion problems in the fan by removing large particulates, and (2) to minimize the quantity of wet sludge produced by the scrubber.

The Research-Cottrell Bahco scrubber at Rickenbacker is designed to automatically compensate for fluctuations in boiler flue gas flow rate. The scrubber is capable of a 1.5 to 1 turndown, but can accommodate a lower heating plant load by addition of make-up air through a vent stack upstream of the scrubber. This type of design, however, leads to large variations in inlet sulfur dioxide gas stream concentrations. These fluctuations are continuously adjusted to maintain overall system stoichiometry.

The sludge from the Research-Cottrell Bahco unit is pumped into a lined pond adjoining the heat plant. The amount of storage at Rickenbacker is estimated to be adequate for at least five years of normal operation.

7. Nekoosa-Edwards Paper Pulp Mill

The Nekoosa-Edwards paper pulp mill in Ashtown, Arkansas, was contacted concerning its FGD system installed in the beginning of 1976. The scrubbing system was designed by Air Pollution Industries to operate on one 50 megawatt equivalent steam boiler fired with coal or fuel oil. The scrubber was a venturi designed to remove both sulfur dioxide and particulates. The intent of Nekoosa-Edwards was to make, from the scrubber effluent, saltcake which would be used at the mill. However, the operation of the FGD system, to date, has been unsatisfactory.

The predominant difficulties with the FGD system have been two-fold. First, the plant has been unable to develop an adequate pH control mechanism. The pH control system monitors the amount of caustic agent, i.e., sodium hydroxide, which goes into the recycle tank, keeping the pH of the scrubber solution at a noncorrosive level. To date, the plant has been plagued with problems in operating the pH control system and has suffered a great deal of corrosion. The second problem concerns the chemical regeneration portion of the system. The intent of the plant was to separate the fly ash from the scrubber liquid and take the scrubber liquid through a series of evaporators where sodium sulfate, i.e., saltcake, would be generated. The plant has been unable to operate the fly ash separation system properly, and there is not enough evaporation capacity for the plant to process the scrubber effluent at full operational capacity.

In spite of the operational problems, the sulfur dioxide and particulate removal efficiencies of the FGD system are 90 and 99 percent, respectively, according to the plant engineer. The waste product from the scrubber is not recycled, at present, and is pumped to the wastewater treatment plant.

The use of other waste streams from the pulp mill as scrubbing liquid was also discussed. The use of caustic waste water from the bleaching plant was considered. This water has a pH of approximately 11 and could supply 2000 gallons per minute of scrubbing liquid. The waste stream was rejected because the sodium content of the stream was judged inadequate for the process design. The plant is presently using approximately 3 gallons per minute of deionization wash water as a supplement to the addition of sodium hydroxide to the scrubbing liquid.

APPENDIX C

COMPONENT CAPITAL COSTS OF INDUSTRIAL FLUE GAS DESULFURIZATION SYSTEMS

This appendix outlines the component capital cost curves and pricing procedures used in developing the capital and annual cost of the industrial FGD systems outlined in the study. The appendix is organized by the following component types: venturi scrubber and cyclonic separator, pumps, fans, motors, starters, ductwork, dust removal equipment, stacks, mechanical collectors, holding tanks, and waste removal units. The specific application of these FGD components may vary between system types. In addition, FGD components exist that were not described below. These miscellaneous components were not considered major operational units of the industrial FGD systems reviewed in this study. Figures C-1 through C-30 are based on December, 1975 cost data while Figures C-31 and C-32 are based on June, 1977 and December, 1967 costs, respectively.

A. Self-Contained, Solid Waste FGD Systems

As explained in Section VI, it was not possible to perform a detailed cost breakdown of the SCSW FGD system due to the greatly varying designs offered by the vendors. Figure C-1 shows the estimated total installed capital cost for these systems.

B. Self-Contained. Liquid Waste and Waste Stream FGD Systems

1. Venturi Scrubber and Cyclonic Separator

The pricing procedure for a high-energy venturi scrubber and cyclonic separator using Figures C-1a through C-5 is as follows:

a) Enter the scrubber inlet gas volume (ACFM)[1/] on Figure C-1 and determine the capital cost of the scrubber and separator unit as depicted by the cost curve. This value is for a system constructed of 1/8 inch carbon steel and includes the cost of the elbow, pumps, and controls, flange-to-flange. The cost curve is applicable to scrubber units with a flow through of 200,000 ACFM or less. If

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[1/] Actual cubic feet per minute.

FIGURE C-1

APPROXIMATE CAPITAL COSTS FOR VARIOUSLY SIZED SELF-CONTAINED, SOLID WASTE FGD SYSTEMS

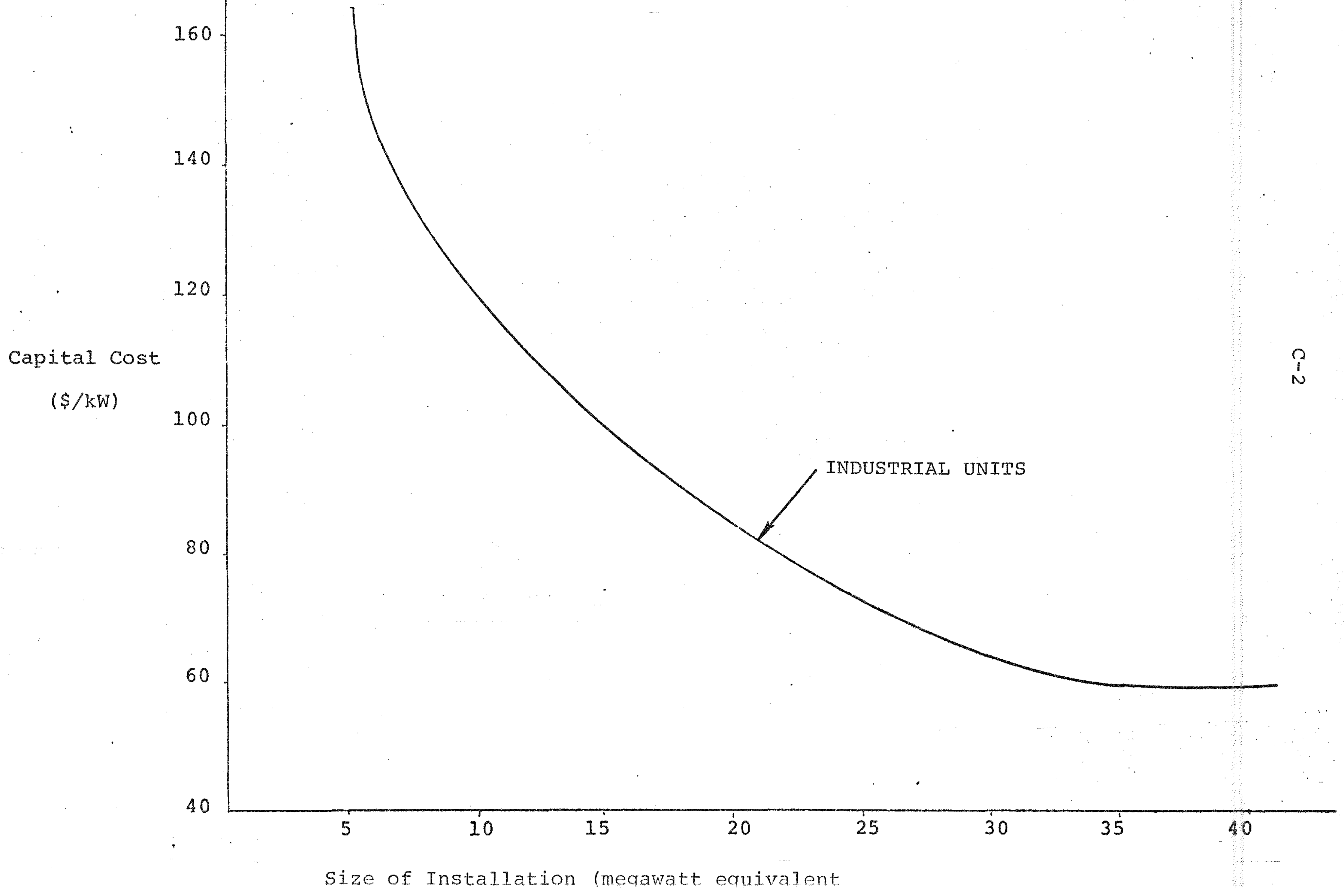
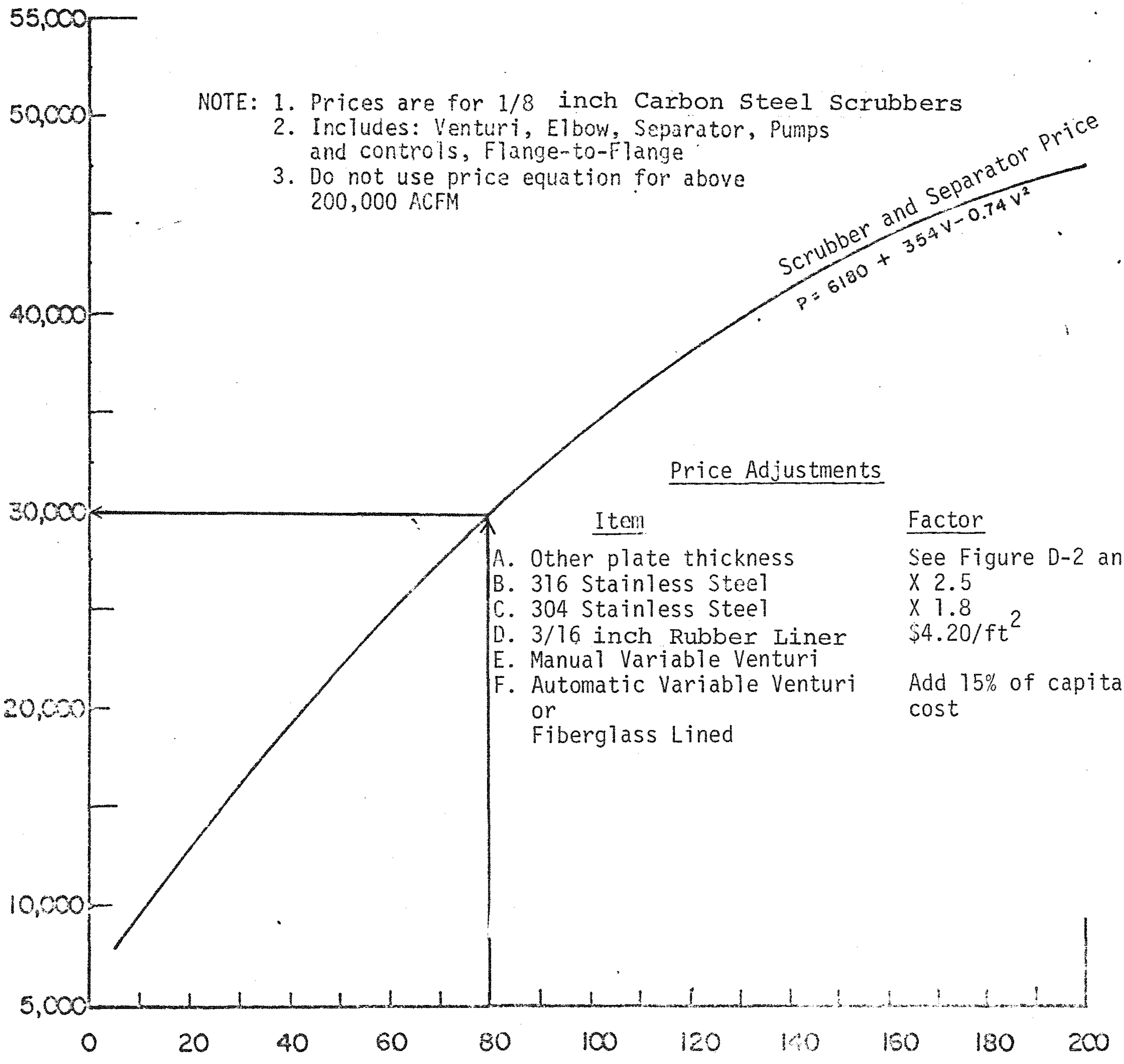


FIGURE C-1a

1/8 INCH THICK CARBON STEEL FABRICATED SCRUBBER PRICE VERSUS VOLUME



NOTE:
1. Prices are for 1/8 inch Carbon Steel Scrubbers
2. Includes: Venturi, Elbow, Separator, Pumps and controls, Flange-to-Flange
3. Do not use price equation for above 200,000 ACFM

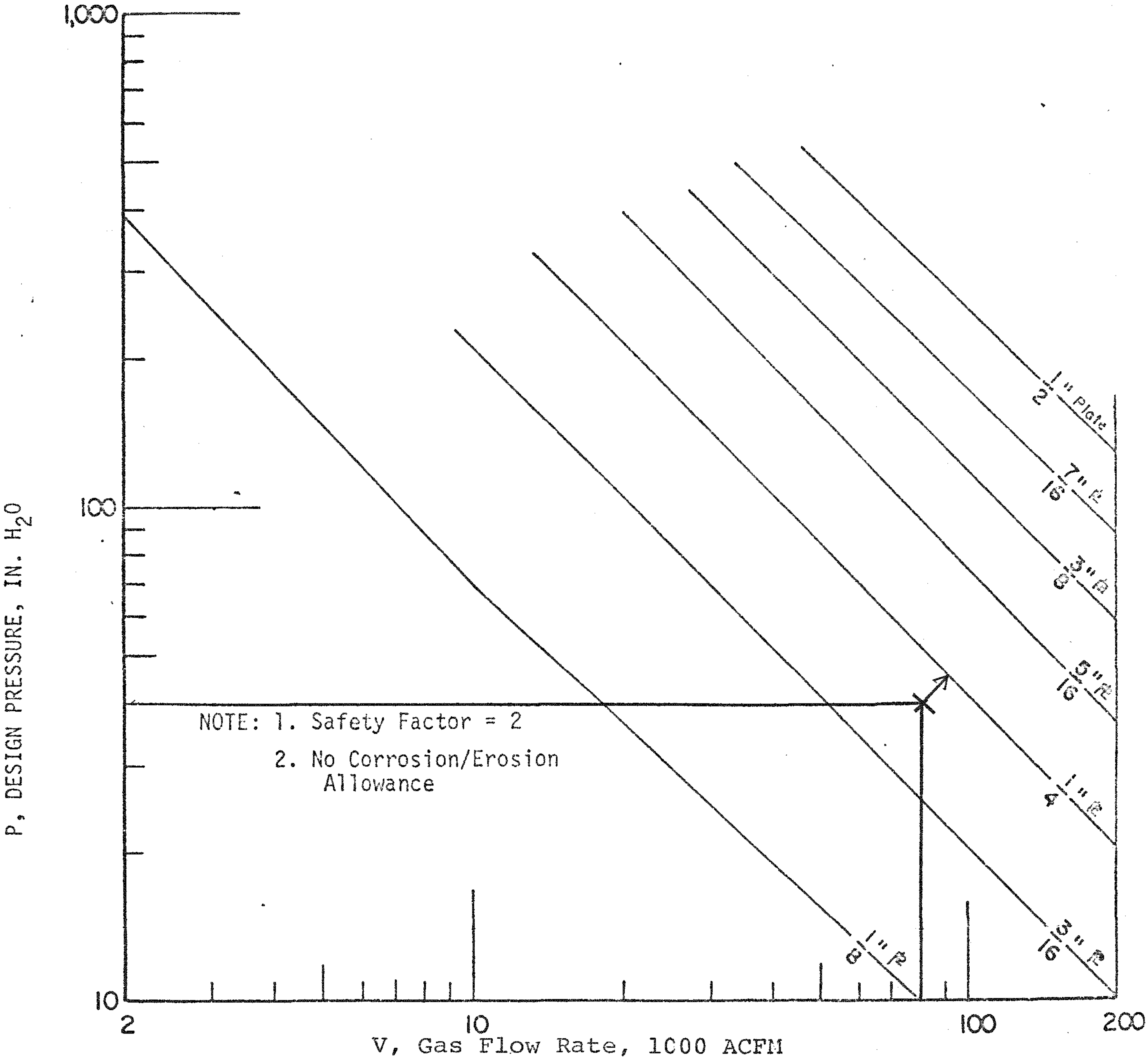
Price Adjustments

Item	Factor
A. Other plate thickness	See Figure D-2 and D-3
B. 316 Stainless Steel	X 2.5
C. 304 Stainless Steel	X 1.8
D. 3/16 inch Rubber Liner	$4.20/ft^2
E. Manual Variable Venturi	
F. Automatic Variable Venturi or Fiberglass Lined	Add 15% of capital cost

SOURCE: "Capital and Operating Costs of Selected Air Pollution Control Systems", GARD, Inc., prepared for the Environmental Protection Agency, Research Triangle Park, N.C., EPA-4501/3-76-014, May 1976.

FIGURE C-2

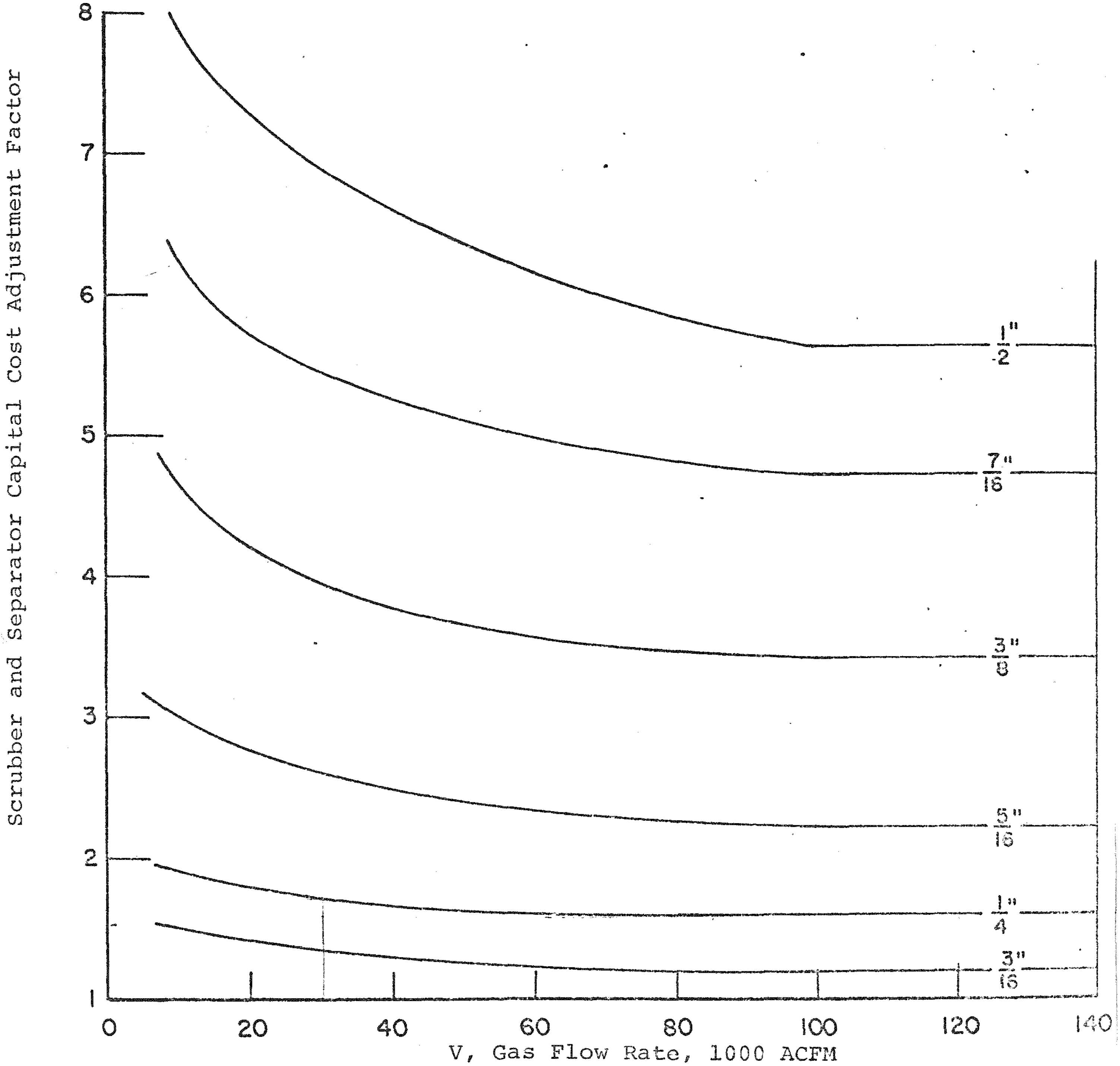
PLATE THICKNESS REQUIRED VERSUS VOLUME AND DESIGN PRESSURE



SOURCE: See Figure C-1.

FIGURE C-3

PRICE ADJUSTMENT FACTORS VERSUS PLATE THICKNESS AND VOLUME



SOURCE: See Figure C-1.

stainless steel, fiberglass, rubber liner, and/or a manual or variable throat venturi scrubber is employed, the price adjustments to the scrubber and separator capital cost should be made as noted.

b) Using Figure C-2, the scrubber and separator plate thickness can be derived by inserting the gas flow rate and design pressure of the unit. The curves include a safety factor of 2 and no corrosion or erosion allowance. The plate thickness should, as a rule, be rounded up to the next highest standard plate thickness.

c) If the plate thickness derived using Figure C-2 is greater than 1/8 inch, determine the scrubber and separator capital cost adjustment factor from Figure C-3. Insert the gas flow rate and plate thickness to attain this factor.

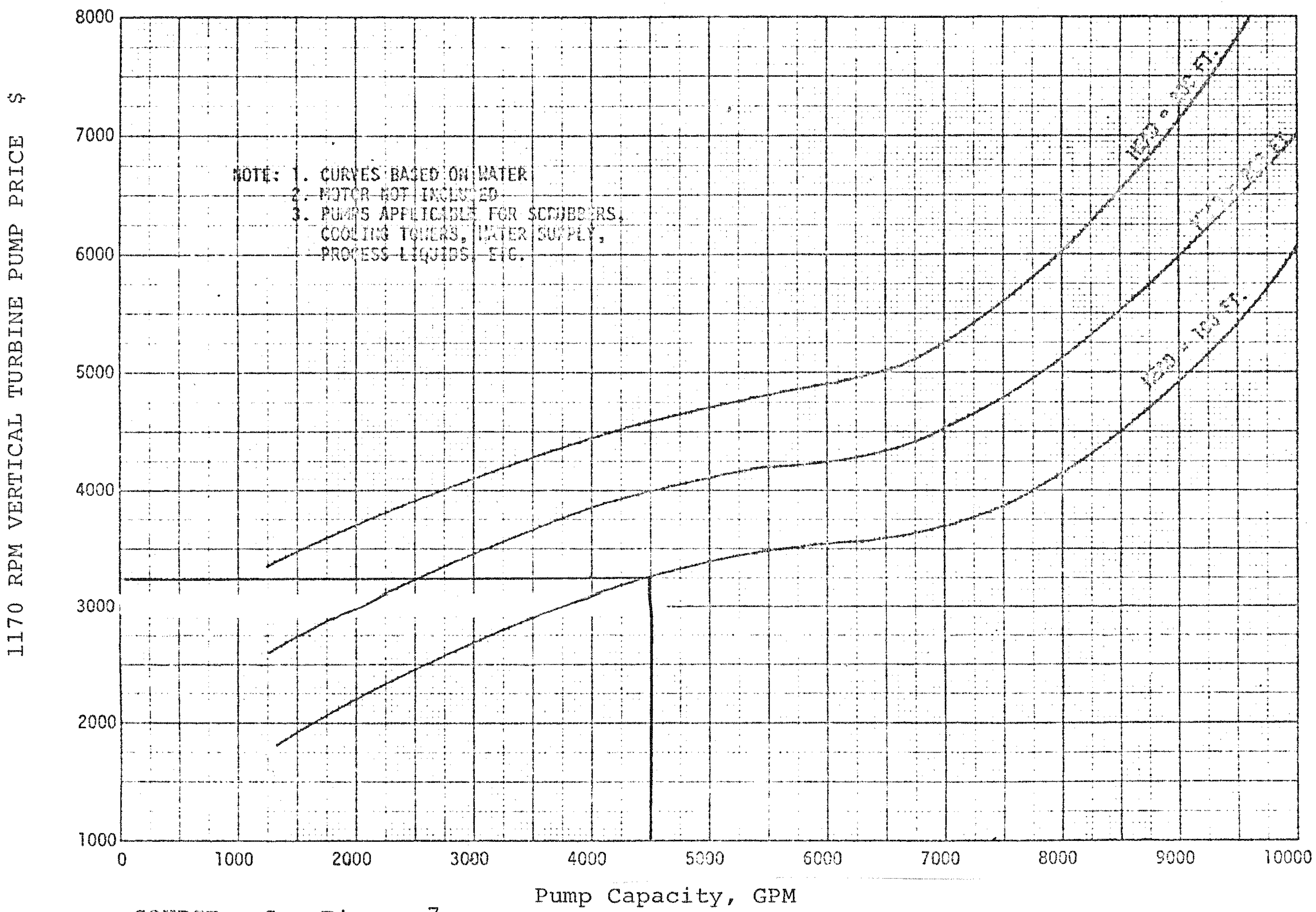
The cost curves for the scrubber and separator unit assumes a scrubber inlet gas velocity of approximately 3,500 fpm and a separator superficial inlet velocity of approximately 600 fpm.

2. Pumps

Capital cost curves for cast iron, bronze fitted, vertical turbine wet sump pumps rated at 1170, 1750, and 3550 revolutions per minute (RPM) are illustrated in Figures C-4, C-5, and C-6, respectively. The curves are based on water, and the pump motor and starter are not included. In each curve, enter the pump capacity (GPM) and the pump head (feet) to derive the pump cost. Using Figure C-7, the pump head may be calculated by inserting the pump capacity. The pump horsepower (HP) should, as a rule, be increased to the next highest level. Using the HP level determined from Figure C-7, calculate the starter and motor price (see sub-section (3)).

FIGURE C-4

CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRICES FOR 1170 RPM

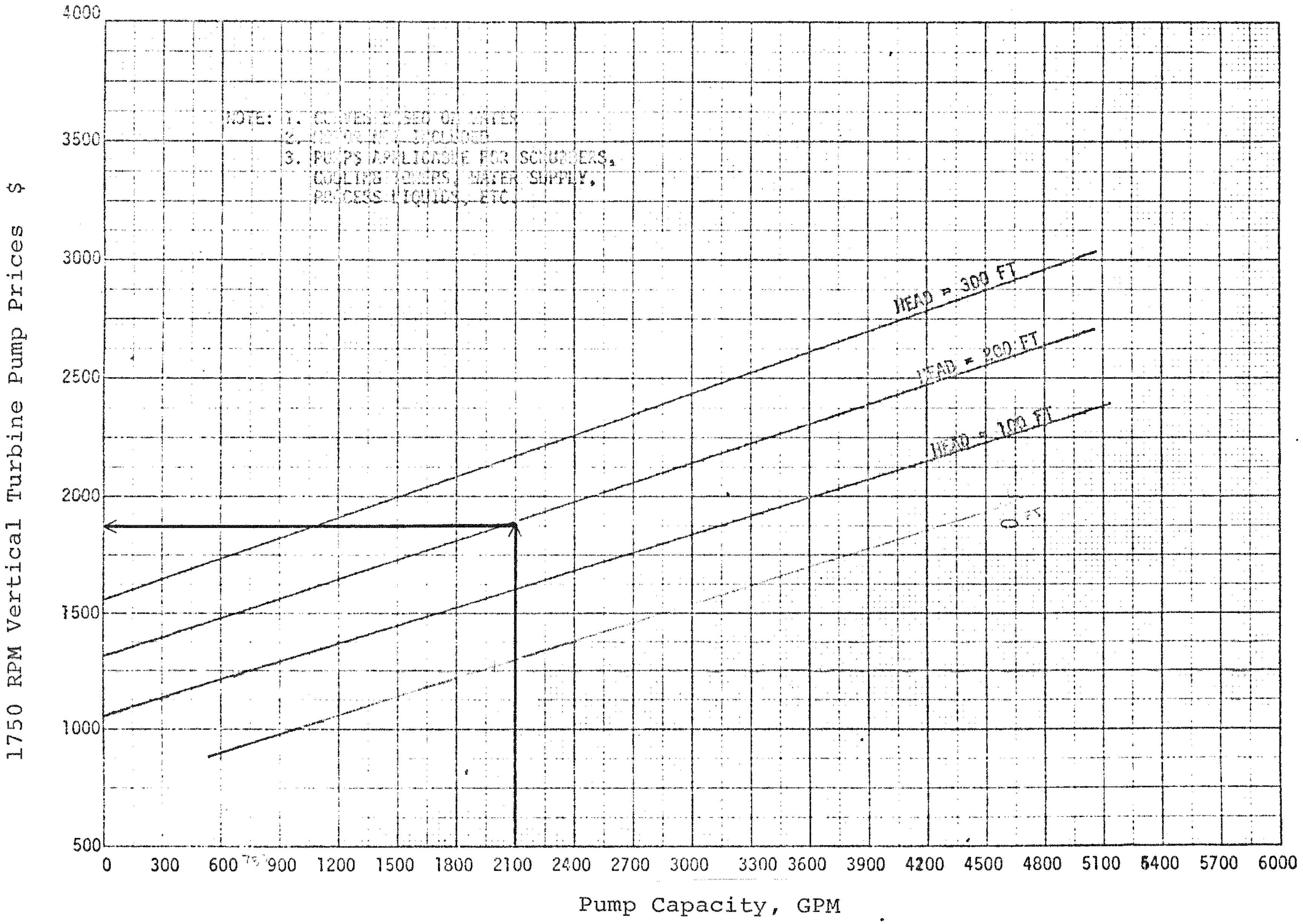


NOTE: 1. CURVES BASED ON WATER
2. MOTOR NOT INCLUDED
3. PUMPS APPLICABLE FOR SCRUBBERS, COOLING TOWERS, WATER SUPPLY, PROCESS LIQUIDS, ETC.

SOURCE: See Figure 7.

FIGURE C-5

CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRCIES FOR 1750 RPM

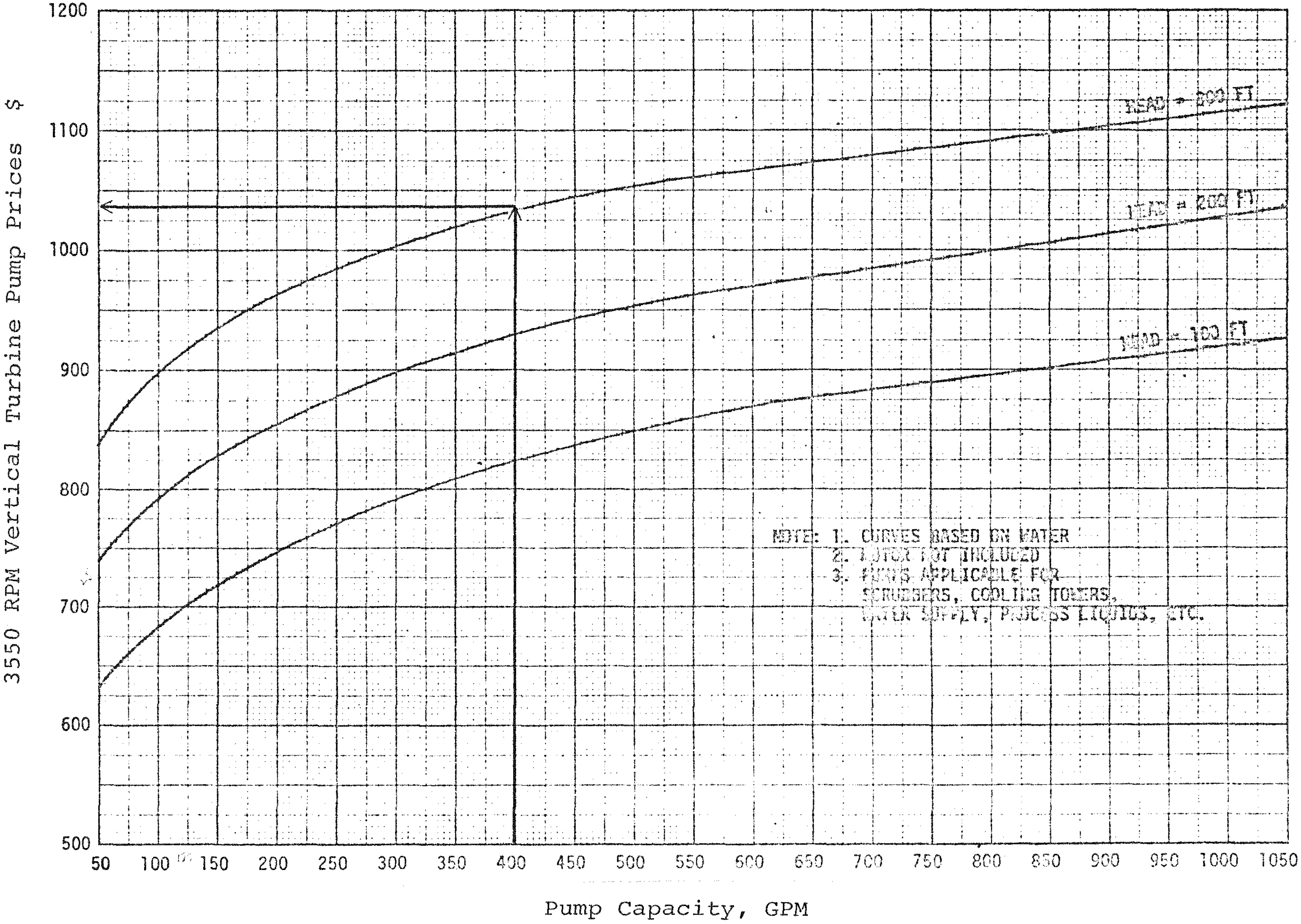


NOTE: 1. CURVES BASED ON WATER
2. MOTOR NOT INCLUDED
3. PUMPS APPLICABLE FOR SCRUBBERS, COOLING TOWERS, WATER SUPPLY, PROCESS LIQUIDS, ETC.

SOURCE: See Figure C-1.

FIGURE C-6

CAST IRON, BRONZE FITTED, VERTICAL TURBINE WET SUMP PUMP PRICES FOR 3550 RPM

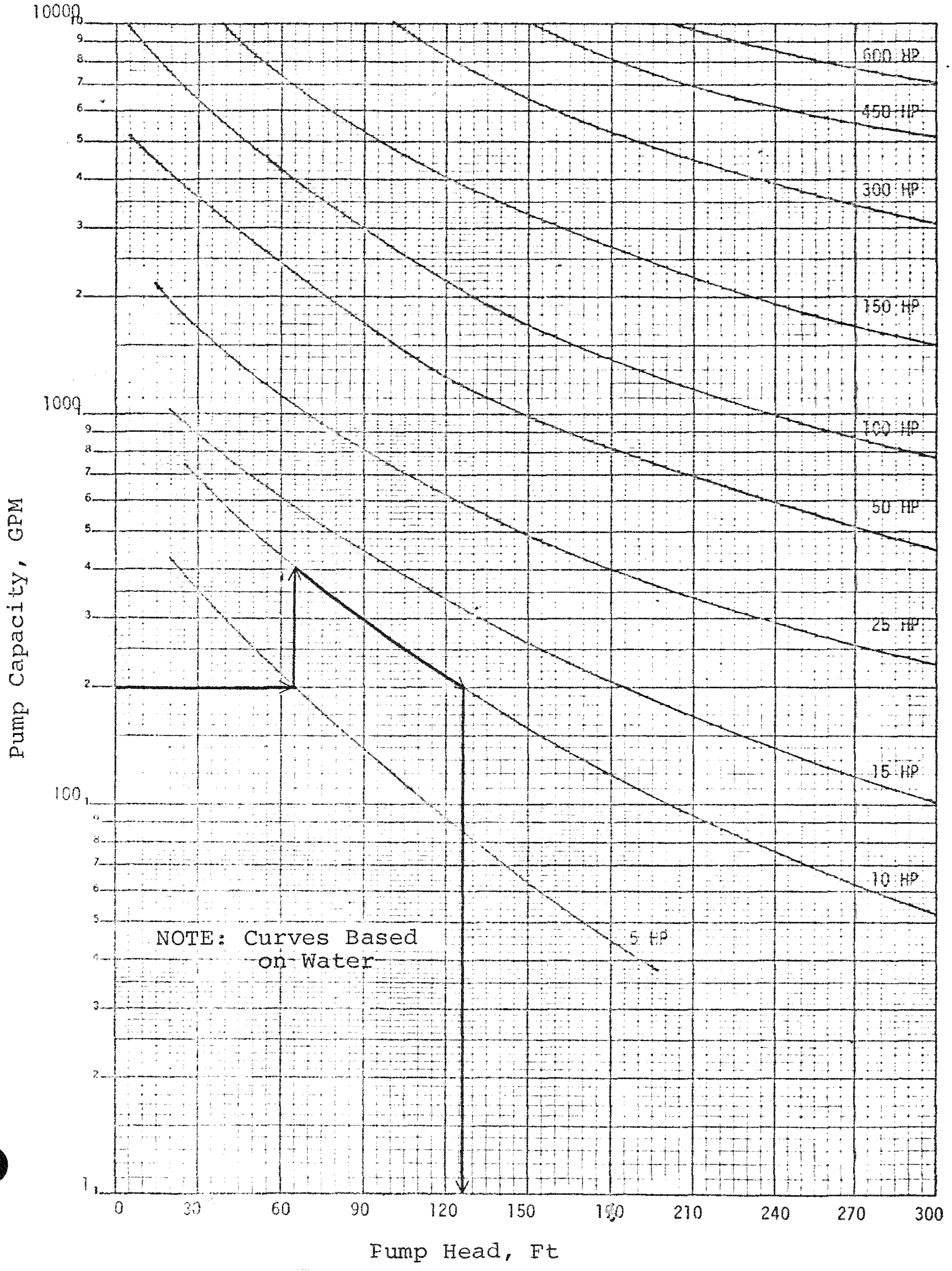


NOTE: 1. CURVES BASED ON WATER
2. MOTOR NOT INCLUDED
3. PUMPS APPLICABLE FOR
SCRUBBERS, COOLING TOWERS,
WATER SUPPLY, PROCESS LIQUIDS, ETC.

SOURCE: See Figure C-1.

FIGURE C -7

PUMP MOTOR HORSEPOWER VERSUS CAPACITY AND HEAD FOR VERTICAL TURBINE PUMPS



NOTE: Curves Based on Water

SOURCE: See Figure C-1.

3. Fans, Motors, and Starters

Capital cost curves for radial tip fan blades operating below 20 inches static pressure (measured at 1 atmosphere and 21°C) are illustrated in Figure C-8. Enter the fan static pressure and air flow rate to derive the fan cost. For high temperature operating conditions, add six percent to the fan price. For stainless steel construction, use a cost correction factor of 2.5. Determine the fan RPM level and motor BHP using Figure C-9 by entering the fan static pressure and air flow at one atmosphere and 21°C. Using Figure C-10, determine the drip-proof motor and starter price (magnetic starter with circuit breaks or explosion proof magnetic starter with circuit breaks) by entering the motor BMP. Table C-1 is a guide to determine motor RPM and Table C-2 lists cost adjustment factors for totally enclosed fan cooled and explosion proof motors. Once the adjustment factor from Table C-2 is selected, multiply this factor by the cost of the drip-proof motor to determine the capital cost for the other motor type.

TABLE C-1

MOTOR RPM SELECTION GUIDE

MOTOR RPM	FAN RPM RANGE
3,600	2,400-4,000
1,800	1,400-2,400
1,200	1,000-1,400
900	700-1,000
6,000	<700

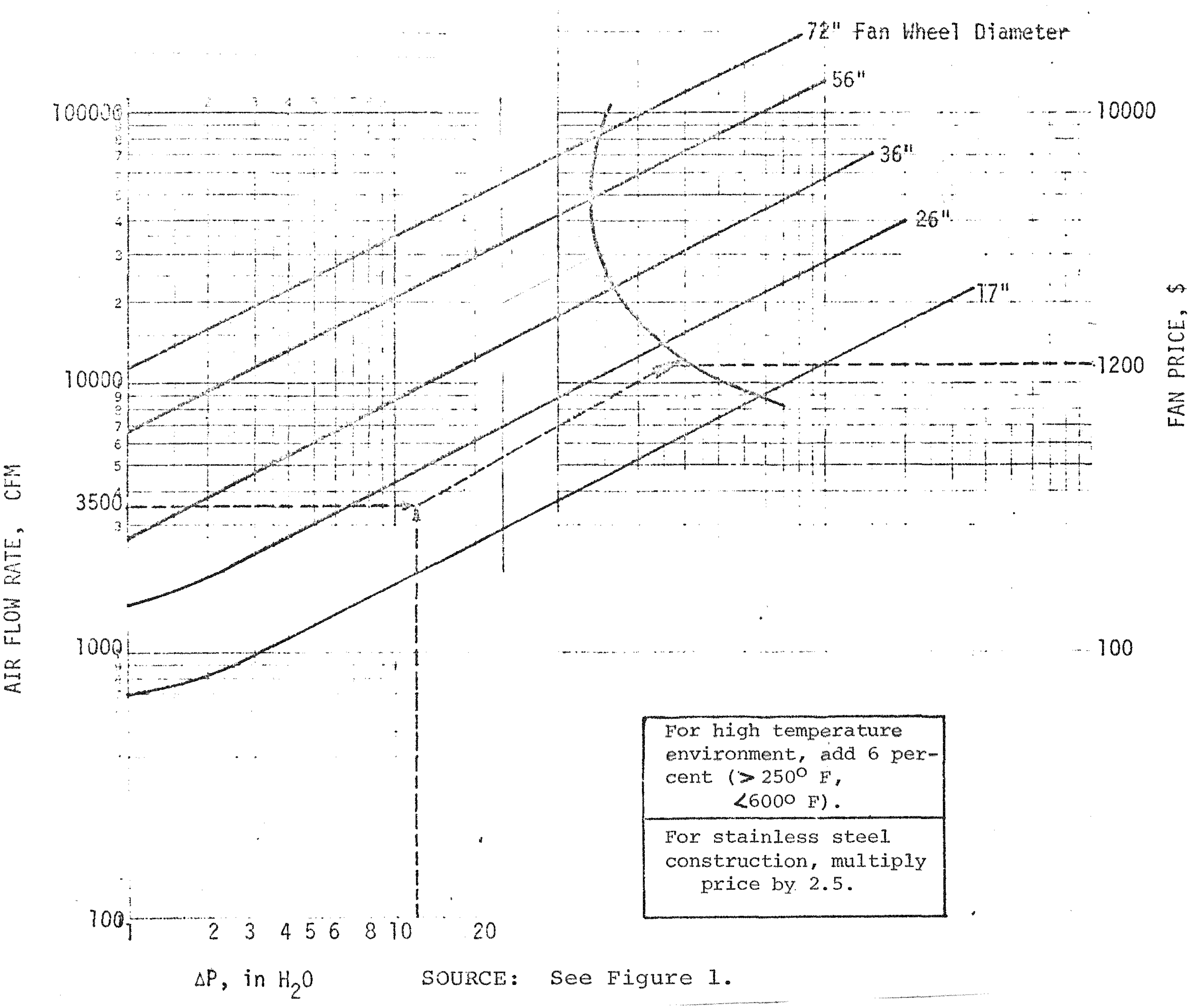
TABLE C-2

COST ADJUSTMENT FACTORS FOR OTHER MOTOR TYPES

HORSEPOWER	TOTALLY ENCLOSED FAN COOLED	EXPLOSION PROOF
≤20	1.3	1.6
>20	1.5	1.7

FIGURE C-8

RADIAL FAN PRICES VERSUS SCFM, AND ΔP FOR ARRANGEMENT NO. 1



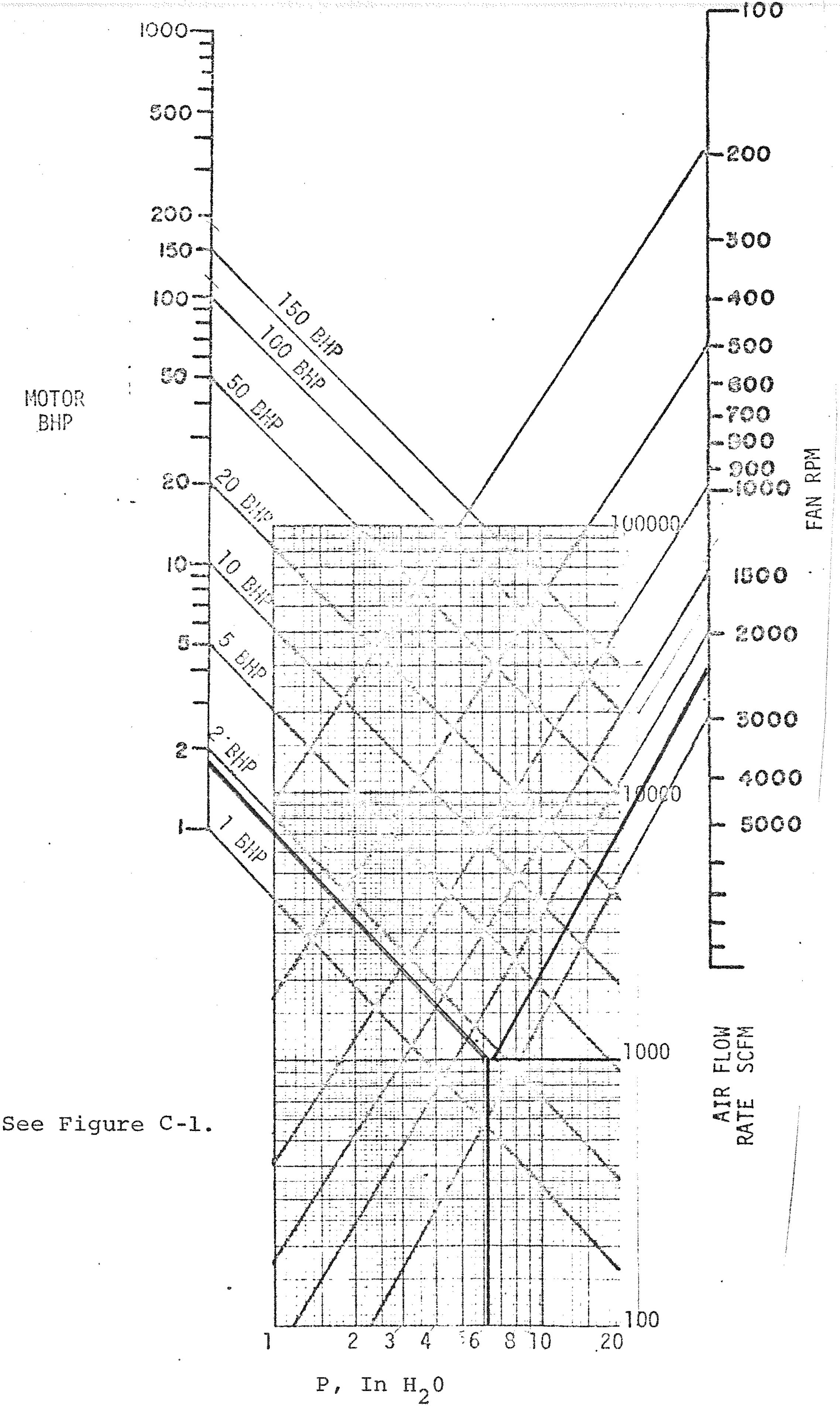
For high temperature environment, add 6 percent (> 250° F, < 600° F).

For stainless steel construction, multiply price by 2.5.

SOURCE: See Figure 1.

FIGURE C-9

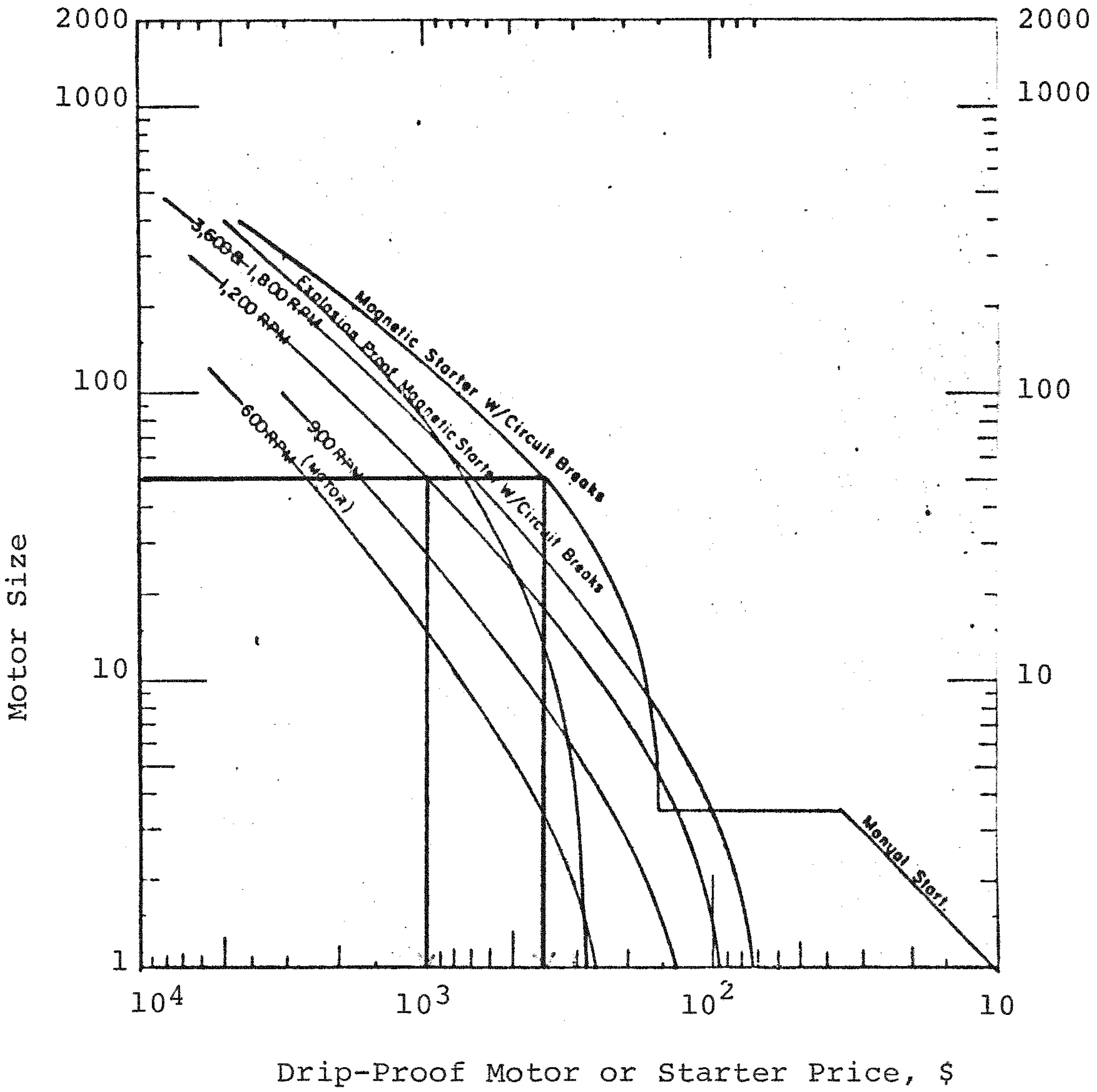
FAN RPM AND MOTOR BHP FOR RADIAL FANS



SOURCE: See Figure C-1.

FIGURE C -10

BHP, FAN RPM AND MOTOR AND STARTER PRICES VERSUS ΔP AND CFM



Note: Prices are for drip-proof motors only, for other types of motors, see Table D-2. Motors are purchased in standard sizes, and may vary from the curve prices shown above.

SOURCE: See Figure C-1.

Figure C-11 depicts the capital cost curves for radial tip blades in applications involving greater than 20 inches fan static pressure (measured at one atmosphere and 21°C). The three curves are for 20, 40, and 60 inches of fan static pressure and air flow rates measured at one atmosphere and 21°C. Figure C-12 illustrates the cost curves for starter and motors in high pressure, high BHP venturi scrubber applications. Enter the air flow rate at SCFM and fan static pressure to determine the starter and motor price. Accuracy of the curves are ±50 percent and will vary as a function of motor RPM, frame size, power, motor enclosure, and starter type.

An inlet or outlet damper is usually required on fans. Figure C-13 contains cost curves for fan inlet and outlet dampers as a function of gas flow rate and fan static pressure. V-belt drives may also be selected in some fan applications. Cost curves for these units are illustrated in Figure C-14 as a function of motor HP and fan RPM. The curves should not be extrapolated above 150 HP and the V-belt closest to the fan RPM should be selected. For direct drive applications, cost at five percent of the motor price.

4. Duct Work

a. Straight Duct

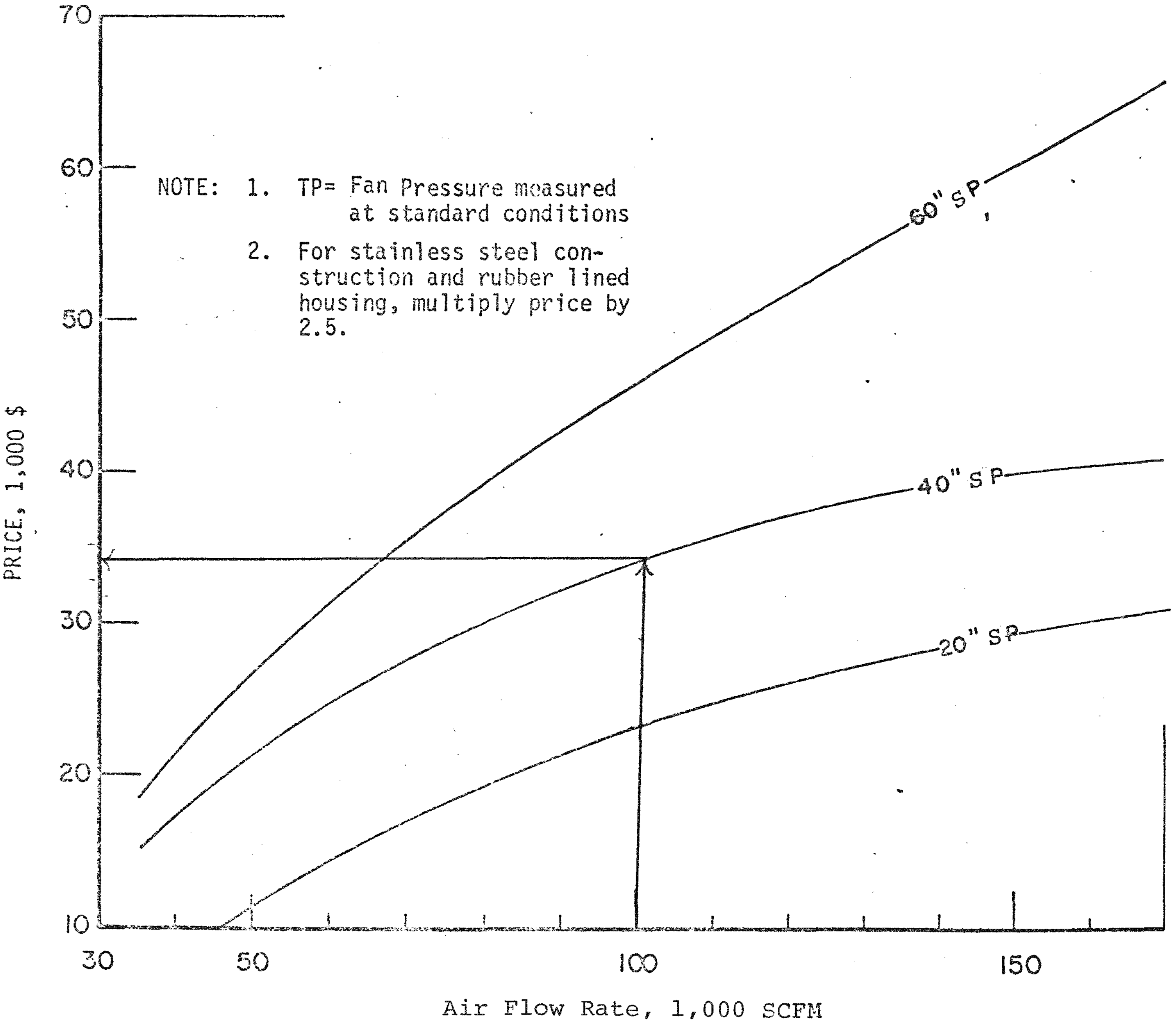
Figures C-15 and C-16 gives the cost of carbon steel, and stainless steel straight duct fabrication per linear foot as a function of duct diameter and plate thickness, respectively. The cost includes flanges every 40 feet.

b. Elbows, Tees, Transitions, and Expansion Joints

Figures C-17 and C-18, illustrates the capital cost curves for carbon steel, and stainless steel elbow duct as a function

FIGURE C -11

RADIAL TIP FAN PRICES



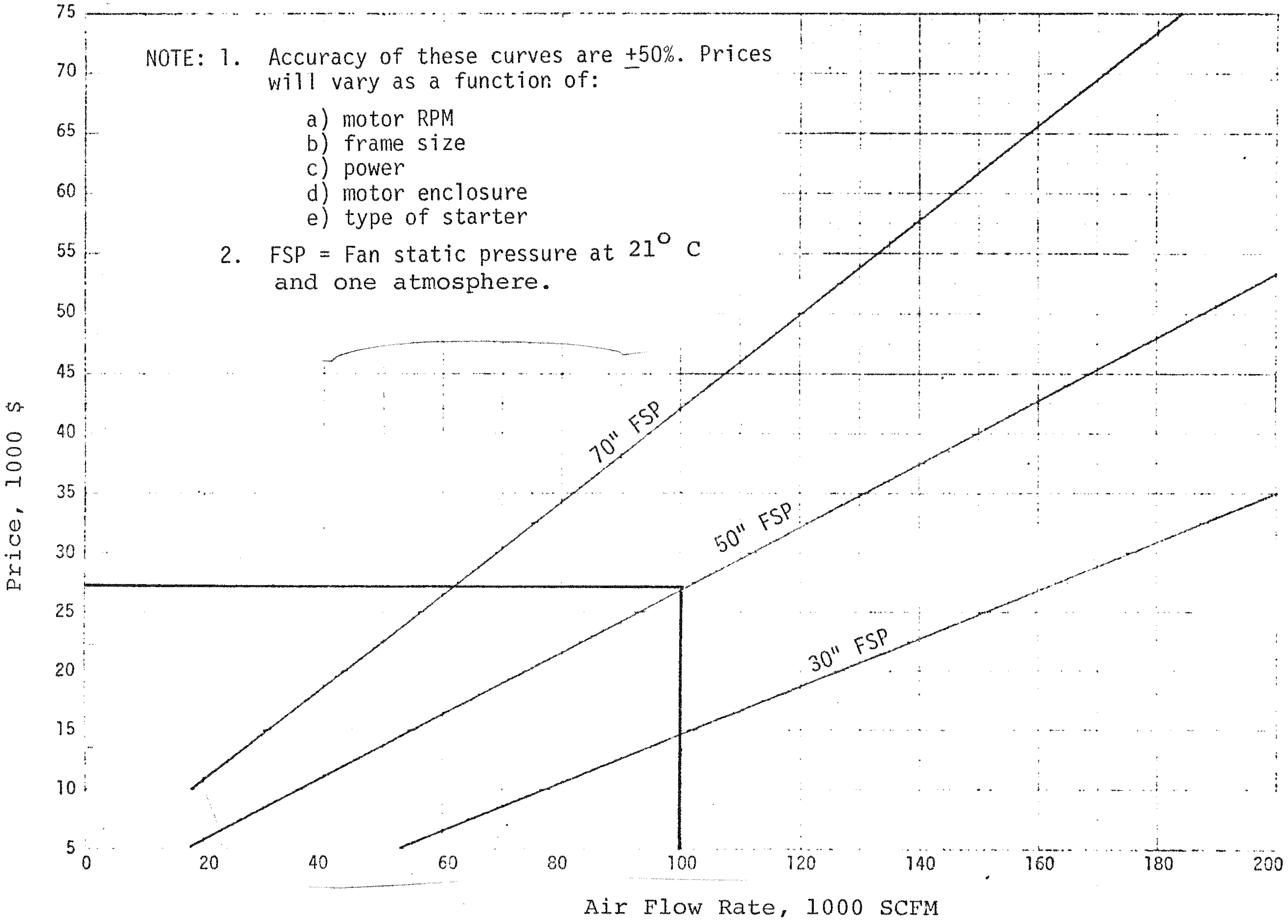
NOTE: 1. TP= Fan Pressure measured at standard conditions

2. For stainless steel construction and rubber lined housing, multiply price by 2.5.

SOURCE: See Figure C-1.

FIGURE C -12

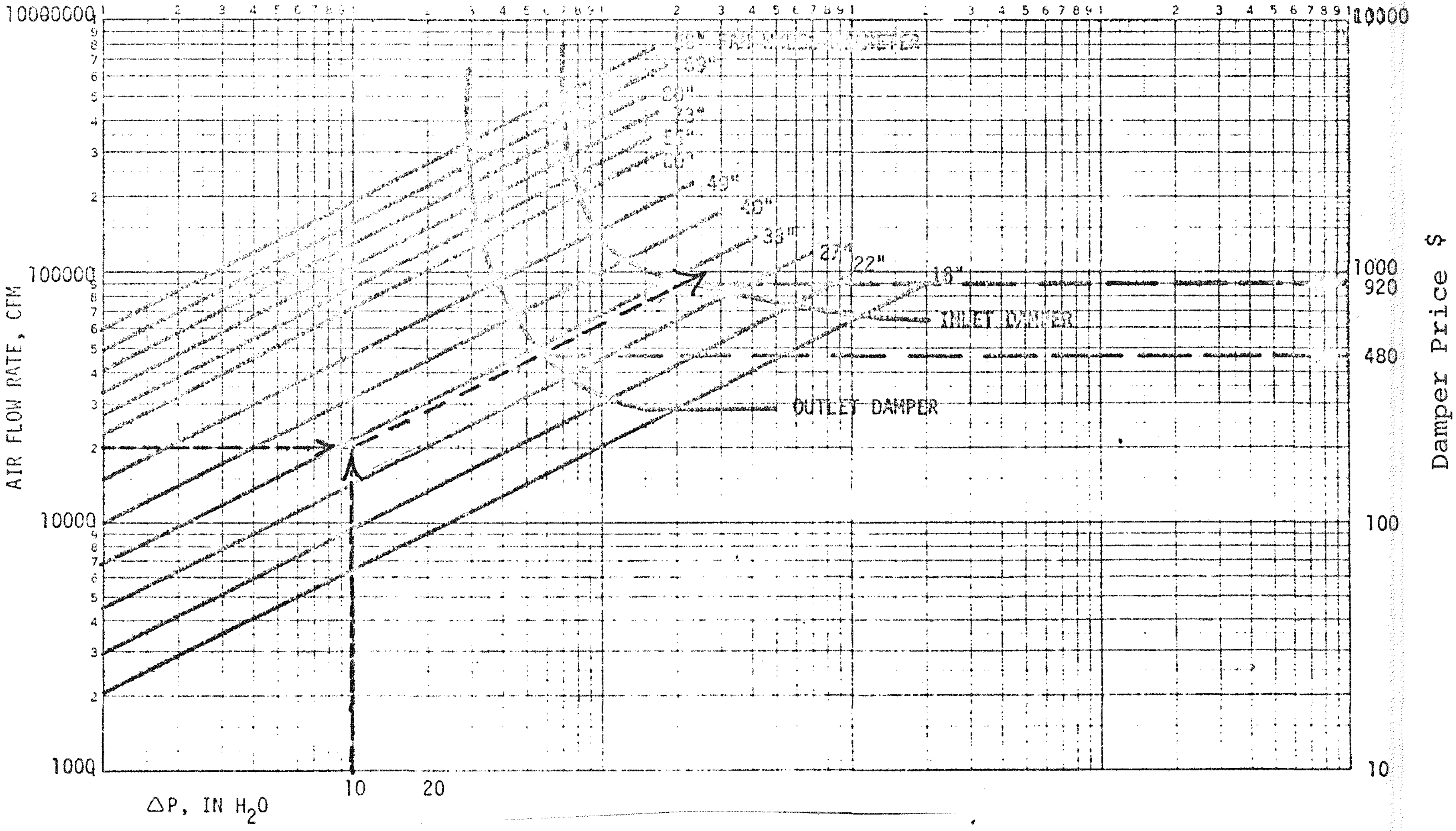
STARTER AND MOTOR PRICES FOR VENTURI SCRUBBER APPLICATIONS (HIGH PRESSURE, HIGH BHP)



SOURCE: See Figure C -1.

FIGURE C-13

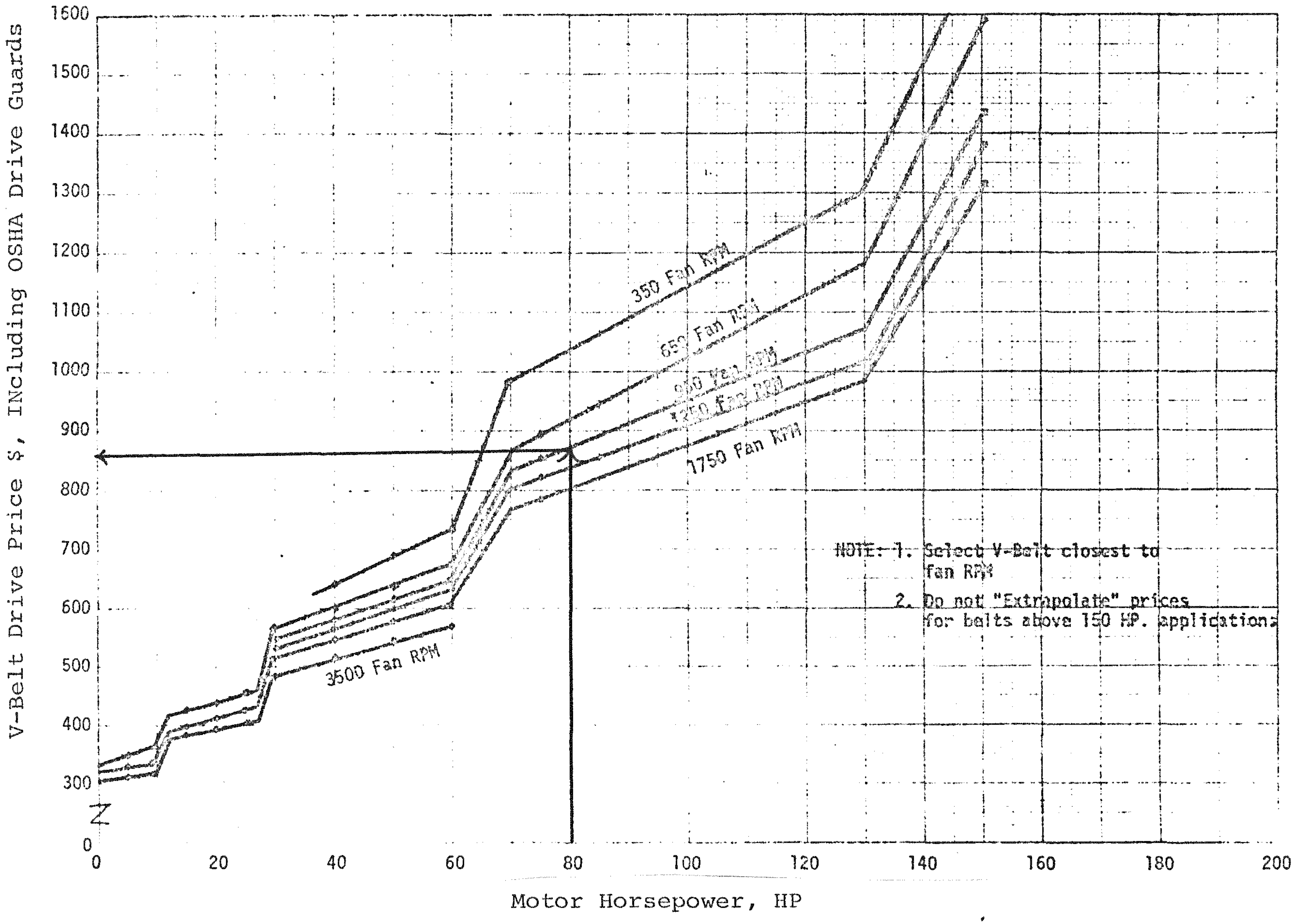
FAN INLET AND OUTLET DAMPER PRICES AS A FUNCTION OF CFM AND ΔP



SOURCE: See Figure C-1.

FIGURE C-14

V-BELT DRIVE PRICES



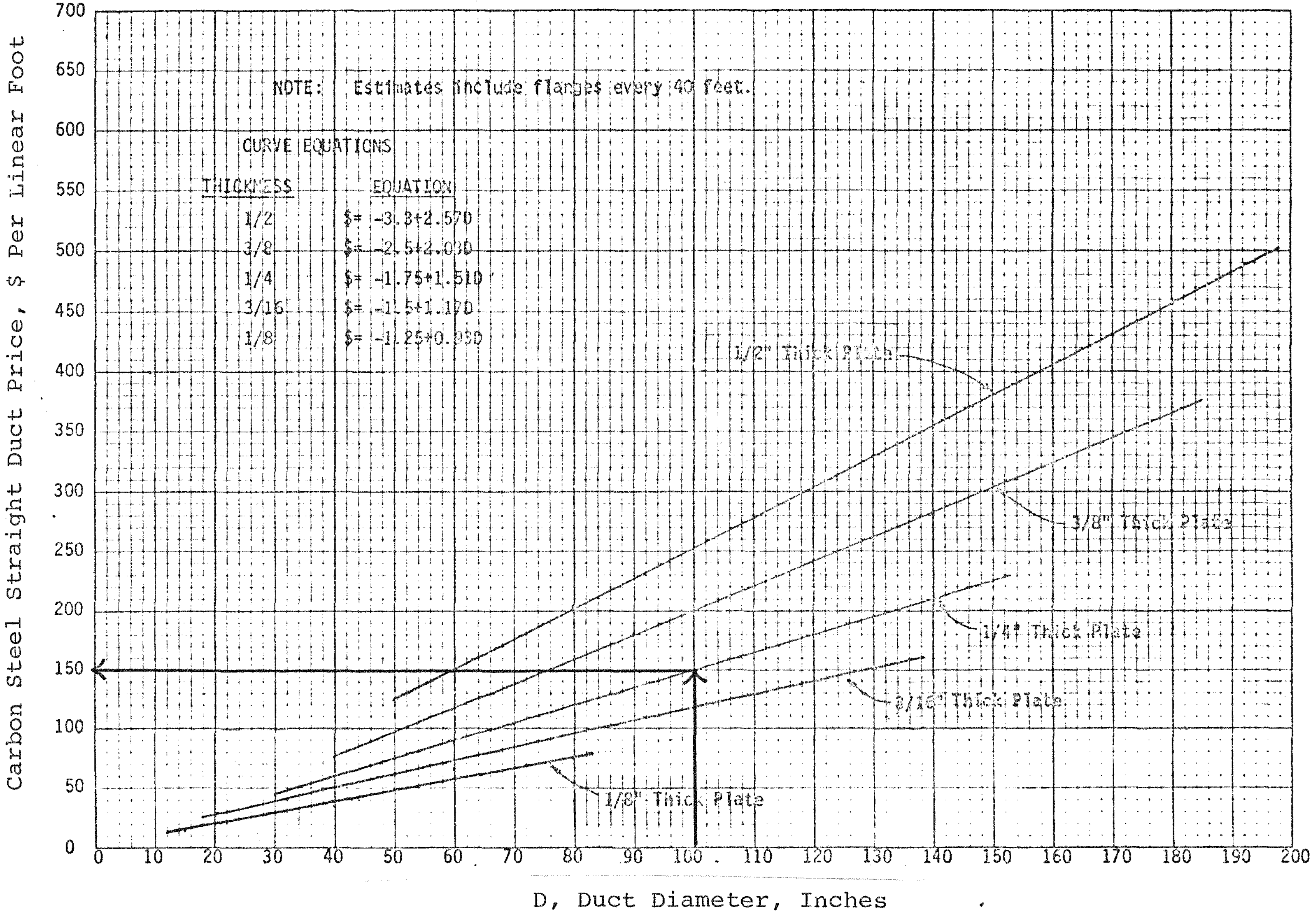
NOTE: 1. Select V-Belt closest to fan RPM

2. Do not "Extrapolate" prices for belts above 150 HP. applications

SOURCE: See Figure C-1.

FIGURE C-15

CARBON STEEL STRAIGHT DUCT FABRICATION PRICE PER LINEAR FOOT VERSUS DUCT DIAMETER AND PLATE THICKNESS



NOTE: Estimates include flanges every 40 feet.

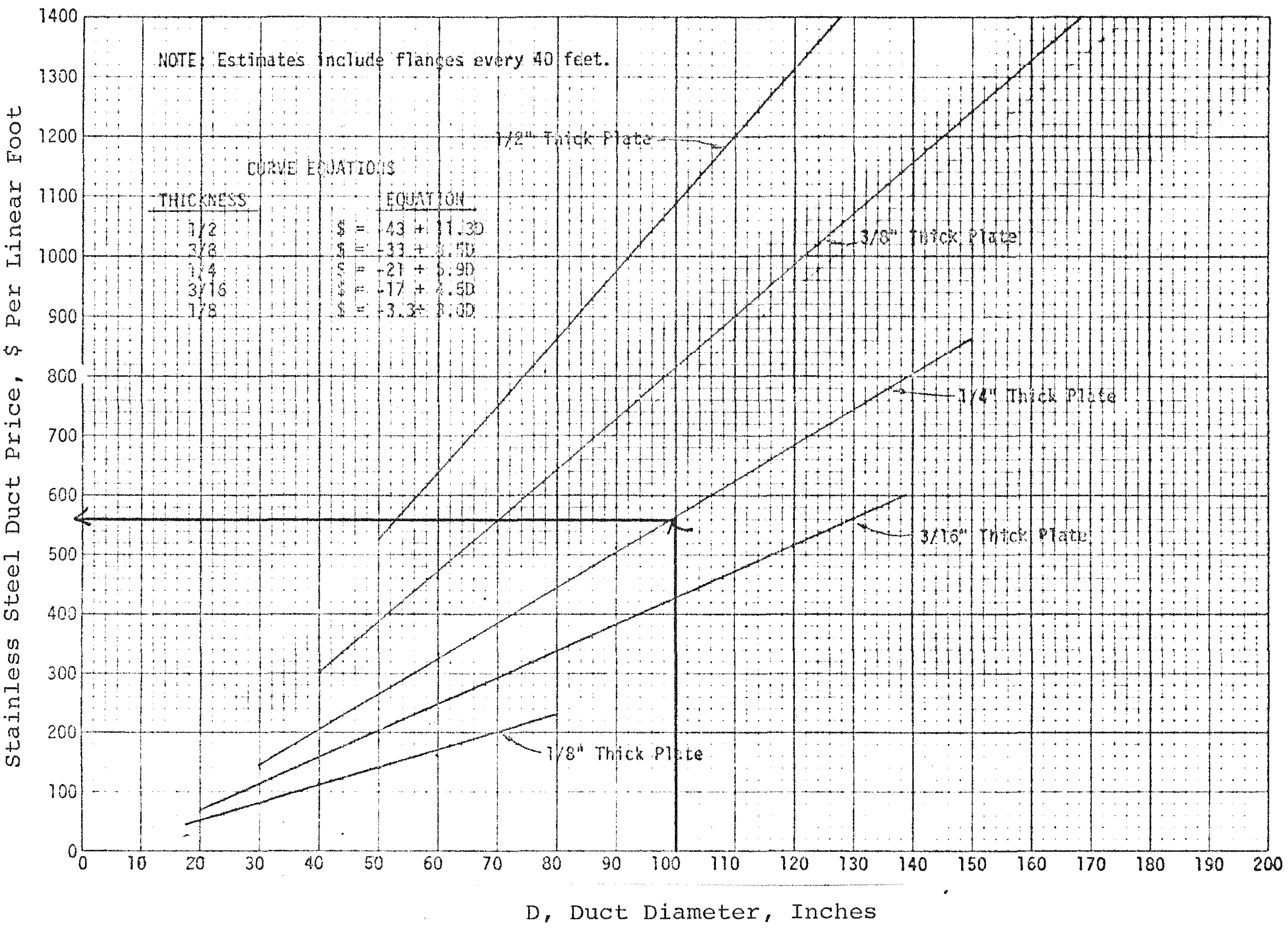
CURVE EQUATIONS

THICKNESS	EQUATION
1/2	$\$ = -3.3 + 2.57D$
3/8	$\$ = -2.5 + 2.03D$
1/4	$\$ = -1.75 + 1.51D$
3/16	$\$ = -1.5 + 1.17D$
1/8	$\$ = -1.25 + 0.93D$

SOURCE: See Figure C-1.

FIGURE C-16

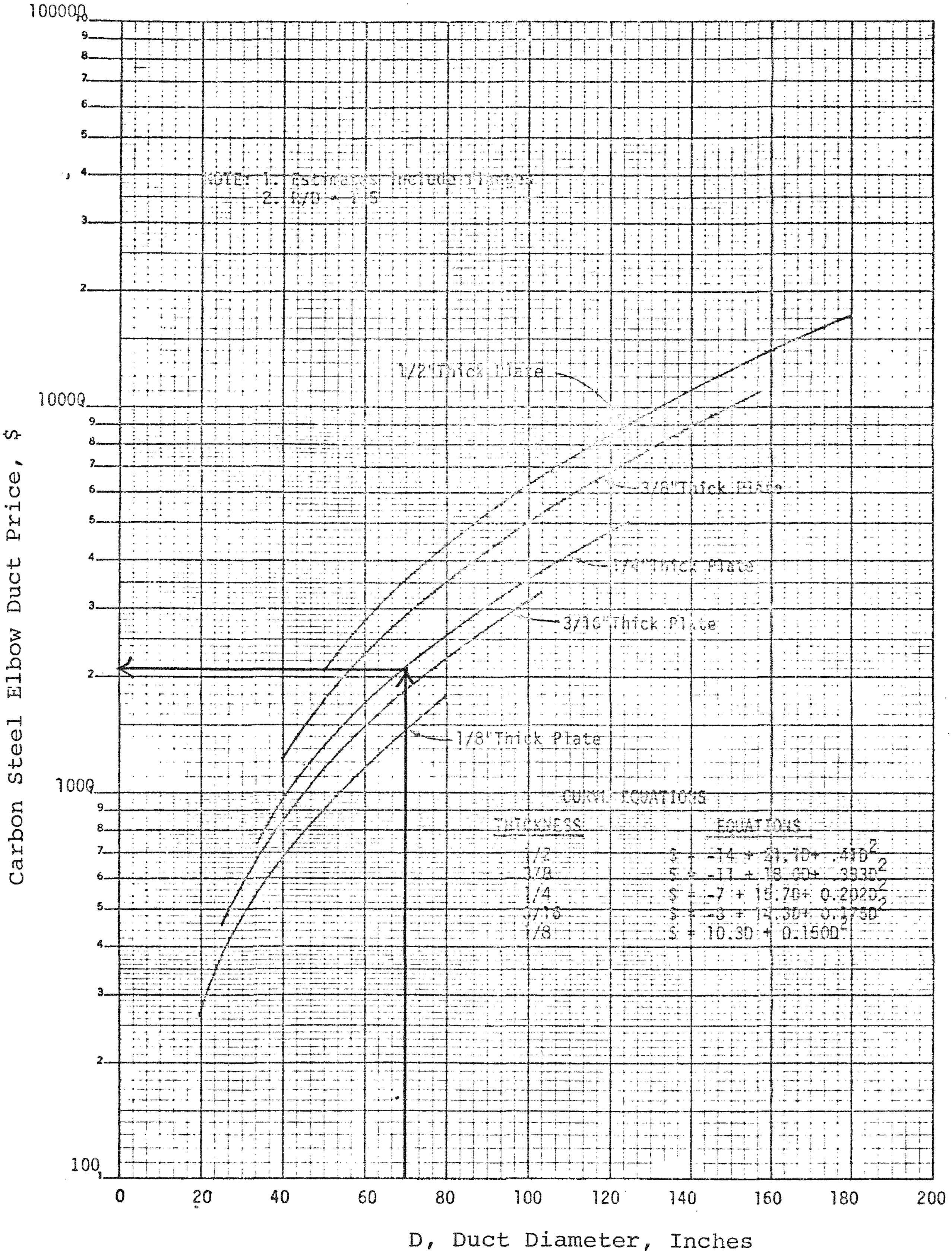
STAINLESS STEEL STRAIGHT DUCT FABRICATION PRICE PER LINEAR FOOT VERSUS DUCT DIAMATER AND PLATE THICKNESS



SOURCE: See Figure C-1.

FIGURE C-17

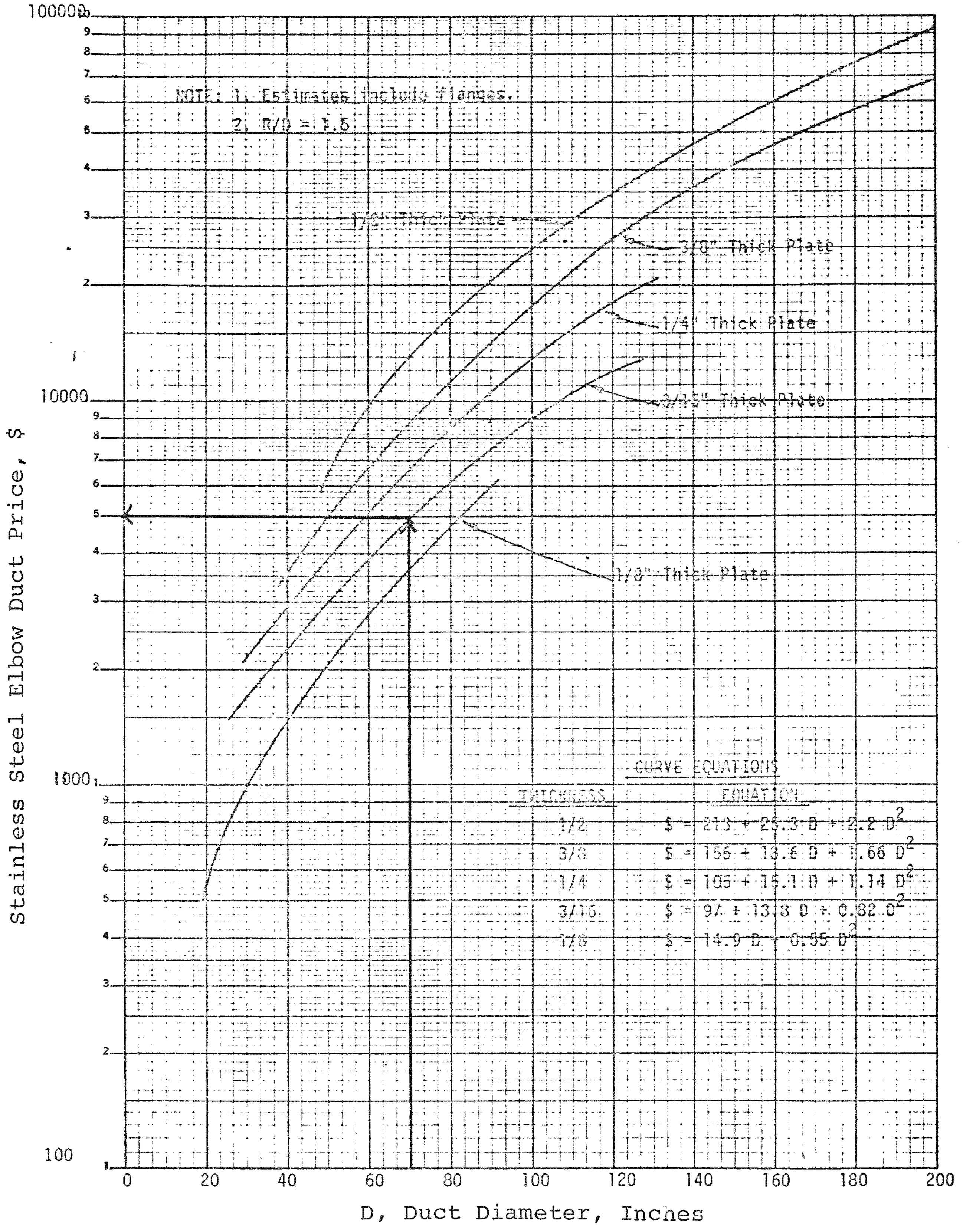
CARBON STEEL ELBOW DUCT PRICE
VERSUS DUCT DIAMETER AND PLAT THICKNESS



SOURCE: See Figure C-1.

FIGURE C-18

STAINLESS STEEL ELBOW DUCT PRICE VERSUS DUCT DIAMETER AND PLATE THICKNESS



NOTE: 1. Estimates include flanges.
2. R/D = 1.5

CURVE EQUATIONS

THICKNESS	EQUATION
1/2	$\$ = 213 + 25.3\,D + 2.2\,D^2$
3/8	$\$ = 156 + 18.6\,D + 1.66\,D^2$
1/4	$\$ = 105 + 15.1\,D + 1.14\,D^2$
3/16	$\$ = 97 + 13.3\,D + 0.82\,D^2$
1/8	$\$ = 14.9\,D + 0.55\,D^2$

SOURCE: See Figure C-1.

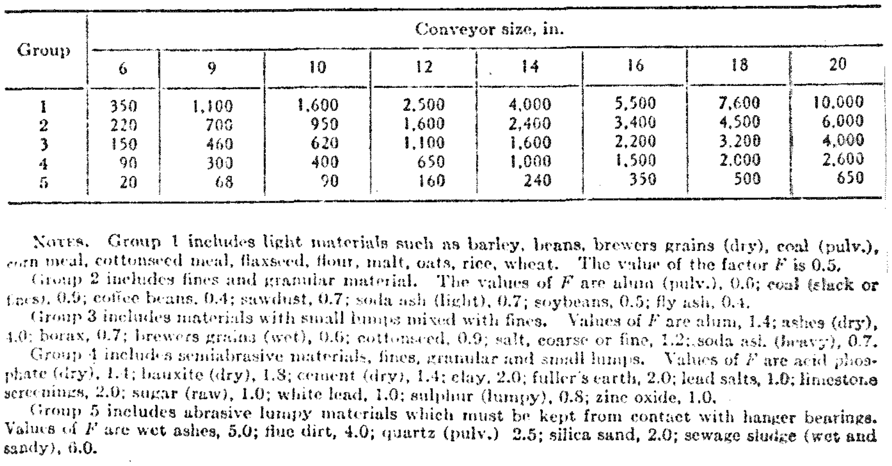
of duct diameter and plate thickness, respectively. The cost curves include flanges. The cost of tees and transitions will be approximately one-third and one-half the cost of an elbow having the same diameter and thickness. Figure C-19 depicts the cost curve for carbon steel expansion joints as a function of duct diameter.

5. Dust Removal Equipment

The screw conveyor is used widely for granular, non-corrosive, non-abrasive materials when the required capacity is moderate, the distance is not more than approximately 200 feet, and the path is not too steep. Table C-3 gives the handling capacities for standard-pitch screw conveyors in each of five groups of materials when the conveyors are operated at the maximum adversed speeds and in the horizontal position.

TABLE C-3

SCREW-CONVEYOR CAPACITIES
(Cu ft per hr)



Group	Conveyor size, in.							
	6	9	10	12	14	16	18	20
1	350	1,100	1,600	2,500	4,000	5,500	7,600	10,000
2	220	700	950	1,600	2,400	3,400	4,500	6,000
3	150	460	620	1,100	1,600	2,200	3,200	4,000
4	90	300	400	650	1,000	1,500	2,000	2,600
5	20	68	90	160	240	350	500	650

NOTES. Group 1 includes light materials such as barley, beans, brewers grains (dry), coal (pulv.), corn meal, cottonseed meal, flaxseed, flour, malt, oats, rice, wheat. The value of the factor F is 0.5.

Group 2 includes fines and granular material. The values of F are alum (pulv.), 0.6; coal (slack or fines), 0.9; coffee beans, 0.4; sawdust, 0.7; soda ash (light), 0.7; soybeans, 0.5; fly ash, 0.4.

Group 3 includes materials with small lumps mixed with fines. Values of F are alum, 1.4; ashes (dry), 4.0; borax, 0.7; brewers grains (wet), 0.6; cottonseed, 0.9; salt, coarse or fine, 1.2; soda ash (heavy), 0.7.

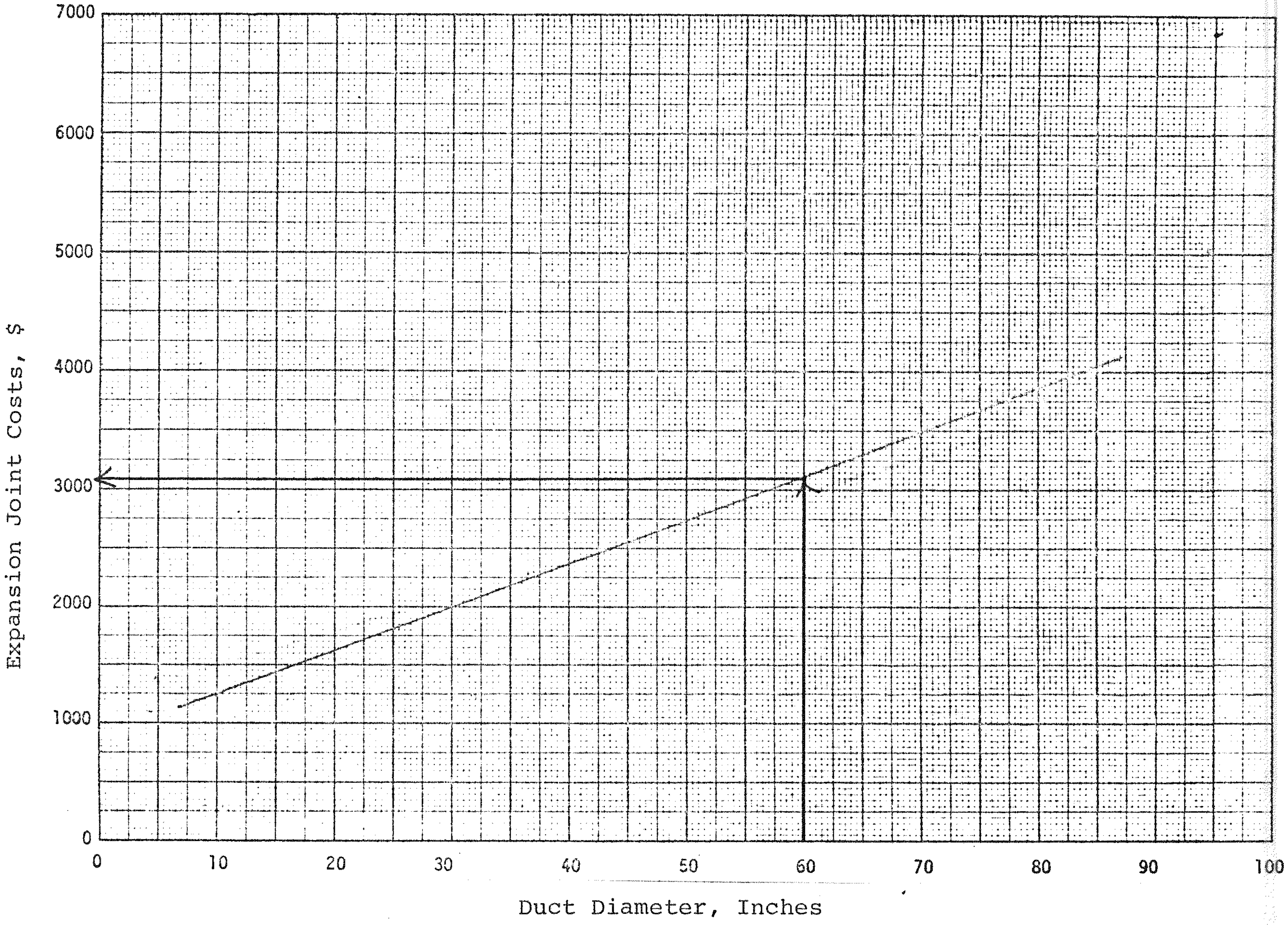
Group 4 includes semiabrasive materials, fines, granular and small lumps. Values of F are acid phosphate (dry), 1.4; bauxite (dry), 1.8; cement (dry), 1.4; clay, 2.0; fuller's earth, 2.0; lead salts, 1.0; limestone screenings, 2.0; sugar (raw), 1.0; white lead, 1.0; sulphur (lumpy), 0.8; zinc oxide, 1.0.

Group 5 includes abrasive lumpy materials which must be kept from contact with hanger bearings. Values of F are wet ashes, 5.0; flue dirt, 4.0; quartz (pulv.) 2.5; silica sand, 2.0; sewage sludge (wet and sandy), 6.0.

SOURCE: Baumeister, T. and Marks, L.S., Standard Handbook for Mechanical Engineers - Seventh Edition, McGraw-Hill Book Company, N.Y., 1951.

FIGURE C-19

CARBON STEEL EXPANSION JOINT COSTS VERSUS DUCT DIAMETER



SOURCE: See Figure C-1.

Figure C-20 illustrates cost curves for a 9 inch and 12 inch screw conveyor as a function of conveyor length. The prices include a trough, screw, drive, fittings, motor, and heavy duty construction.

6. Stacks

The cost curves for fabricated carbon steel stacks under 100 feet of varying plate thicknesses (1/4, 5/16, and 3/8 inch) are contained in Figures C-21 and C-22. Stack cost includes flanges, stack, stainless steel cables, clamps, and surface coating. The cost curves are a function of stack height and diameter.

Figure C-23 contains cost curves for tall steel stacks over 200 feet with and without steel liners and insulation, foundation, and installation. The cost curves assume a 30 psf loading, minimal seismic risk, and psf soil bearing capacity, and are a function of stack height and inner diameter.

7. Mechanical Collectors

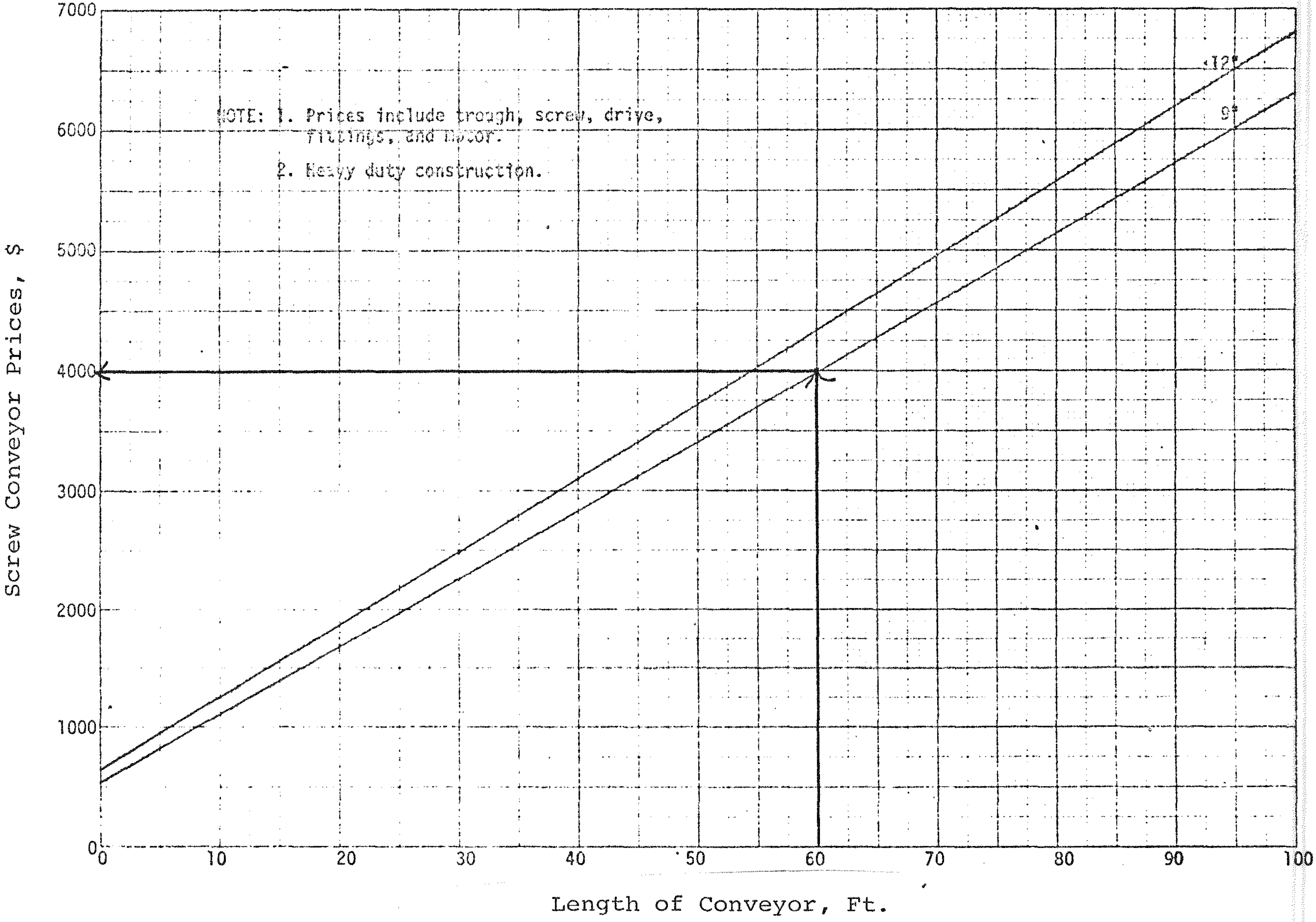
Figure C-24 depicts an estimating method to determine the inlet area of a single unit mechanical collector as a function of air flow capacity. Figures C-25 through C-28 contains cost curves for mechanical collectors and components as a function of inlet area. Figure C-25 and C-26 contains cost curves for carbon steel and stainless steel mechanical collectors of various plate thicknesses, respectively. Figures C-27, C-28, and C-29 contains cost curves for mechanical collector supports, dust hopper, and scroll outlet.

8. Holding Tank

Figure C-30 contains a cost curve for a field-fabricated, rubber lined holding tank. The cost curve is based on an assumed

FIGURE C-20

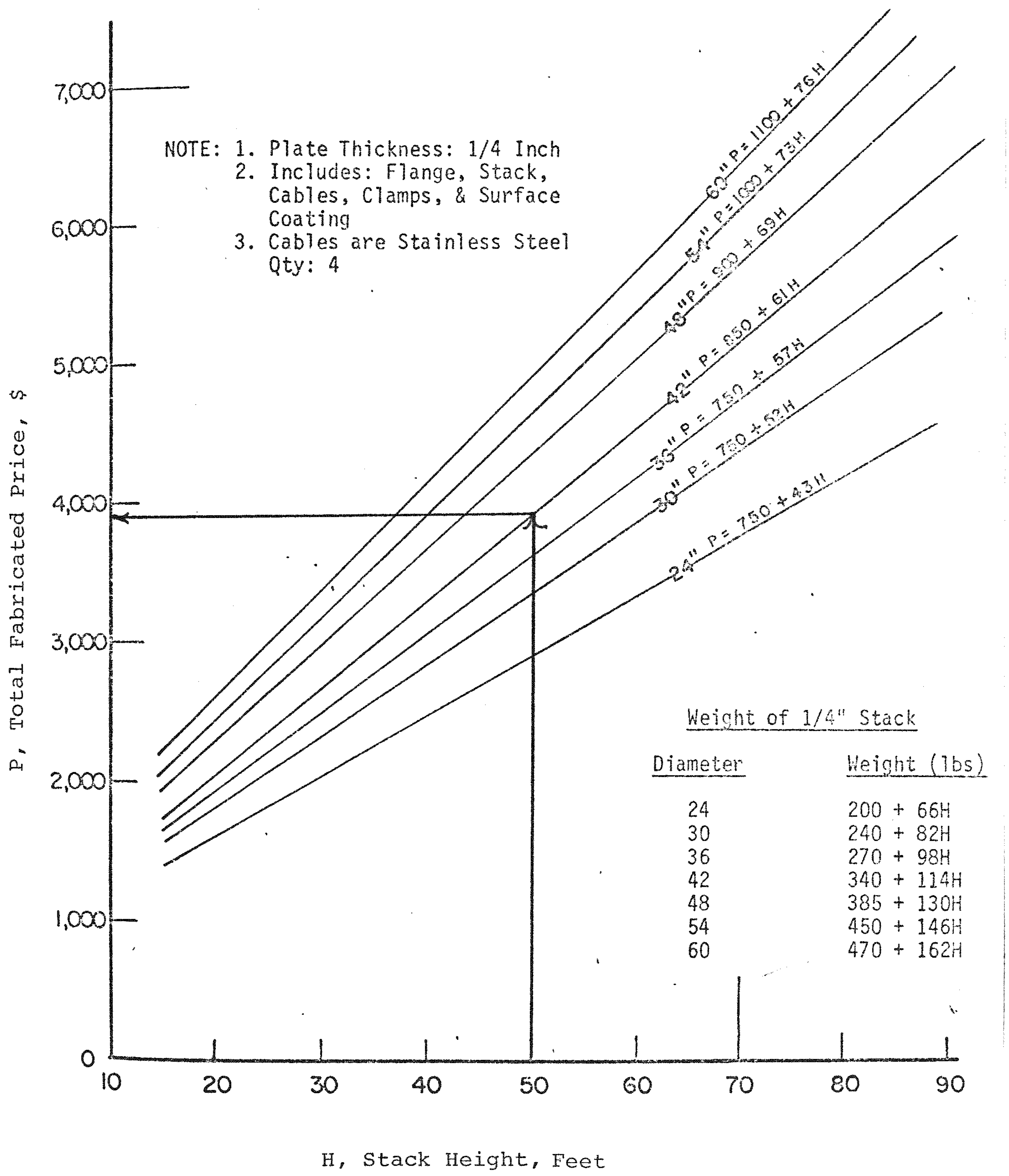
PRICES FOR SCREW CONVEYORS VERSUS LENGTH AND DIAMETER



SOURCE: See Figure C-1.

FIGURE C-21

FABRICATED CARBON STEEL PRICE VERSUS



NOTE:
1. Plate Thickness: 1/4 Inch
2. Includes: Flange, Stack, Cables, Clamps, & Surface Coating
3. Cables are Stainless Steel Qty: 4

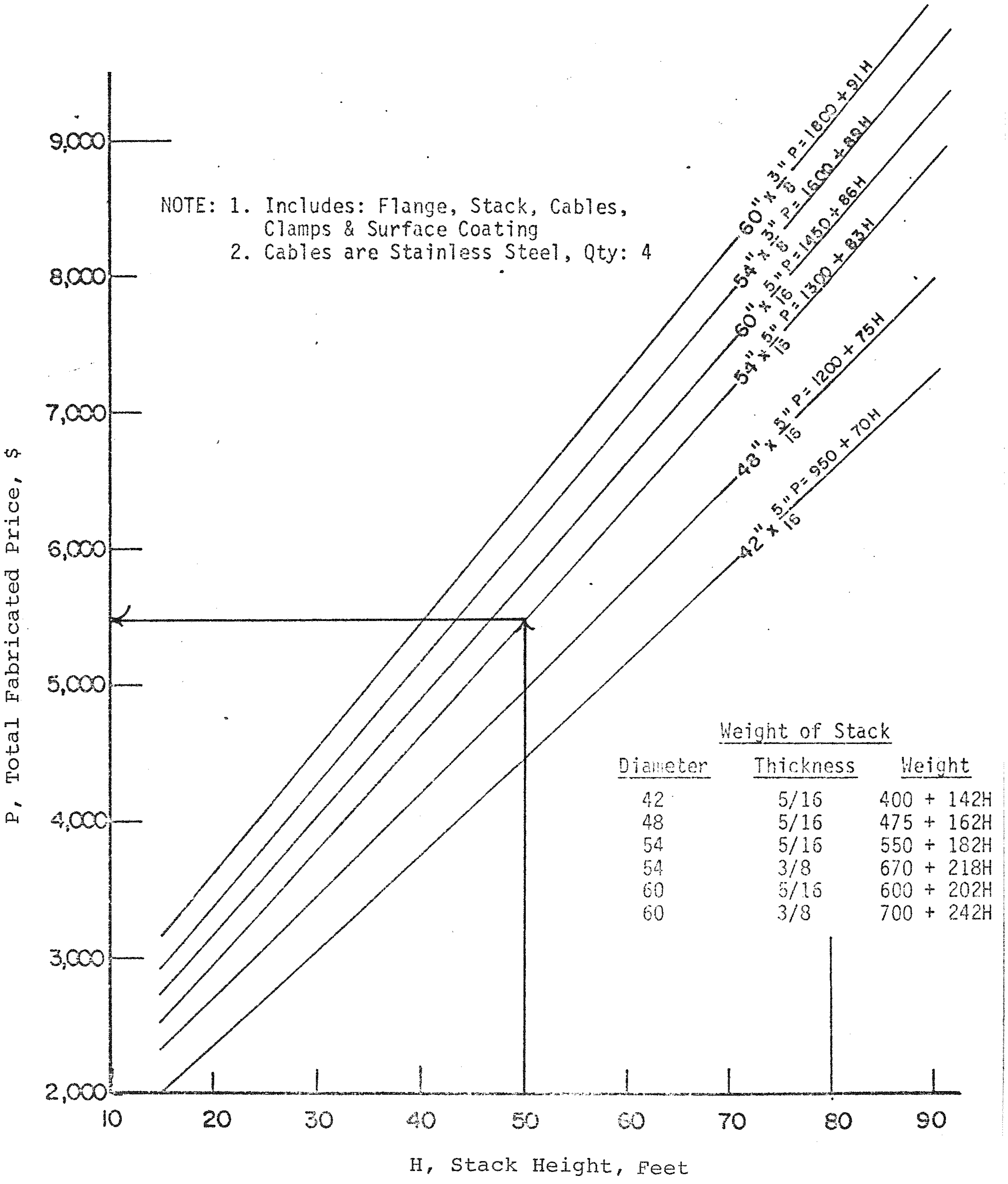
Weight of 1/4" Stack

Diameter	Weight (lbs)
24	200 + 66H
30	240 + 82H
36	270 + 98H
42	340 + 114H
48	385 + 130H
54	450 + 146H
60	470 + 162H

SOURCE: See Figure C-1.

FIGURE C-22

FABRICATED CARBON STEEL STACK PRICE VERSUS STACK HEIGHT AND DIAMETER FOR 5/16 AND 3/8 INCH PLATE



NOTE: 1. Includes: Flange, Stack, Cables, Clamps & Surface Coating
2. Cables are Stainless Steel, Qty: 4

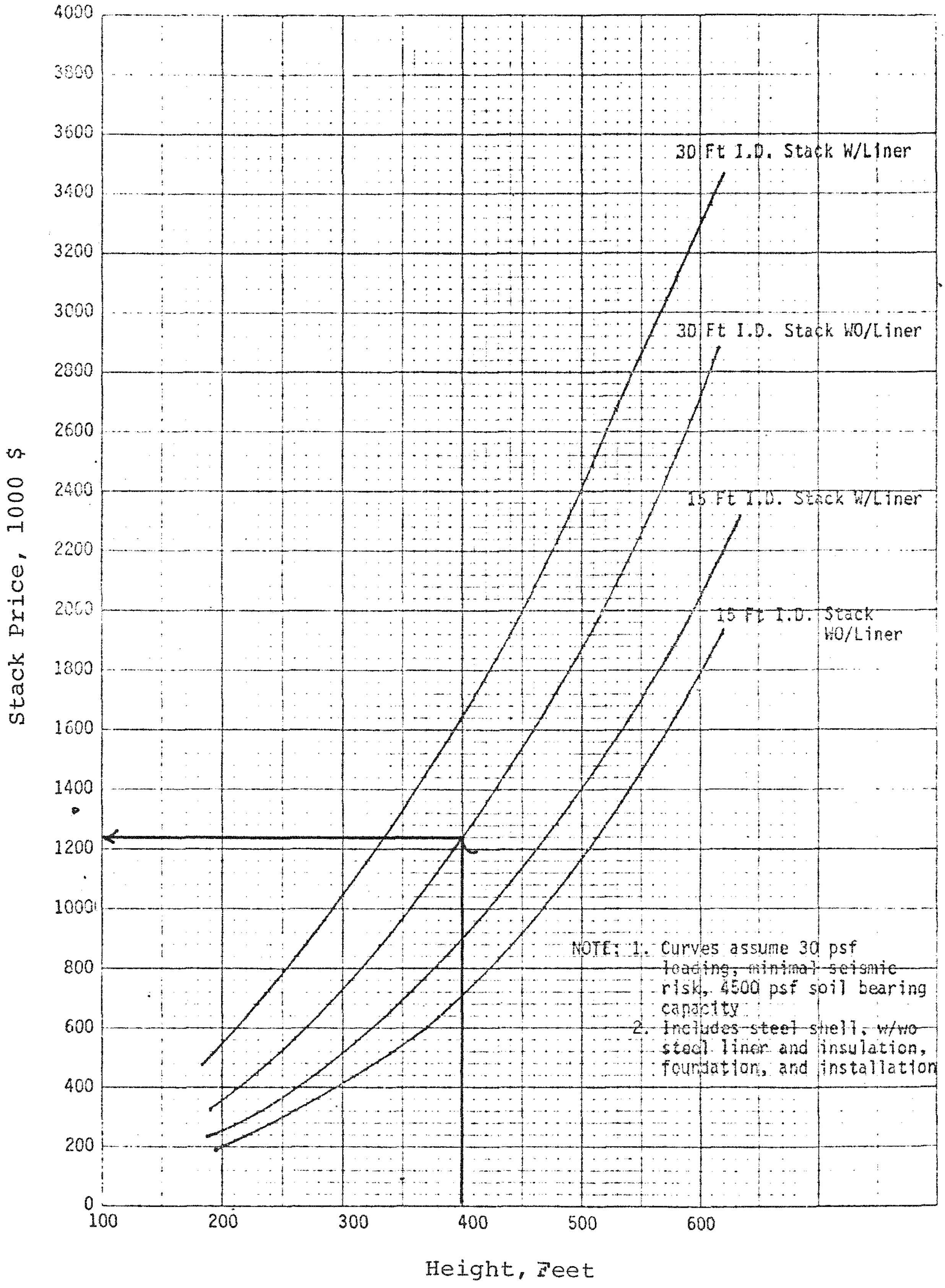
Weight of Stack

Diameter	Thickness	Weight
42	5/16	400 + 142H
48	5/16	475 + 162H
54	5/16	550 + 182H
54	3/8	670 + 218H
60	5/16	600 + 202H
60	3/8	700 + 242H

SOURCE: See Figure C-1.

FIGURE C-23

PRICES FOR TALL STEEL STACKS, INSULATED AND LINED

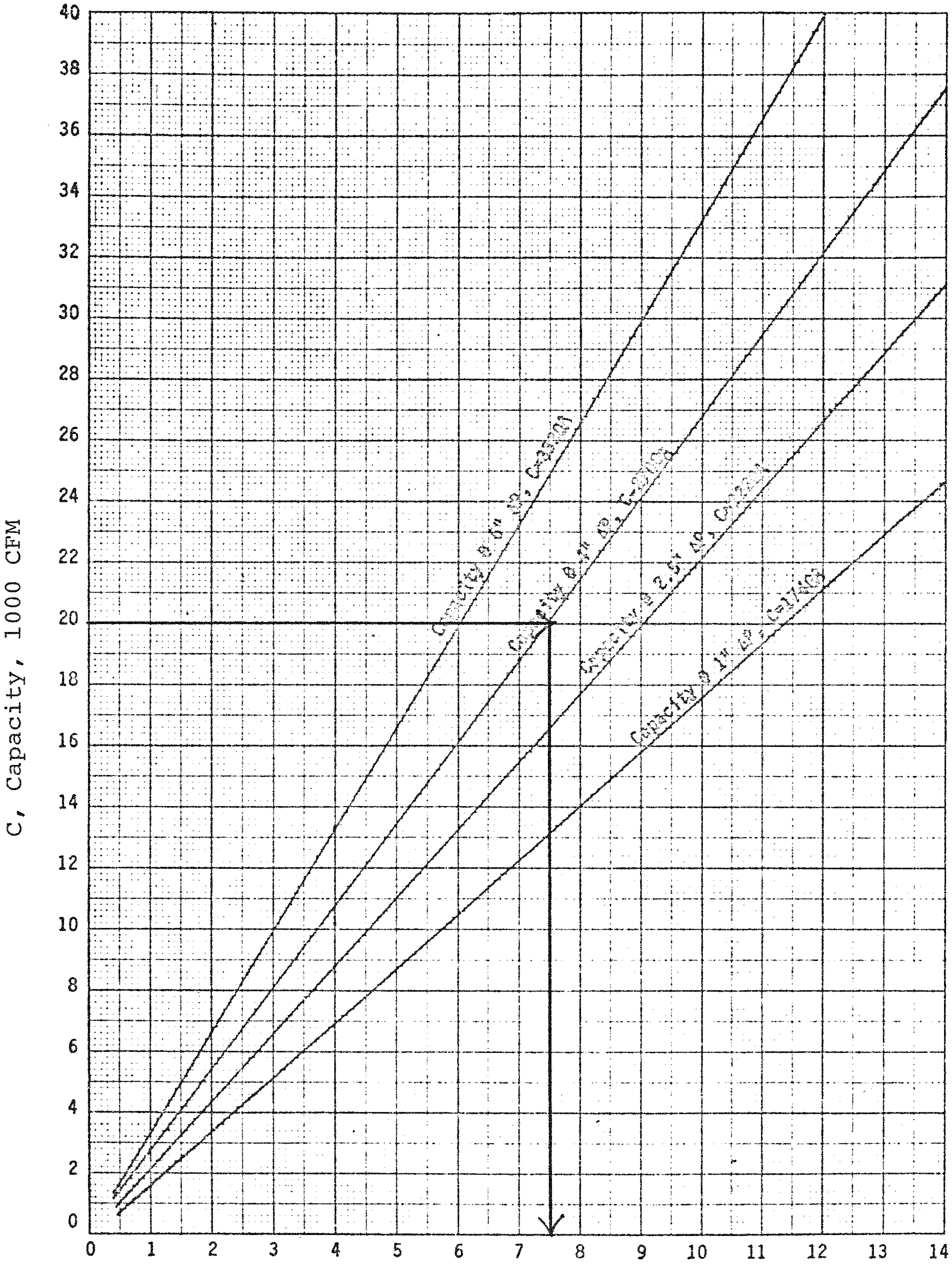


NOTE: 1. Curves assume 30 psf loading, minimal seismic risk, 4500 psf soil bearing capacity
2. Includes steel shell, w/wo steel liner and insulation, foundation, and installation

SOURCE: See Figure C-1.

FIGURE C-24

CAPACITY ESTIMATES FOR MECHANICAL COLLECTORS

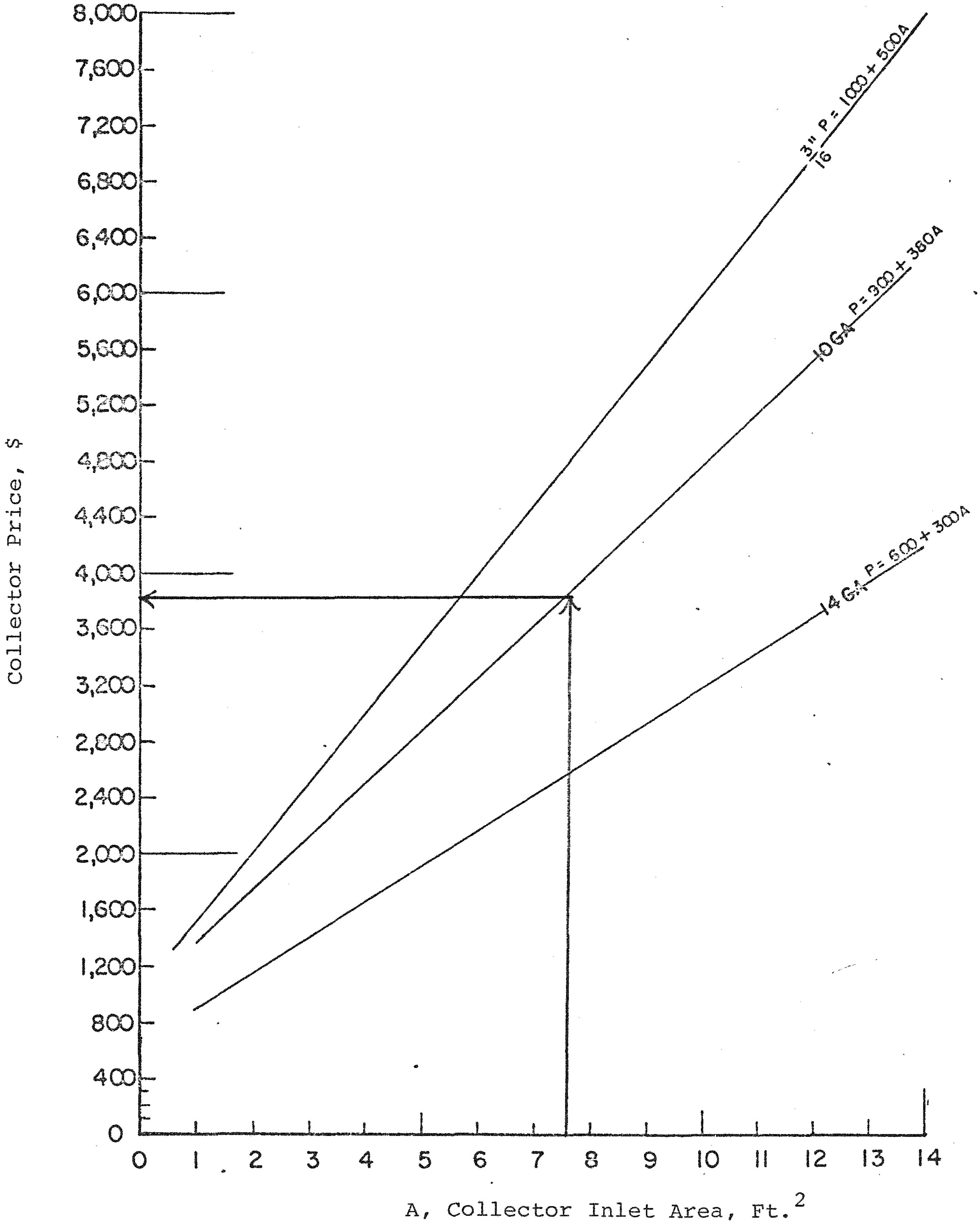


A, Collector Inlet Area, Sq. Feet

SOURCE: See Figure C-1.

FIGURE C -25

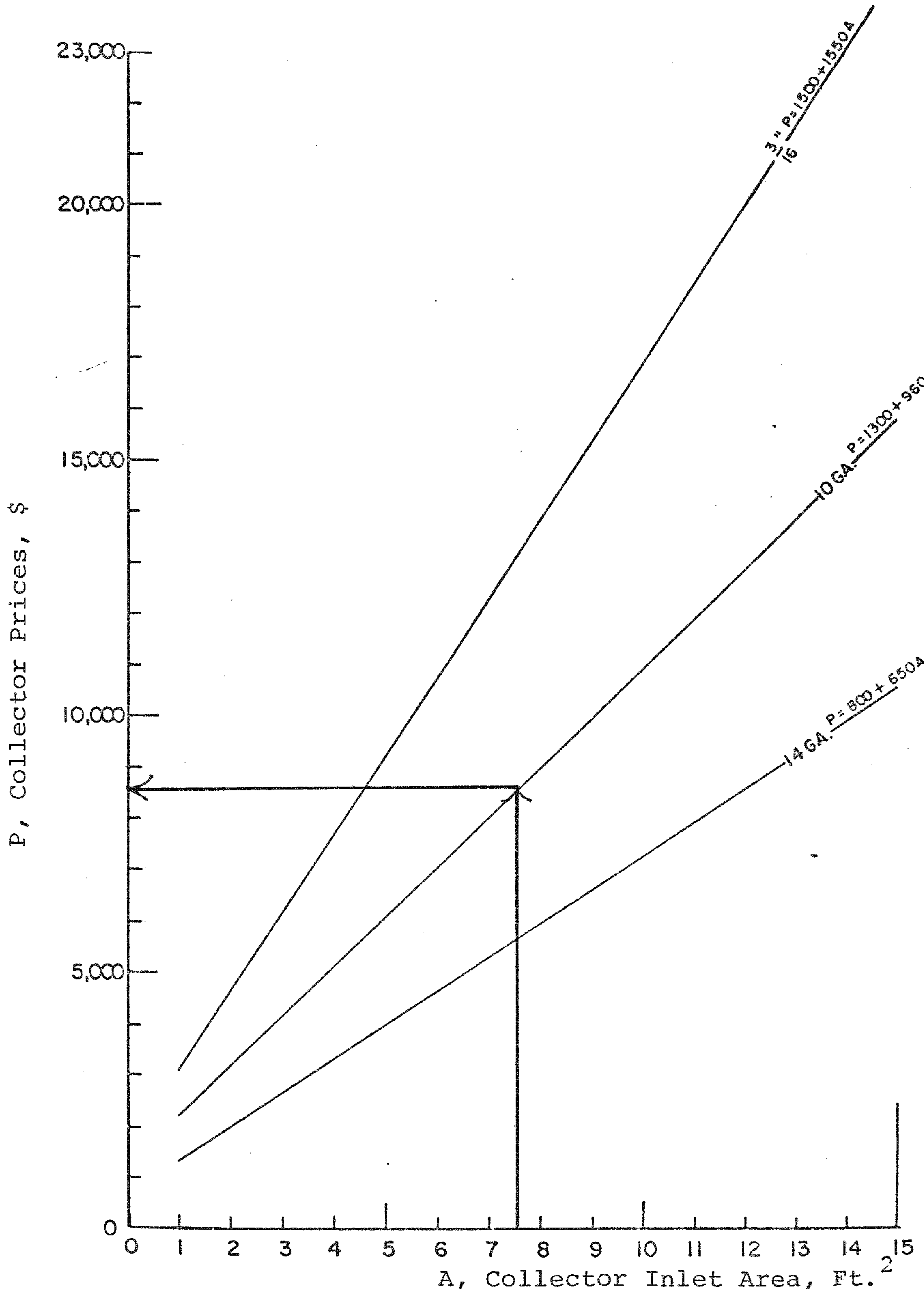
MECHANICAL COLLECTOR PRICES FOR CARBON STEEL CONSTRUCTION VERSUS INLET AREAS



SOURCE: See Figure C-1.

FIGURE C-26

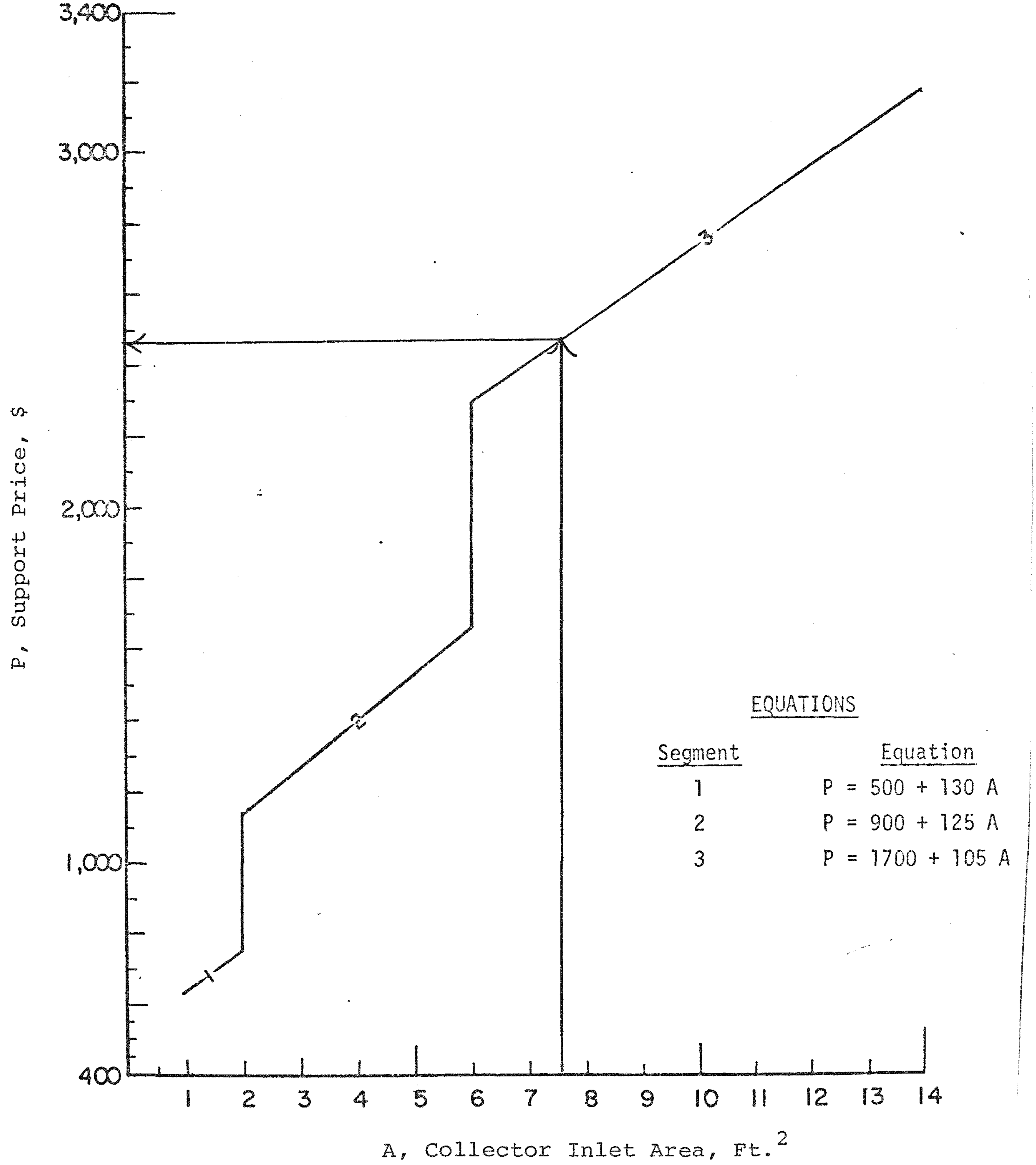
MECHANICAL COLLECTOR PRICES FOR STAINLESS STEEL CONSTRUCTION VERSUS INLET AREA



SOURCE: See Figure C-1.

FIGURE C-27

MECHANICAL COLLECTOR SUPPORT PRICES
VERSUS COLLECTOR INLET AREA



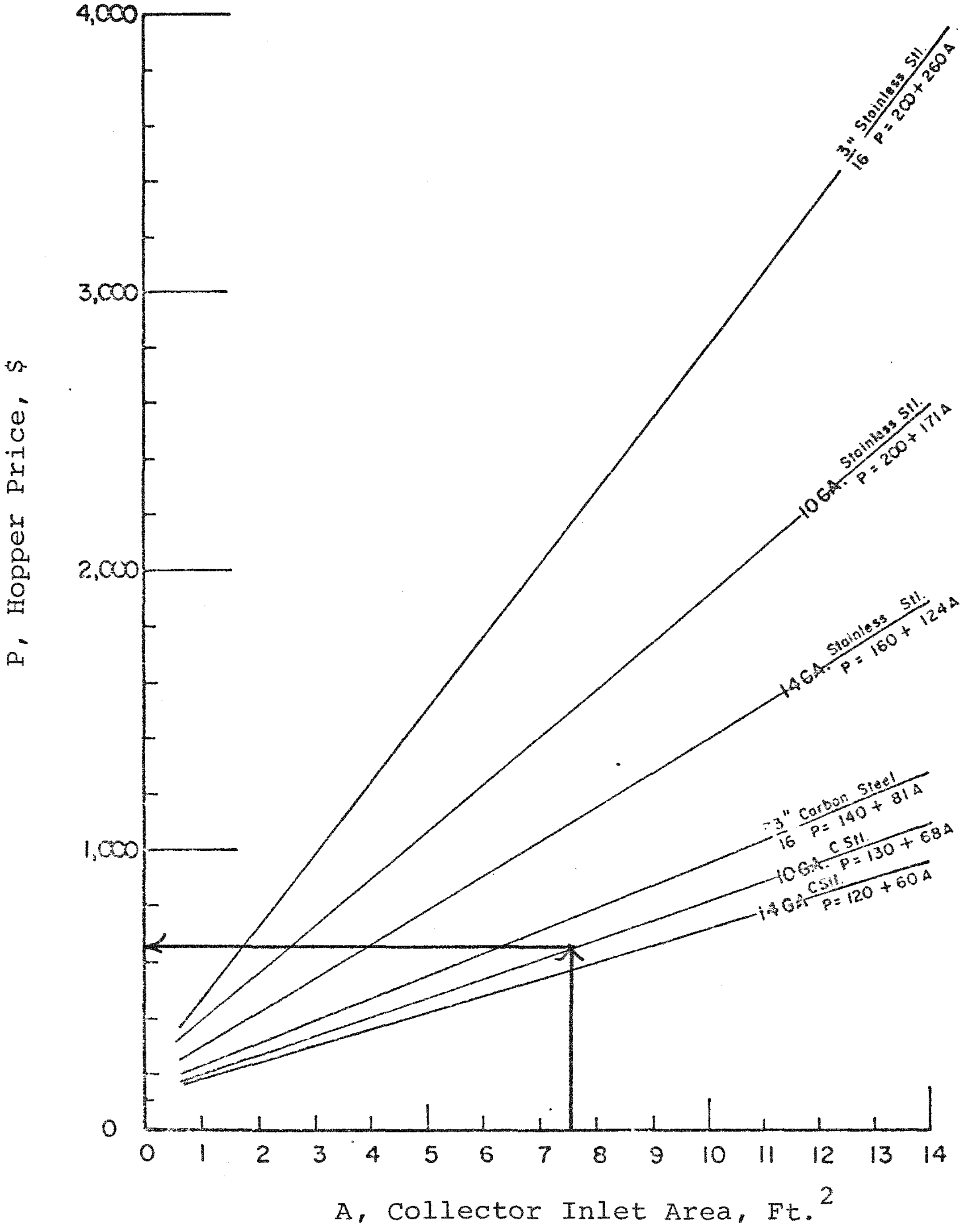
EQUATIONS

Segment	Equation
1	P = 500 + 130 A
2	P = 900 + 125 A
3	P = 1700 + 105 A

SOURCE: See Figure C-1

FIGURE C-28

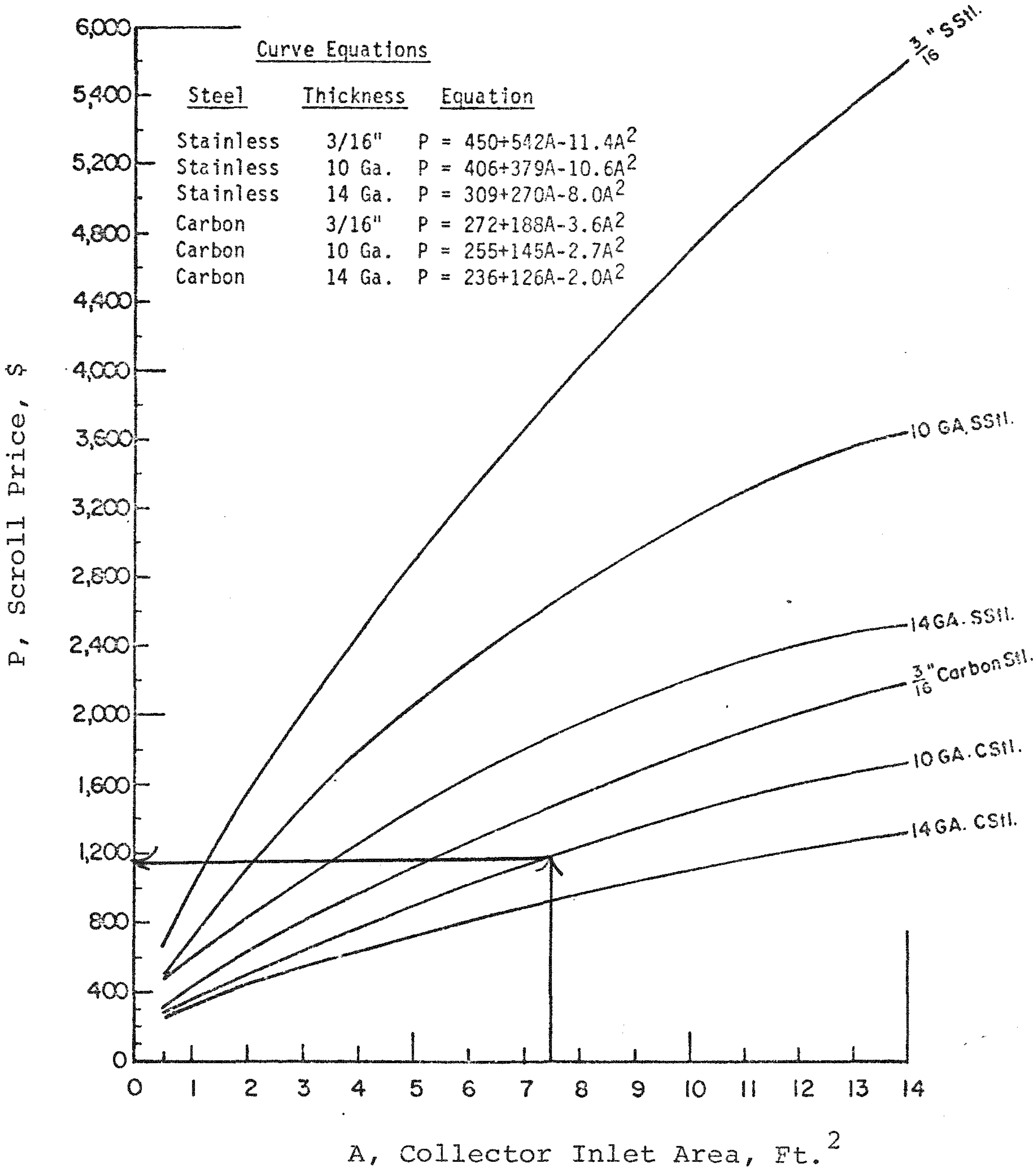
MECHANICAL COLLECTOR DUST HOPPER PRICES FOR CARBON AND STAINLESS STEEL CONSTRUCTION VERSUS COLLECTOR INLET AREA



SOURCE: See Figure C-1.

FIGURE C-29

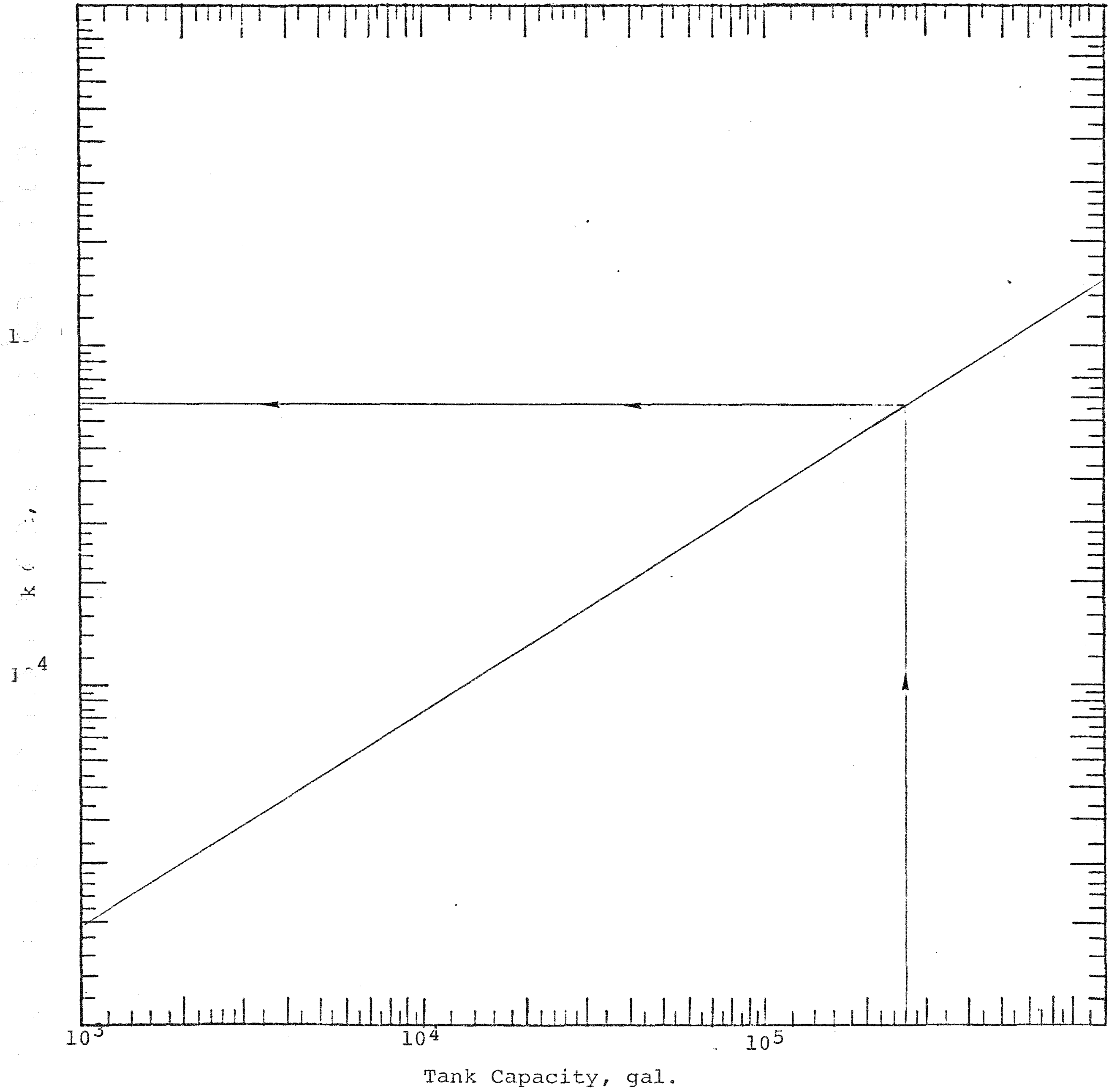
MECHANICAL COLLECTOR SCROLL OUTLET PRICES FOR CARBON AND STAINLESS STEEL CONSTRUCTION VERSUS COLLECTOR INLET AREA



SOURCE: See Figure C -1.

FIGURE C-30

HOLDING TANK COSTS



SOURCE: "Simplified Procedures for Estimating Flue Gas Desulfurization Systems", Ponder, T.C., Et. Al., PEDCo-Environmental Specialists, Inc., Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., EPA-6001/2-76/150, June 1976.

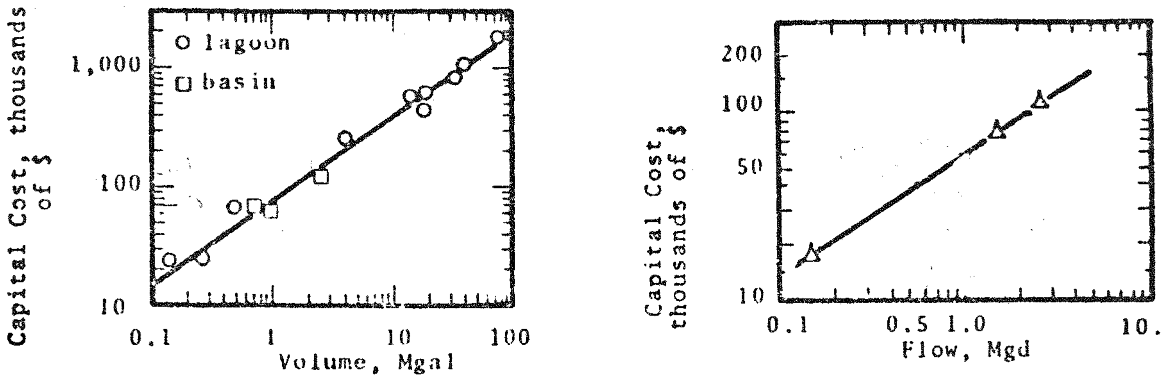
value of $12.50 per square foot of tank area, and is a function of tank capacity.

9. Waste Removal Units

Figure C-31 illustrates the capital cost curves of the following effluent treatment and disposal unit operations: (a) aerated lagoons and equilization basins, (b) neutralization facilities, (c) oil separators, (d) primary clarifier, (e) lagoons, and (4) vacuum filters. The selection of one of these units depends on the FGD system design characteristics.

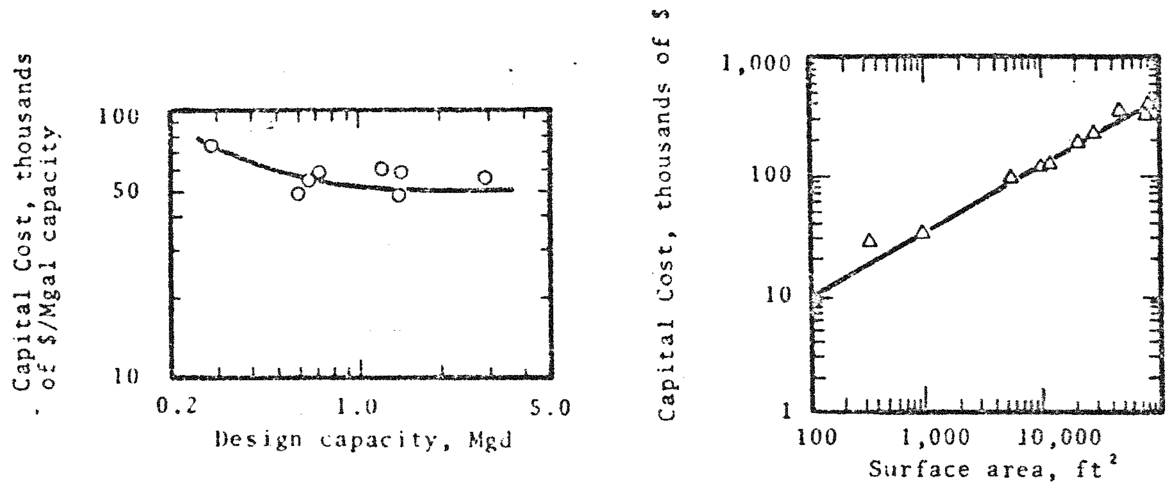
FIGURE C-31

CAPITAL COST CURVES OF VARIOUS SCRUBBER EFFLUENT AND DISPOSAL SYSTEMS



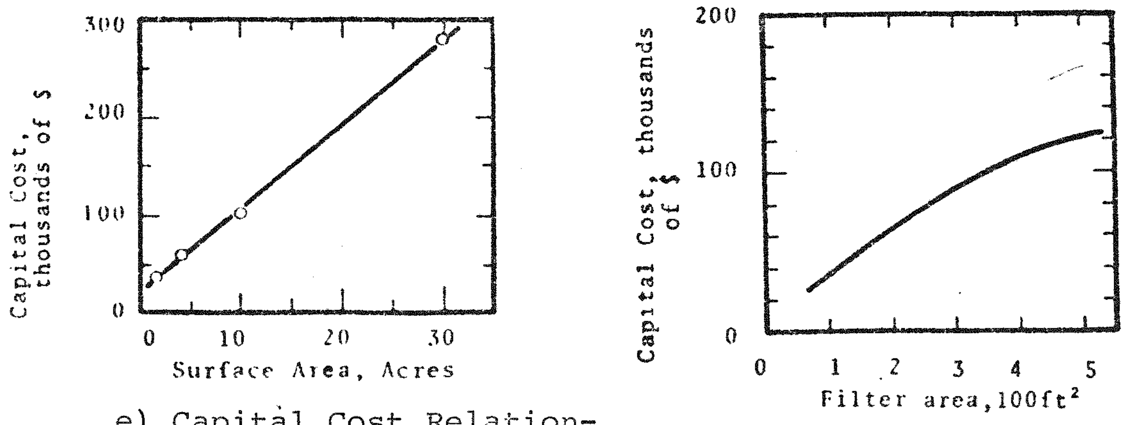
a) Cost Versus Volume of Aerated Lagoons and Equilization Basins

b) Capital Cost Relationship, Neutralization Facilities



c) Capital Cost Relationship, Oil Separators

d) Cost Versus Surface Area, Primary Clarifier



e) Capital Cost Relationship for Lagoons

f) Capital Cost Relationship, Vacuum Filters

SOURCE: "Wet Scrubber System Study - Volume 1, Scrubber Handbook", A.P.T., Inc., prepared for the Environmental Protection Agency, July 1972.

APPENDIX D

OPERATING COST PARAMETERS FOR INDUSTRIAL FLUE GAS DESULFURIZATION

This appendix outlines the unit costs assumed in developing the operating and annual costs for industrial scale FGD systems. The appendix gives the assumed costs for electricity, chemicals, water, solid waste removal, maintenance and manpower. Costs are end of 1975 estimates unless otherwise noted.

1. Electrical Power

Table D-1 shows the typical charges for power to industrial users in cities with a population greater than 50,000. Three levels of service demand on consumption are shown. The average charge was approximately 44¢/Kwh and this figure was used in case studies. Bills for larger users than this would probably be lower.

2. Chemicals

The three basic chemicals used in the model FGD systems are lime, sodium carbonate and sodium hydroxide (50% solution). The costs of these materials can vary greatly depending on plant location, chemical purity and mining condition. The assumed costs shown are on Table D-2.

TABLE D-1

ESTIMATED AVERAGE COST OF INDUSTRIAL ELECTRICAL POWER

City	Billing Demand Energy Consumption 150 kW/30,000 kWh	300 kW/6,000 kWh	1,000 kW/20,000 kWh
Albuquerque, New Mexico	3.88	3.86	3.60
Atlanta, Georgia	4.19	3.91	3.72
Austin, Texas	4.56	4.35	4.03
Baltimore, Maryland	4.48	4.34	4.09
Boston, Massachusetts	5.35	5.38	5.38
Detroit, Michigan	5.51	5.50	3.84
El Paso, Texas	3.17	2.96	2.78
Kansas City, Missouri	4.13	3.91	3.60
Long Beach, California	4.02	3.58	3.30
Louisville, Kentucky	2.62	2.48	2.46
Miami, Florida	4.24	3.85	3.11
New York, New York	8.40	8.40	8.40
Okalhoma City, Oklahoma	2.67	2.51	2.24
Seattle, Washington	1.24	1.13	1.07
AVERAGE	4.18	4.01	3.69

SOURCE: "Typical Electric Bills," Federal Power Commission, 1976.

TABLE D-2

ASSUMED CHEMICAL COSTS

($/Ton)

Chemical	FOB Mine	Transport	Delivered
Lime	28	12	40
Sodium Carbonate	50	30	80
Sodium Hydroxide	170	30	200

3. Water

Water costs are a function of geographical location, volume and type of service. Table D-3 shows the estimated cost of water in fourteen major cities and the increased cost if water is delivered outside the city boundaries. The costs shown are for potable water, and since this quality water is not needed in the FGD system, many plants may have their own raw water supply which could be used for the FGD system, significantly reducing the $0.366/1,000 gallons assumed in this analysis.

4. Solid Waste Disposal

Costs for disposal of the solid waste generated by the FGD system are very much a function of the location of the plant. For purposes of this analysis, it was assumed that the cost per ton to remove FGD solid waste would be the same as to remove bottom or fly ash from a boiler. A cost of $2/Ton of waste was assumed. Plants which have sizable amounts of land may have a lower cost while plants in concentrated urban areas may have a significantly higher cost.

TABLE D-3

ESTIMATED AVERAGE COST PER THOUSAND GALLONS OF WATER IN 1974

	Dec. 1974 [a/] $ per 1,000 Gal.	Out of City [b/] Limits Market
Albuquerque, New Mexico	.233	100%
Atlanta, Georgia	.526	70%
Austin, Texas	.486	50%
Baltimore, Maryland	.220	Varies
Boston, Massachusetts	.646	None
Detroit, Michigan	.197	37-40%
El Paso, Texas	.240	$5.00/month
Kansas City, Missouri	.324	8%
Long Beach, Calfornia	.312	50%
Louisville, Kentucky	.553	None
Miami, Florida	.244	None
New York, New York	.704	None
Oklahoma City, Oklahoma	.282	34%
Seattle, Washington	.155	50%
AVERAGE	.366	

SOURCE: Dallas Rate Survey, Journal AWWA, May 1975.

[a/] For users consuming more than 100,000 cubic feet per year.

[b/] Potential increase in cost if located outside city limits.

5. Maintenance Costs

The cost of maintaining any FGD system and of purchasing normal supplies is a function both of system type and size, as well as operating hours. There has been insufficient operating experience with most FGD systems to provide firm guidance as to maintenance costs. Based on limited discussions with vendors, a factor of 2 percent of total installed cost for WS and SCLW systems and 3 percent for SCSW systems has been assumed. This percent is also assumed not to vary with the hours of operation of the equipment.

6. Manpower

The type of manpower used at the FGD systems reviewed in this study were normal boiler-house personnel. No special skills or advanced training was required for the operation of any system visited. Plant operators and vendors indicated that an hourly rate of $12-15 was appropriate for these individuals. This rate includes administrative overhead allocation, supervision, and fringe benefits, as well as straight salary.