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OPERATION AND MAINTENANCE OF PARTICULATE CONTROL DEVICES ON COAL-FIRED UTILITY BOILERS

Industrial Environmental Research Laboratory
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OPERATION AND MAINTENANCE OF PARTICULATE CONTROL DEVICES ON COAL-FIRED UTILITY BOILERS

by

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ABSTRACT

The subject of control of fine particulate from coal-fired utility boilers with electrostatic precipitators, wet scrubbers, and fabric filters is addressed. Utility personnel who are responsible for the selection of fine particulate control equipment are presented with guidelines on the significant design and cost data correlations based on current design practice for electrostatic precipitators and actual operating and cost data for wet scrubbers and fabric filters. Fractional efficiency prediction models are presented for electrostatic precipitators and wet scrubbers which allow comparison of capital and operating costs under different coal/boiler application conditions and different levels of fractional efficiency on particles in the size range of 0.2 to 0.4 microns.

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SUMMARY

Although the specific health effects of fine particulate emissions are still under investigation, our knowledge of their capability for penetration deep into the human respiratory system warrants immediate consideration of control measures. This report is concerned with control of fine particulate emissions from coal-fired utility boilers, which represent a large-scale emission source. Three classes of conventional control devices are considered: electrostatic precipitators, wet scrubbers, and fabric filters. The report is organized into three major sections, which cover (1) control device design, (2) operation and maintenance procedures, and (3) relationship of fractional collection efficiency and costs to other operating parameters.

CONTROL SYSTEM DESIGN PARAMETERS

Numerous factors enter into selection of a control system for a specific application, however, they can be categorized as those related to (1) emission rates specified by Federal, state, and local regulations, (2) particle characteristics (electrical, physical, chemical), (3) gas stream characteristics (temperature, pressure, velocity, etc.), (4) site restrictions, and (5) costs of control.

Electrostatic Precipitators (ESP's)

When considering an ESP design, it is necessary first to define a proposed installation in terms of certain known or determined factors:

- Type of coal (moisture, ash, sulfur, other constituents)
- Ash chemical analysis
- Particulate bulk electrical resistivity
- Type of boiler (pulverized-coal-fired, stoker-fired, cyclone-fired) and resulting particle size distribution
- Total gas throughput (acfm)*
- Applicable emission standard or regulation

From these known factors, two basic design parameters stand out as the most influential in the precipitator design:

- Specific collection area (SCA, collection area: ft^2/1000 acfm)
- Power density (watts/ft^2 of collecting area)

Specific precipitator design parameters (see Table 2-4) include:

- Precipitator capacity
- Type of rappers, electrodes, etc.

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* Although it is the policy of EPA to use the metric system for quantitative descriptions, the British system is used in this report. Readers who are more accustomed to metric units are referred to the conversion table on page xxv.

- Electrical energization values for each section
- Performance-related parameters

Given these parameters, the following items can be estimated:

- Mass and fractional collection efficiencies
- Capital and operating costs

Considerable information is presented in the form of equations for computation of such factors as precipitator size, plate height, treatment velocity, ducting, sectionalization, and energization. In addition, graphical correlations are presented for selected combinations of boilers and coal to relate the input variables to optimum design and to capital and operating costs. A modified migration velocity(w_k), first proposed by Matts and Öhnfeldt is used to estimate SCA requirements for cold and hot precipitators. The modified migration velocity is an improvement over the standard Deutsch Anderson migration velocity (w), since once the particle size distribution is known, w_k can be treated as a constant for a given application whereas w can not be. The modified migration velocity is used almost exclusively by the Australian power industry, and its usage is on the increase in the United States.

Because of the larger amounts of smaller-sized particles and increased carbon carryover, cyclone boilers are shown to require higher SCA's than pulverized boilers. This applies to both cold- and hot-precipitators and on all types of coal, although to a lesser extent on lignite coal. The SCA requirements for cold precipitators on bituminous and subbituminous coal vary with the percent sulfur in the fly ash; for lignite, the percent Na_2O governs SCA requirements. The SCA's required for hot precipitators are in a much narrower band than those for cold precipitators, and depend on the Na_2O and Fe_2O_3 contents of the fly ash.

Power density for bituminous pulverized-coal applications is influenced by the sulfur content of the coal. Low-sulfur coal produces a reduction in maximum power density achievable compared with high-sulfur coal, and requires additional plate area to compensate.

For lignites, Na_2O influences the design power density in much the same manner as does the sulfur content of bituminous coal, although to a lesser extent.

The considerations that weigh heavily in the evaluation of hot-side versus cold-side precipitator applications are coal constituents, mode of firing, and temperature effects.

Wet Scrubbers

Three major categories of wet scrubbers are evaluated:

- Gas-atomized spray scrubbers including the conventional venturi and the flooded-disc venturi.

- Three-stage turbulent-contact absorber (TCA), also known as a moving-bed scrubber.
- Preformed spray scrubber.

Assuming that the same factors are known or determined for scrubbers as are indicated for the analysis of precipitators, the following key design parameters have the greatest effect on the efficiency of the scrubber:

- Pressure drop
- Liquid-to-gas (L/G) ratio
- Gas velocities

Other specific design parameters include the following:

- Gas-handling capacity per module
- Total number of modules required
- Water requirement/water recirculation
- Availability of equipment/downtime
- Total power consumption as a fraction of generated power

A detailed checklist (Appendix C) is provided to use in the evaluation of a wet scrubber design for collection of particulate; these design parameters are also summarized (Table 2-9) as they pertain to wet scrubbers now operating in the United States.

Graphical correlations were not developed for scrubbers because the data base was inadequate.

Fabric Filters

Only three fabric filter systems are now operating domestically for particulate collection on coal-fired utility boilers. The key design factors for fabric filtration systems are air-to-cloth ratio, pressure drop, cleaning mode, frequency of cleaning, composition and weave of fabric, degree of sectionalization, type of filter housing, and gas conditioning or cooling requirement. These design data for the three utility-size fabric filter systems operating in the United States are summarized (Table 2-16), and capital/operating costs are presented for these installations.

OPERATION AND MAINTENANCE PROCEDURES

This section of the report provides a set of procedures for operation and maintenance of precipitators, wet scrubbers, and fabric filter systems installed on coal-fired utility boilers. The procedures presented for precipitators are much more detailed than those for scrubbers or fabric filters. Preoperational checklists, start-up procedures, and the salient features of efficient normal operation, troubleshooting, inspection, and maintenance are presented for each of the three types of control systems; common malfunctions are also discussed, particularly with respect to precipitators.

In precipitator operation, which is based on the electrical charging and collection of particles, the components and controls associated with transformer-rectifier sets, rappers, and vibrators are the heart of the system. Because the precipitator incorporates high-voltage components, particular emphasis is given to safety considerations, including proper connection and grounding. Inspection and maintenance procedures are directed toward achieving reliable functioning of the total precipitator system, including electrical/mechanical components. An extensive troubleshooting chart (Table 3-2) lists the symptom, probable cause, and remedy for numerous ESP malfunctions, the most common of which are discharge wire breakage and ash hopper plugging.

Scrubber operation in removal of particulates from power plant effluent has encountered its own characteristic problems, including a potential for corrosion, scaling, and plugging. These problems emphasize the need for research and development of scrubber technology. The operating/maintenance procedures outlined here are designed to minimize malfunctions. Problem areas that require frequent inspection are summarized for each scrubber type; adherence to manufacturer's recommendations as they apply to each specific system/unit is urged. In normal operation, efficiency of a scrubber system for collection of submicron particles is related most closely to maintaining proper levels of pressure drop and L/G ratio.

A lack of historical data on fabric filter operation limits the determination of the effects of operating and maintenance procedures on baghouse efficiency. On the basis of available data, operations at the Sunbury fabric filter installation are discussed briefly. Maintenance practices are focused on surveillance to detect and prevent potential problems. Visual inspection of the stack emission, smoke-density instruments, and pressure-drop recorders are used to indicate malfunctions.

Most maintenance time at Sunbury has been spent on bag replacement, collapse fan repairs, and air-operated dampers. Procedures are outlined for isolation of a malfunctioning compartment and performance of repairs and maintenance; detection of collapse fan and damper failure are also discussed.

FRACTIONAL EFFICIENCY RELATIONSHIPS

This section deals further with the major variables that define a specific application (coal type, boiler type), relating them to efficiency of the control device for collection of particles of specified size. A computer model is used to predict percentage of particle penetration as a function of particle size. Predictive modeling is limited, however, by the deficiency of currently available methods for measuring particle size distribution, pointing out the need for development of a reliable technique for fine-particle measurement. Such a technique is a prerequisite for future compliance monitoring of fine-particle emissions.

Mathematical models for determining fractional efficiency as applied to ESP's and wet scrubbers are described. Predicted performance is presented graphically, and wherever possible is compared with actual performance data.

The computer models for precipitators show a minimum of efficiency in the particle size range of 0.2 to 0.4 micron. This observation is verified by field tests (Figures 4-5 through 4-7). If properly designed, precipitators are particularly efficient in the collection of particles in the submicron range.

The computer models for wet scrubbers show predicted performance down to a particle size of 0.2 micron, at which level they show minimal efficiency. Although precise comparison is not possible because of the lack of accurate particle size data the gas-atomized spray scrubber is predicted to perform better than either the TCA or high-pressure spray-type scrubbers. Test data on venturi and TCA scrubbers generally confirm the results of the computer model; however the test data do not indicate that the gas-atomized spray scrubber will perform better in every instance than the other types of scrubbers, as predicted by the computer model.

For hot and cold side precipitators, on the basis of stated assumptions, capital and operating costs for given levels of total mass and fractional efficiencies for a variety of coal and boiler types are summarized. These cost comparisons show a precipitator on a pulverized boiler to be cheaper than on a cyclone boiler at equal overall mass efficiency levels, and show the hot side precipitator to be more economically attractive to a cold precipitator on either a pulverized or cyclone fired boiler. All precipitator cost comparisons underscore the fact that total mass as well as fractional efficiency should be considered when establishing standards for control of fine particulate, regardless of the control device being considered.

METRIC CONVERSION FACTORS

To convert English units	Multiply by	To obtain SI units
British thermal unit (Btu)	1054	Joule (j)
Cubic foot (ft^3)	0.0283	Cubic meter (m^3)
Degrees fahrenheit	5/9 (°F-32)	Degrees Celsium (C)
Foot	0.3048	Meter (m)
Gallon (U.S. Liquid)	0.0038	Cubic meter (m^3)
Gallon (U.S. Liquid)	3.7854	Liter (l)
Horsepower (hp)	746.0	Watt (w)
Inch	0.0254	Meter (m)
Inch	2.54	Centimeter (cm)
Inches of water	248.8	Pascal (pa)
Pound	0.4536	Kilogram (kg)
Ton, short	0.9072	Metric ton (kkg)

1.0 INTRODUCTION

1.1 PURPOSE OF REPORT

This report presents a set of guidelines by which operators of coal-fired electric utility boilers and environmental control personnel can (1) select a feasible particulate control method for a specific application to comply with air pollution control regulations, (2) follow operational and maintenance practices that will maintain high particulate collection efficiencies and minimize malfunctions, and (3) relate the total mass efficiencies of various control devices to their efficiencies for collection of particulate in specific size fractions.

The high-efficiency control devices considered in this report for use on coal-fired power plant boilers are hot and cold electrostatic precipitators, wet scrubbers, and fabric filters.

It should be noted that the vast majority of coal-fired electric utility boilers in the United States that control particulate emissions are equipped with precipitators, either alone or in series with a mechanical collector. Consequently, much more information is available on the design, operation and maintenance, and fractional efficiency of precipitators than of wet scrubbers or fabric filters in this application. The availability of information accounts for the relatively greater depth of coverage of precipitators in some sections of this report.

1.2 SIGNIFICANCE OF PARTICULATE EMISSIONS

Many undesirable effects have been related to the discharge of particulate matter into the atmosphere. Particulates constitute a health hazard, cause poor visibility, function as a transport vehicle for gaseous pollutants, and (in many cases) are highly active both chemically and catalytically.[1]

Concerning the health effects of particulates, the severity and scope of the problems caused by submicron particulates are not yet well defined. Fine particulates constitute a large category of pollutants rather than being a single pollutant. Once dispersed, they behave (depending on size) similarly to coarse particles and gases; they remain suspended and diffuse, are subject to Brownian motion, follow fluid flow around obstacles, and can penetrate deep into the respiratory system.

Particles larger than 5 microns diameter are deposited in the nasal cavity or nasopharynx. Increasing numbers of smaller particles are deposited in the lungs, where over 50 percent of the particles between 0.01 and 0.1 micron penetrating the pulmonary compartment are deposited. This ability of particulates to penetrate the respiratory system and be captured is mainly a function of their geometry rather than their chemical properties. In addition, particles in these smaller size ranges are difficult to measure.

The resulting health effects of the captured fine particulates depend largely on their chemical or toxic qualities, excepting for long, fibrous materials whose physical qualities also provide potential for irritation of tissue. Because of the many factors as yet unknown, it is unwise to generalize concerning health effects of fine particulates.

1.3 SCOPE OF THE REPORT

Section 2.0 of the report discusses control system design parameters. Experience with control device operation, engineering judgment, and current design practice provide the data base for discussion of electrostatic precipitator design, relating input variables to basic design variables.

The discussion of design parameters for wet scrubbers includes venturi, flooded disc, turbulent contact absorber (TCA), and high-pressure spray scrubbers. This discussion is based primarily on the detailed presentation of Sondreal and Tufte[2].

The use of fabric filters for control of particulates from coal-fired boilers is a recent alternative; data are available for only three installations.

Section 3.0 describes maintenance and operational procedures that contribute to operation of the particulate collection devices with maximum efficiency. The discussion emcompasses start-up, shutdown, and normal operational procedures; common malfunctions are also discussed.

The fractional collection efficiencies of ESP's, wet scrubbers, and fabric filters are discussed in Section 4.0. Reliable data on particle size distribution are not readily available because of the high degree of operator error and the technical limitations of some particle sizing instrumentation. Because awareness of the potential adverse health effects of fine particulates is relatively recent, programs for systematic measurement of particle size distribution have been undertaken only in the past few years.

The particle size distribution data available for this study show an appreciable amount of scatter in the mean and standard deviation of size distributions for the same coal/boiler application. Although coal type does influence particle size distribution, the effect of boiler type is stronger. Therefore, values for coal type, boiler type, overall mass collection efficiency, and typical particle size distribution data selected on the basis of boiler type were used to develop computer models to predict fractional efficiencies of ESP's and wet scrubbers. For ESP's and scrubbers the predicted data are compared with actual operating data.

A computer model is not presented for predicting fractional efficiencies of fabric filters, only test data.

Section 5.0 presents conclusions regarding the use of precipitators, scrubbers, and fabric filters on coal-fired utility boilers. Advantages, disadvantages, and costs to install and operate each type of control device are compared. The effectiveness of each device in collecting fine particles is also discussed.

2.0 CONTROL SYSTEM PARAMETERS

2.1 SUMMARY OF CONTROL DEVICES

Among the utilities in the United States producing (as opposed to buying and selling) electric power through year-end 1975, there were 1166 coal-fired units (boilers). Approximately 582 of these are equipped with pollution control devices designed to operate with an overall mass particulate collection efficiency of 95 percent or greater. A list of these installations is presented in Appendix A. Of that number, approximately 75 percent of the units have cold-side electrostatic precipitators, 16 percent have a mechanical collector and a cold-side precipitator, 7 percent have hot-side precipitators, 1.5 percent have wet scrubbers, and 0.5 percent have mechanical collectors only. In addition, three fabric filter systems are collecting fly ash from coal-fired utility boilers.

Hybrid systems are certainly of interest, but for a number of reasons their consideration exceeds the practical limits of this document. For example, the reason for use of hybrid systems is primarily the tightening of emission regulations, often requiring addition of a control system to one already in operation. This patchwork approach, in which control devices are added in series or in parallel, does not constitute a sound basis from which to generalize concerning optimum design of hybrid systems. Therefore, this document deals only with cold-side and hot-side electrostatic precipitators; wet scrubber systems including venturi, flooded disc, turbulent contact absorbers (TCA), and high-pressure spray scrubbers; and fabric filters.

The information presented on electrostatic precipitators consists of current design relationships. It is based on designs that have met or surpassed guaranteed efficiency. Current design practice is considered rather than historical data because design is influenced strongly by time-related factors. Among the factors influencing changes in design practice are the Clean Air Act of 1970 (as amended), provision of increased control device reliability as a result of vendor competition, and increased attention to coal composition, thereby strengthening the basis for electrostatic precipitator design.

The primary source of data on wet scrubbers for this study is "Scrubber Developments in the West" by Sondreal and Tufte.[2] This source includes the operating experience of the Four Corners Station of Arizona Public Service; the Dave Johnston Station of the Pacific Power and Light Company; the Valmont, Cherokee, and Arapahoe Stations of the Public

Service Company of Colorado; and the Clay Boswell and Aurora Stations of the Minnesota Power and Light Company.

The use of fabric filters for emissions control in coal-fired power plants is limited to three utility plants, located at Nucla, Colorado; Sunbury, Pennsylvania; and Holtwood, Pennsylvania.

2.2 COMPARISON OF ALTERNATIVE CONTROL SYSTEMS

2.2.1 Selection and Evaluation

A number of factors must be carefully weighed in selection of a control device for a specific application. Some of the important considerations are presented in Table 2-1. These factors apply in general to precipitators, wet scrubbers, and fabric filters. When a device is installed and operational, its performance can be compared with that of other devices in operation. The performance of conventional control equipment is currently judged with respect to overall mass collection efficiency. As discussed in Section 4 of this report, fractional efficiency and overall efficiency, both on a mass basis, should be considered in establishing fine particle emission standards.

2.2.2 Economic Rationale for Evaluating Costs

A number of methods are available for determining the cost competitiveness of different devices, utilizing such concepts as discounted cash flow, present worth, and capi-

Table 2-1. FACTORS BEARING ON CONTROL DEVICE SELECTION

Characteristics of particles and gas stream	Facilities, costs, legal factors
Particle characteristics	Plant facility
Electrical properties (precipitators only)	Waste treatment
Resistivity	Space restriction
Dielectric constant	Product recovery
	Water availability
Physical properties	Cost of control
Surface properties	Engineering studies
a. abrasiveness	Hardware
b. porosity	Auxiliary equipment
Density	Land
Shape	Structures
Hygroscopic nature	Installation
Adhesivity	Start-up
Cohesivity	Power
	Waste disposal or recycle
Chemical properties	Water
Ignition point (precipitators, fabric filters)	Materials
Chemical composition	Gas conditioning
	Labor
	Maintenance
Particulate concentration	Taxes
Size distribution	Interest on borrowed capital
	Depreciation
Gas stream characteristics	Insurance
Flowrate	Return on investment
Temperature	
Pressure	Regulations
Viscosity	
Chemical composition	Maximum particulate and SO_2 emission rates allowed by Federal, state, and local laws
Acid constituents	
Alkaline constituents	
Sulfur oxide content	
Moisture content	

talized cost. A simple approach based on the rate of return on incremental investment to determine the economically superior control device is presented below.[3]

As an illustration, let T_A and T_B be the capital investments required for control devices A and B, respectively, for a specific application (e.g. 99.5 percent overall mass collection efficiency for fly ash particles having a resistivity of 10^{10} ohm-cm). Let the corresponding total annual operating costs be O_A and O_B.

If $T_A < T_B$ <u>and</u> $O_A < O_B$, it is obvious that control device A is more economical. Similarly, control device B would be clearly more attractive if $T_A > T_B$ <u>and</u> $O_A > O_B$. However, if $T_B > T_A$ and $O_B < O_A$, the choice can be made on the basis of annual savings that can be realized when the additional investment is made. Thus, the incremental investment of $(T_B - T_A)$ for control device B yields an annual savings of $(O_A - O_B)$ compared with control device A.

If $$\frac{O_A - O_B}{T_B - T_A} > Z$$

where Z is the desired (or acceptable) return on investment, then it is profitable to invest in device B.

Alternatively, if $(O_A - O_B)/(T_B - T_A) < Z$, then control device A is preferable. This is because additional capital required for device B (i.e., $T_B - T_A$) can be invested elsewhere, so that the return on the additional investment of ($T_B - T_A$) is greater than the acceptable limit of Z.

2.3 DESIGN CONSIDERATIONS - ELECTROSTATIC PRECIPITATORS

This section of the report is intended to provide insight into the major parameters that must be weighed in design of an electrostatic precipitator. The basic procedure is a simple one; given certain input variables (coal type, boiler type, and emission standard) and applying experience and theory, one can arrive at a design that meets the criteria for efficiency and cost. The procedure is summarized in Table 2-2.

An application can be characterized in a very general way by a coal type and a boiler type. The available literature provides an enormous number of possible application areas that might be defined. The following list summarizes some of the important types of coal currently used by utilities and their characteristics.

<u>Low-sulfur western</u> (subbituminous and bituminous)

High and low sodium
High moisture
High ash
High and low calcium + magnesium

<u>Low-sulfur eastern</u> (bituminous)

Low sodium
High and low iron
High and low silica + alumina
High and low magnesium + calcium

Table 2-2. DESIGN CONSIDERATION FOR AN ESP

System input	
	Coal type
	Boiler type
	Federal or state emission standard
Basic design parameters	
	Total acfm
	Total collection area
	Power density
Specific design parameters	
	Firing method and coal characteristics
	Ash chemical analysis
	Precipitator size
	Rapping, electrodes, etc.
	Electrical energization
	Performance parameters
System output	
	Overall and fractional mass efficiency
	Capital cost
	Operating cost

High-sulfur (bituminous)

High and low sodium
High and low iron

Lignite

High and low sodium
High moisture
Low sulfur

Following are the major types of boilers now used by utilities:

Pulverized-coal-fired

Wet bottom
Dry bottom

Stoker-fired

Spreader
Underfeed

Cyclone-fired

Screened
Open

Within the constraints of availability of data and desirability of keeping the application areas to a manageable number, the following scheme has been adopted for discussion of the graphical correlations presented later in Section 2.0. For cold-side electrostatic precipitators the overall mass efficiency levels are 95, 97.5, 99, 99.5, and 99.9 percent. The major applications are (1) pulverized-coal-firing of bituminous, subbituminous, and lignite coals, and (2) cyclone firing of bituminous coal. The influencing coal characteristics are sodium and sulfur contents (for lignites and low-sulfur coals in general).

For hot-side electrostatic precipitators at the same efficiency levels, the major applications are pulverized-coal and cyclone firing of typical western (subbituminous) and eastern (bituminous) coals. The influencing coal characteristics are percent iron and sodium oxides.

In most cases the graphical correlations presented represent a range of values that could extend above or below the plotted curve.

Table 2-3 provides an approximation of expected emissions from the boiler types under consideration. With some refinements in the inlet fly ash characteristics, Section 4.0 provides a comparison of precipitator performances for the different application areas at various levels of fractional and overall mass collection efficiency. The capital and operating costs associated with attaining those levels are also provided.

2.3.1 Basic Design Parameters

The objective is to determine from coal type, boiler type, and emission standard the values for gas volumetric throughput (acfm), total plate collection area (ft^2), and power density (watts per ft^2 of collecting plate). These three parameters form the basis for precipitator design.

Table 2-3. EMISSIONS FROM DIFFERENT BOILER TYPES

Boiler	Loadings	Particle size	Combustible content in fly ash,%
Stoker	Low to medium, depending on coal ash	Coarse, 20%<10μm	40-60
Cyclone	Low	Fine, 80%<10μm	10-30
Pulverized-coal	High to medium, depending on coal ash and type bottom	Medium, 50%<10μm	<5

The total gas volume to be treated is known, since it is determined by the conditions of combustion. (Conditions of time, temperature, and turbulence of combustion together with precipitator approach ductwork determine the degree of turbulence of the gas to be treated, a matter of no small consequence in performance of an electrostatic precipitator. In the discussion of design that follows, it is assumed that generation of large-scale turbulent eddies due to structural design of approach ductwork and hoppers has been minimized).

Knowing the total acfm and the specific collection area (SCA, ft^2/1000 acfm), one can determine the total collection area required to meet an emission standard. Following are the equations for calculating SCA and required efficiency:

$$SCA = \frac{16.67 \ln^2(1-\eta)}{w_k}$$

$$\eta = [1 - (\frac{\chi}{(10^6/H.V.)(ASH)(A.C.)})] 100$$

where

η = Overall mass collection efficiency, percent

w_k = Modified migration velocity, ft/sec.

χ = Emission standard, lb/10^6 Btu

H.V. = Heating value of the coal, Btu/lb

ASH = Ash in the coal, fraction by weight

A.C. = Ash carryover, fraction by weight

The required overall mass efficiency, therefore, is a function of the coal heating value and ash content as well as the fraction of ash carryover, which is a function of boiler type. The modified migration velocity is a function of electrical energization of the precipitator, gas properties, and particle size entering the precipitator. It is often conveniently linked with resistivity level, such that for a moderate resistivity of 10^9 ohm-cm the value will be between 1.6 and 1.9, ft/sec whereas for a very resistive dust it may approach 0.5 ft/sec.

A digression is in order at this point to clarify the usage of w_k (modified migration velocity) in contrast to the effective migration velocity w, which is used in the conventional Deutsch-Anderson efficiency equation. The effective migration velocity w is a function of several factors, including precipitation length, overall mass collection efficiency, and gas velocity. The variation in w within a given precipitator is caused by changing particle size distribution, as precipitation proceeds in the direction of gas flow.

The modified migration velocity, w_k, as presented by Matts and Öhnfeldt[4] can be treated as independent of changing current and voltage levels, and particle size distribution within a precipitator as the precipitation process proceeds in the direction of gas flow. However, changes in the properties of the dust entering the precipitator (resistivity, size distribution) produce a change in w_k just as they also change the conventional w. This report does not present actual values of w_k; it only explains the method by which w_k is used in the modified Deutsch-Anderson equation.

The third basic design parameter is power density required to establish the necessary voltage-current characteristics of the corona, given the fly ash entering the precipitator. Power density is a function of electrical resistivity, particle size and gas composition, gas temperature, and gas pressure. It is often conveniently linked with resistivity, such that for a moderate resistivity of

10^9 ohm-cm the value will be approximately 2.5 watts/ft^2. For a high-resistivity application the design value will be in the neighborhood of 0.5 to 1.0 watt/ft^2.

It appears that resistivity plays a significant role in selection of w_k and power density, yet there is no precise method of predicting resistivity from the coal type and firing conditions for the numerous cold-side applications.

2.3.2 Specific Design Parameters

Table 2-4 is a compilation of design parameters and input variables grouped in logical categories.

Information from the first two categories has been used in definition of the design approach. The last category, performance-related parameters, includes two of the basic system design parameters. As explained in Section 4.0, this category will help to define the system output parameters and the overall and fractional mass collection efficiencies for various application areas. The remaining categories, precipitator size; rapping, electrodes, etc,; and electrical energization, are discussed in the following subsections.

Precipitator Size

One of the first structural parameters to be determined is the width of the precipitator(s). This value is dependent on total number of ducts, which is calculated as follows.

$$\text{Total no. ducts} = \frac{\text{ACFM}}{(\text{T.V.})(60)(\text{P.S.})(\text{P.H.})} \qquad \text{Eq. 1}$$

Table 2-4. DESIGN PARAMETERS AND DESIGN CATEGORIES FOR ELECTROSTATIC PRECIPITATORS

Firing method and coal characteristics

Firing method
% ash
% sulfur
% moisture (as received)
Btu/lb (wet)
Sample source
ASTM class
Mine, state
Mine, county
Mine name
Seam name

Ash chemical analysis

SiO_2
Al_2O_3
Fe_2O_3
TiO_2
CaO
MgO
K_2O
Na_2O
Li_2O
P_2O_5
SO_3
Sample source
Mean
Deviation
Sample type

Precipitator capacity

No. precipitators
No. chambers (units)/precipitator
No. ducts/chamber (unit)
Duct spacing
Plate height
Treatment length
Section lengths and total no. of each (per precipitator)
Collecting area
No. electrical sections parallel to gas flow (per precipitator)
No. electrical sections across gas flow (per precipitator)
No. hoppers parallel to gas flow (per precipitator)
No. hoppers across gas flow (per precipitator)

Rapping, electrodes, etc.

Type discharge electrode
Ft. discharge electrode/vibrator or rapper
Type discharge electrode vibrator or rapper
Type collecting electrode
Sq ft collecting electrode/rapper
Type collecting electrode rapper

Electrical energization (of each electrical section)

Watts/ft^2 of collecting electrode
Ft^2 of collecting electrode/T-R
Mode (switching)
Corona kilovolts
Milliamperes/1000 ft^2 of collecting electrode
Milliamperes/T-R
Milliamperes/ft^2 of discharge electrode

Performance-related parameters

Gas flow
Gas temperature
Gas (treatment) velocity
SCA
Overall mass collection efficiency
Fractional mass collection efficiency
Inlet grain loading
Outlet grain loading
Generated plant power output
Fuel burning rate

where, ACFM = Total gas volumetric throughput, acfm
T.V. = Gas (treatment) velocity, fps
P.S. = Plate spacing, ft
P.H. = Plate height, ft

Treatment velocity (T.V.) is a function of resistivity of the fly ash. Values of T.V. should range from 3.0 to 4.0 fps in high-resistivity, in cold-side ESP applications, and in low-resistivity applications (hot-side or cold-side). For most other applications the values should range from 3.0 to 5.5 fps.

Plate spacing (P.S.) is more or less fixed by the precipitator manufacturer and his experience with different types of fly ash and by velocity distribution across the precipitator, as well as the plate type. Plate spacing usually ranges from 6 to 15 inches. Most precipitators in the United States have 9-inch spacing, but precipitator designers are now showing a great deal of interest in larger spacings.

Plate height (P.H.) is selected from consideration of simultaneously maintaining the required treatment velocity and also maintaining an adequate aspect ratio, which is the ratio of the length of a precipitator to its height. Historically, this value varies between 0.5 and 1.5, with a present-day average of approximately 1.3.[5] Plate heights usually range from 24 to 45 feet. The practical limitation on plate height imposed by structural stability is obvious.

Each manufacturer limits the practical plate heights in accordance with his overall design.

The total number of ducts indicates the width of the box. What is required now is some indication of chamber-wise sectionalization of the precipitator, as indicated in Figure 2-1. Chamber-wise (parallel) sectionalization is sectionalization across the gas flow, whereas series sectionalization is in the direction of gas flow.

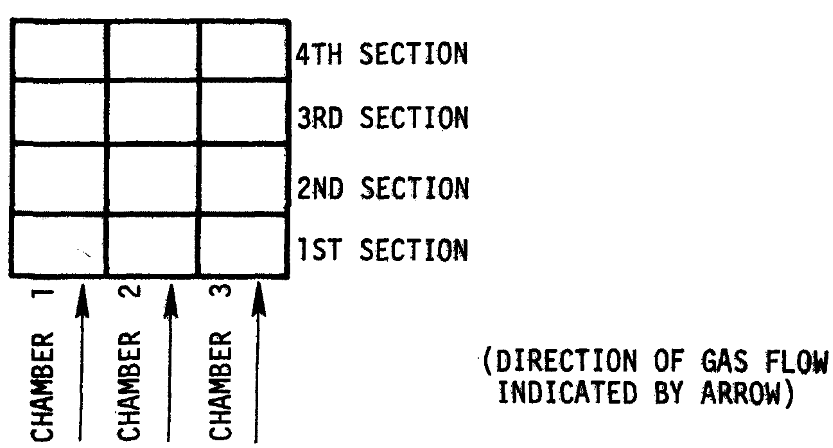

Figure 2-1. Sectionalization of the precipitator.

A practical procedure from the standpoint of energization and reliability is to limit the total number of ducts per unit. A precipitator will have a number of chambers determined by the total number of ducts, which itself is determined from Eq. 1 and its associated criteria. The total number of precipitators needed will depend upon the degree of reliability required, space limitations at the utility site, and relative ease with which the effluent gas may be distributed to the precipitator(s).

The second general design equation provides a guide to the length of the precipitator. As mentioned before, the length is dependent on the selection of treatment velocity, plate spacing, plate height, volumetric throughput, and total collecting plate area.

$$\text{Treatment Length} = \frac{\text{total collecting plate area}}{(\text{no. precip.})(\text{chambers/precip.})(\text{ducts/chamber})(\text{P.H.})(2)} \qquad \text{Eq. 2}$$

The design treatment length will be determined by selection of an integer value of standard section lengths that may be offered by the precipitator manufacturer. If it is found, for example, that four sections are required, two of one length and two of another, the structural considerations such as hopper spans determine the positioning of the sections in the direction of gas flow. The size of the T-R*

* Transformer-rectifier set.

sets is selected to provide lower current density at the inlet, where corona suppression is likely to decrease collection efficiency, and higher current density at the outlet, where there is a greater percentage of fine particles.

Mechanical sections result from the chamber-wise and section-wise sectionalization of an electrostatic precipitator. Hopper selection is based upon the size of the mechanical sections.

Rapping, Electrodes, etc.

The geometry of the discharge electrodes (fine, barbed, rigid, etc.) will determine the current-voltage characteristics. The smaller the wire or the more pointed its surface, the greater the value of current for a given voltage.

Typical values for length of discharge wire per vibrator or rapper are 3300 feet for hot-side applications and 3000 feet for cold-side applications. These values, however, should not be taken as absolute because actual practice varies widely and values range from 2500 to 3500 ft per vibrator or rapper.

For cold-side precipitators, 2000 square feet of collection area is a typical value for one rapper. For hot-side applications, the value is typically 2500 square feet per rapper. Again, there is a wide variation in actual practice, and values range from 2000 to 3000 ft per rapper.

Baffles are used to provide stiffness for support of the collecting plate and a region of low turbulence to minimize reentrainment of fly ash, particularly during rapping. Although a variety of plates is commercially available, their functional characteristics are not substantially different.[6]

Rappers can be pneumatic, electromagnetic, or mechanical. Single-impact (magnetic-impulse, gravity-impact) rappers are often used. The rapping intensity is determined by the height of the rapper when released from its elevated position and by the plunger weight. The weight of the plunger may range from 8 to 32 pounds. The frequency of rapping is essentially determined empirically by observing the values of opacity and overall mass efficiency measured as the intensity of rapping is varied.

Mechanical rappers are lifted by means of a rotating shaft to which a number of rappers are attached. Impact can be provided in a horizontal direction. Intensity and frequency of raps are determined by the weight of the rapping hammers and shaft speed, respectively.

Electrical Energization

The way in which a precipitator is energized strongly affects its performance. Electrical energization involves the number and size of the transformer-rectifier (T-R) sets, the number of electrical sections, half wave-full wave (HW-FW) operation, and changes in the voltage-current characteristics as precipitation proceeds in the direction of gas flow.

Selection of design power density is often conveniently based on resistivity of the fly ash. Table 2-5 illustrates design values of average power density as a function of resistivity.

Table 2-5. DESIGN POWER DENSITY

Resistivity, ohm-cm	Power density, watts/ft^2 of collecting plate
10^{4-7}	4.0
10^{7-8}	3.0
10^{9-10}	2.5
10^{11}	2.0
10^{12}	1.5
$>10^{12}$	1.0

For a cold-side precipitator an average operating voltage may be between 25 and 45 KV for 9-inch spacing, whereas for a hot-side precipitator typical values range from 20 to 35 KV for 9-inch spacing. Knowing power density and operating voltage, one can estimate the current density (ma/ft^2). The value of ma/ft^2 of collecting electrode is not constant for each point in the precipitator. At the inlet section, where the dust loading is greatest, the voltage-current characteristics differ significantly from those at the outlet, since the probability of corona suppression is greater at the inlet and the percentage of fine particles is greater at the outlet.

A mechanical section by definition may become an electrical section if it can be separately energized. Within an electrical section one may have a chamber-wise or section-wise high tension split, or both (see Figure 2-2).

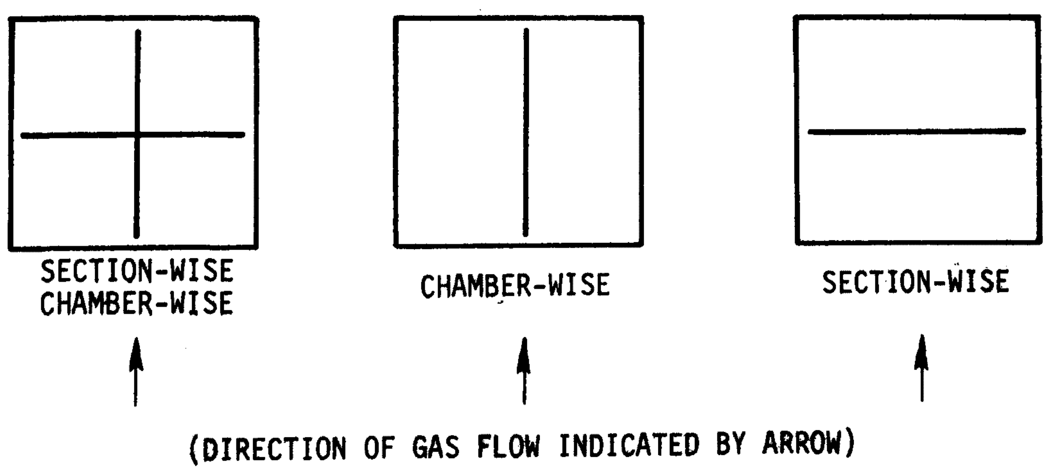

Figure 2-2. High-tension splits of a mechanical section.

The advantage of splitting a mechanical section both chamber- and section-wise is greater reliability; this is achieved at an increase in cost.

Reliability increases with the degree of sectionalization in the direction of gas flow. For a precipitator that is highly sectionalized in the direction of gas flow, randomly generated failure patterns generally produce a predicted efficiency in a narrower band than for a precipitator with less sectionalization in the direction of gas flow.[7]

Reliability of the precipitator is involved not only with sectionalization of a given collection area but also with the addition of collection area or electrical sections. At the discretion of the designer and in accordance with specifications of the utility, the degree of reliability can be defined in terms of a redundant capacity, which is a function of anticipated failure and time between maintenance periods. In this context, redundancy may be defined as that additional area in a precipitator that compensates for the "normal" level of unavailable collecting area. How much additional area will be required is a function of the utility fuel specifications and the designer's experience with the fuel(s). To provide a reliable yet cost-competitive design, the designer must have detailed information, such as ultimate, proximate, and ash chemical analyses for all potential fuels.

The basic consideration in energizing the precipitator is to maximize the power input to achieve the highest efficiency from a given collection area. The decision regarding degree of sectionalization, however, is made independently of the way in which the precipitator is to be energized, since the number, size, and mode of operation (half wave or full wave) of the T-R sets can be manipulated to provide the required current density within each electrical section of the precipitator. Following is a brief commentary on the rationale for half wave-full wave operation.

In spark-limited operation on a cold-side precipitator treating high-resistivity ash, half-wave operation allows time during the off half cycle to recover from the sparking condition (spark quenching). Complete decay of the charging field and of collection efficiency during the off half cycle is avoided because of the capacitive effect of high-resistivity fly ash, which tends to maintain the field potential.

In operation of hot-side precipitators, since fly ash resistivity has been reduced by virtue of the increased temperature of operation, the capacitive effect of the fly ash is reduced. Thus the charging field decays more in half-wave than in full-wave operation.

Selection of the mode of operation depends somewhat on site-specific factors; in fact the variability of performance in full-scale precipitators may overwhelm any differences due to operation in either half-wave or full-wave mode.

In summary, the design of precipitator sectionalization and energization is based on maximizing the power input to the precipitator to achieve the highest efficiency from a given collection area while minimizing loss of performance as a result of various failure patterns. Reliability of precipitator performance is a function of fuel specifications, utility requirements, and design experience. The way in which a precipitator is energized depends on the sectionalization configuration and the current density to be supplied to each electrical section, as determined by chemical and physical characteristics of the fly ash, dust loading, and characteristics of the gas stream. The number, size, and mode of operation of the T-R sets can be fitted to the sectionalized configuration after the bus section design has been established.

2.4 INTERPRETATION OF GRAPHICAL CORRELATIONS FOR COLD- AND HOT-SIDE ELECTROSTATIC PRECIPITATORS

The preceding discussion of precipitator design shows that three parameters are of central interest: gas volumetric throughput (acfm); total collecting area (ft^2); and power density (watts/ft^2 of collecting plate). The graphical correlations discussed in this section relate input variables to these basic design variables and to the capital and operating costs for each case. As indicated earlier, the designer's judgment, experience, and understanding of precipitator theory allow him to select the values of overall mass efficiency, SCA, and power density required for given coal type, boiler type, and Federal emission standard. A word of caution is needed however. It is not intended that the broad-based approach presented here should provide information that can be directly applied to a specific site or installation. A number of highly practical points must be considered in the overall design, including such nonideal conditions as gas nonisoturbulence, gas sneakage, and particle reentrainment. In addition, many points of detail are to be considered in electrical energization and structural design.

The data presented in the graphs are based on current design practice. The SCA values are shown for various coal/boiler applications and efficiency levels in relation to sulfur, percent Na_2O, and percent Fe_2O_3 in the fly ash. For this study, sufficient data were not available on the cyclone firing of subbituminous and lignite coals or on power density relationships for hot-side precipitators to develop correlations. Also, data were insufficient to allow meaningful correlations with regard to stoker-fired boiler applications.

Current design and/or performance data are also presented for comparison with the graphical correlations. If SCA values for the design data are based on the conventional Deutsch-Anderson migration velocity (w), direct comparison with the graphical correlations is difficult because they are based on the modified migration velocity (w_k). As stated previously, the modified migration velocity is an improvement over the conventional migration velocity, since once the particle size is determined, w_k can be treated as a constant for a given application; w cannot be treated as such. The modified migration velocity is used almost exclusively in the Australian power industry where they have found that well-designed and maintained precipitators invariably conform closely to a w_k relationship. Actual test points from an intensive series of pilot tests at Wallerawang, Australia, in 1969, as well as actual full-load installations, have shown the validity of the w_k concept.

2.4.1 SCA as a Function of Significant Ash Constituents Cold-Side Electrostatic Precipitators

For bituminous coal (pulverized-coal and cyclone-fired) and subbituminous coal (pulverized-coal-fired) the sulfur content is very important in determining the SCA required since it affects resistivity. Recall that the governing equation for SCA is

$$SCA = \frac{16.67 \ln^2(1 - \eta)}{w_k}$$

As the percent sulfur decreases, resistivity increases, w_k decreases at a given temperature, and the SCA increases. With very high resistivities, one can expect a value of w_k approaching 0.5 ft/sec. The utility will sometimes specify that a slightly inflated value of SCA be used to provide a degree of redundancy or reliability so that a more stringent future emission standard may be met relatively easily. In other instances, the utility may specify additional treatment length. The expression of the redundant capacity may vary, but the result is the same.

Figures 2-3 and 2-4 present SCA as a function of sulfur content of bituminous coal for pulverized-coal and cyclone firing, respectively.

The SCA's required for cyclone firing of bituminous coal (Figure 2-4) are 30 to 40 percent higher than those for pulverized-coal firing. The fly ash emitted from a cyclone-fired boiler is approximately 20 to 30 percent of the total coal ash produced upon combustion, whereas for a dry ash pulverized-coal-fired unit it is about 80 percent. Even though less ash is carried over to the precipitator with the cyclone-fired boiler, the particle size distribution makes precipitation difficult (compare $\bar{x}$ = 6.0 and σ = 3.33 for

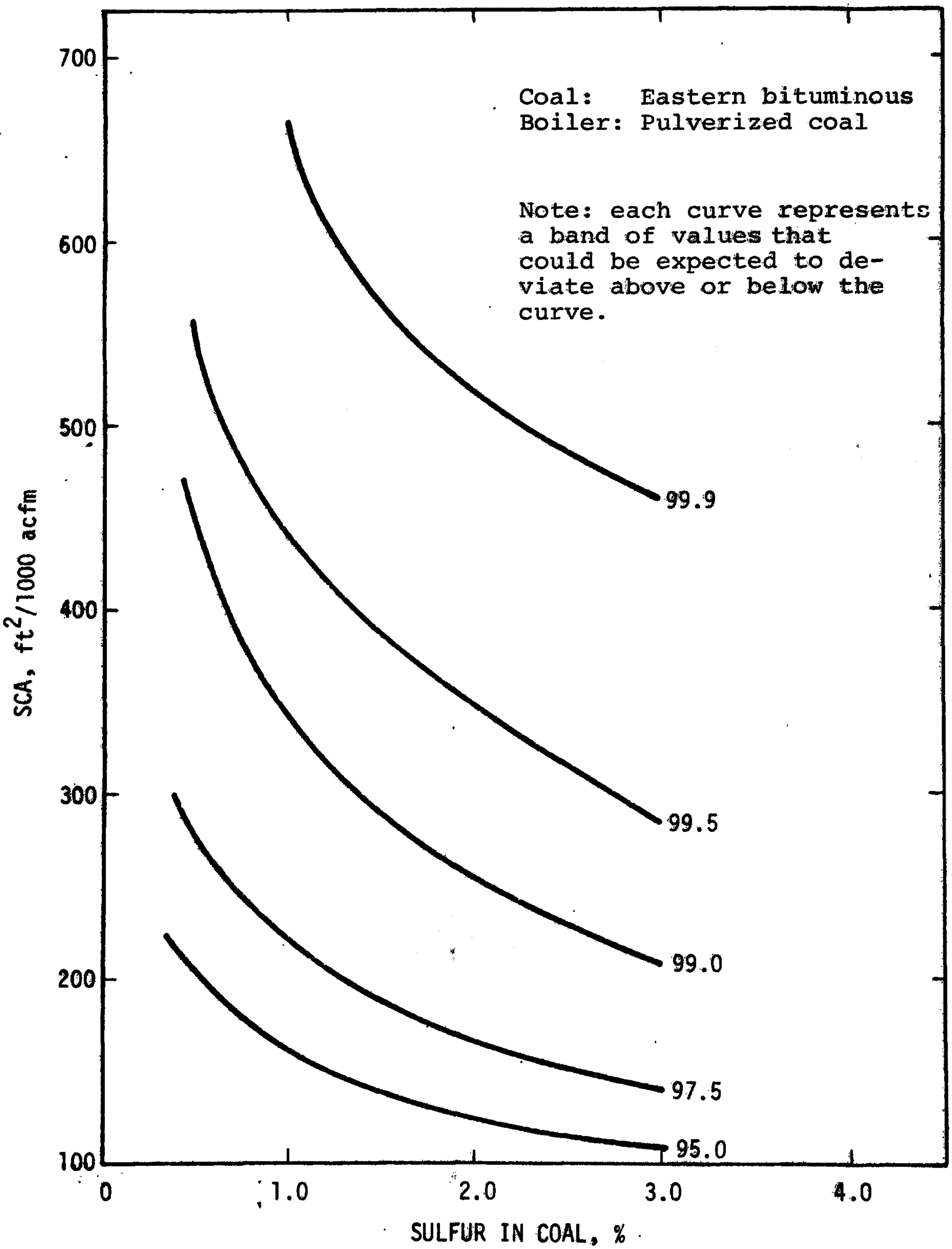

Figure 2-3. SCA versus sulfur content: cold-side ESP, pulverized eastern bituminous.

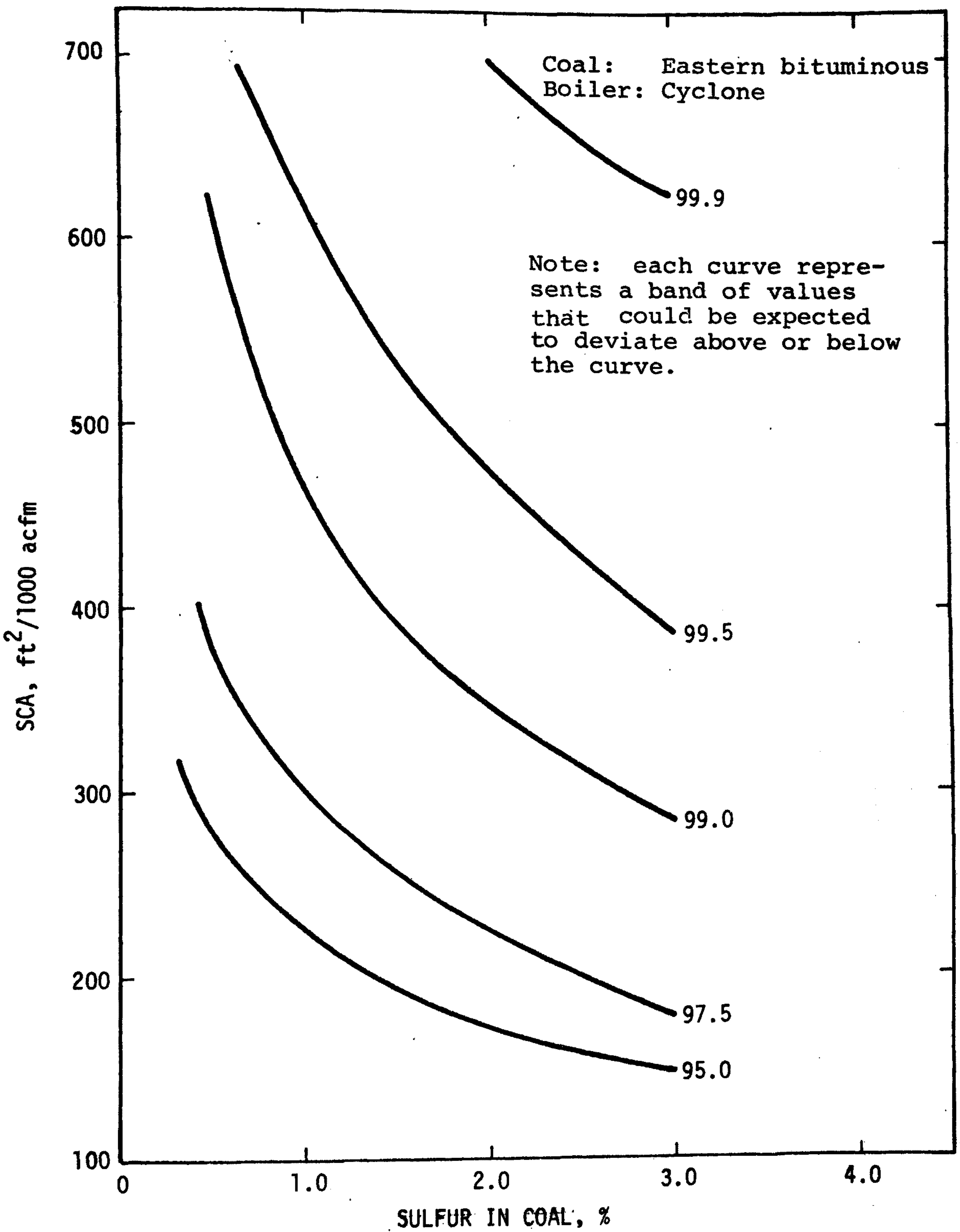

Figure 2-4. SCA versus sulfur content: cold-side ESP, cyclone-fired eastern bituminous.

cyclone firing with $\bar{x} = 12$ and $\sigma = 3.8$ for pulverized-coal firing).[8] Also, the increased carryover of unburned carbon from a cyclone boiler can adversely alter the precipitability of the fly ash. Carbon particles tend to reentrain more easily than fly ash particles. Since the carbon particles are more conductive, they tend to discharge upon contact with collection electrodes and become reentrained.

Table 2-6 presents a number of design parameters for precipitators recently specified by the Tennessee Valley Authority (TVA) for compliance with various state particulate emission regulations. The coal supply for all of these plants will probably be eastern bituminous, and all of the boilers are pulverized-coal-fired. The method by which these precipitator specifications were prepared is not known.

Assuming that the coal is bituminous, all but one of the SCA requirements as a function of coal sulfur content appear to lie within the range of the curves presented in Figure 2-3. The SCA of 672 for an efficiency of 98.5 percent with 0.6 percent sulfur bituminous coal at Bull Run appears rather stringent. It may be that these precipitators are designed for western coal.

It should be noted that since all of the TVA precipitators are retrofit designs, the inlet concentrations may

Table 2-6. PRECIPITATOR PARAMETERS RECENTLY SPECIFIED BY TVA

Plant name	No. of units	No. of precips.	Boiler type	Efficiency specified, %	Gas flow, acfm	Coal[a] Sulfur, %	Coal[a] Ash, %	SCA ft²/1000 acfm	New or retrofit
Bull run	1	4	PC	98.5	2,800,000	0.6	22	672	Retrofit
Gallatin 1 & 2	2	2	PC	99.5	700,000	1.5	28	386	Retrofit
Gallatin 3 & 4	2	2	PC	99.5	816,000	1.5	28	386	Retrofit
Johnsonville 1-6	6	6	PC	98.7	575,000	2.0	18	220	Retrofit
Kingstone 1-4	4	4	PC	99.2	500,000	0.9	25	450	Retrofit
Kingston 5-9	5	5	PC	99.2	700,000	0.9	25	450	Retrofit
Colbert 5	1	2	PC	99.5	2,000,000	1.5	25	325	Retrofit
Widows Creek	6	6	PC	99.6	575,000	0.7	30	495	Retrofit
Shawnee 1-10	10	10	PC	98.0	584,000	1.0	27	345	Retrofit

[a] Bituminous.

differ from those which would be typical of a new precipitator design; therefore, comparison with Figure 2-3 should be made with this in mind.

At sulfur contents about 1.5 to 2.0 percent, the SCA requirements of eastern bituminous and western subbituminous pulverized coals are similar. Below this range, a dramatic increase in SCA is noted as percent sulfur in the coal decreases, especially for the subbituminous pulverized coals, mainly because most experience on subbituminous is with western coals high in resistive components like Ca and Mg, as shown in Figure 2-5. The SCA requirement (SCA-488) for precipitators on Units 1 and 2 at the Jim Bridger pulverized-coal-fired generating station is plotted on Figure 2-5. This station fires low sulfur subbituminous western coal. When Unit 1 was tested in April, 1975, the collection efficiency ranged from 99.5 to 99.6 percent (99.3% guaranteed) with all gas paths in service. The Matts-Öhnfeldt modified migration velocity (w_k) was used in sizing this precipitator.[9] The requirement for high-SCA cold-side electrostatic precipitators causes one to consider the advantages of a hot-side electrostatic precipitator (see next section).

SCA values for boilers firing pulverized lignite are shown in Figure 2-6 as a function of sodium content of the

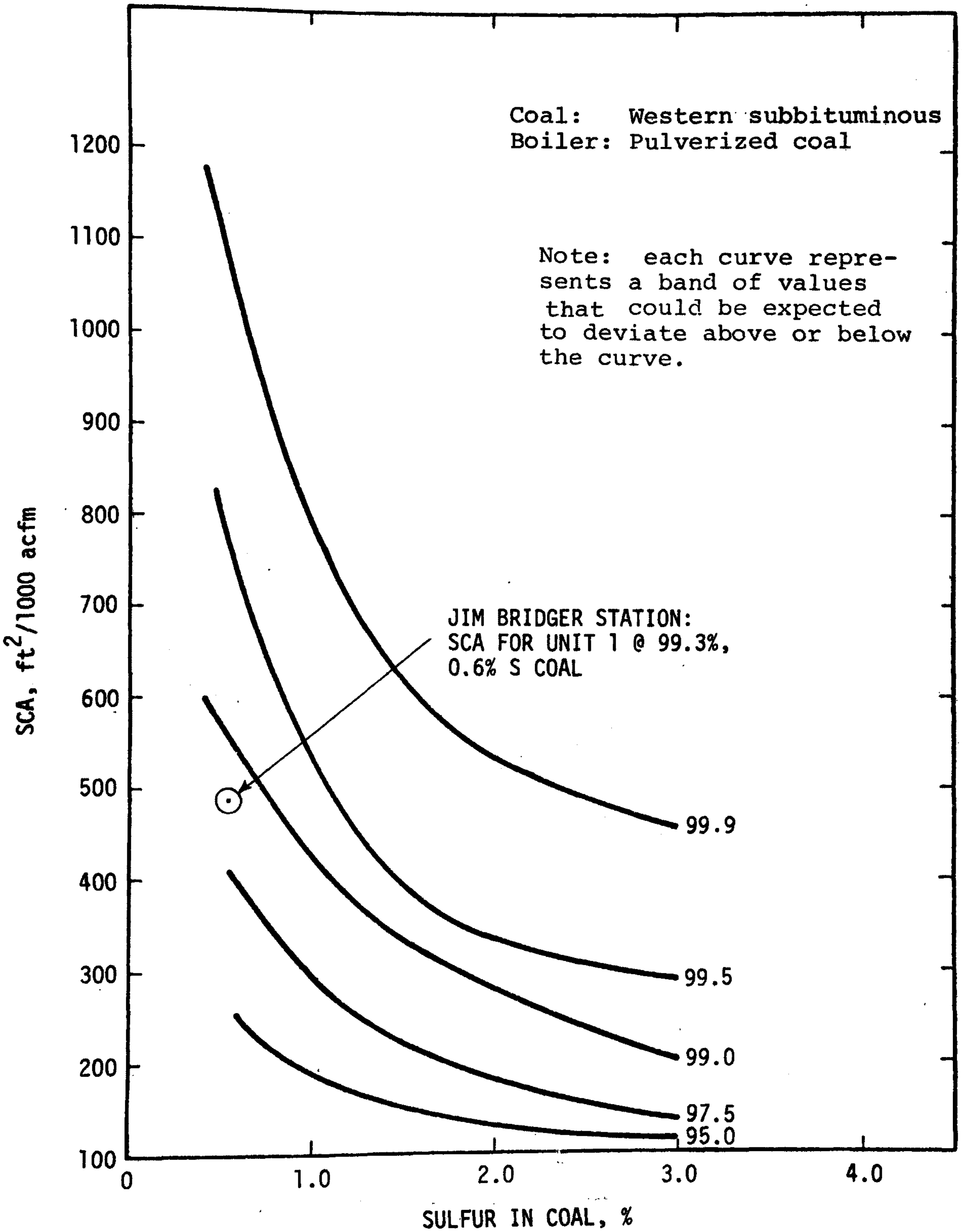

Figure 2-5. SCA versus sulfur content: cold-side ESP, pulverized western subbituminous.

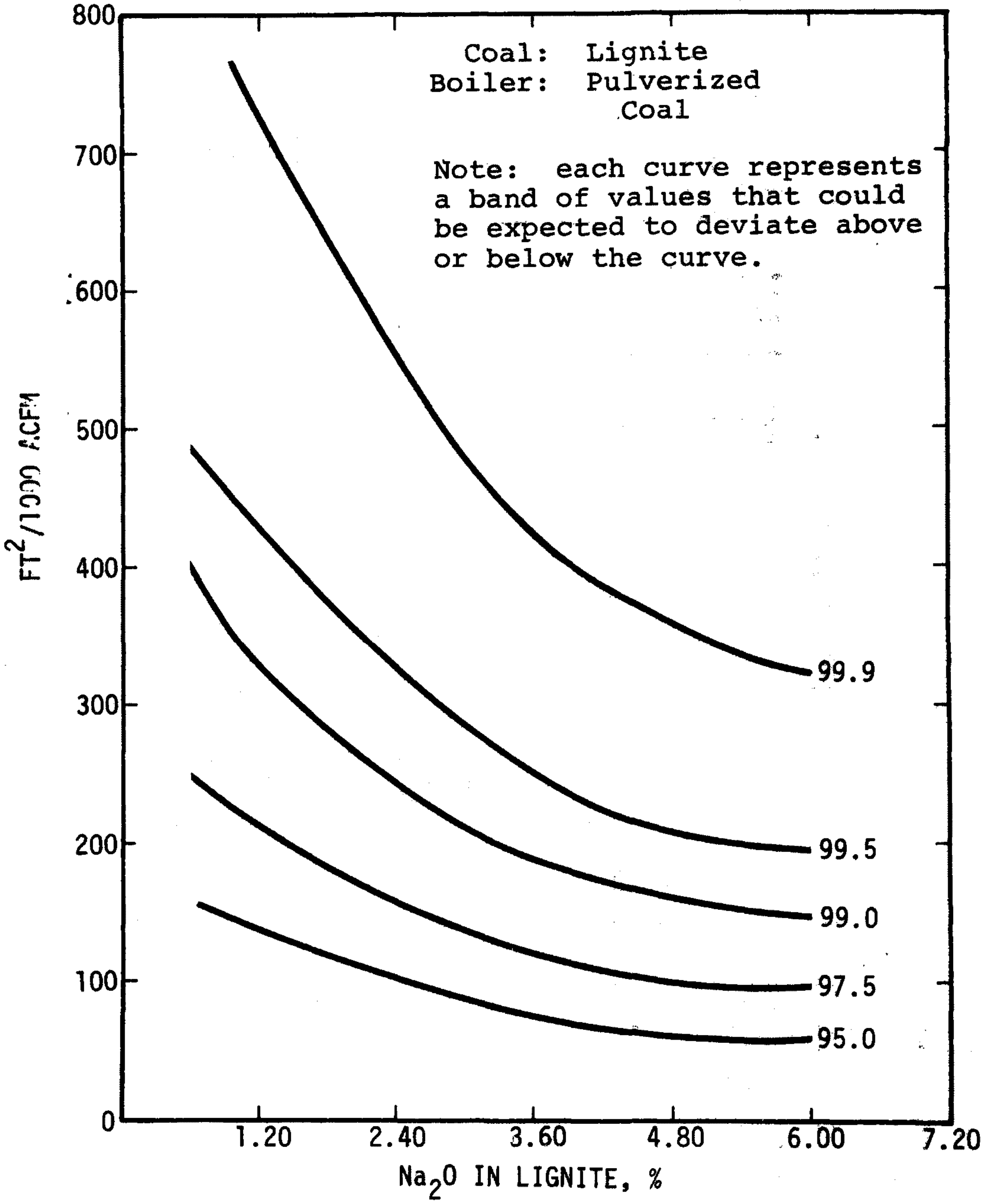

Figure 2-6. SCA versus sodium content: cold-side ESP, pulverized lignite.

lignite. Although the data on cyclone boilers are inadequate for plotting, it was found with one specific lignite-fired cyclone boiler that increasing percentage of sodium in the coal apparently (1) fused other constituents in the ash and caused retention of ash in the boiler; (2) produced coarser fly ash particles; (3) lowered the electrical resistivity of the fly ash; and (4) improved the optical properties of the stack plume. If, as is indicated in (2) the fly ash particle is coarser, then one would not expect a difference in SCA requirements for cyclone and pulverized-coal firing of lignite as great as that for cyclone and pulverized-coal firing of bituminous coal (recall 30 to 40 percent). The precipitator design and operating data shown in Table 2-7 for power plants burning North Dakota lignite seem to bear out this observation; however, this table does not show a comparison between new cyclone and pulverized-coal firing boilers designed by the same company.

The general class of western coals presents a problem in selection of a design SCA value for cold-side electrostatic precipitators. The effect of resistivities exhibited by ashes of these coals is complicated by the high probability of back corona. Also, as mentioned previously, the unburned carbon particles emitted from cyclone boilers can be a significant factor in design for firing of both eastern and western coals.

Table 2-7. ESP DESIGN AND TEST DATA FOR POWER PLANTS BURNING NORTH DAKOTA LIGNITES[9]

Utility company	Basin Electric Power Cooperative		Minnkota Power Cooperative		Otter Tail Power Company				Montana Dakota Utilities		United Power Association
Station	Leland Olds 1	Leland Olds 2	Milton R. Young 1	Milton R. Young 2	Hoot Lake 2	Hoot Lake 3	Ortonville	Big Stone	Heskett 1	Heskett 2	UPS - Stanton
Location	Stanton, North Dakota		Center, North Dakota		Fergus Falls, Minnesota		Ortonville, Minnesota	Milbank, South Dakota	Mandan, North Dakota		Stanton, North Dakota
Boiler capacity, MW	215	440	235	438	61	79	21	440	25	66	160
Firing method	PC	CYC	CYC	CYC	PC	PC	Spreader-stoker	CYC	Spreader-stoker	spreader stoker	PC
ESP vendor	Research Cottrell	Western	Research Cottrell	Wheel-abrator	Research Cottrell	Research Cottrell	Research Cottrell	Wheelabrator	Research Cottrell	Research Cottrell	Research Cottrell
New or retrofit installation	Retrofit	New	Retrofit	New	Retrofit	Retrofit	Retrofit	New	Retrofit	Retrofit	Retrofit
Completion date	11/74	9/75	6/75	5/77	5/72	4/72	6/72	5/75	6/75	6/75	5/76
Flue gas											
temperature, °F	360	373	385	380	330	310	345	288	418	333	350
volume, 1000 acfm	1000	2100	1170	2200	280	390	133	2330	189	452	854
velocity in ESP, fps	5.0	5.00	5.55	5.00	4.23	5.07	4.25	5.25	3.80	4.28	5.17
Specific collection area, ft²/1000 acfm	320	267	288	375	252	236	280	355	352	280	235
Number of TR sets	16	40	16	32	4	4	4	24	6	10	12
Collecting surface/TR set, ft²	19,970	14,040	21,050	25,800	17,650	23,075	310	34,400	11,100	12,650	16,720
Collecting surface/Rapper, ft²	2500	1755	2630	1120	3530	2560	2070	1120	1850	2090	2785
Inlet loading, gr/acf	2.30	1.30	1.00	1.0 to 2.7	1.87	2.09	0.97	1.17	2.5 to 4.1	0.3 to 0.6[a]	NA[b]
Outlet loading, gr/acf	0.0125	0.0125	0.01	0.006	0.015	0.015	0.0042	0.014	0.0225	0.021	NA
Design efficiency, %	99.50	99.05	99.00	99.40	98.50	98.50	98.90	98.80	99.45	97.00	98.00
Measured efficiency, %	99.45	NA	99.82	NA	99.00	99+	99+	99.63	0.01 gr/ft³ [c]	0.01 gr/ft³ [c]	NA
Migration velocity (w), cm/sec	8.26	NA	11.15	NA	9.28	9.9	8.4	8.01	NA	NA	NA

[a] ESP downstream of mechanical collector.

[b] Data not available.

[c] Only outlet loading has been measured to date.

Hot-Side Electrostatic Precipitators

In contrast to the situation with cold-side electrostatic precipitators, the design SCA for a hot-side electrostatic precipitator at a gas temperature of about 700°F is a strong function of the iron and sodium contents of the fly ash. In general, eastern coals will have relatively high iron content (ranging from 5 to 40 percent with a moderate value of around 9 percent) and relatively low sodium content (0.2 to 1.2 percent). Western subbituminous coals characteristically have lower iron contents, in the neighborhood of 5 percent Fe_2O_3, a percentage that would be a moderate to high for lignite coals. Figure 2-7 shows that with pulverized-coal firing, design SCA's for eastern low-sulfur coals are lower than those for western low-sulfur coals. The higher SCA's in western coal applications result from the lower amounts of conductive constituents, namely iron and sodium, in western coals. Generally the influence of iron content on SCA is greater than that of sodium content because the differences in iron content of eastern and western coals are greater. The SCA's for cyclone firing, as shown in Figure 2-8, are again typically 30 to 40 percent higher than for pulverized-coal firing, the skewness of particle size distribution being responsible for the difference.

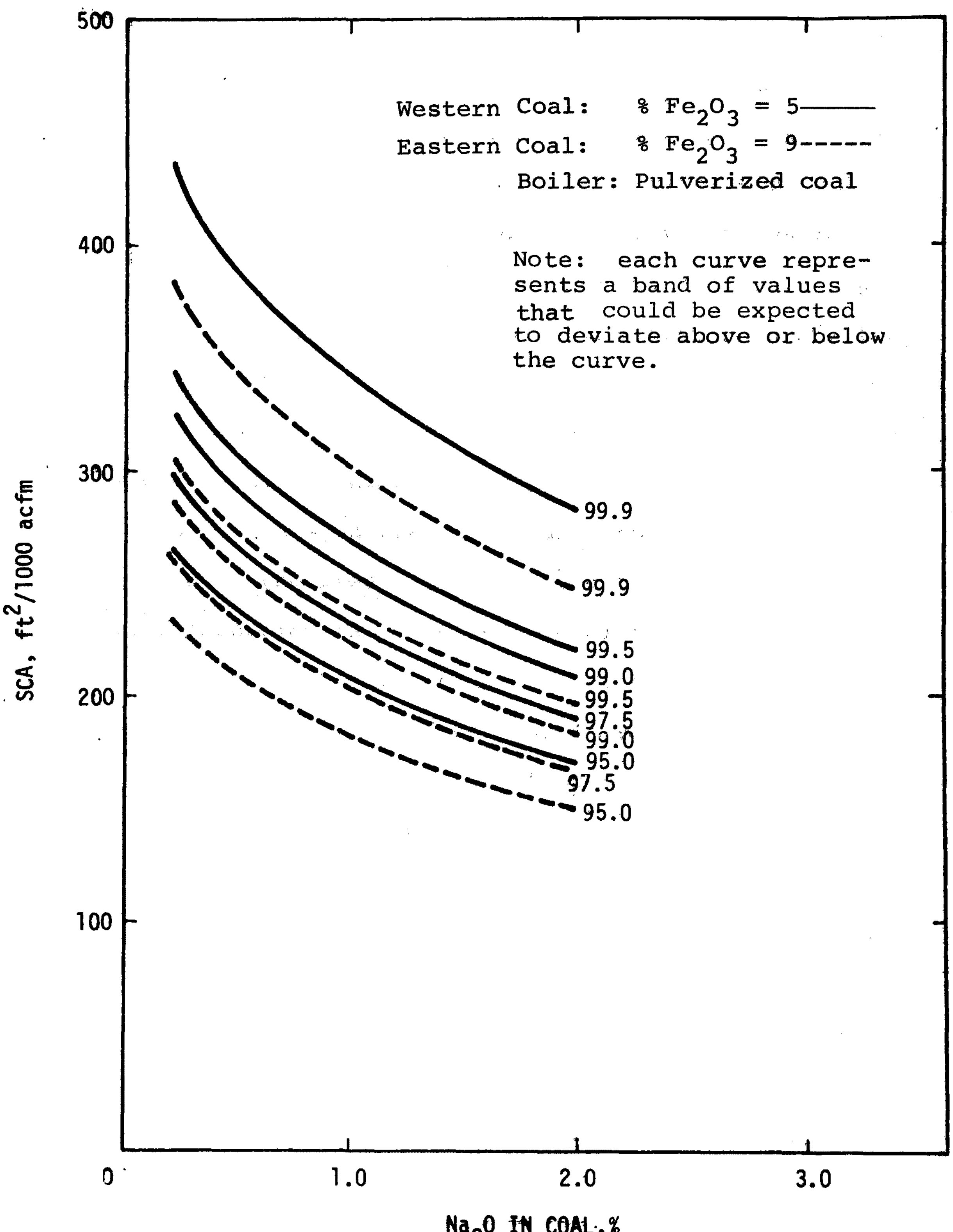

Figure 2-7. SCA versus sodium content: hot-side ESP, pulverized-coal firing.

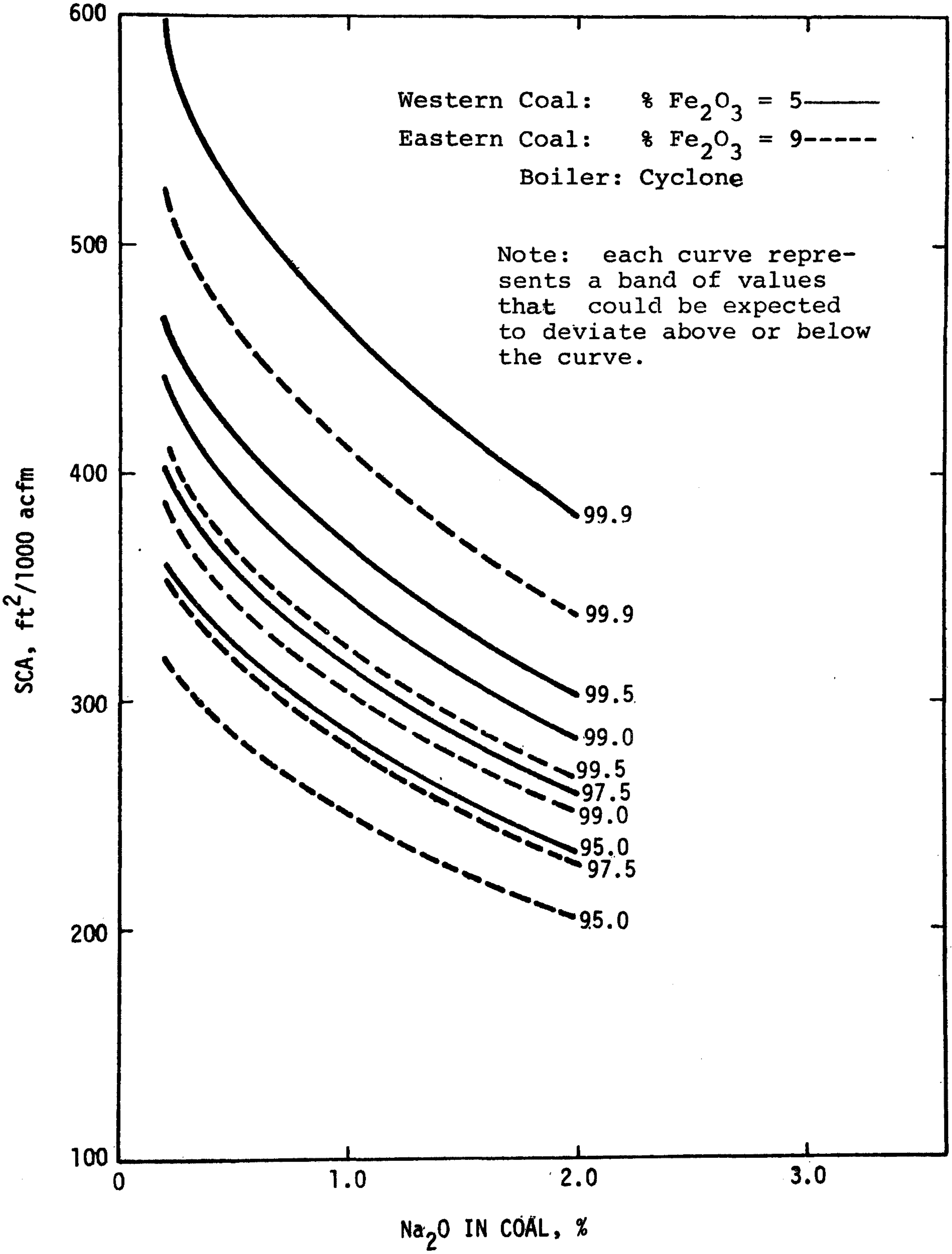

Figure 2-8. SCA versus sodium content: hot-side ESP, cyclone firing.

A hot-side precipitator may overcome the potential back corona problem prevalent with cold-side precipitators, but introduces two additional problems. Higher gas temperature causes an increase in the gas volume flow rate by slightly over 50 percent (assuming 700 and 300°F temperatures for representative hot-side and cold-side precipitators, respectively). This increased gas volume would require a greater collection area than is needed for a cold-side precipitator with the same SCA. Furthermore, the higher temperature increases the current density and reduces the sparkover voltage associated with the lower gas density. The result is operation of the precipitator at reduced voltages, with a concurrent reduction in the effective migration velocity, again requiring additional plate area although higher current levels can partially offset the effect of operating at reduced voltages. Both of these effects are offset by the lower SCA requirement associated with the higher temperature of operation because of reduced resistivity (often by 2 orders of magnitude). Performance data as shown in Figure 2-9, as well as the correlations presented in this report verify the reduced SCA requirement for hot-side precipitators.

The decision to select a hot-side or a cold-side precipitator is based on economics. This must be carefully evaluated for each application.

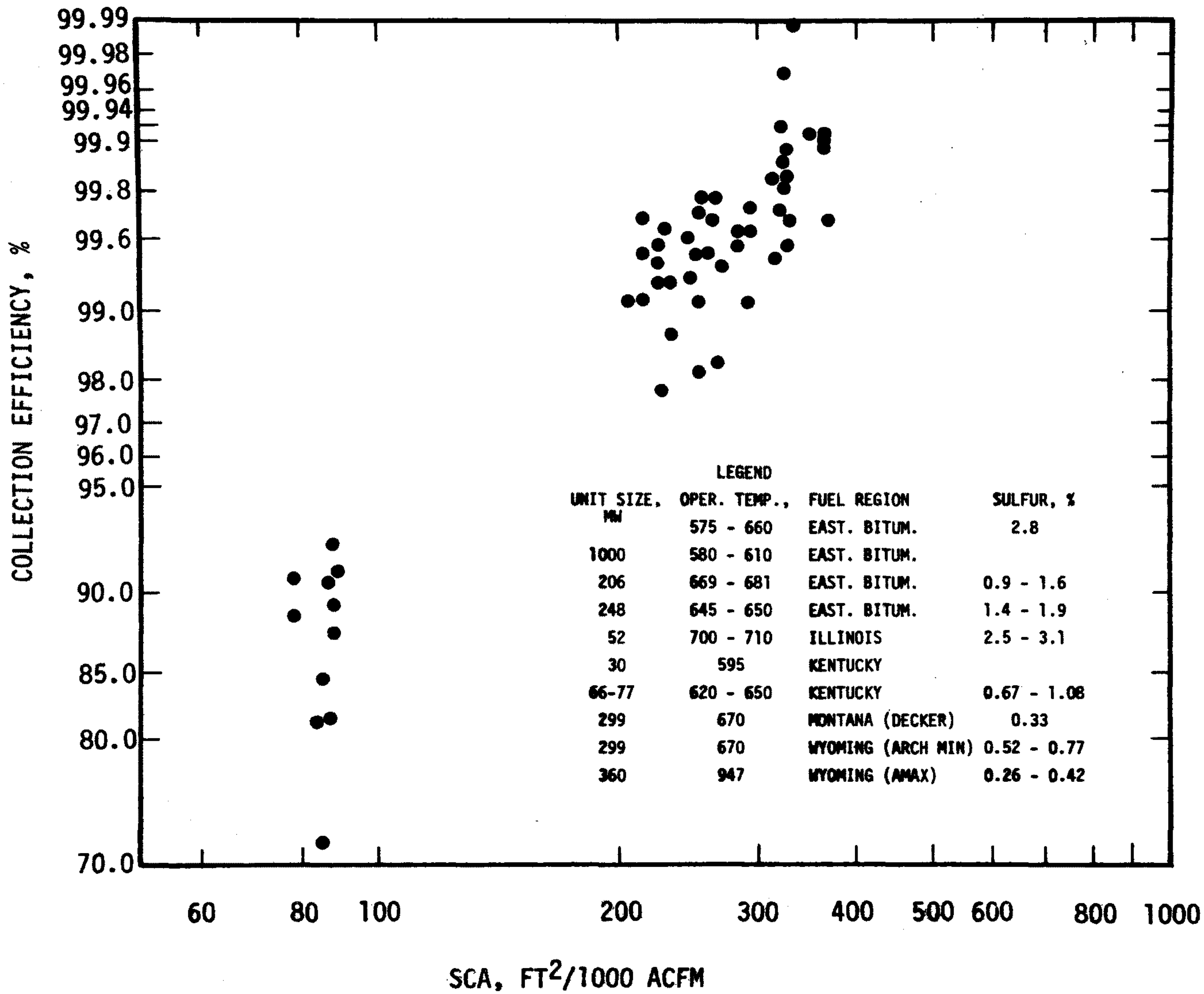

Figure 2-9. Performance versus SCA of hot-side precipitators.

2.4.2 Power Density as a Function of Significant Ash Constituents

Power density is a function of electrical resistivity, particle size, gas temperature, gas composition, and gas pressure. The value for typical design power density for pulverized-coal firing of bituminous coal is presented in Figure 2-10 for cold-side precipitators.

With high-sulfur-content coal, the fly ash is more conductive. This situation is characterized by high current and moderate working voltage. Since the milliamp rating determines the size of the transformer-rectifier sets, the T-R sets are large in anticipation of the great power demand of the highly conductive fly ash. With low sulfur content and higher resistivity (low conductivity) the current and voltage are lower. The initial effect in high-resistivity cases is increased sparking, requiring a voltage reduction in order to hold a designated spark rate. Lower corona current and power input does cause a decrease in efficiency for a given collection area. In order to compensate for lower power, the particle residence time is increased; this entails increasing the size of the precipitator until the total power requirements for the desired efficiency are met. Note that the corona power per precipitator is lower, but increased area increases the total corona power to the desired level. For this reason the effect of efficiency on power density is not shown in Figure 2-10.

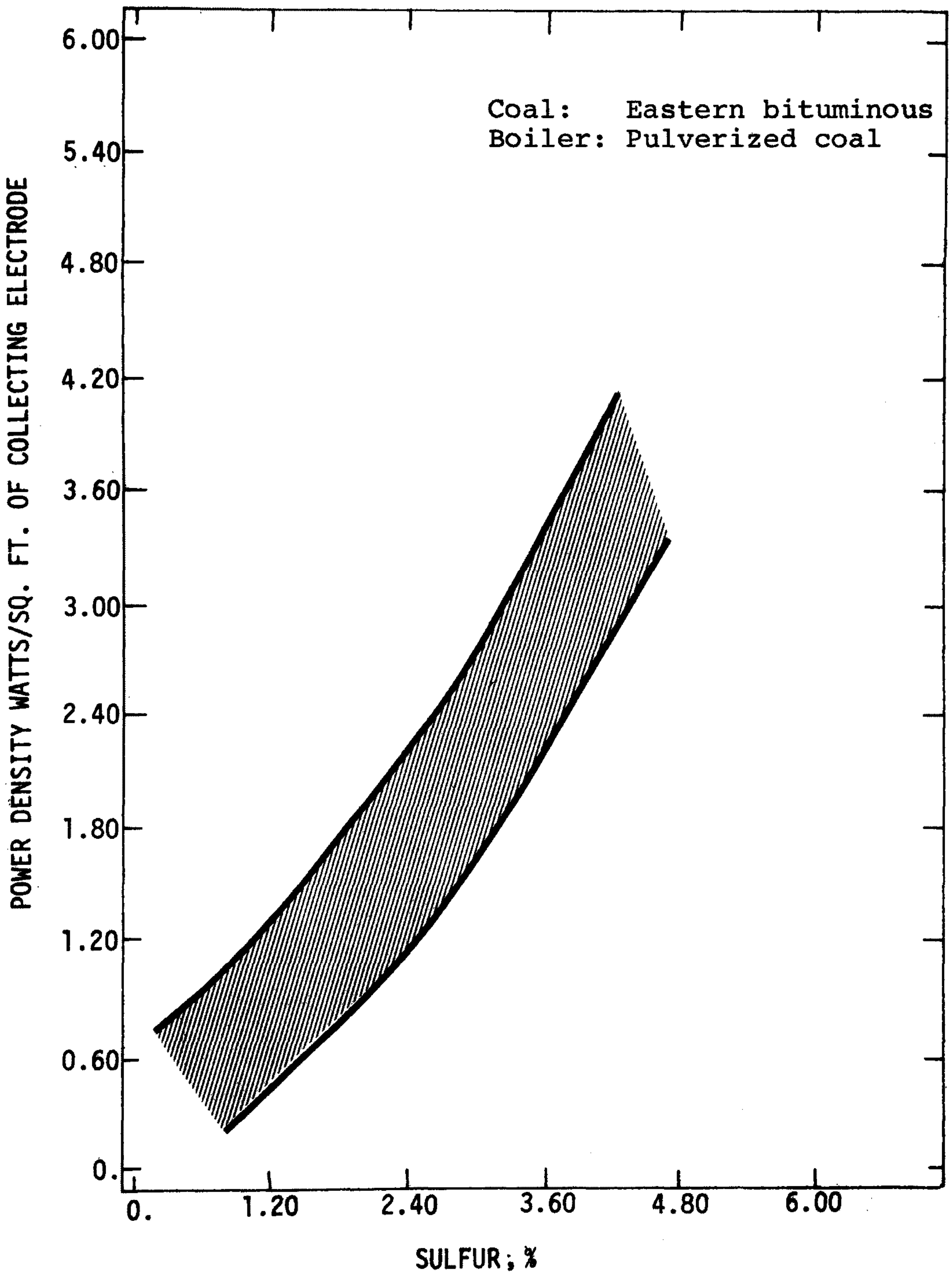

Figure 2-10. Power density versus sulfur content: cold-side ESP, pulverized eastern bituminous.

The reasoning above applies similarly to the firing of pulverized lignites (Figure 2-11). Here, however, the effect of sodium content governs the design power density.

A correlation for cyclone firing of bituminous coal is unavailable. Carbon carryover is responsible for higher power inputs than in pulverized-coal firing, but the magnitude of the shift cannot be demonstrated. The presence of smaller particles with cyclone firing can reduce corona power by suppressing corona current at a given voltage through space charge phenomena. Submicron particles of fairly high loadings would be necessary to produce a significant effect. The increased conductivity of the particle cloud due to the presence of unburned carbon, however, more than offsets the small-particle effect.

Although the values are not plotted, it can be expected that at sulfur contents above 1.5 to 2.0 percent for firing of pulverized subbituminous coal the relationship between percent sulfur and power density is similar to that in pulverized bituminous coal applications. Below 1.5 percent sulfur, the effect of sodium content is overriding, and high sodium content will induce high power.

In general, an increase in gas temperature reduces gas density, reduces sparkover potential, and increases the rate of rise of current with voltage. For hot-side electrostatic

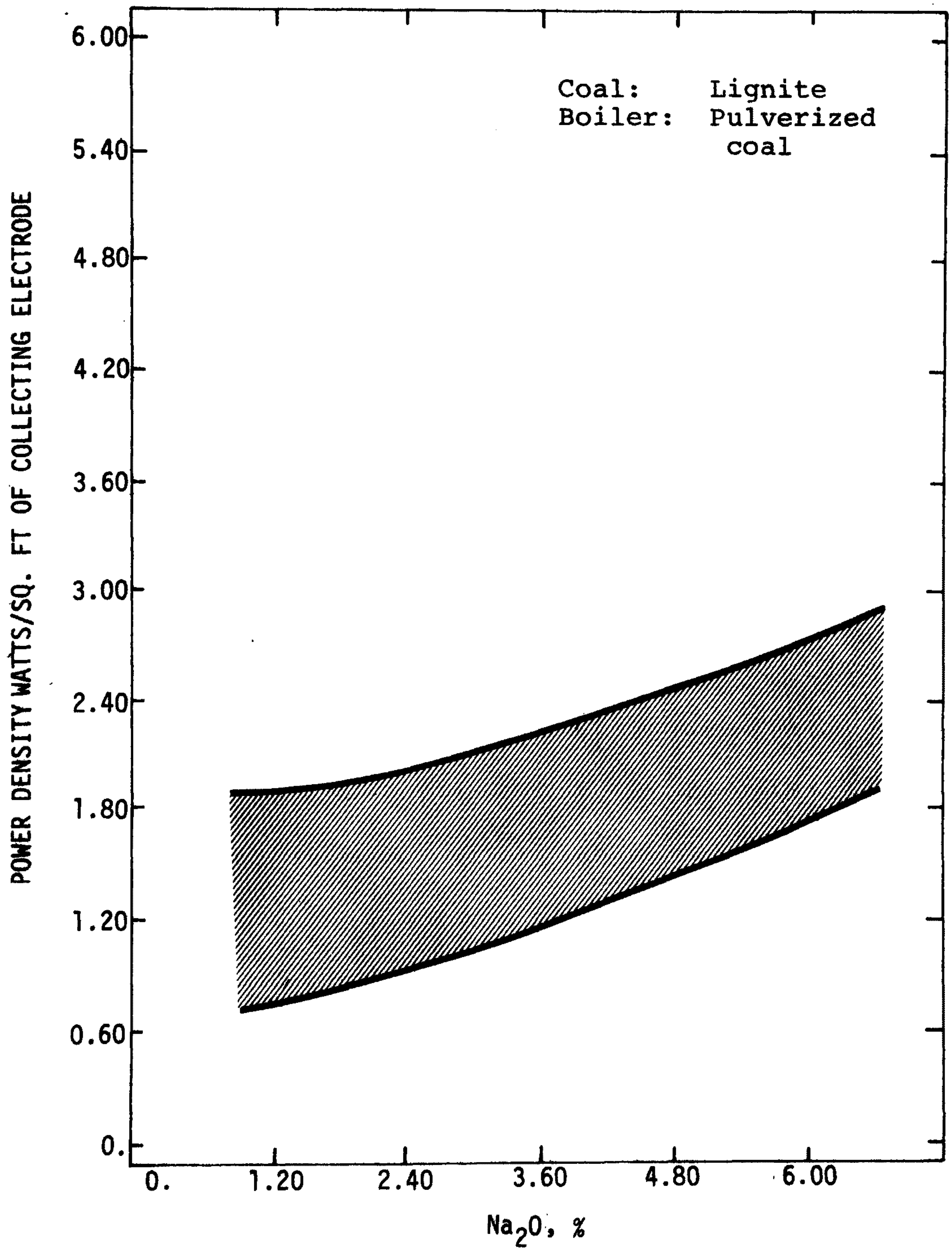

Figure 2-11. Power density versus sodium content: cold-side ESP, pulverized lignite.

precipitators (up to 1000°F), the net result is that increased gas temperature will likely yield an increase in power density.

2.4.3 Cost as a Function of Power Plant Output

Cost models were used to develop capital and operating costs on a consistent basis for cold-side and hot-side electrostatic precipitators for the various application areas as a function of plant power output (MW). These costs are presented graphically in Appendix B; Figures B-1 through B-12 present capital cost and Figures B-13 through B-24 represent annualized operating costs. Capital cost in $/kW represents the flange-to-flange installed capital cost to the user (December 1975). The values include costs for the basic collector, foundation, engineering, and erection; costs for approach ductwork and fans are not included.

Operating cost in mills/kWh includes annual labor cost, annual maintenance cost, power cost, and annual capital charges. The capital charges are based on depreciation at 7 percent of capital investment (service life of the control device, 15 years) and an interest rate of 12 percent. The total interest charge over the life of the equipment is obtained by summing the annual interest charges on the undepreciated investment. It can be shown that the average annual interest charge is (X/2) percent of the initial capital investment when the interest rate is X. Thus, based on these assumptions the annual capital charge is 13 percent of the capital investment.

The unit electricity cost is assumed to be 3.0 cents/kWh. Required operating availability of the electrostatic precipitator as a function of boiler availability, is taken at 85 percent (7446 hours/yr).

The many cases defined in Figures B-1 to B-24 are summarized in Table 2-8 with respect to the increase in cost and SCA associated with the controlling ash constituent for a given application. In line with the increase in SCA with the change from cyclone to pulverized-coal firing of bituminous coal (usually 30 to 40 percent, may be as high as 85 percent), one would expect a constant increase in cost (Cases 1 and 2). The increase in cost is fairly constant irrespective of boiler power output, that is, ± 2 percent.

The dramatic increase in SCA, capital cost, and operating cost for Case 3 is somewhat misleading. One would not expect to find a subbituminous coal with 3.0 percent sulfur, in the U.S.A. In general, however, the costs do increase markedly at low sulfur levels and high efficiencies. The high resistivity of the fly ash requires conservatively low apparent migration velocities on the order of 0.6 to 0.75 ft/sec.

Table 2-8. TRENDS IN CAPITAL AND OPERATING COSTS OF ESP'S AS A FUNCTION OF COAL AND BOILER TYPES (AT 99.5 PERCENT OVERALL MASS COLLECTION EFFICIENCY)

Case	Coal type	Boiler type	ESP type	Direction of change of coal constituent causing increase in cost	Increase in SCA as a result of decrease in sulfur or Na_2O	Increase in cost, %[a]		Reference figure no.	
						Capital cost	Operating cost	Capital cost	Operating cost
1	Bitum.	PC[e]	Cold	3.0 · 0.6% sulfur	83	70	34	B-1	B-13
2		CYC	Cold	3.0 0.6% sulfur	83	70	34	B-2	B-14
3	Subbit.[b]	PC	Cold	3.0 0.6% sulfur	155	125	75	B-3	B-15
4	Lignite	PC	Cold	6.0 1.2% Na_2O	236	101	77	B-4	B-16
5	Western[c]	PC	Hot	2.0 0.2% Na_2O	56	48	43	B-5, B-6	B-17, B-18
6	Eastern[d]	PC	Hot	2.0 0.2% Na_2O	56	48	43	B-7, B-8	B-19, B-20
7	Western	CYC	Hot	2.0 0.2% Na_2O	56	48	43	B-9, B-10	B-21, B-22
8	Eastern	CYC	Hot	2.0 0.2% Na_2O	56	48	43	B-11,B-12	B-23, B-24

[a] The increase in capital cost over the entire range of plant power outputs considered for a given decrease in % sulfur or % Na_2O is fairly constant and may vary at most by ±2%.

[b] The sulfur range for this case is somewhat misleading. One would not expect to find a subbituminous coal with 3.0% sulfur. Therefore, the value cited for cost increase is not particularly meaningful.

[c] 5% Fe_2O_3 content with % Na_2O ranging from 0.2 to 2.0.

[d] 9% Fe_2O_3 content with % Na_2O ranging from 0.2 to 2.0.

[e] Pulverized-coal-fired boiler.

[f] Cyclone-fired boiler.

2.5 DESIGN CONSIDERATIONS - WET SCRUBBERS

Various categories of wet gas scrubbers are available on the market today. Within each category are numerous design variations, each manufacturer offering his own design. Thus, selection of a particular scrubber for a specific job is a complex task. Some of the wet scrubbers are specially designed and recommended for particulate collection rather than gaseous absorption. The following discussion, briefly describes four types of wet scrubbers that are operating on western coal utilities for particulate removal:[2]

- Chemico Venturi Scrubber
- Research Cottrell's Flooded-disc Scrubber[10]
- UOP Three-stage TCA (Turbulent Contact Absorber)
- Krebs-Elbair High-pressure Spray Scrubber

Table 2-9 presents a summary of operating parameters for wet scrubbers in the western United States.

For a specific job, the scrubber is judged by its performance in removing particulate matter over a given range of particulate size. Of course, consideration is given also to the amount of net energy spent to clean a unit mass of gas per unit time. With the increasing stringency of permissible emission limits in recent years, special interest is now focused on collection efficiencies of fine particles in the size range 5 μm and below.

The key parameters affecting particulate collection for all scrubbers are pressure drop, liquid/gas ratio (L/G), particle size distribution, and gas velocities. Besides these key parameters, the following general information is also required to justify the choice of equipment:

General Parameters

a) Gas handling capacity/module
b) Total number of modules required
c) Capital cost
d) Annual operating cost
e) Water requirement; water recirculation
f) Availability of the equipment; necessary downtime
g) Indication of fractional collection efficiency of the device
h) Total power consumption as a fraction of the generated power.

The following paragraphs describe the four types of wet scrubbers, emphasizing the variables that influence their performance. This discussion, together with the available operating data,[2] should provide information useful to utility operators in considering installation of wet scrubbers for particulate removal.

2.5.1 Category 1: Chemico Venturi

In conventional terminology, this device is also called a gas-atomized spray scrubber. The collection process mainly relies upon acceleration of the gas stream to provide impaction and intimate contact between the particulates and fine liquid droplets generated as a result of gas atomization. This is a high-energy-consuming device designed for high-efficiency particulate collection. Typically, the pressure drop in utility use is on the order of 20 inches of water or more. Collection efficiency increases with pressure drop and ratio of liquid to gas circulation. There is, however, an optimum L/G value above which additional liquid rate is not effective at a given pressure drop. In this device the pressure drop can be increased by increasing the gas velocity. The high gas velocities, which can reach 40,000 fpm, cause a high rate of wear. Not enough evidence is available to indicate the superiority of this device for fine particulate removal as applied to coal-fired boilers.[11]

Concerning the earlier-mentioned parameters relevant to scrubber operation, not enough data on this device are available to allow full evaluation. The available operating data are given in Table 2-9.

2.5.2 Category 2: Research-Cottrell Venturi, Flooded-Disc Scrubber

In Research-Cottrell's flooded-disc scrubber, the primary mechanism for particulate removal is impaction. Slurry and flue gas pass through an orifice whose area depends upon the vertical position of the disc. The resultant shearing force will create slurry droplets, which combine with particulate. The system pressure drop is a function of the gas velocity in the orifice and, to a lesser degree, the liquid velocity in that region. Although the efficiency of particle collection increases with increasing pressure drop, the inlet particle size distribution will

Table 2-9. CONDENSED SUMMARY OF OPERATING WET SCRUBBERS IN WESTERN UNITED STATES

	Arizona Public Service	Pacific Power and Light	Public Service Company of Colorado			Minnesota Power and Light		Southern California Edison	Arizona Public Service	Nevada Power Company	Montana-Dakota Utilities
	Four Corners	Dave Johnston plant	Valmont station	Cherokee station	Arapahoe station	Clay Boswell plant	Aurora plant	Mohave station	Cholla station	Reid Gardner station	Lewis and Clark station, Unit
Design and operating parameters:											
Start-up date	12/71	4/72	11/71	11/72-7/74	9/73	5/73	6/71	11/73	10/73	3/74	12/75
Application	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	SO_2	SO_2 and Particulate	SO_2 and particulate	Particulate
Reagent								Lime	Limestone	soda ash	Limestone
Vendor	Chemico	Chemico	UOP	UOP	UOP	Krebs	Krebs	So. Cal. Edison	Research-Cottrell	Combustion Equip. Assoc.	Research-Cottrell
Design	Venturi	Venturi	3-stage TCA[a]	3-stage TCA[b]	3-stage TCA[b]	High-pressure spray	High-pressure spray	horizontal 4-stage spray[c]	Venturi and packed tower[a]	venturi and wash tray[d]	Venturi, flooded disc[e]
Firing method	PC	PC	PC	PC	PC	PC	PC				Pulverized coal
No. of equipped boilers	3	1	1	3	1	1	2	1	1	2	1
No. of scrubber modules	6	3	2	9	1	1	2	1	2	2	1
Installed scrubber capacity, MW	575	330	118	660	112	350	116	170	115	250	55
Reheat?	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
Bypass?	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
Capital costs, $/kw	52	24	30	31	41	NA	NA	NA	57	44	NA
Coal	NM subbit	WY subbit	WY subbit	CO bitum	WY subbit	MT subbit	MT subbit	AZ bitum	NM bitum	UT bitum	Mont. - lignite
Sulfur in coal, %	0.68	0.5	0.6	0.7	0.6	0.8	0.8	0.38	0.5	0.6	0.45
Ash in coal, %	22	12	5.2	9.4	5.2	9	9	9	9.6	9	9.0
Calcium oxide in ash, %	4	20	20	5	20	11	11	15	NA	8-18	NA
L/G, gal/1,000 acf	9	13	50	50	50	8	8	20 per stage	15 to venturi 45 to tower	10	13 (based on inlet), 17 (based on outlet)
Pressure drop, in. H_2O	28	15	10-15	10-15	10-15	4	4	6	20	18	13
Open or closed loop	Open	Intermittent open	Open	Open	Open	Open	Open	Closed	Open	Open	Closed
Water requirement, acre ft/yr.	3,400	800	340	1,900	300	1,500	3,500	220	205	550	154
Acre-ft/MW yr	5.91	2.42	2.88	2.95	2.68	4.29	30.2	1.29	1.78	2.20	2.8
Elec. power requirement, MW.	20	7-8	6	26.4	4.5	3	1	2.7	2.8	2.4	0.5
Elec. power, % of generating capacity	3-4	2.3	5.09	4.00	4.02	0.86	0.86	1.56	2.43	0.96	1
Manpower, total operators	8	NA	NA	NA	NA	NA	NA	6	4	4	2
Inlet dust loading, gr/scfd.	12	4	0.8	0.4 to 0.8	0.8	3	2	0.07	1.2	0.3 to 0.6	1.4 (average)
Inlet SO_2, ppm	650	500	500	500	500	800	800	200	450	400	520 (average)
Particulate removal, %	99.2	0.04 gr/scf exit	0.02 gr/scf exit	0.02 gr/scf exit	0.02 gr/scf exit	99	98	70-98	99	97	98.0
SO_2 removal, %	30	40	40	20	40	20	20	70-97	90 with tower	84-95	15 (minimum)
Availability, %	80	NA	80	59-85	20-40	NA	NA	85	91 5	70-94	NA
Particulate coll. eff., %	99.2	99.0	99.75	95.0-97.5	97.5	99	98				

[a] Preceded by mechanical collector, gas stream split 60 percent to scrubber, 40 percent to ESP.

[b] Preceded by mechanical collector and electrostatic precipitator.

[c] Slipstream from a 790 MW boiler; 170 MW equivalent scrubber was preceded by a 98 percent efficient coldside ESP; scrubber was experimental and has since been disconnected.

[d] Preceded by 80 percent efficient mechanical collector.

[e] Preceded by mechanical collector.

determine the gas and liquid velocities required to achieve the desired overall mass collection efficiency.

Since venturi scrubbers generally require higher energy input than other types of wet scrubbers used for particulate collection, accurate determination of the optimum pressure drop is required. Therefore, the liquid-to-gas ratio, gas velocity, disc position, and inlet particle size distribution are all important parameters to consider.

2.5.3 Category 3: UOP, Three-Stage TCA Scrubber

This device is also known as a moving-bed scrubber, for which design details are available in the literature.[11,12] In principle, dusty gas passes upward through a bed of spheres, which may or may not go into a fluidized state depending upon the gas velocity and the density of the spheres. Scrubbing liquid is sprayed from above the spheres, resulting in formation of a turbulent zone around the spheres. In the UOP design, lightweight hollow plastic spheres go into random motion with the formation of a turbulent layer above the sphere as a result of gas flow. Dust enters the scrubber at the bottom countercurrently, contacts the main liquor, and bubbles with the liquor upward through the turbulent layer. Inertial impaction and interception are the primary collection mechanisms. The solid particles that are captured by the liquid are drained out the bottom of the scrubber. Energy consumption of this device is relatively low, with a typical pressure drop of 4 inches of water per stage and L/G ratio approximately 20 to 25 gpm per 1000 cfm. Although the device is not as efficient as the venturi scrubber for particulate removal, it has definitely better gas absorption characteristics. Provision of additional stages does not improve particle collection.[11] The special advantage of the system is high throughput gas velocities, up to 1100 fpm. In addition to the general parameters for wet scrubbers, the following are key variables for TCAs:

a) Diameter of the collecting sphere
b) Gas viscosity, temperature
c) Stage height, (height of the expanded bed)
d) Interstitial gas velocity (depends on the effective bed porosity)

Some of these variables are given in the operating data, Table 2-9.

2.5.4 Category 4: Krebs-Elbair Scrubber

This device is also categorized as a preformed spray scrubber. High-pressure spray nozzles (100 to 200 psig) are used to generate liquid droplets (300 to 600 μm in diameter), which are projected at high velocity against a membrane in the direction of gas flow. The membrane is made up of vertical bars closely spaced to act as venturis. The spray nozzles are arranged so that a rebound zone of fast-moving drops is established at the membrane surface. When the dirty gas enters the scrubber, the solid large particles are captured by the high-speed water drops (concurrent flows), mainly by the impaction mechanism. At the membrane the gas is suddenly accelerated, acting as linear venturis to do more scrubbing. Particle size distribution has a significant effect on the overall performance. Theoretically, the device can be considered as a hybrid scrubber, a combination of a concurrent spray tower and a venturi scrubber with the following important key variables:

a) Nozzle type
b) Average droplet size generated
c) Orientations of nozzles
d) Liquid flow rate per nozzle
e) Speed of the droplet
f) Average droplet number and density
g) Gas residence time
h) Length of the concurrent flow path
i) Linear size of the membrane opening

Gas retention time is very low, on the order of 2 to 3 seconds. Gas throughput velocities are very high, up to 600 fpm. Because of the low retention time, diffusional forces are not very effective in capturing submicron particles. In general, the device is not efficient enough to compete with a high-pressure venturi scrubber. The main disadvantage of this device is potential plugging of the nozzles. The gas pressure drop is on the order of 3 to 4 inches of water. There is excessive pressure drop across the nozzles, however.

A checklist for obtaining design and operating data on scrubbers used for particulate control is presented in Appendix C.

2.5.5 Costs for Particulate Scrubbers

Capital Costs

Available capital costs for operating particulate only scrubbers, as summarized in Table 2-9, range from \$30/kW to \$52/kW.

Detailed cost information is provided by Ensor et al.[13] on the Unit 3 particulate scrubber at the Cherokee Station. The total cost of the scrubber was \$4,400,000, or \$29/kW, based on a nameplate rating of 150 MW. This figure represents the total installed cost of the scrubber, which was completed in 1972. The 1975 cost of the same scrubber would be about \$5,800,000, and with modification for better performance and availability would increase to \$7,370,000, or \$49/kW. Table 2-10 presents a breakdown of the capital costs of the Cherokee Unit 3 particulate scrubber.

Annual Costs for Scrubbers

Ensor et al.[13] has also provided a detailed analysis of the operation and maintenance costs for the Cherokee Unit 3 particulate scrubber. The estimates are for direct costs only and do not include items such as general plant overhead or charges against capital (depreciation, interest, taxes, etc.). The total direct operating costs are approximately \$495,000/year. Based on 75 percent availability of the scrubber, this amounts to a cost of 0.50 mills/kWh. These costs are summarized in Table 2-11.

Table 2-10. CHEROKEE NO. 3 SCRUBBER
CAPITAL COST BREAKDOWN
1972 DOLLARS[13]

Account	Installed cost		Percent
Excavation and earthwork		$ 19,100	0.4
Concrete		100,800	2.3
Structural steel and buildings		324,300	7.4
Process equipment			
Scrubber vessel	$463,900		
Ductwork	224,600		
Presaturator	65,600		
Scrubber fans and motors	194,900		
Sootblowers	50,700		
Sootblowing air compressors	56,100		
Reheater	42,200		
Dampers and isolation gates	53,400		
Recirculation pumps and motors	48,900		
Miscellaneous pumps and motors	6,500		
Stack lining	86,900		
Instrument air compressors	10,700		
Monitoring equipment	16,400		
Miscellaneous equipment	16,500	1,337,300	30.6
Piping		235,000	5.4
Electrical		444,300	0.2
Painting		28,000	0.6
Instrumentation		263,900	6.0
Insulation		110,700	2.5
Indirect field costs (includes field supervision and payroll expenses; construction supplies; temporary facilities; demolition; construction equipment)		385,000	8.8
PSCC overhead costs		74,600	1.7
Engineering		404,400	9.2
Pre start-up and revisions		67,800	1.6
Post start-up and maintenance		143,800	3.3
Contractor fee		369,000	8.4
Interest during construction		69,300	1.6
TOTAL		$ 4,377,300	100.0

Table 2-11. CHEROKEE NO. 3 SCRUBBER OPERATING COSTS (1972)[13]

	Annual quantity	Unit cost, $	Total annual cost, $	Percent of total annual operating cost
Operating labor				
Control operator	585 man-hr	8.23/man-hr[a]	4,800	1.0
Auxiliary tender	1460 man-hr	6.31/man-hr[a]	9,200	1.9
Operating supervision	260 man-hr	8.82/man-hr[a]	2,300	0.5
Utilities[b]				
Electricity	23,000,000 KWH	0.006/KWH	138,000	27.9
Steam	98,600 metric ton (217,000 M lb)	1.54 metric ton (0.80/M lb)	151,900	30.7
Water	566,000 metric ton (1,248,000 M lb)	0.0066/metric ton (0.003/M lb)	3,700	0.7
Air	2650×10^3 m^3 (98,800 MSCF)	$5.83/10^3$ m^3 (0.165/MSCF)	15,500	3.1
Maintenance				
Labor			35,400	7.1
Instrument repair labor	585 man-hr	7.56/man-hr[a]	4,400	0.9
Material			12,300	2.5
Operating Supplies				
Lime	c	c	54,000	10.9
Polyethylene balls	1178 M	37.0/M	43,500	8.8
Miscellaneous				
Increase in ash handling	c	c	20,000	4.0
Total			495,000	100.0

[a] Includes 26% for overhead.

[b] Based on 75% on-line lime.

[c] Public Service Co. of Colorado estimates.

Annualized operating costs for other operating particulate scrubbers are not available.

2.6 DESIGN CONSIDERATIONS FOR FABRIC FILTERS

Fabric filters are basically simple devices. The removal of particulate from waste gases is accomplished by forcing the gases to flow through the fabric filter media which removes the particulates by one or more of the following mechanisms:

(1) Inertial impaction
(2) Diffusion to the surface of an obstacle because of Brownian diffusion
(3) Direct interception because of finite particle size
(4) Sedimentation
(5) Electrostatic phenomena

Parameters that are important in fabric filtration system design include air-to-cloth ratio, pressure drop, cleaning mode and frequency of cleaning, composition and weave of fabric, degree of sectionalization, type of housing, and gas cooling. Each of these factors is discussed briefly below, and available data are tabulated for the fabric filters now installed in utility plants.

2.6.1 Air-to-Cloth Ratio

A major factor in the design and operation of a fabric filter, the air-to-cloth (A/C) ratio is the ratio of the quantity of gas entering the filter (cfm) to the surface area of the fabric (ft^2). The ratio is therefore expressed as cfm/ft^2 or sometimes also as filtering velocity (ft/min). Most often only the first member of the ratio term is given, e.g. an A/C ratio of 1.5 implies 1.5 (cfm)/1.0 (ft^2). In general, a lower ratio is used for filtering of gases containing small particles or particles that may otherwise be difficult to capture. Selection of the ratio is generally based on industry practice or the recommendation of the filter manufacturer. Design A/C ratios for the fabric filters now installed in U.S. utility plants range from 1.9 to 2.8.

2.6.2 <u>Pressure Drop</u>

Pressure drop in a fabric filter is caused by the combined resistances of the fabric and the accumulated dust layer. The resistance of the fabric alone is affected by the type of cloth and the weave; it varies directly with the air flow. The permeability of various fabrics to clean air is usually specified by the manufacturer as the air flow rate (cfm) through 1 ft^2 of fabric when the pressure differential is 0.5 in. H_2O in accordance with the American Society for Testing and Materials (ASTM). At normal filtering velocities the resistance of the clean fabric is usually less than 10 percent of the total resistance.[14] The spaces between the fibers are usually larger than the particles that are collected. Thus the efficiency and low-pressure drop of a new filter are initially low. After a coating of particles is formed on the surface, the collection efficiency improves and the pressure drop also increases. Even after the first cleaning and subsequent cleaning cycles, collection efficiency remains high because the accumulated dust is not entirely removed.

The pressure drop through the accumulated dust layer has been found to be directly proportional to the thickness of the layer. Resistance also increases with decreasing particle size.[14] Even though several studies have been devoted to filtration theory, it is difficult to relate collection efficiency and pressure drop on an industrial scale. Maximum pressure drop on existing utility fabric filters is 5 to 6 in. H_2O.

2.6.3 Cleaning of Fabric Filters

Various cleaning methods are used to remove collected dust from fabric filters to maintain a nominal pressure drop of 2 to 6 in. H_2O. Mechanical shaking or reversed air flow are generally used to force the collected dust off the cloth.

Many mechanical shaking methods are in use. High-frequency agitation can be very effective, especially with deposits of medium to large particles adhering rather loosely. In such cases, high filtering velocities can be used and higher pressure drops can be tolerated without danger of blinding the cloth.

In a relatively new cleaning method, an intermittent pulse jet of high-pressure air (100 psi) is directed downward into the bag to remove the collected dust. In some designs the air is introduced at lower pressures, but these systems may require a greater quantity of cleaning air. Felted fabrics are used in conjunction with the pulse-jet cleaning method. This type of cleaning, however has not yet found use in the U.S. electric utility industry. A qualitative comparison of cleaning methods is given in Table 2-12.

In the fabric filter installation at the Nucla power plant, the bags are cleaned by a combination of shaking and reverse air flow. The normal cleaning cycle, shown in Table 2-13, is actuated by a pressure transducer near the inlet to the induced-draft fan. The pressure switch is normally set to initiate cleaning when the pressure drop across the bags exceeds about 4 in. H_2O. Once started, the cleaning cycle proceeds through all six compartments, with a 17-second interval between compartments. The pressure drop across the baghouse is about 1.2 in. H_2O lower after cleaning.[15]

The repressure air (also reverse air or collapse air) is supplied by a separate blower that constantly circulates 5600 cfm of flue gas from the outlet side of the baghouse. When no compartment is undergoing repressure, the gas is exhausted back into the duct leading to the induced-draft

Table 2-12. COMPARISON OF FABRIC FILTER CLEANING METHODS[14]

Cleaning method	Uniformity of cleaning	Bag attrition	Equipment ruggedness	Type fabric	Filter velocity	Apparatus cost	Power cost	Dust loading
Shake	Average	Average	Average	Woven	Average	Average	Low	Average
Rev. air	Good	Low	Good	Woven	Average	Average	Med. low	Good
Plenum pulse	Good	Low	Good	Felt, woven	High	High	Med.	High
Pulse-jet	Average	Average	Good	Felt, woven	High	High	High	V. high
Vibrating, rapping	Good	Average	Low	Woven	Average	Average	Med. low	Average
Sonic assist	Average	Low	Low	Woven	Aberage	Average	Med.	

Table 2-13. NORMAL CLEANING SEQUENCE FOR EACH COMPARTMENT OF THE NUCLA BAGHOUSE[15]

Event	Duration, Seconds	Damper Positions
Settle	54	Main damper closed, repressure damper closed
Repressure	15	Main damper closed, repressure damper open
Settle	56	Main damper closed, repressure damper closed
Shake	10	Main damper closed, repressure damper closed
Settle	56	Main damper closed, repressure damper closed
Repressure	15	Main damper closed, repressure damper open
Settle	34	Main damper closed, repressure damper closed
		Main damper open, repressure damper closed
Interval	17	Initiate next compartment cleaning

fan. When repressuring is initiated, the main damper is already closed and the repressure damper opens, allowing the filtered flue gas to flow through the dirty bags in the opposite direction to normal filtration at a velocity of 1.09 fpm. This gas then exits the compartment and joins the dirty flue gas entering the remaining five compartments.[15]

Following the first reverse air flow and after about 1 minute of settling time the bags are shaken. The amplitude is not known and is not divulged by the manufacturer; frequency was measured at 4 cycles per second.[15] The shaking action appeared gentle and is most likely performed to ensure loosening of the cake from the bag.

At the Sunbury plant the bags are cleaned by reversing the gas flow through a compartment using a collapse air fan. This partially collapses the bags and allows some of the dust to be released and fall into the hopper below. Collapse fan airflow is discharged into the baghouse inlet flue where any entrained fly ash is filtered by the bags.

Each compartment is cleaned in the following manner:

1. The gas inlet damper to the compartment closes, shutting off the flow of "dirty" flue gas to this compartment.

2. The collapse damper opens, allowing a reverse flow of "clean" flue gas from the outlet flue to be pulled through the bags, partially collapsing and thus cleaning the bags.

3. The collapse damper closes.

4. The gas inlet damper opens, returning the compartment to the filtering mode.

2.6.4 Frequency of Cleaning

So that no sizable portion of the total fabric will be out of service for cleaning at any given time, the time required for cleaning should be a small fraction of the time required for dust deposition. With shake cleaning equipment, for example, a common cleaning-to-deposition time ratio is 0.1 or less.[16] With a ratio of 0.1, 10 percent of the compartments in the baghouse are out of service at all times during operation. Therefore, the frequency of cleaning should be designed to minimize this ratio.

2.6.5 Selection of Fabric

Selection of fabric is generally based on the operating temperature and on the resistance of the fabric to abrasion and corrosiveness of the gases. Table 2-14 shows typical characteristics of various fabrics,[14] which include cotton, wool, fiberglass, and man-made fibers. Many fabric weaves are also available, or the fabric may be felted, in a process whereby the identity of the separate yarns tends to be replaced by a more uniform mat. The felted fabrics are almost always cleaned by reverse jet or pulse-jet methods. Fabric characteristics may also be altered by further treatment for specific purposes, such as to decrease adhesion or improve wearability. Fiberglass bags are normally supplied with a lubricating substance to reduce abrasion.

Table 2-14. FABRIC FILTER CHARACTERISTICS[14]

Fiber	Operating Exposure, °F		Supports Combustion	Air Permeability[a], cfm/ft²	Composition	Abrasion[b]	Mineral Acids[b]	Organic Acids[b]	Alkali[b]	Cost[c] Rank
	Long	Short								
Cotton	180	225	Yes	10-20	Cellulose	G	P	G	G	1
Wool	200	250	No	20-60	Protein	G	F	F	P	7
Nylon[d]	200	250	Yes	15-30	Polyamide	E	P	F	G	2
Orlon	240	275	Yes	20-45	Polyacrylonitrile	G	G	G	F	3
Dacron[d]	275	325	Yes	10-60	Polyester	E	G	G	G	4
Polypropylene	200	250	Yes	7-30	Olefin	E	E	E	E	6
Nomex®[d]	425	500	No	25-54	Polyamide	E	F	E	G	8
Fiberglass	550	600	Yes	10-70	Glass	P-F	E	E	P	5
Teflon®[d]	450	500	No	15-65	Polyfluoroethylene	F	E	E	E	9

a cfm/ft² at 0.5 in. w.g.

b P = poor, F = fair, G = good, E = excellent.

c Cost rank, 1 = lowest cost, 9 = highest cost.

d Du Pont registered trademark.

A recent study[16] conducted to determine the feasibility of applying fabric filters on coal-fired industrial boilers involved four different filter media: Nomex^R felt, Teflon^R felt, Gore-Tex^R, and Dralon^R. Weights and permeabilities are shown in Table 2-15. The study concluded that filtration with Nomex achieved the lowest outlet dust concentrations and provided higher collection efficiencies than with the other fabrics both with and without cleaning being done. Teflon felt operated at the lowest pressure drop, and the dust-release properties of Teflon felt and Gore-Tex appeared better than those of Nomex and Dralon. However, it is expected that the life of Nomex will be short because of hydrolytic attack, unless the fabric is protected or treated to resist attack. Thus far only fiberglass bags have been used on the coal-fired utility boilers at Nucla, Sunbury, and Holtwood.

2.6.6 Degree of Sectionalization

Design of the degree of sectionalization or the number of separate filter compartments requires knowledge of the variation in gas flow with respect to process or plant ventilation, the sizes of commercially available units, and the expected frequency of maintenance.[16] Individual compartments in small collectors may contain as little as 100 ft^2 of fabric surface; some large collectors with a capacity of 50,000 cfm may contain only one compartment.[16] Multiple

Table 2-15. CHARACTERISTICS OF NOMEX,® TEFLON,® GORE-TEX,® AND DRALON® [16]

Filter Media	Weight, oz/yd^2	Permeability cfm sq ft @ 1/2 in. H_2O ΔP
Nomex® Felt[a]	14	25-35
Teflon® Felt[b] Style 2663	22-24	15-35
Teflon® Felt Style 2063	18-20	25-65
Gore-Tex®[c]	4-5 + Laminate	8-15
Dralon-T® Felt[d]	13-15	20-30

[a] High temperature resistant nylon fiber (polyamide).

[b] Tetrafluoroethylene (TFC) Fluro-Carbon.

[c] Expanded Teflon (polytetrafluroethylene) with interfacing air filled pores.

[d] Homopolymer of 100% acrylonitrile.

Registered trademarks: Nomex® and Teflon® -- E.I. du Pont de Nemours and Company; Dralon® -- Farbenfabriekn Bayer AG; Gore-Tex® -- W. L. Gore and Associates.

compartments of any size may be selected, depending upon availability. The largest size to date has a capacity of 4.5×10^6 acfm.

The Nucla and Sunbury Stations contain 6 and 14 compartments per baghouse, respectively, with 5161 ft^2 and 8262 ft^2 per compartment, respectively.

In existing utility applications, at least one compartment will be out of service during the cleaning cycle.

2.6.7 Filter Housing

Configuration of the filter housing depends on the required fabric surface area and on the temperature, moisture content, and corrosiveness of the gases. When the baghouse is designed so that the dirty gas enters the inside of the bags under positive pressure, housing may be needed only for weather protection or for emission measurements. Both the Nucla and Sunbury baghouses are enclosed and insulated to keep the temperature above the dew point. At Sunbury, the baghouse enclosures, including the interior partitions, are constructed of 14-gauge mild steel and are of all welded construction. The 14-gauge partitions and welded construction were decided upon to insure gastight construction to permit safe entering of isolated compartments for routine inspections and minor maintenance while the baghouse is in service.

The floor area required for a baghouse depends on the filtering surface area and size of the bags. For example, 1750 ft^2 of filtering area can be provided in about 80 ft^2 of floor area by using bags 6 inches in diameter and 10 feet long. If 12-inch-diameter bags are used, they must be about 14 feet long to provide the same filtering area in the same floor space, though 12-inch-diameter bags can easily be obtained in length of 20 feet or more when there is adequate head room. This configuration (12 in. x 20 ft) would provide a baghouse having about 2500 ft^2 of filtering area in the same floor space (80 ft^2).[17] The length/diameter ratio affects the stability of vertical bags, so care must be taken to ensure that bags do not rub together during operation or cleaning. The length/diameter ratio ranges from 5 to 40,[14] and the Nucla and Sunbury ratios are 33 and 30, respectively.

Design consideration must be given to allow adequate space below the filter bags for the collecting hopper. The hoppers are commonly designed with 45-degree or 60-degree sloping sides to provide adequate sliding. The dust collected in the hopper can be removed by screw conveyors, rotary valves, trip gates, air slides, and other methods.

The most common construction material for the housing is steel; other materials, such as concrete and aluminum, are also used. Corrugated asbestos cement paneling is often used for exterior roofing and siding, with interior walls and partitions made of steel.[17]

2.6.8 Gas Conditioning or Cooling

Frequently, gases to be cleaned are too hot to directly undergo cleaning in a baghouse and they are therefore cooled before entering the filtration system. Gas cooling, however, is not required for fabric filters used on coal-fired utility boilers, because most are equipped with air preheaters.

2.6.9 Tabulation of Design Factors

Values for some of the design factors discussed above are presented in Table 2-16 for the three filtration systems currently operating in the electric utility industry. Boiler and fuel characteristics for these installations are shown in Table 2-17. The fabric used at all three installations is made of fiberglass. Note that the Teflon-coated fiberglass used at Sunbury weighs less than the fabric used at Nucla, even with a lower permeability.

2.6.10 Costs for Fabric Filters

2.6.10.1 Capital Costs - Nucla Station - An engineering analysis of the installation was performed by Ensor, et al.[9] [1976] to (1) assemble information on capital and operating costs, (2) determine reliability, and (3) identify any major problems. Ensor used the records of Colorado Ute, Jelco, Inc. (constructor) and Stearns-Rogers (engineer).

Table 2-16. DESIGN FACTORS FOR FABRIC FILTRATION SYSTEMS OPERATING AT COAL-FIRED POWER PLANTS

	Nucla Plant	Sunbury Plant	Holtwood Plant
Baghouse manufacturer	Wheelabrator-Frye, Inc.	Western Precipitation	Wheelabrator-Frye, Inc.
Baghouse capacity, acfm	86,240[a]	222,000	200,000
Type of baghouse	Suction (size 814, model 264, Series 8)	Suction	Suction
Air-to-cloth ratio	2.79	1.92	2.42
Maximum pressure drop, in. H_2O	6	5	N/A
Bag fabric	Graphited Fiberglass	Teflon-coated fiberglass	Fiberglass
Fabric weight	10.5 oz/yd^2	9.5 oz/yd^2	N/A
Fabric permeability	86.5 cfm/ft^2	75 cfm/ft^2	N/A
Cleaning method	Shaking and reverse air flow	Reverse air flow	Shaking and reverse air flow
Bag size	8 in. diameter x 22 ft length	12 in. diameter x 30 ft length	8 in. diameter
Total no. of bags	672	1,260	N/A
Total filter area	30,964 ft^2	115,668 ft^2	N/A
No. of compartments in baghouse	6	14	N/A

N/A: Not available.

[a] 3 Baghouses; each 86,240 acfm.

Table 2-17. BOILER AND FUEL CHARACTERISTICS FOR UTILITY PLANTS USING FABRIC FILTRATION SYSTEMS

	Nucla Plant	Sunbury Plant	Holtwood Plant
<u>Boiler Data</u>:			
No. of boilers	3	4	N/A
Firing method	Stoker	Pulverized	Pulverized
Rated capacity, MW	39 (total)	175 (total)	N/A
Steam rate/boiler, lb/hr	131,800	400,000	700,000
<u>Fuel Characteristics</u>:			
Coal type	Western coal HV, 12,000 Btu/lb 0.5 - 0.7% sulfur 14-20% ash 45% fixed carbon	80% anthracite silt and 20% petroleum coke normally used. Minimum coke is 15% and maximum coke is 35%. Rest is anthracite silt <u>Coke</u>: 3.7-5.9% sulfur 0.1-4.9% ash 81.8-90.7% fixed carbon <u>Anthracite Silt</u>: 0.4-1.2% sulfur 22.8-49.3% ash 44.5-65.5% fixed carbon	Anthracite fines (No other data available)

Since the Nucla plant was retrofitted with baghouses and other additional equipment, some of the costs may be unique to the Nucla site. Table 2-18 presents a summary of Ensor's estimate. The unit costs of $87/kw or $12.97/acfm include everything associated with the control devices. The costs are escalated from 1973/1974 to 1976 at 10 percent per year. Remote location, small size, lack of skilled labor at the site all contributed to abnormally high cost.

Table 2-18. SUMMARY OF CAPITAL COST
NUCLA STATION BAGHOUSES[9]

		%
Equipment and Installation		
Baghouse and general	$1,740,000	67
Ash conveyor system	250,000	9
Retrofit items	210,000	8
TOTAL FIELD COST[a]	$2,200,000	84
Indirect Owner Costs	120,000	5
Engineering and Fee	300,000	11
1973/1974 INSTALLED SYSTEM COST	$2,620,000	100
Estimated Escalation to 1976	680,000	25
1976 INSTALLED SYSTEM COST	$3,300,000	
Unit Factors (1976)	- $87/kw - $13/acfm - $36/ft^2 filter (gross)	

[a] Includes material, labor, supervision, field overhead, and constructor's fees.

2.6.10.2 Capital Costs - Sunbury Station - For the Sunbury baghouse system, the 1973 total cost was about $5.5 million, including the ash slurry handling system. This cost is for four baghouses, each having a capacity of 222,000 acfm.[18] Escalated to 1976 at 10 percent per year, the installed cost is $42/kw or $8/acfm. If the baghouse cost alone is considered, the capital cost works out to be $25/kw or $5/acfm. Unfortunately, the costs for Sunbury cannot be compared directly with those for Nucla since the baghouses are made by different manufacturers and have different capacities, which might affect the cost per kw or acfm. It is reasonable to conclude, however, that the 1976 installed capital cost would range from about $42 to $87/kw ($8 to $13/acfm) for a baghouse having a capacity in the range of 86,000 to 220,000 acfm. These values are based on the 1973 Nucla and Sunbury costs of $29 and $65/kw ($6 and $10/acfm) and assumption of an inflationary rate of 10 percent per year. A detailed breakdown of installation costs for the Sunbury system is shown in Table 2-19.[18] Some of Sunbury's steam is used other than in the two 87.5-MW turbines, so that $/kw are slightly higher than would be expected.

Since selection of control devices cannot be made on the basis of capital cost alone, and since complete data on operation and maintenance costs of fabric filters on coal

Table 2-19. SUNBURY STEAM ELECTRIC STATION BAG FILTER INSTALLATION COST BREAKDOWN[18]

Expenditure Description	Material cost, $	Labor cost, $	Total cost, $
Western Precipitation contract			
Four baghouses	1,266,985	1,020,000	2,285,985
Design and engineering - baghouse			493,400
Design and engineering - hopper enclosures			69,740
Vacuum cleaning system	30,415	43,820	74,235
Extra platforms, caged ladders, etc.	95,105	21,205	116,310
Supplements and contingencies			161,030
Western Precipitation contract		Subtotal	3,201,700
Land and land rights			1,500
Structures and improvements			
Foundation - baghouse	37,800	45,900	83,700
Clearing site - ash lines		9,200	9,200
Clearing site - seal water lines		500	500
Clearing site - elec. conduit		87,200	87,200
Clearing site - storm drain & sewer ln		6,900	6,900
Grading (crushed stones)	2,000	3,000	5,000
Pump house			
Foundation	6,600	7,000	13,600
Superstructure	40,000	37,000	77,000
Drainage system	6,500	7,900	14,400
Light and power system	16,500	2,700	19,200
Heating system	3,700	1,600	5,300
Precipitator roof alterations	17,500	32,600	50,100
Structures and improvements		Subtotal	372,100

Table 2-19 (continued). SUNBURY STEAM ELECTRIC STATION BAG FILTER INSTALLATION COST BREAKDOWN[18]

Expenditure Description	Material cost, $	Labor cost, $	Total cost, $
Boiler plant equipment			
Ash removal system - bag filter			
Piping and fittings	190,000	135,000	325,000
High-capacity intake and accessories	50,000	37,000	87,200
Electrical connections	1,500	1,000	2,500
Ash slurry systems			
Piping, valves, and fittings	175,000	113,400	288,400
Slurry tank and accessories	11,400	4,600	16,000
Pumps & drives	57,000	26,300	83,300
Electrical connections	500	400	900
Raw water pump			
Foundations	7,700	7,000	14,700
Pumps and drives	15,400	7,000	22,400
Piping, valves, and fittings	28,500	16,700	45,200
Electrical connections	2,500	900	3,400
Booster pumps			
Foundation	4,400	10,500	14,900
Pumps & drives	24,600	7,900	32,500
Piping, valves, and fittings	12,500	15,000	27,500
Electrical connections	3,500	1,500	5,000
Mechanical hoppers-expansion	26,400	59,400	85,800
Multiclones in mesh collectors-replace		51,000	51,000
Piping for extended mech. hopper	700	3,900	4,600
Air piping, valves, and drives	6,800	10,500	17,300
Platforms and walkways	21,500	40,900	62,500
Boiler plant equipment		Subtotal	1,190,000

Table 2-19 (continued). SUNBURY STEAM ELECTRIC STATION

BAG FILTER INSTALLATION COST BREAKDOWN[18]

Expenditure Description	Material cost, $	Labor cost, $	Total cost, $
Accessory electric equipment			
Conduit	4,000	11,000	15,000
Power and control cable			
Power cable	7,900	10,900	18,800
Control cable	23,500	14,400	37,900
Accessory electric equipment		Subtotal	71,700
Misc. power plant equipment			
Communication			
Public address system	200	100	300
Overheads			
Engr. and supervision-indirect			109,400
Contract engineering			15,000
Engr. and supervision-direct			
Civil			75,000
Mechanical			85,800
Sta. electrical			37,000
Cost analysis and inspection			64,500
Allow. for funds used during constr.			240,000
Temporary construction power			6,000
Construction supervision			10,000
Removal cost			23,100
Salvage recovered			3,000 Cr
Overheads		Subtotal	662,800
Total construction costs (1973)			5,500,100
Escalation to 1976 @ 10%/yr			1,821,000
1976 Installed system cost			7,321,000
		Unit factors (1976)	- $42/kW - $8/acfm - $16/ft² filters (gross)

fired boilers are not available, no attempt is made here to compare the costs of fabric filters with costs of precipitators and scrubbers.

2.6.10.3 Maintenance and Operating Costs - Nucla Station - Ensor, et al.,[9] defined operating costs as any additional costs incurred by the utility attributable to the operation of the baghouse. The costs were estimated from Colorado Ute records and estimated by the plant personnel. Table 2-20 summarizes the operating costs for 1976, which were estimated at 1.53 mills/kwh based on a 55 percent capacity factor (all direct and indirect costs).

After a review of plant maintenance records Ensor, et al., found that the major maintenance item has been the replacement of bags. Table 2-21 summarizes maintenance records for the Nucla plant. The trend in labor maintenance requirements are illustrated in Figure 2-12. During the initial months of operation, it was discovered that severe bag erosion at the inlet of the bags resulted in premature bag failure. During a 6-month period starting in September 1974, gas straighteners, called "thimbles", were installed at the inlet of the bags. The thimbles resulted in a major decline in maintenance.

During the first 2 years of operation, 18 percent of the 2016 bags were replaced (32,577 baghouse hours of

Table 2-20. NUCLA FABRIC FILTER SYSTEM

OPERATING COST ESTIMATE (1976)[9]

Direct Costs	$/year	%	mills/kwh (b)
Operation labor (a)	(9,500)	(3.3)	(0.05)
Maintenenace labor	2,500	0.9	0.01
Maintenance material	8,500	3.0	0.05
Utilities	31,000	10.8	0.16
Ash handling	11,000	3.8	0.06
Subtotal, Direct	53,000	18.5	0.28
Interest Costs			
Depreciation	127,000	44.3	0.68
Interest	81,000	28.2	0.43
Insurance	3,000	1.0	0.02
Taxes	23,000	8.0	0.12
Subtotal, Indirect	234,000	81.5	1.25
TOTAL	287,000	100	1.53

a Not added since no new costs were incurred.

b Based on 188 million kwh/year or 55 percent capacity.

Table 2-21. BAGHOUSE MAINTENANCE SUMMARY[a] [9]

Maintenance Category	Period[b] Dec 1973 July 1974	Aug 1974 Jan 1975	Feb 1975 July 1976	Aug 1975 Dec 1976	Total
Bag Replacement	106/24	99/19	46/7	13/4	264/54
Control System	67/15	66/11	22/4	42/10	197/40
Dampers and Actuators	19/6	35/9	20/6	26/7	100/28
Reverse Air Fans	40/7	80/10	10/2	2/1	132/20
Pressure Taps	2/1	23/6	4/1	2/1	31/9
Hopper Heaters	1/1	16/3	14/4	0/0	31/8
Miscellaneous	12/4	7/2	0/0	9/1	28/7
Subtotal	247/58	326/60	116/24	94/24	783/166
Routine	6/2	6/2	6/2	6/2	24/8
Total	253/60	332/62	122/26	100/26	807/174

[a] Units: man hours/occurrences

[b] The four periods have the same amount of baghouse operating time.

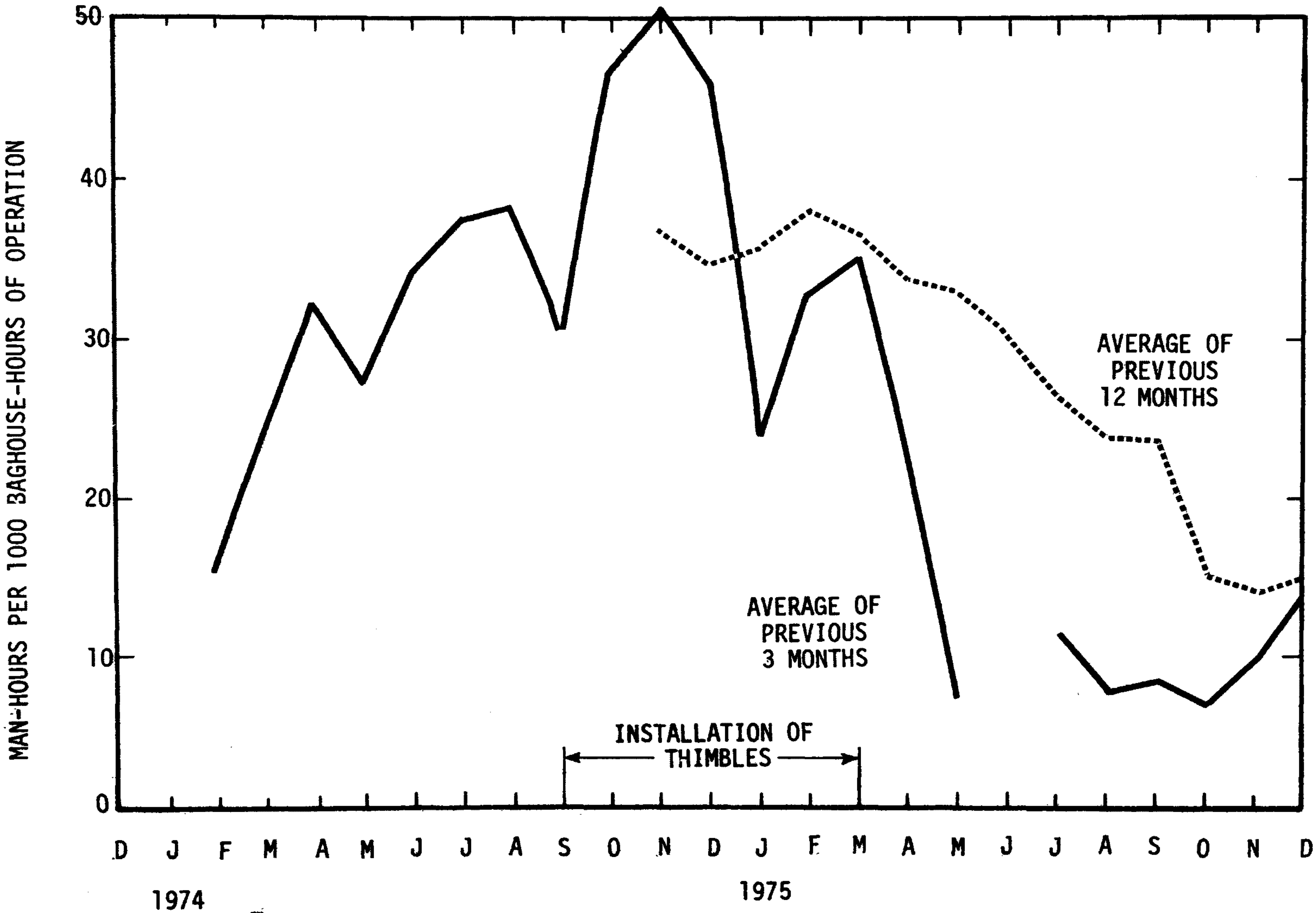

Figure 2-12. Maintenance labor requirements for the Nucla baghouse.

operation). Most of the bags were replaced before thimble installation.

The following equipment requires regular maintenance:

- the control system
- dampers and actuators
- reverse air for drives
- plugged pressure taps
- hopper heating system
- freezing of compressed air lines

Ensor, et al., analyzed the reliability of the baghouse from various points of view. The various estimates of reliability are summarized in Table 2-22.

Table 2-22. RELIABILITY OF UNIT[9]

Reliability Type	Precent of Time
Noninterference with boiler operation	100.0
Ability to produce clear stack opacity	99.4
Compartment reliability	99.8

2.6.10.4 Maintenance and Operating Costs - Sunbury Baghouse - Yearly operating and maintenance costs as estimated by the Sunbury plant superintendent are given in Table 2-23.[18] These costs, excluding complete baghouse bag replacement material and labor costs, for the four baghouses for 1973 and 1974 were $0.037 and $0.036/acfm, respectively, based on the design flow rate of 222,000 acfm per baghouse.[18] Table 2-23 indicates that mechanical maintenance costs have been increasing while electrical maintenance costs have been decreasing. This is believed to reflect some electrical problems during and after start-up and wearing of the collapse air fans with age.

Table 2-23. ESTIMATED OPERATING AND MAINTENANCE COSTS OF THE SUNBURY STEAM ELECTRIC STATION BAGHOUSE

Cost Description	1973 Cost, $	1974 Cost, $	First 6 Months 1975 Cost, $	Cost Incurred Through June 1975, $
Collapse fans power consumption	18,600	18,600	9,300	46,500
Air compressor power consumption	Insignificant	Insignificant	Insignificant	Insignificant
Complete bag replacement				
Boiler 1A				
material			48,000	48,000
labor			11,000	11,000
Boiler 2A				
material		48,000		48,000
labor		11,000		11,000
Boiler 2B				
material			48,000	48,000
labor			11,000	11,000
Instrument department labor	950	950	450	2,350
Mechanical maintenance labor	2,130	5,840	6,270	14,240
Electrical maintenance labor	7,410	3,800	2,910	14,120
Construction department labor	3,950	2,350	-	6,300
Total costs	33,040	90,540	136,930	260,510

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3.0 OPERATION AND MAINTENANCE OF PARTICULATE CONTROL DEVICES ON COAL-FIRED BOILERS

As with other complex equipment, the successful functioning of pollution control systems depends not only on sound design and proper installation, but also on proper operation. Plant personnel who use and maintain the equipment ideally will understand the engineering principles on which the system is based and will apply this knowledge both in routine operation/maintenance and in emergency situations.

3.1 OPERATION AND MAINTENANCE OF ELECTROSTATIC PRECIPITATORS

Problems with electrostatic precipitators can arise when the precipitator is brought on line and also after extended operation. Since the possible causes of poor precipitator performance are diverse, it is impractical to outline a single procedure for determining the nature of a specific problem. When a malfunction occurs, the operator must depend on his theoretical understanding of the equipment, backed by his practical experience. This section, therefore, provides background information on precipitator operation, together with detailed maintenance and troubleshooting procedures for the major component categories.

Since the basic precipitator functions are those of charging and collection of particles, the components and controls associated with the transformer-rectifier sets, rappers, and vibrators constitute the heart of the system.

The procedures presented here are those suggested by Research Cottrell, Inc. Although other manufacturers might recommend different procedures as dictated by details of system design, most of the major components, and therefore the operating procedures, are similar. Where it is possible, the recommended practices are interpreted in terms of their effects on equipment performance.

3.1.1 Background on Precipitator Operation

Electrostatic precipitation requires two groups of equipment: (1) the precipitation chamber, in which the suspended particles are electrified and removed from the gas, and (2) the high-voltage transformer and rectifier, which function to create the strong electrical field in the chamber.

The chamber consists of an outside shell (precipitator shell) made of metal, tile, or other material. Suspended within the shell are grounded steel plates (collecting electrodes) connected to the grounded steel framework of the supporting structure and to an earth-driven ground. Suspended between the plates are metal rods or wires (discharge electrodes) insulated from ground, which are negatively charged at voltages ranging from 70,000 to 105,000 volts. The great difference in voltage of the wires and the collecting plates sets up a powerful electrical field between them, which imparts a negative charge to the solid particles suspended in the gas stream. Understanding of this phenomenon requires some knowledge of electricity and chemistry; for practical purposes it is enough to know that the particles become electrically charged. The negatively charged particles are attracted to the collecting plates, which are at ground potential. The particles cling to the collecting plate and become electrically inert. Removal of the collected dust is best achieved by rapping the plates at an intensity and frequency that causes the dust to fall from the plates in sheets into a receiving hopper. Rapping that is too intense or too frequent will clean the collection plate but may also cause reentrainment of the collected dust into the gas stream.

The gas that entered the precipitator laden with particles is channeled through the precipitator outlet, while the dust collected in the hopper is removed via an ash handling system.

Figure 3-1 illustrates the major components of a fly ash precipitator with top housing (as opposed to insulator compartments, which are used in both hot- and cold-side

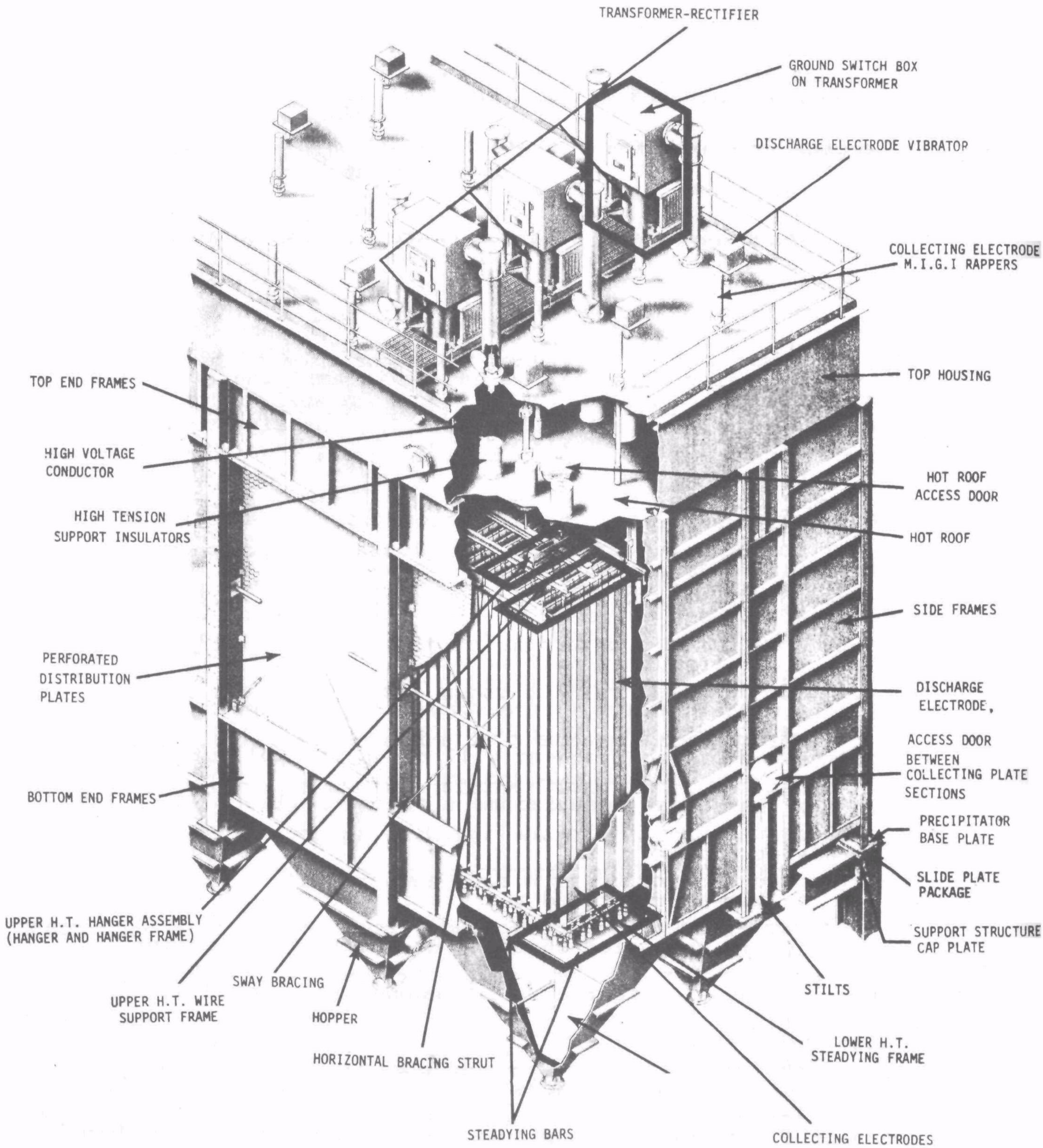

Figure 3-1. Typical electrostatic precipitator with top housing.

applications. In recent years, however, top housings have not been used in hot-side applications because of expansion problems. The remainder of this section describes the major precipitator components.

3.1.1.1 Transformer-Rectifiers - The transformer-rectifier unit consists of a high-voltage transformer, high-voltage silicon rectifiers, and high-frequency choke coils. The unit converts the low-voltage alternating current to high-voltage unidirectional current suitable for energizing the precipitator.

The transformer, rectifiers, and choke coils are submerged in a tank filled with a dielectric fluid. The tank is equipped with high-voltage bushings, liquid level gauge, drain valve, ground lug, filling plug, lifting lugs, and surge arrestors, which discharge any harmful transients appearing across the dc metering circuit to ground.

The electrical equipment described below comprises the components necessary to produce and control the high-voltage unidirectional power required to energize the electrostatic precipitator. The transformer-rectifier and control unit provide a complete system for energizing with either half-wave or full-wave voltages. Not all precipitator installations incorporate all of these subcircuits, but most will include many of the features; some of the automatic features described here may be done manually on some installations.

A subsystem that automatically maintains and limits optimum current and voltage to the high-voltage transformer, which is connected to the discharge wires.

Silicon controlled rectifiers (SCR's), which provide a wide range of precipitator current and voltage control.

A current-limiting reactor, which limits current surges during precipitator sparking.

Automatic restart to initiate system operation after a line voltage failure or temporary ground condition in the precipitator.

Overload protection for the high-voltage rectifiers.

Panels containing component modules; the SCR power circuit, dc overload circuits, relays, control transformers, resistors, main contactor, and current transformer and other components are mounted in the control cabinet and are completely accessible for servicing. Positive ventilation for the control unit is provided by an intake fan located near floor level. Ventilating air is exhausted through an opening (grill-protected) in the upper rear of the control unit.

The transformer enclosure is a square metal housing bolted to the top of the transformer tank. The enclosure protects the transformer bushings and electrical connections from weather and also ensures, via a key interlock system, that none of the electrical connections or bushings can be handled until the associated control cabinet has been deenergized and grounded.

The transformer pipe and guard are used to feed the high-voltage output of the transformer-rectifier to the support bushings, which in turn are connected to the upper high-tension support frame, from which the discharge wires are suspended. Figures 3-2 and 3-3 illustrate rapper and insulator assemblies and their relationship to the ESP system.

During normal operation, optimization of applied power to the precipitator is accomplished by automatic power controls, which vary the input voltage in response to a signal generated by the sparkover rate. Provisions are also included to make the circuit current sensitive to overload and to allow control in the event that spark level cannot be reached. Although the circuits may vary among installations, many of the features described below are common.

When the circuit breaker and control circuit on/off switch are closed, power flows through the current-limiting reactor, current transformer, and current signal transformer to the primary of the high-voltage transformer. The SCR's act as a variable impedance and control the flow of power in the circuit. An SCR is a three-junction semiconductor device that is normally an open circuit until an appropriate gate signal is applied to the gate terminal, at which time it rapidly switches to the conducting state. Its operation is equivalent to that of a thyroton. The amount of current that flows is controlled by the forward blocking ability of the SCR's. This blocking ability is controlled by the

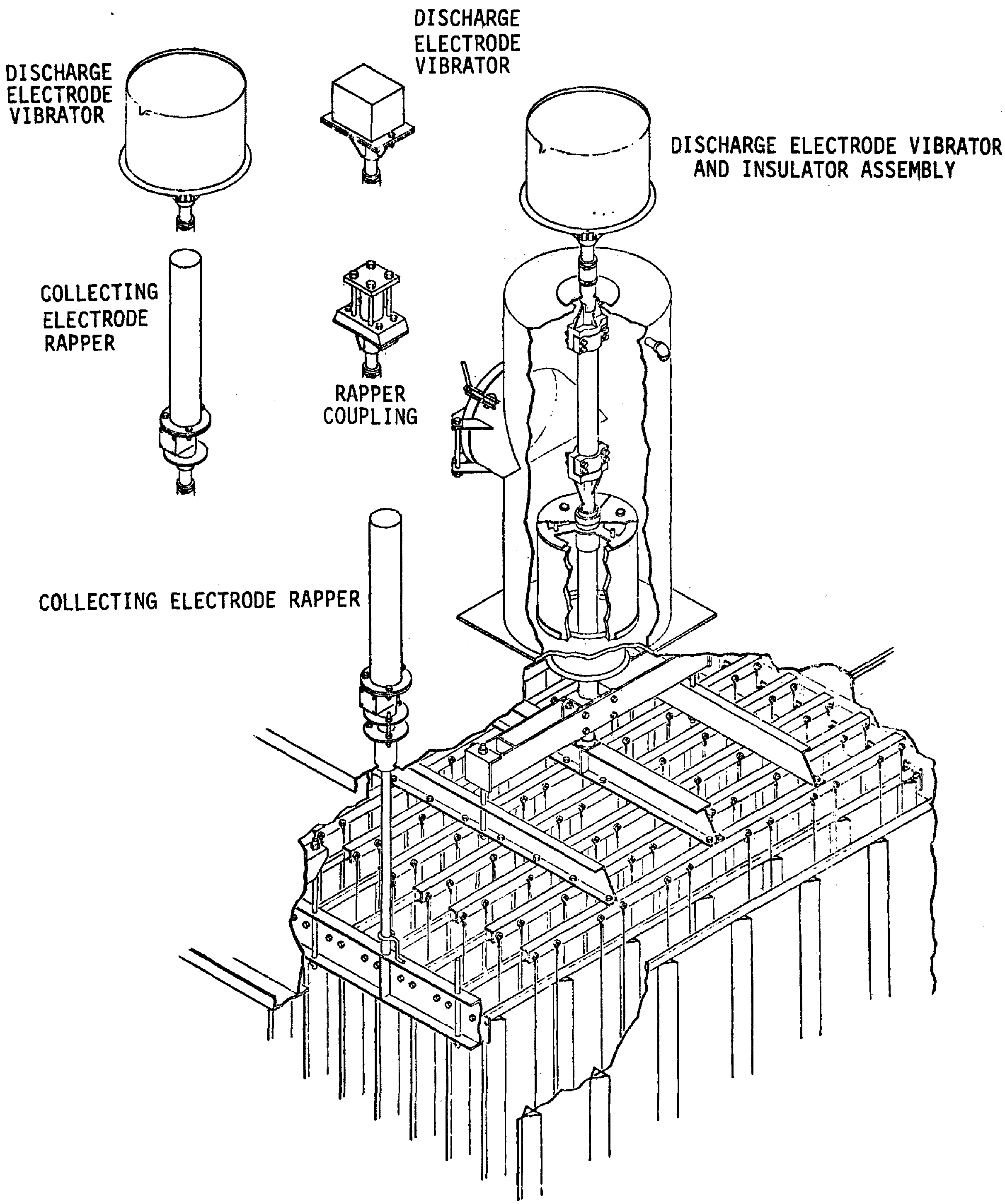

Figure 3-2. Vibrator and rapper assembly, and precipitator high-voltage frame.

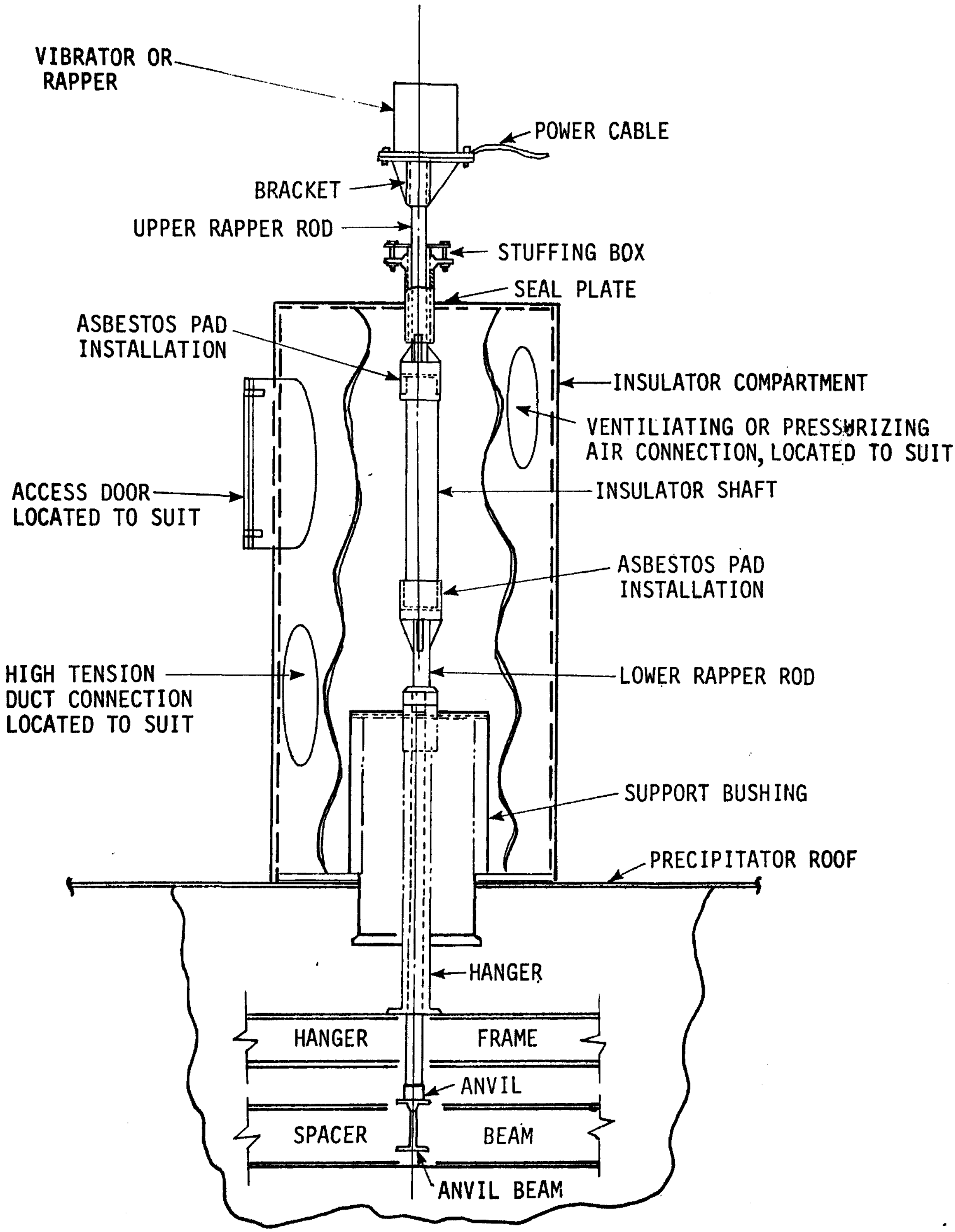

Figure 3-3. Typical precipitator insulator compartment and cleaning assembly..

firing pulse to the gate of the SCR. The current-limiting reactor reshapes the current wave form and limits peak current due to sparking.

The firing circuit module provides the proper phase-controlled signal to fire the SCR. The timing of the signal is controlled by (1) the potentiometer built in the module, (2) the signal received by the automatic controller, and (3) the signal received by the spark stabilizer.

The automatic control circuit performs three functions: spark control, current-limit control, and voltage-limit control.

Spark control is based on storing electrical pulses in a capacitor for each spark occurring in the precipitator. If the voltage of the capacitor exceeds the present reference, an error signal will phase the mainline SCR's back to a point where the sparking will stop. Usually this snap-action type of control will tend to overcorrect, resulting in a longer downtime than is desirable. At low sparking rates, about 50 sparks per minute, the overcorrection is more pronounced, resulting in reduced voltage for a longer period, with subsequent loss of dust and reduced efficiency.

Proportional control, another method of spark control, is also based on storing of electrical pulses for each spark occurring in the precipitator. The phaseback of the mainline SCR's, however, is proportional to the number of sparks in the precipitator. The main advantage of proportional control over spark control is that the precipitator determines its own optimum spark rate, based on four factors: temperature of the gas, ash resistivity, dust concentration, and internal condition of the precipitator. In summary, with proportional spark rate control, the precipitator determines the optimum operating parameters. With conventional spark control, the operator selects the operating parameters, which may not be correct.

Some precipitators operate at the maximum voltage or current settings on the power supply with no sparking. In collection of low-resistivity dusts, where the electric field and the ash deposit are insufficient to initiate sparking, the no-spark condition may arise. The fact that the precipitator is not sparking does not mean necessarily that the unit is underpowered. The unit may have sufficient power to provide charging and electric fields without sparking.

The voltage-limit control feature of the automatic control module limits the primary voltage of the high-voltage transformer to its rating. A transformer across the primary supplies a voltage signal that is compared to the setting of the voltage control, as in the case of the current limit. The voltage control setting is adjusted for the primary voltage rating of the high-voltage transformer.

When the primary voltage exceeds this value, a signal is generated that retards the firing pulse of the firing module and brings the primary voltage back to the control setting.

For current-limit control, a transformer in the primary circuit of the high-voltage transformer monitors the primary current. The voltage from this transformer is compared with the setting of the current control, which is adjusted to the rating of the transformer-rectifier unit. If the primary current exceeds the unit's rating, a signal is generated, as with spark control, which retards the firing pulse of the firing circuit and this brings the current back to the current-limit setting.

With all three control functions properly adjusted, the control unit will energize the precipitator at its optimum or maximum level at all times. This level will be determined by conditions within the precipitator and will result in any one of the three automatic control functions operating at its maximum, i.e., maximum voltage, maximum primary current, or maximum spark rate. Once one of the three maximum conditions is reached, the automatic control will prevent any increase in power to reach a second maximum. If changes within the precipitator so require, the automatic control will switch from one maximum limit to another.

Other features include secondary overload circuits and an undervoltage trip capability in the event that the voltage on the primary of the high-voltage transformer falls below a predetermined level and remains below that level for a period of time. A time-delay relay is also used to provide a delay period in the annunciator circuit while the network of contacts is changing position for circuit stabilization due to an undervoltage condition.

An SCR mainline control diagram (Figure 3-4) illustrates operation of the system described above.

3.1.1.2 Rappers - The rapper equipment is a completely electrically operated system for continuously removing dust from the collecting plates within the precipitator. The system is composed of a number of magnetic-impulse, gravity-impact rappers that are periodically energized to rap the collecting plates for removal of dust deposits. The main components of the system are the rappers and the electrical controls.

The magnetic-impulse, gravity-impact rapper is a solenoid electromagnet consisting of a steel plunger surrounded by a concentric coil, both enclosed in a watertight steel case. The control unit contains all the components (except the rapper) needed to distribute and control the power to the rappers for optimum precipitation. The electrical controls provide a number of separate adjustments so that all rappers can be assembled into a number of different groups, each of which can be independently adjusted from zero to maximum rapping intensity.

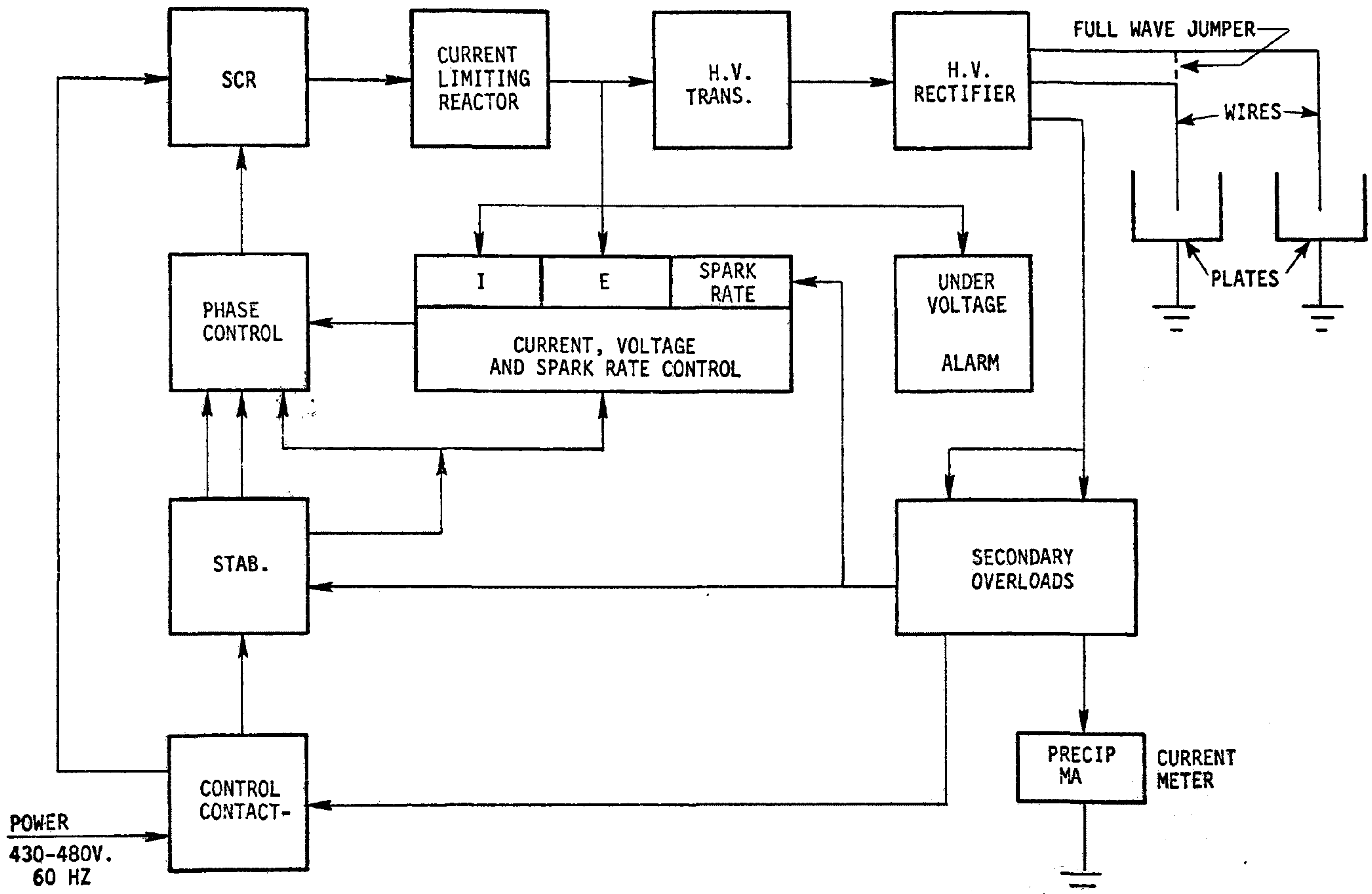

Figure 3-4. SCR mainline control.

During normal operation, a short-duration, dc pulse through the coil of the rapper supplies the energy to move the steel plunger. The plunger is raised by the magnetic field of the coil and then is allowed to fall back and strike a rapper bar, which is connected to a bank of collecting electrodes within the precipitator. The shock transmitted to the collecting electrodes dislodges the accumulated dust.

The electrical controls provide a number of separate adjustments so that rappers can be assembled into a number of different groups and each group independently adjusted according to transmissometer readings. The controls are adjusted manually to provide adequate release of dust from collecting plates while preventing undesirable stack puffing.

In some applications, the magnetic impulse, gravity impact rapper is also used to clean the precipitator discharge wires. In this case the blow is imparted to the electrode supporting frame in the same manner, except that an insulator isolates the rapper from the high voltage of the electrode supporting frame.

Some installations have mechanical rappers. In these installations each frame is rapped by one hammer assembly mounted on a shaft. A low-speed gear motor is linked to the hammer shaft by a drive insulator, fork, and linkage assembly. Rapping intensity is governed by the hammer weight, and rapping frequency is governed by the speed of rotation of the shaft.

3.1.1.3 Vibrators - The purpose of a vibrating system is to create vibrations in either the collecting plates or the discharge wires to dislodge accumulations of particles so that the plates or wires are kept in optimum operating condition. For collection of fly ash, vibrators are not normally used to clean the collecting electrodes.

The vibrator is an electromagnetic device, the coil of which is energized by alternating current. Each time the coil is energized, the vibration set up is transmitted to the high-tension wire supporting frame and/or collecting plates through a rod. The number of vibrators depends on the number of high-tension frames and/or collecting plates in the system.

The control unit contains all devices for operation of the vibrators, including means of adjusting the intensity of vibration and the vibration period. Alternating current is supplied to the discharge wire vibrators through a multiple cam-type timer to provide the sequencing and time cycle for energization of the vibrators.

For each installation, a certain intensity and time period of vibration will produce the best collecting efficiency. Insufficient intensity of vibrating will result in heavy buildups of dust on the discharge wires, which can cause the following adverse operating conditions:

> It reduces the spark-over distance between the electrodes, thereby limiting the power input to the precipitator.
>
> It tends to suppress the formation of negative corona and the production of unipolar ions required for the precipitator process.
>
> It alters the normal distribution of electrostatic forces in the treatment zone. Unbalanced electrostatic fields can cause the discharge wires and the high-tension frame to oscillate.

Upper Precipitator

On all positive and on some negative pressure installations a pressurizing fan is supplied (located on the cold roof) to force air into the top housing and down through the support bushings. This air prevents the process gases in the precipitator from entering the top housing and contaminating the support and high-tension frame rapper (vibrator) insulators. Electric heaters are also used to warm the inflowing air.

In place of a top housing, some installations have insulator compartments. The insulator compartment is a steel enclosure that surrounds the high-tension frame support insulators and rapper rod insulators. Fans are provided to prevent condensation of moisture on the high-voltage support insulator, and sometimes electric heaters are installed near each bushing in each insulator compartment.

The purpose of the high-tension anvil beam, which is part of the high-tension frame, is to transfer the impact of the high-tension vibrator to the discharge wires.

Discharge Wires

The discharge electrodes are small-diameter wires suspended from a structural steel wire supporting frame, held taut by individual cast iron weights at the lower end and stabilized by a steadying frame at the top of the cast iron weights. Unshrouded and shrouded discharge wires are illustrated in Figures 3-5 and 3-6, respectively.

Collecting Plates

The gas flows horizontally in the precipitator through individual gas ducts formed by the collecting plates. The discharge wires are located midway between the plates for the purpose of ionizing the gases and imparting an electric charge to the dust particles. It is important that the plate and wire spacing be held to close tolerances. Figure 3-7 illustrates the type of collection plate used in most ESP's manufactured by Research Cottrell.

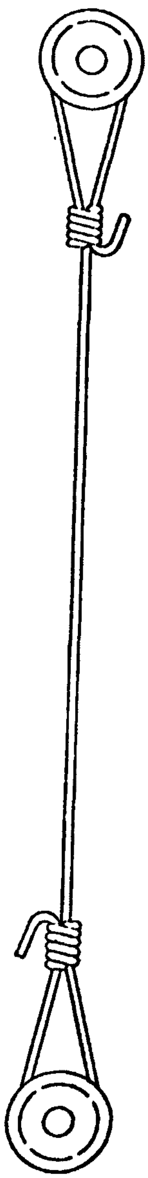

Figure 3-5. Discharge electrode unshrouded.

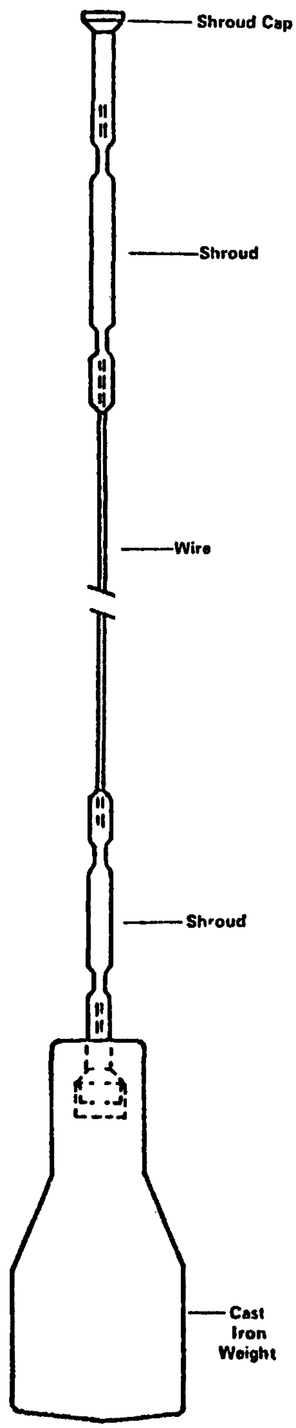

Figure 3-6. Discharge electrode shrouded.

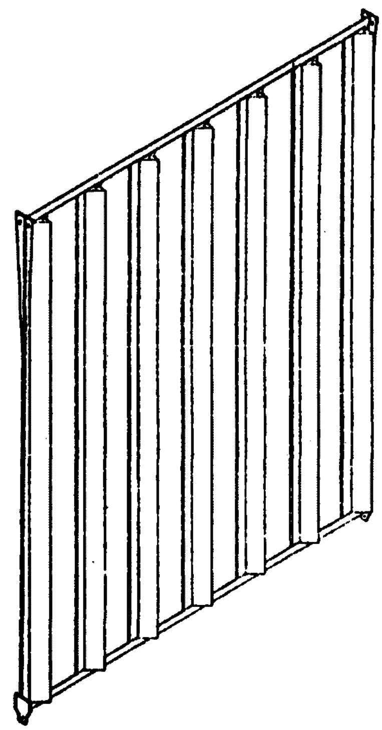

Figure 3-7. Precipitator collecting electrodes.

Lower Precipitator

The lower steadying frame limits or restricts the horizontal movement of the discharge wires.

The foregoing discussion summarizes the design and operation of the major precipitator components. The following section outlines inspection and maintenance procedures that will promote reliable functioning of the total precipitator system.

3.1.2 Precipitator Start-Up and Shutdown Procedures

Operation of an electrostatic precipitator involves high voltage, which is dangerous to life; although all practical safety measures are incorporated into the equipment, extreme caution should be exercised at all times. An electrostatic precipitator is, in effect, a large capacitor which, when de-energized, can retain dangerous electric charges. Therefore, grounding mechanisms provided at each access point should be used before entering the precipitator.

3.1.2.1 Preoperational Checklist - Before placing the equipment in operation, plant personnel should perform a thorough check and visually inspect the system components in accordance with recommendations of the manufacturer. A complete checklist of items is presented in Appendix C. Some of the major items that should be checked are summarized below:

Control unit

Proper connections to control

Silicon rectifier unit

Rectifier-transformer insulating liquid level
Rectifier ground switch operation
Rectifier high-voltage connections made
High-voltage bus transfer switch operation

High-tension connections

High-tension bus duct
Proper installation
Vent ports properly installed

Equipment grounding

Precipitator grounded
Transformer grounded
Rectifier controls grounded
High-tension guard grounded
Conduits grounded
Rapper and vibrator ground jumpers in place

3.1.2.2 Air Load Tests - After the precipitator is inspected (i.e., preoperational check adjustment of the rectifier control, and check of safety features) the air load test is performed. Air load is defined as energization of the precipitator with minimum flow of air (stack draft) through the precipitator. Before introduction of an air load or gas load (i.e. entrance of dust-laden gas into the precipitator), the following components should be energized:

Collecting plate rappers
Perforated distribution plate rappers
High-tension discharge electrode vibrators
Bushing heaters - housing/compartments
Hopper heaters - vibrators - level indicators
Transformer rectifier
Rectifier control units
Ventilation and forced-draft fans
Ash conveying system

The purpose of the air load test is to establish reference readings for future operations, to check operation of electrical equipment, and to detect any improper wire clearances or grounds not detected during preparation inspection. Air load data are taken with the internal metal surfaces clean. The data consist of current-voltage characteristics at intervals of roughly 10 percent of the T-R milliamp rating, gas flow rate, gas temperature, and relative humidity.

For an air load test the precipitator is energized on manual control. The electrical characteristics of a precipitator are such that no sparking should occur. If sparking does occur, an internal inspection must be made to determine the cause. Usually, the cause is (1) close electrical clearances and/or (2) the presence of foreign matter, such as baling wire, that has been left inside the precipitator.

After the precipitator has been in operation for some time, it may be necessary to shut it down to perform internal inspections. At such times it would be of interest to take air load data for comparison with the original readings.

3.1.2.3 Gas Load Tests - The operation of a precipitator on gas load differs considerably from operation on air load with respect to voltage and current relationships. The condition of high current and low voltage characterizes the air load, whereas low current and high voltage characterize the gas load. This effect governs operation of the precipitator and the final setting of the electrical equipment.

In general, optimum precipitator efficiencies are obtained when the dc voltage applied to the precipitator is just at the threshold of sparking. The spark rate at this point will be on the order of 50 to 150 sparks per minute and may be controlled at this level with automatic control.

3.1.2.4 Shutdown Procedure - To shut down the precipitator, the operator opens the control circuit start/stop switch and then opens the main circuit breaker. Before entering the system, the operator should follow all safety procedures. Proper grounding of all precipitator parts is important. The key interlock system prevents access to the interior of each transformer-rectifier ground switch enclosure until the individual set is de-energized and the ground connections are made. This system prevents access to the interior of the precipitator, including top housing or insulator compartments, precipitator roof doors, side doors, and hopper doors, until the transformer-rectifiers of each precipitator are de-energized and ground connections are made. Purging the system with ambient air may also be desirable from the standpoint of plant personnel who must inspect the internal parts of the precipitator.

3.1.3 Inspection and Maintenance During Normal Operation

Following are detailed directions for plant personnel who are assigned responsibility for inspection and maintenance of the precipitator system. Although electrical portions of the system require very little maintenance, the items enumerated should be attended regularly if the equipment is to give optimum service. It is good practice to assign to one operator on each shift the task of checking and recording data on electrical equipment at the start of the shift.

3.1.3.1 Transformer-Rectifier Sets and Associated Equipment and Controls - Check the liquid level in the transformer weekly. If it is low, fill the tank to the level indicated on the gauge with the dielectric liquid specified on the nameplate. Dielectric fluid should be handled with extreme caution.

Clean high-tension insulators, bushings, and terminals during each outage to minimize surface leakage. Glazed porcelain is best cleaned with a damp cloth and a nonabrasive cleaner.

Once each year or more often, clean the contacts of relays and dress them with a fine grade of crocus cloth.

Check the dustop filter weekly. The air filter assembly, easily attached and convenient for servicing, is mounted on the control cabinet.

Transformer Enclosure

Inspect all bushings and insulators. Replace those that are damaged; clean those that are dusty with a nonabrasive cleaner.

Clean all interlocks and lubricate with powdered graphite to ensure smooth and proper action.

Lubricate all bearing points on the ground-operated lever, connecting rods, and bevel gears.

Check all electrical connections to ensure that they are corrosion-free and tight. Loose electrical connections can cause electrical erosion of connections and failure of metering circuits and electrical components in both the control cabinet and transformer.

Overhead HW-FW Switchgear

Inspect all insulators for cracks, chips, and/or duct buildup. Replace all damaged insulators and remove dust accumulations with a nonabrasive cleaner.

Inspect all visible contacts to be sure that they are free of corrosion and pitting due to electrical arcing. Handcleaning, filing, and/or wire-wheel cleaning may be required.

Inspect for a tight fit on all couplings associated with transformer output bushings and switching insulators.

Lubricate mechanical bearing surfaces under the switching insulators to ensure smooth and proper operation.

Pipe and Guard

Remove all internal rust and/or scaling. Rust appearing on the internal walls of the guard could peel off and fall against the pipe, causing a ground on the secondary of the transformer.

Check the condition of the wall and post insulators for signs of electrical tracking (arcing), dust buildup, and cracked insulators. Clean or replace parts as required.

Check the pipe to ensure that all connections to wall bushings and post insulators are tight and that the pipe elbows used to redirect the pipe at various turns in the guard are tight and secure.

Ensure against water leakage by checking and maintaining the seal on the inspection plates of the pipe and guard.

When replacing the inspection covers, be certain to reinstall the ground jumper between the guard and cover plate; this ensures that any static charge or high-voltage leak goes to ground.

3.1.3.2 Plate Rappers

Cold Precipitator

Check the rapper assemblies periodically for any possible binding of the plunger or misalignment of assembly. The maximum amount of energy can be transmitted from coil to plunger only when the plunger is properly located with respect to the coil. Any deviation will decrease the energy transmitted. Adjusting bolts allow changes of the distance between the lower casing and the mounting and thereby allow variation of the plunger insertion in the coil.

If boot seal or service sheet gasket has deteriorated, dismantle the rapper assembly and inspect the rapper rod sleeve for ash accumulation. Packed ash in this area will dampen shock wave to the collecting plate and cause excessive ash accumulation on the plates (wires). [A boot seal is the rubber seal that is stretch-fitted over the end of the rapper rod. On negative-pressure installations, the boot seal prevents air and water from entering the precipitator chamber through the rapper rod guide sleeve. On positive-pressure installations, the boot seal prevents precipitator gases from flowing up the rapper and guide sleeve and entering the rapper coil tube.]

Inspect striking end of plunger to insure that the end has not been flared or otherwise deformed due to excessive height in its lift and/or misalignment.

When reassembling the rapper assembly after maintenance has been performed, make certain that the coil and coil cover are plumb and level, and that the plunger is properly aligned in a vertical plane on the rapper rod.

The maintenance checks outlined above apply also to wire rappers.

Hot Precipitator

As with cold precipitators, inspect each rapper to ensure that it is operational and that the rapper plunger is lifting at its prescribed height. If a rapper is not operational, check the coil for electrical continuity and grounds. If the problem is not in the coil, check the field wiring and the rapper control cabinet for malfunctions.

As with cold precipitators, with the rappers de-energized, check the plungers to see that they slide easily into the coil tubes. If a plunger does not move smoothly, dismantle the coil cover and inspect the coil tube for accumulations of debris or ash.

Check the area where the rapper rod passes through the packing ring retainer plate for signs of ash. If the retainer plate is loose, retighten, being careful that the plate is tightened equally on all sides and that the plate is parallel with the nipple flange on the stuffing box. If gas leaks are found, the packing glands should be inspected.

When leaks in the packing are discovered, dismantle the rapper assembly and inspect the stuffing box support assembly for ash accumulations.

When reassembling the rapper assembly after maintenance, make sure that the coil and coil cover are plumb and level and that the plunger sits full-face on the rapper rod.

The maintenance checks outlined above apply also to wire rappers on hot precipitators.

3.1.3.3 Vibrators

Cold Precipitator

Inspect each vibrator for proper gas setting.

Inspect boot seal for holes or tears and replace if necessary.

Inspect the service sheet gasket between the guide plate and the mounting nipple for signs of deterioration and replace if necessary.

If boot seal or service sheet gasket has deteriorated, dismantle the rapper rod assembly and inspect the vibrator rod nipple for ash accumulation. Packed ash in this area will dampen the vibrations to the discharge wires and cause excessive ash accumulation, close electrical clearances, and reduced precipitator performance.

Hot Precipitator

In addition to the instructions for vibrators on cold precipitators, check the area where the rapper rod passes through the packing ring retainer plate for ash or for sign of inleakage of air and/or water. This condition is indicative of a loose retainer plate providing an inadequate seal between the packing and the rapper rod or of failure of the packing rings. A loose retainer plate should be tightened and in case of gas leakage, the packing should be replaced.

3.1.3.4 Upper Precipitator

Top Housing

Inspect the fan to ensure that it is working and that the filters are in good condition.

Inspect vent elbows for accumulation of foreign matter, which would reduce or cut off the air flow.

Check access doors, inspecting the gaskets for signs of deterioration and leaks. Replace defective gaskets and lubricate door lugs and hinges as required.

Check that interlocks are clean, and lubricate with powdered graphite.

Inspect the upper rapper (or vibrator) rod on the high-tension frame to ensure that it is centered in its guide nipple and that no fly ash has packed between the nipple and the rapper/vibrator rod. If the rapper/vibrator rod needs to be centered in the nipple, cover the insulator with an asbestos blanket, and with a torch cut the nipple loose from the cold roof. Reposition the nipple, centering the rod, and reweld the nipple to the cold roof. Care must be taken that the new weld is a complete seal; water and ambient air could flow through pinholes and contaminate the insulators.

Note: Whenever it is necessary to do any welding on the high-tension wire supporting frame, the electrical bus connection to the high-tension support bushing should be disconnected. A heavy, temporary ground, sufficient to carry total welding current, should be solidly connected to the high-tension frame. The disconnected bus should be securely grounded at both ends; i.e., in the rectifier ground switch enclosure and at the support bushing end.

Insulator Compartments

Energize high-tension frame vibrators and check for smooth operation. Check field wiring and vibrator control cabinet if an inoperative vibrator is found. Vibrator insulator nuts and all pipe plugs should be secure.

Check all nipples and seals.

Inspect all dampers in the duct connections to the compartments to ensure that they are in the open position. Operate pressurizing fan and check that air is flowing uniformly into each insulator compartment.

The vent elbow should be equipped with a pipe plug unless the installation is operating under negative pressure. If the installation is under negative pressure, there should be no plug. Inspect the elbow for ash and/or other foreign material.

Inspect the pipe and guard through the inspection hatch to ensure that the inside surface is free from ash accumulation and/or rust and scale. Remove all ash accumulations and/or rust and scale buildups to prevent high-voltage arcing from the pipe to the guard. Inspect insulators to ensure that they are free from cracks, chips, and dust accumulations. Replace any cracked or chipped insulators and clean dirty insulators with a nonabrasive cleaner.

Inspect the gasket on the inspection door for deterioration and leaks; replace worn or leaky gaskets. Make sure that all bolts are in place and securely fastened. Determine that interlock is operable and well-lubricated with powdered graphite.

Inspect upper rapper rod - see Section 3.1.3.3.

Inspect the rapper rod insulator for ash accumulations, chips, cracks, and electrical tracking. Electrical tracking that has not damaged the glazed surface of the insulator and ash accumulations should be cleaned off with a nonabrasive cleaner. Replace cracked, chipped, or glaze-damaged insulators.

Inspect the area between the rapper rod and the hanger pipe for packed ash accumulations. Remove any accumulation as it tends to dampen the vibration transmitted to the upper high-tension frame. Check to see that the rapper rod is centered in the support pipe. If the support pipe is off center, chances are that the weld between the lower rapper rod and the upper high-tension frame has broken. Recenter the rod and reweld it to the high-tension frame. As with the upper rapper rod, inspect the insulator clamp, ensuring that all bolts are in place and tight.

Check the high-tension frame support pipe. Inspect the round nut screwed onto the support pipe to prevent pipe movement.

Remove the cover plates and inspect the inside and outside surfaces of the support insulator for dust accumulations, electrical tracking, cracks, and chips. Dust accumulations and electrical tracking that have not damaged the glazed surface of the insulator should be cleaned with a nonabrasive cleaner.

Plate Hanger Anvil Beam

Inspect the anvil beam hanger rod clips to ensure that they are straight. Excessively heavy plate rapping can in time cause these clips to bend, causing the plate bank to shift out of alignment. This shift results in electrical clearances out of tolerance and reduced precipitator performance.

Inspect the hanger rods to ensure that none are broken, missing, or bent. Broken, missing, or bent hanger rods usually cause out-of-tolerance electrical clearance and reduced precipitator performance. Replace any defective hanger rods.

Inspect the area behind the plate hanger anvil beam for packed fly ash. Remove fly ash, since it can force the beam out of plumb.

Inspect the weld between the rapper rod and the anvil beam. If this weld is broken or cracked, it should be replaced.

Upper High-Tension Frame

Check bolts and welds on the high-tension frame.

Replace broken, bent, or missing support rods.

Check wire support angles for broken welds where they attach to the spacer beam. Repair broken welds, making sure that the wire support angles are parallel and on 9-inch centers.

Check to determine whether the high-tension frame is level both perpendicular and parallel to the gas flow. If the frame is not level in the direction of gas flow, adjust at the appropriate high-tension frame support rods. If the frame is not level perpendicular to the gas flow, adjust at the appropriate high-tension frame hanger pipes.

Check for excessive accumulation of fly ash on this frame. Accumulations are excessive if they interfere with specified clearances of 4-1/2 inches ± 1/4 inch between the discharge wires and collecting plates or if they create a clearance of less than 4-1/2 inches between the high-tension frame and any other grounded surface.

3.1.3.5 Discharge Wires

Whenever possible, determine the condition of the discharge wires with regard to dust buildup. The amount of buildup will indicate whether the high-tension vibrators, when furnished, are operating at the proper intensity.

The discharge wires should be kept as clean as is practical.

Inadequate rapping of the discharge wires can result in heavy dust buildup, with localization of the corona current and excessive sparking.

A deposit on the discharge wires results from many things, including poor gas distribution and characteristics of the dust. Doughnut-shaped deposits often are formed. They are composed generally of finer dust particles. Deposits on the discharge wires do not necessarily result in poor performance, although depending on resistivity, power supply range, and uniformity of the deposit, they can cause reduced efficiency.

The discharge wires should be perfectly centered between the plates from top to bottom for optimum precipitator operation. Any broken discharge wires should be removed and if time permits, replaced with new wires. Since a cast iron weight is connected to each wire at its lower end, a resistance will be felt when pulling on the wire. A wire that gives no resistance is broken.

Broken wires can sometimes be seen from catwalks located between the collecting plate banks. With a flashlight, look down each duct noting any bottle weight that is hanging on its bottle guide and any wires that are out of alignment.

The location of a broken wire that is removed but not replaced should be recorded on a permanent log sheet. This recording will save time during future outages when time permits the installation of a new wire. A record of broken wire locations is also helpful in determining the cause of wire breakage, i.e. if a number of wires break in the same area of the precipitator, there are alignment problems. If the wire breakage is random, the breakage is probably caused by ash buildups on wires or plates.

The damaged wire may be cut away and the replacement wire brought into the precipitator through the top upper high-tension frame area, placed in the proper duct, lowered into place, and attached.

3.1.3.6 Collecting Plates

Whenever the precipitator is out of service and internal inspections are possible, the collecting plates should be checked for proper alignment and spacing. Check all hangers. Make sure that spacers at the bottom of the plates do not bind plates to prevent proper rapping. Check the lower portion of all plates and the portion of plates adjacent to any door openings for signs of corrosion. If corrosion is present, it usually indicates air inleakage through hoppers or around doors.

Observe the dust deposits on the collecting plates before starting any cleaning of the precipitator. The normal thickness of collected fly ash is about 1/8 inch with occasional buildups of 1/4 inch. If the buildup exceeds this amount, the intensity of the plate rappers should be increased. If the collecting plates are almost metal clean, this may be an indication of high gas velocity, extremely coarse fly ash, too high a rapping intensity, or too low an operation voltage for good precipitation. This condition may be noted if a section has been shorted out prior to the inspection.

The plate may be in effect removed from service by removing the discharge wires surrounding it. When bellying or bowing of the plates is noted, the concave side of the plate may be heat-treated with a torch, depending upon the severity of the deformity.

3.1.3.7 Lower Precipitator Steadying Frame

During periods when the hoppers are overfull, fly ash exerts pressure on the guide rings and can severely bend them. If the rings are bent upward, they usually lift the weight and cause a slack wire. Slack wires cause excessive sparking and/or grounds inside the precipitator. If the rings are bent in the horizontal plane, clearances will be reduced and sparking will increase, resulting in reduced efficiency.

Cast iron weight rings that are bent out of their normal configuration must be straightened. This can usually be done by hand.

Inspect the steadying bars for cracked or broken welds where they mount to the steadying bar support. Perform any needed repairs.

Make sure that the lower steadying frame is level both in the direction of gas flow and perpendicular to gas flow. If the frame is not level, readjust the support wires, adjusting both until the frame is level. Place equal tension on each of the support wires connected to adjusting bolts, since slack wires will cause excessive sparking.

Inspect the steadying frame for downward bow in the steadying bars (usually occurs after operating the precipitator at overdesign temperatures). Downward bows can usually be removed by cutting a wedge-shape slot in the vertical member of the steadying bar angle, pushing with jacks or pulling with a block and tackle until the frame is straight, then welding an additional piece of angle iron inside the steadying bar angle and across the wedge slot.

Inspect the steadying frame for twisting. A twisted frame causes excessive weight on some wires and slackness in others. To straighten a twisted frame, grasp one end of the frame and twist the frame until that end is straight and level. While holding the frame in this position, weld the frame to the hopper walls. Repeat for the other end of the frame. Once the frame has been welded to the hopper walls and is straight and level, using a torch, stress-relieve the frame by heating each connection between the steadying bar supports and the steadying bars until it glows to a cherry red. After all joints have been relieved, allow the frame to cool, then cut it free of the hopper walls. If the frame is still twisted, repeat the procedure. If after the second heating the frame is still twisted, a new frame will have to be installed.

When checking the lower steadying frame antisway insulators, check the surface for ash accumulation, glaze damage caused by electrical tracking, cracks, and chips. Insulators with ash accumulation and/or electrical tracking that has not damaged the glazed surfaces may be cleaned with a nonabrasive cleaner. Cracked, chipped, broken, or glaze-damaged insulators must be replaced.

3.1.3.8 Hoppers

It is extremely important to establish a regular schedule of hopper emptying at the start of operation and adhere to it as closely as possible, preferably once a shift. If the hoppers are allowed to fill over a 24-hour period or longer, the electrical components may short out and precipitation will cease. Also, if a fly ash hopper is allowed to stand for more than 24 hours, the dust tends to pack, cool off, and absorb some moisture from the gases. The dust is then extremely hard to remove, and the presence of moisture can start corrosion of the hopper steel. Dust often tends to build up in the upper corners of the hoppers, especially if they have been filled completely at any time.

Any abnormal buildups should be removed. If this condition becomes chronic, it is an indication of low operating temperatures, insufficient heat insulation, or inadequate hopper emptying. Heat tracing of the hoppers will usually correct this condition unless it is due to inadequate hopper emptying.

3.1.3.9 Precipitator Shell

Combustion of coal usually produces small amounts of sulfur dioxide and sulfur trioxide, as well as CO_2, O_2, and moisture. The traces of sulfur trioxide result in fairly rapid corrosion of the interior of gas ducts, fans, and dust-collecting equipment if these interior surfaces become cool for any reason. It is therefore recommended that thorough internal inspection be made during the first year of operation. If interior corrosion is noted, apply some means of correction as soon as possible. Heat insulation applied to exteriors of the corroded components will normally correct this condition. In installations where boiler loads are periodically low, covering the interior surfaces of side frames, end frames, and roof with gunite will prevent damage to the steel.

3.1.4 Maintenance Schedule and Troubleshooting

3.1.4.1 Annual Inspection/Maintenance

Prior to any inspection, it is of utmost importance that the precipitator is de-energized and grounded and the necessary precautions are taken to ensure that the equipment cannot be energized during the internal inspection.

Dust Accumulations

Observe the dust accumulations on both plates and wires. The discharge wires should have only a slight coating of dust with no corona tufts (doughnut-shaped ash accumulations). Thickness of dust buildup on plates is normally between 1/8 and 1/4 inch. If the plates have more than 1/4 inch of dust, the rappers are not cleaning properly.

Discharge Wires

Replace any broken discharge wires, necked-down wires, or fatigued wires to avoid the possibility of breaking during operation. Breakage of just one wire may render an entire precipitator section inoperative. Record the exact location of all wire failures as well as the location of breakage on the wire.

Alignment of Plates and Wires

The plate-to-wire clearance at both top and bottom of plates should not be less than 4-1/4 inches, while the minimum acceptable plate-to-wire clearance at the vertical midpoint of the plates is 4 inches (assuming 9-inch duct spacing). Close electrical clearances create excessive sparking and prevent optimum operation.

High-Tension and Plate Rappers

Check all high-tension and plate rappers for misalignment and/or binding of the rapper rods through the roof sleeves. Binding in this area prevents transmission of rapper energy to the collecting plates and high-tension discharge wires and results in excessive dust accumulations.

High-Tension Frame Support Bushing

The internal and external surfaces of the high-tension frame support bushing must be maintained free of dust to guard against high-voltage electrode tracking across insulator surfaces. This condition will lead to thermal fracturing of the bushings through heat concentration. Clean all high-voltage insulators and check thoroughly for sign of cracks; replace where necessary. All electrical connections should be secure.

High-Voltage Electrical Control Cabinet

Clean all components of dust accumulation and lubricate where necessary. Replace the ventilating fan filter.

Transformer-Rectifier Sets

Check the oil level in the high-voltage transformer and add the proper oil if necessary. Check all bushings, terminals, and insulators for dust buildup and evidence of electrical tracking. Check the surge arrestor gap setting on the high-voltage transformer and readjust if necessary. Check high-voltage switchgear and interlocks.

Hoppers

Check for dust buildup in upper corners of hoppers and debris such as fallen wires and weights in the hopper bottom and valves. Inspect antisway insulators to see that they are clean and not cracked. If a discharge electrode weight has dropped 3 inches, this indicates a broken wire.

Precipitator Shell

Interior corrosion could indicate inleakage of air or moisture through the housing. Exterior inspection should focus on loose insulation and joints, air leakage, and general damage as well as corrosion.

3.1.4.2 Daily Inspection and Readings

Record all control set electrical readings once per shift. Any abnormalities in shift-to-shift readings may well be the first clue of a malfunction within the precipitator. In addition, the daily log should include boiler operating data, flue gas analysis, coal analysis, verification of transmissometer calibration, and a record of all transmissometer readings.

Rappers

Ensure that all collecting plate and discharge wire (high-tension) rappers are functioning properly and operating at the proper intensity level. Lack of rapping will result in dust buildup on both the plates and wires, which reduces electrical clearances and necessitates operation of the equipment at reduced power levels. Over-rapping of the internals leads to reentrainment of collected dust; therefore, it is important that proper intensity values be used for optimum precipitator performance.

Hoppers

Thoroughly check all hoppers, particularly the unloading mechanism and system, for proper operation. Overfilling of hoppers can lead to very serious damage of internal components. Check thoroughly for air inleakage at the hoppers. The siphoning of cold ambient air into the hoppers usually results in formation of condensation and agglomerating of dust, resulting in plugging of the hopper.

A troubleshooting chart for ESP's is presented in Table 3-1.

3.1.5 Precipitator Malfunctions

Many precipitator components are subject to failure or malfunction, which can lead to increased emissions. Faulty design, installation, or operation of the precipitator can cause these malfunctions. The reduction in efficiency is variable and depends on the severity of the malfunction. Many malfunctions are interrelated, with one malfunction causing another. A brief discussion follows on common precipitator malfunctions and how they affect emissions.

The most common malfunctions associated with precipitators stem from broken discharge wires and plugged ash hoppers. Other problems result from failure of rappers or vibrators and suspension insulators, changes in coal specifications, and boiler-related malfunctions or variations.

3.1.5.1 Broken Discharge Wires - When a discharge electrode breaks, it usually causes an electrical short circuit between the high-tension discharge wire system and the grounded collection plate. This electrical short trips the circuit breaker, disabling a section of the precipitator. Electrical erosion, mechanical fatigue, and ash hopper buildup are three common causes of electrode wire failure, along with many others.

Table 3-1. TROUBLESHOOTING CHART FOR ESP OPERATION

Symptom	Probable cause	Remedy
Spark meter reads high, primary voltage and current very unstable	Misadjustment of automatic control, loss of limiting control	Readjust automatic control, replace automatic control
Neither spark rate, current, nor voltage at maximum	Misadjustment of automatic control, automatic control not at maximum, failure of signal circuits	Readjust setting of automatic control, readjust automatic control, check signal circuits
No spark rate indication, voltmeter and ammeter unstable, indicating sparking	Failure of spark meter, failure of integrating capacitor, spark counter sensitivity too low	Replace spark meter, replace capacitor, readjust potentiometer on automatic control
No response to current-limit adjustment, response to other adjustments	Controlling on spark rate or voltage limit, failure of automatic control, current signal to automatic control defective	None needed if unit is operating at maximum spark rate or voltage adjustment, reset voltage or spark rate if neither is at maximum, replace automatic control, check signal circuit
No response to voltage-limit adjustment, response to current adjustment	Controlling on current limit or spark rate, voltage signal to automatic control defective, failure of automatic control	None needed if unit is operating at maximum current or spark rate, reset current and spark rate adjustment if neither is at maximum, check voltage circuit, replace automatic control
No response to spark rate adjustment, response to other adjustment	Controlling on voltage or current, failure of automatic control	None needed if unit is operating at maximum voltage or current, reset voltage and current adjustment if neither is at maximum, replace automatic control
Precipitator current low with respect to primary current, low or no voltage across ground return resistors	Surge arrestors shorted, H.V. rectifiers failed, H.V. transformer failed, ground or partial ground in the ground return circuit	Reset or replace surge arrestors, replace H.V. rectifiers, replace H.V. transformer, repair ground return circuit

Table 3-1 (Cont'd). TROUBLESHOOTING CHART FOR ESP OPERATION

Symptom	Probable cause	Remedy
	Transformer-Rectifier Controls	
No primary voltage, no primary current, no precipitator current, vent fan on, alarm energized	DC overload, misadjustment of current limit control, overdrive of SCR's	Check overload relay setting, check wiring and components, check adjustment of current-limit control setting, check signal from firing circuit module
No primary voltage, no primary current, no precipitator current, vent fan off, alarm energized	Control panel fuse blown, loss of power supply, circuit breaker tripped	Replace fuse or reset circuit breaker, check supply to control unit, reset circuit breaker
Control unit trips out on overcurrent when sparking occurs at high currents	Overload circuit incorrectly set	Reset overload circuit
High primary current, no precipitator current	Short circuit in primary current, transformer or rectifier short	Check primary power wiring, check transformer and rectifiers
No primary voltage, no primary current, no precipitator current, vent fan on, alarm not energized	SCR and/or diode failure, no firing circuit	Replace, check signal from firing circuit
Low primary voltage, high secondary current	Short circuit in secondary circuit or precipitator	Check wiring and components in H.V. circuit and pipe and guard. Check precipitator for interior dust buildup, full hoppers, broken wires, ground switch left on, ground jumper left on, foreign materials on H.V. frames or wires, broken insulators
Abnormally low precipitator current and primary voltage with no sparking	Misadjustment of current and/or voltage limit controls, misadjustment of firing circuit control	Check settings of current and voltage limit controls
Spark meter reads high-off scale, low primary voltage and current, no spark rate indication	Continuous conduction of spark counting circuit, spark sounter counting 60 cycles peak, failure of automatic control	De-energize, allow integrating capacitor to discharge and re-energize, adjust spark control circuit, replace automatic control

Table 3-1 (Cont'd). TROUBLESHOOTING CHART FOR ESP OPERATION

Symptom	Probable cause	Remedy
Primary current and secondary current normal, primary voltmeter drops from normal to zero and remains for a second then jumps back to normal, repeating this sequence rhythmically	Broken wire, swinging frame	Remove broken wire, check for broken anti-sway bushings
	Rapper Controls	
Circuit breaker trips	Short circuit or component failure in control circuit or power transformer	Check wiring and component
Fuses blown, indicator light not flashing	Control circuit failure, rapper coil failure, distributor switch firing two coils at once	Replace defective component, replace coil, repair or realign distributor switch
Indicator light not flashing, no fuse failure	Control circuit not operating effectively, no rotation of distributor switch	Repair or replace component, check motor and drive train
No manual intensity control	Failed potentiometer, faulty intensity control module	Replace potentiometer, replace intensity control module
	Vibrators and Controls	
Vibrator inoperative	Vibrator coil open circuited, vibrator improperly adjusted	Replace coil, adjust vibrator
Abnormal ammeter reading	Vibrator improperly adjusted, vibrator coil short circuited	Adjust vibrator, replace coil
Line breaker trips	Short circuit in control wiring	Check circuit

The impact of wire failures on precipitator availability and efficiency is a function not only of the frequency of failure, but also the degree of sectionalization and the difficulty involved in removing failed wires during unit operation. Most precipitators do not have suitable isolation dampers to allow safe access to the interior while the boiler is in operation; thus, the unit must shut down for removal of these broken wires. Inadequate sectionalization causes a greater drop in efficiency, and a number of wire breaks in different sections may seriously impair the operation of the precipitator.

Design methods that can reduce wire failures include fabricating discharge electrodes of the proper materials and applying shrouds and rounded surfaces to reduce localized sparking.[1] Frequent inspection can help prevent failures through detection of problems such as inadequate rapping and ash hopper buildup before they cause wires to fail. Because of the great number of wires in a precipitator, some wire failure is to be expected, even with a good operation and maintenance program.

3.1.5.2 Collection Hoppers and Ash Removal - Inadequate ash removal is a major cause of precipitator malfunctions. Most problems associated with hoppers are related to proper flow of the dust. Improper adjustment of the hopper vibrators or failure of the conveyor system is usually the cause of the hoppers failing to empty. Low flue-gas temperature, which permits moisture condensation, can also cause plugging of the hopper. This results from carrying the boiler exit gas temperature too low or from excessive leakage of ambient air into the hopper.

Buildup of ash can cause short-circuiting of the precipitator. It can also cause excessive sparking, which erodes electrodes and sometimes pushes internal components out of position, causing misalignment that can drastically affect performance. Reentrainment of ash also increases emissions.

Since ash buildup can affect so many of the precipitator components, a proper inspection schedule of the ash removal system is an important factor in the elimination or minimizing of many common precipitator malfunctions.

3.1.5.3 <u>Rappers or Vibrators</u> - Poor performance can result from rapping forces that are either too mild or too severe. Although some reentrainment always occurs, effective rapping minimizes the amount of material reentrained in the gas stream. Rapping that is too intense and frequent results in a clean plate, which causes the collected dust to become reentrained rather than falling into the hopper. Inadequate rapping of the discharge electrode results in a heavy dust buildup with localization on the corona, low corona current, excessive sparking, impaired performance, and possible grounding of the high-voltage system.

The first step in dealing with problems related to rappers and vibrators is to determine the adequacy of the rapping acceleration. An accelerometer can be mounted on the plates for this purpose. An optical dust-measuring instrument in the gas stream is commonly used to adjust the rappers.

If discharge electrodes are kept as clean as possible with minimum reentrainment, rapping intensity is then limited only by the possibility of mechanical damage to the electrodes and support structure.

3.1.5.4 Insulator/Bushing Failure - Suspension insulators are used to support and isolate the high-voltage parts of precipitators. Inadequate pressurization of the top housing of the insulators can cause ash deposits and/or moisture condensation on the bushing, which may result in electrical breakdown. Fouling and cracking of insulators reduce the effective voltage levels and collector performance but rarely decommission a bus section.

Corrective or preventive measures include inspection of ventilation fans for the top housing and availability of a spare fan for emergencies. Frequent cleaning and checking the fans for damage from vibration are also necessary to ensure trouble-free operation.

Table 3-2 lists common precipitator malfunctions, their causes, the effects on emissions, and the corrective action required.

3.1.6 Operational Procedures and Firing Practices That Affect Emissions[2]

In addition to precipitator malfunctions, a number of operating and coal boiler firing practices can affect precipitator emissions. Changes in these practices can also cause precipitator malfunctions, which may in turn degrade performance.

3.1.6.1 Gas Volume - Any increase in boiler load that results in excessive flow through the precipitator will cause a loss in efficiency. For example, if a precipitator is designed for a velocity of 3 ft/sec and an efficiency of 99 percent, an increase in velocity to 4 ft/sec (a 33 percent load increase) will decrease the efficiency to about 97 percent.

3.1.6.2 Temperature - A change in operating temperature may also affect precipitator efficiency. Particle resistivity varies greatly in the temperature range of 200 to 400°F. Ignoring the effects of temperature on gas volume, the impact of temperature on efficiency depending on the coal composition could be as follows, assuming a 1.5 percent sul-

Table 3-2. SUMMARY OF PROBLEMS ASSOCIATED WITH ESP'S

Malfunction	Cause	Effect on ESP Efficiency[a]	Corrective action	Preventive measures
1. Poor electrode alignment	1) Poor design 2) Ash buildup on frame hoppers 3) Poor gas flow	Can drastically affect performance and lower efficiency	Realign electrodes Correct gas flow	Check hoppers frequently for proper operation
2. Broken electrodes	1) Wire not rapped clean, causes an arc which embrittles and burns through the wire 2) Clinkered wire. Causes: a) poor flow area, distribution through unit is uneven; b) excess free carbon because of excess air above combustion requirements or fan capacity insufficient for demand required; c) wires not properly centered; d) ash buildup resulting in bent frame, same as c); e) clinker bridges the plates & wire shorts out; f) ash buildup, pushes bottle weight up causing sag in the wire; g) "J" hooks have improper clearances to the hanging wire; h) bottle weight hangs up during cooling causing a buckled wire; i) ash buildup on bottle weight to the frame forms a clinker and burns off the wire	Reduction in efficiency because of reduced power input, bus section unavailability	Replace electrode	Boiler problems: check space between recording steam & air flow pens, pressure gauges; fouled screen tubes. Inspect hoppers Check electrodes frequently for wear Inspect rappers frequently
3. Distorted or skewed electrode plates	1) Ash buildup in hoppers 2) Gas flow irregularities 3) High temperatures	Reduced efficiency	Repair or replace plates Correct gas flow	Check hoppers frequently for proper operation; check electrode plates during outages
4. Vibrating or swinging electrodes	1) Uneven gas flow 2) Broken electrodes	Decrease in efficiency caused by reduced power input	Repair electrode	Check electrodes frequently for wear

[a] The effects of precipitation problems can only be discussed on a qualitative basis. There are no known emission tests of precipitators to determine performance degradation as a function of operational problems.

Table 3-2 (Cont'd). SUMMARY OF PROBLEMS ASSOCIATED WITH ESP'S

Malfunction	Cause	Effect on ESP Efficiency[a]	Corrective action	Preventive measures
5. Inadequate level of power input (voltage too low)	1) High dust resistivity 2) Excessive ash on electrodes 3) Unusually fine particle size 4) Inadequate power supply 5) Inadequate sectionalization 6) Improper rectifier and control operation 7) Misalignment of electrodes	Reduction in efficiency	- Clean electrodes; gas conditioning or alterations in temp. to reduce resistivity; Increase sectionalization	Check range of voltages frequently to make sure they are correct In situ resistivity measurements
6. Back corona	1) Ash accumulated on electrodes - causes excessive sparking requiring reduction in voltage charge	Reduction in efficiency	Same as above	Same as above
7. Broken or cracked insulator or flower pot bushing leakage	1) Ash buildup during operation causes leakage to ground 2) Moisture gathered during shutdown or low load operation	Reduction in efficiency	Clean or replace insulators & bushings	Check frequently Clean and dry as needed; check for adequate pressurization of top housing
8. Air inleakage through hoppers	1) From dust conveyor	Lower efficiency - dust reentrained through ESP	Seal leaks	Identify early by increase in ash concentration at bottom of exit to ESP
9. Air inleakage through ESP shell	1) Flange expansion	Same as above, also causes intense sparking		
10. Gas bypass around ESP: - dead passage above plates - around high-tension frame	1) Poor design - improper isolation of active portion of ESP	Only few percent drop in efficiency unless severe	Baffling to direct gas into active ESP section	Identify early by measurement of gas flow in suspected areas
11. Corrosion	1) Temperature goes below dew point	Negligible until precipitator interior plugs or plates are eaten away; air leaks may develop causing significant drops in performance.	Maintain flue gas temperature above dew point.	Energize precipitator after boiler system has been on line for ample period to raise flue gas temperature above acid dew point

[a] The effects of precipitation problems can only be discussed on a qualitative basis. There are no known emission tests of precipitators to determine performance degradation as a function of operational problems.

Table 3-2 (Cont'd). SUMMARY OF PROBLEMS ASSOCIATED WITH ESP'S

Malfunction	Cause	Effect on ESP Efficiency[a]	Corrective action	Preventive measures
12. Hopper pluggage	1) Wires, plates, insulators fouled because of low temperature 2) Inadequate hopper insulation 3) Improper maintenance 4) Boiler leaks causing excess moisture 5) Ash conveying system) gasket leakage malfunction) blower malfunction) solenoid valves 6) Misadjustment of hopper vibrators 7) Material dropped into hopper - from bottle weights 8) Solenoid, timer malfunction 9) Suction blower filter not changed	Reduction in efficiency	Provide proper flow of ash	Frequent checks for adequate operation of hoppers. Provide heater thermal insulation to avoid moisture condensation
13. Inadequate rapping, vibrators fail	1) Ash buildup 2) Poor design 3) Rappers misadjusted	Resulting buildup on electrodes may reduce efficiency	Adjust rappers with optical dust measuring instrument in ESP exit stream	Frequent checks for adequate operation of rappers
14. Too intense rapping	1) Poor design 2) Rappers misadjusted 3) Improper rapping force	Reentrains ash, reduces efficiency	Same as No. 13	Same as No. 13 Reduce vibrating or impact force
15. Control failures	1) Power failure in primary system 2) Transformer or rectifier failure a. insulation breakdown in transformer b. arcing in transformer between high voltage switch contacts c. leaks or shorts in high voltage structure d. insulating field contamination	Reduced efficiency	Find source of failure and repair or replace	Pay close attention to daily readings of control room instrumentation to spot deviations from normal readings
16. Sparking	1) Inspection door ajar 2) Boiler leaks 3) Plugging of hoppers 4) Dirty insulators	Reduced efficiency	Close inspection doors; repair leaks in boiler; unplug hoppers; clean insulators	Regular preventive maintenance will alleviate these problems

[a] The effects of precipitation problems can only be discussed on a qualitative basis. There are no known emission tests of precipitators to determine performance degradation as a function of operational problems.

fur coal, and 99 percent guarantee at 325°F (fly ash application):

Temperature, °F	Efficiency, %
200	≈99.6
325	99
400	≈99.4

Any change in the sulfur content of the coal along with other parameters such as sodium, would cause the above efficiencies to change differently with temperature. Changes in fuel are discussed below.

3.1.6.3 Fuel - Any significant change in the type of fuel being fired will affect precipitator performance. Sulfur content is one of the significant factors. For example, changing from a bituminous coal with 2 percent sulfur to a subbitiuminous western coal with 0.5 percent sulfur can result in a design efficiency of 99.5 percent dropping to 90 percent or less. Other chemical constituents, such as sodium oxide, in the ash can affect performance by reducing bulk resistivity (see Section 2.0).

The unit should be designed for the lowest quality expected fuel.

3.1.6.4 Inlet Loading - Since a precipitator is designed to remove a certain percentage (by weight) of the entering material, a 50 percent increase of the inlet concentration will cause the outlet concentration to increase by the same amount if no other factors change. This increase can be expected to result in greater opacity.

3.1.6.5 Carbon - Variations in firing practice or coal pulverization that affect the quantity of combustibles in the fly ash also have been impact on precipitator performance. Carbonaceous materials readily take on an electrical charge in a precipitator but lose their charge quickly and are readily reentrained. The carbon particle is very conductive and is also large and light in comparison with the other fly ash constitutents.

These are the major operating parameters to be considered in preventing a deterioration in performance.

3.1.7 Reduced ESP Collection Efficiency as Related to Number of Bus Sections Not in Operation

Although ESP collection efficiency is reduced by malfunctions such as breakage of discharge wires and deterioration of power supply components, rectifiers, insulators, and similar equipment, a unit can often be kept in compliance with particulate emission regulations by reducing boiler load. Figure 3-8 (top graph) illustrates collection efficiency of a four-field ESP with 24 bus sections as a function of the gross boiler load, depending on the number of bus sections out and whether they are in series or parallel. The bottom graph shows the efficiency needed by the ESP to meet a state regulation of 0.38 $lb/10^6$ Btu as a function of

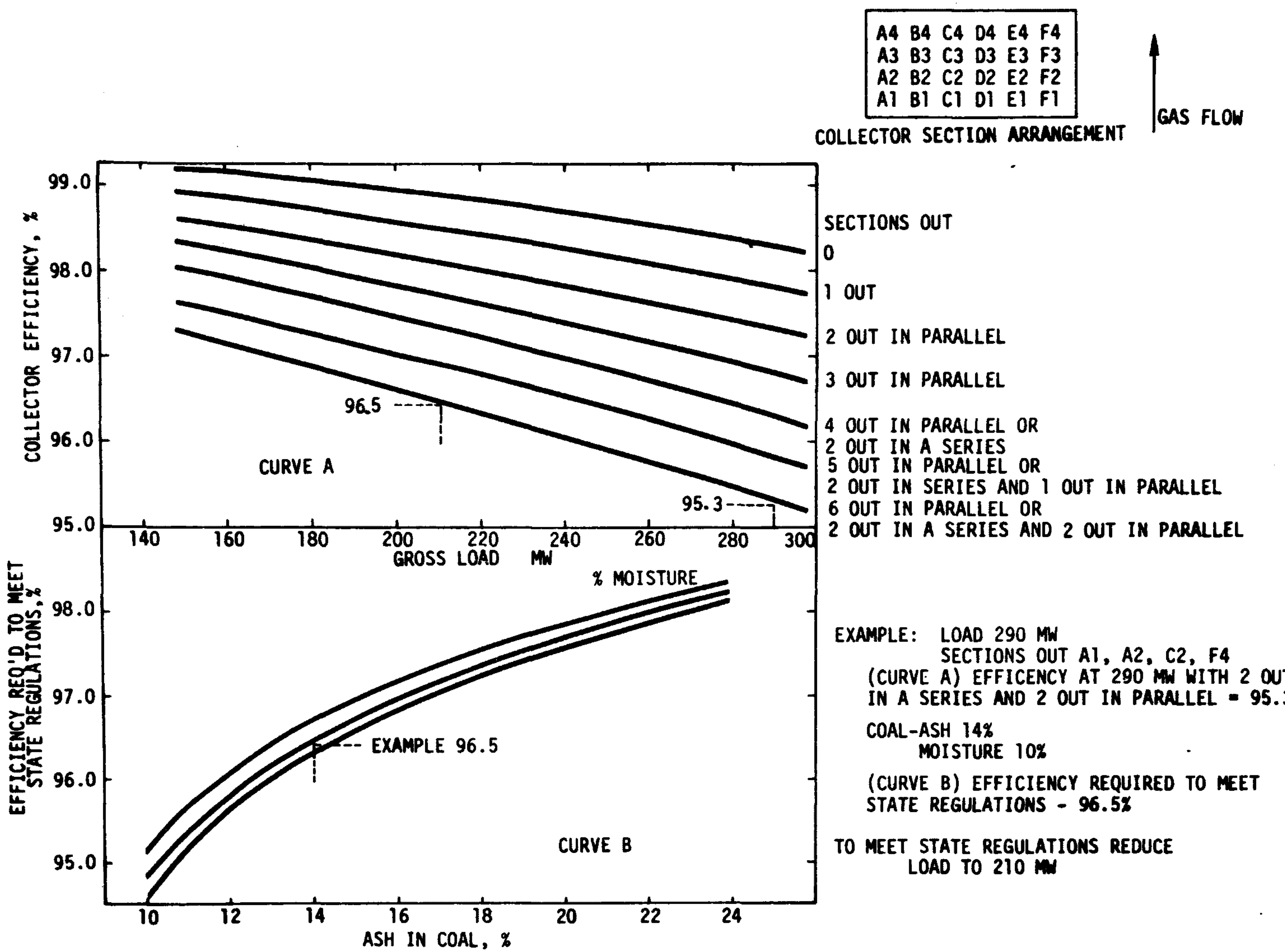

Figure 3-8. Typical operating curve to meet emission regulations with partial malfunctions of ESP.

the ash content of coal (assuming a heating value of 11,000 Btu/lb).

These types of graphs are extremely helpful to the utility operator. Knowing the ash content of the coal he is firing and knowing which bus sections of his ESP are inoperative, he can easily tell from the top graph how much the boiler load must be reduced to keep emissions in compliance with regulations. Charts of this type must be developed for each boiler-ESP combination.

3.2 OPERATION AND MAINTENANCE OF WET SCRUBBERS

The selection of wet scrubbers over electrostatic precipitators for use with coal-fired boilers has been motivated in many instances by the relatively poor performance of the first electrostatic precipitators on boilers firing low-sulfur Western coals. A few years ago scrubbers were beginning to look like a good prospect for collection of fly ash. A number of scrubbers were installed for collection of particulate from boilers burning low-sulfur Western coal. Examples are the Pacific Power and Light Company, Public Service of Colorado, and Minnesota Power and Light Company. At the Arizona Public Service Cholla Station, removal of both SO_2 and particulate was accomplished. Six commercial-scale scrubber modules have been installed in the West to remove SO_2 from power plant stack gas.[3] This report, however, considers only those scrubbers designed principally for the collection of fly ash.

Of the new Western coal-fired boilers being built,[4] virtually all are using precipitators for particulate control followed by scrubbers for removal of SO_2. This situation is the reverse of what was projected a few years back. Several of the problems that contributed to this change in control plans are as follows:[4]

- With the scrubber, the fan can no longer be operated dry, creating potential for corrosion and imbalance.
- In many cases, the desulfurization system cannot be bypassed without also bypassing the particulate removal system.
- The chemistry of the SO_2 system and the total slurry solids content are affected by the particulate loading.

Many of the problems with wet scrubbers arose from the newness of the application. The occurrence of erosion, corrosion, scaling, and plugging underscores the need for development of scrubber technology. Both corrosion and buildup decrease the efficiency of particulate removal, the finer particles being the ones most likely to escape collection. No clear trend emerges as to the preferred scrubber system for use in collection of fly ash from utility boilers. Not enough scrubbers have been installed to allow meaningful performance evaluations. Of the pilot and full-scale units placed in operation thus far, only three have been used with any success: the gas-atomized spray scrubber (venturi and flooded-disc scrubbers), the preformed spray impingement scrubber (spray tower type), and the turbulent contact absorber (TCA) (moving-bed scrubber type). The installations[3] that serve as a basis for the discussions that follow are the Four Corners Station of Arizona Public Service; the Dave Johnston Station of the Pacific Power and Light Company; the Valmont, Cherokee, and Arapahoe Stations of the Public Service Company of Colorado; and the Clay Boswell and Aurora Stations of the Minnesota Power and Light Company. Using available information, the remainder of this section describes these scrubber systems and the maintenance procedures used to maintain efficient operation.

3.2.1 Gas Atomized Spray Type Scrubber

3.2.1.1 Description - In devices of this type a moving gas stream atomizes liquid into drops and then accelerates the drops. Acceleration of the gas provides impaction forces as well as intimate contact with the liquid stream. The typical gas atomized spray devices are the venturi scrubber and the flooded disc scrubber. Whereas in the venturi liquid is introduced at the throat, in the flooded disc scrubber the liquid is introduced slightly upstream of the throat, flows over the edge of the disc, and is atomized.

Within this category many differences in design and operation are noted with respect to the following items: method of adjusting pressure drop (the difference being with regard to the true venturi and the annular orifice); the method of introducing water (spray or cascade); and the method of eliminating moisture (spinning vanes or multi-centrifugals). In any event, most gas atomized spray scrubbers incorporate the converging and diverging section typical of the venturi throat.

High-efficiency particulate wet scrubbers of the venturi type are being used at the Four Corners Plant of the Arizona Public Service Company, and at the Dave Johnston Plant of Pacific Power and Light Company. At the Four Corners plant, as shown in Figure 3-9, flue gas from the air preheaters enters the venturi and is then channeled through a mist eliminator, a wet induced-draft fan, another mist eliminator, and steam reheaters (although reheaters have not been used recently). Scrubber liquor is recycled continuously from the cyclone separator back to the venturi. Blowdown from the cyclone is sent to the thickener, lime is added, and the thickener underflow is diluted before being sent to ash ponds.

The installation at the Dave Johnston Station is somewhat different (Figure 3-10). Flue gas from the air preheater enters the venturi and is channeled through the mist eliminator, a wet induced-draft fan, and a wet stack. No reheat is used, and, as with the Four Corners scrubber, there is no bypass.

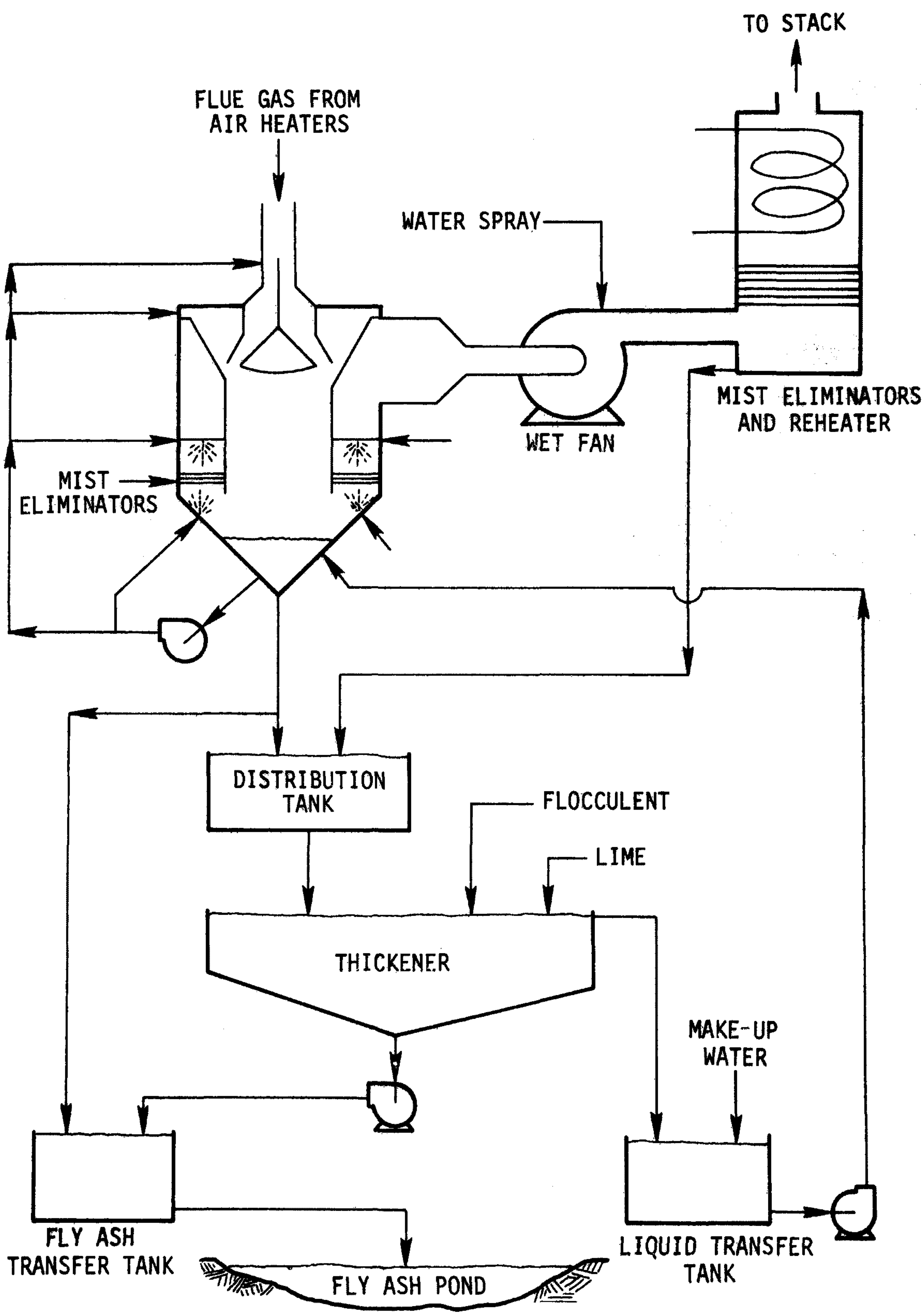

Figure 3-9. Simplified flow diagram of fly ash scrubbers, Four Corners plant.[3]

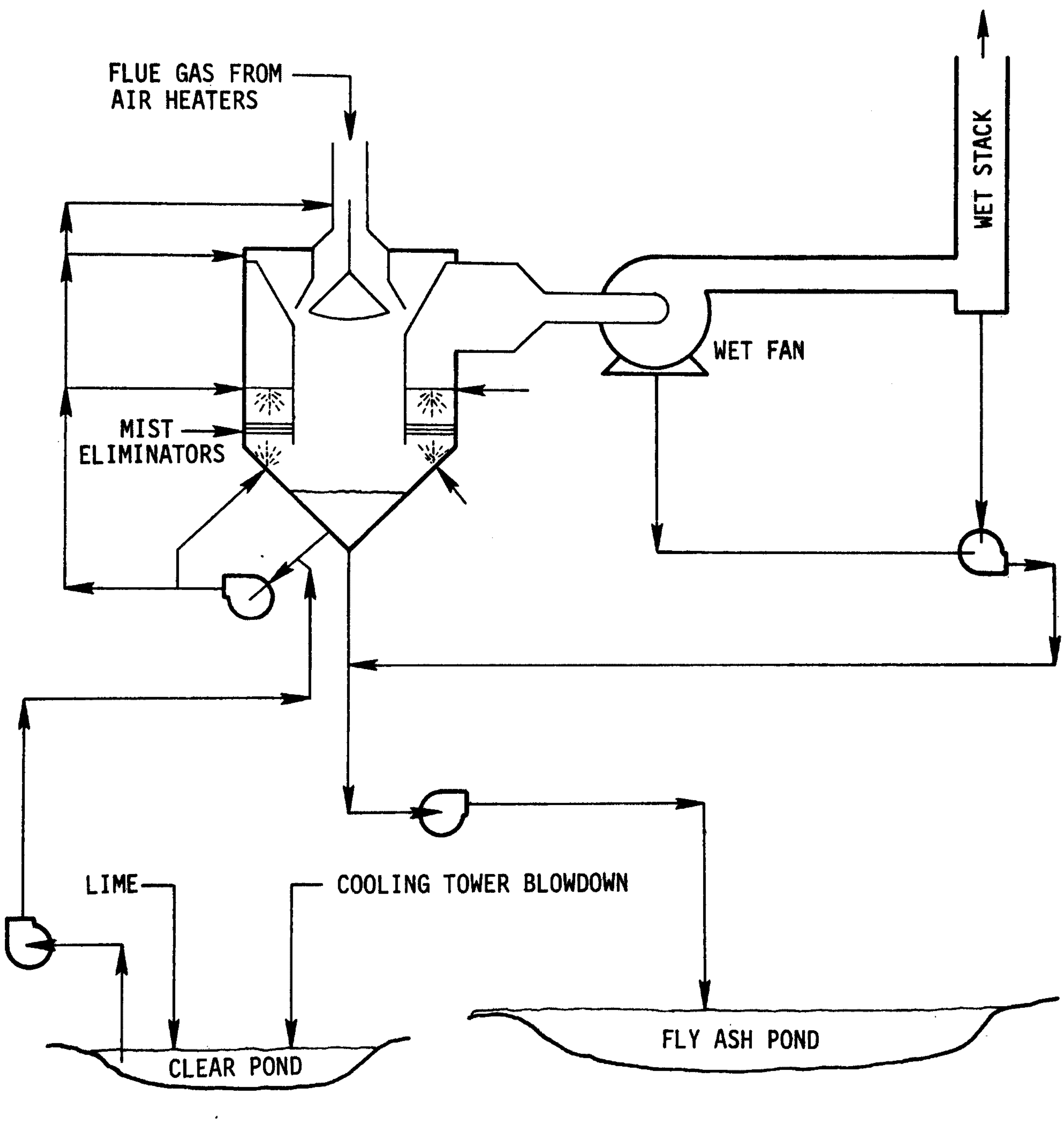

Figure 3-10. Simplified flow diagram of fly ash scrubbers, Dave Johnston plant.[3]

Scrubbing liquor is continuously recycled from the bottom of the venturi back to the plumb bob and to the deflector surrounding the bob. Blowdown from this loop is pumped directly to the ash ponds, where the solids settle without addition of thickener. Clear liquor from the settling pond along with cooling tower blowdown are pH treated and pumped to the recycle loop.

At the Lewis and Clark Station,[5] the gas, after passing through a mechanical collector, is pushed through the flooded disc by a forced-draft fan. A limestone slurry is used as a reagent for pH control. The flue gas then passes through a mist eliminator and out the stack. A portion of the liquid reagent is recycled. The remainder is discharged to a waste pond. Figure 3-11 presents a simplifed diagram of the Lewis and Clark station's flooded disc scrubber.

3.2.1.2 Normal Operation - In view of the few applications of scrubbers for collection of fly ash from coal-fired utility boilers and the wide variations in design within any scrubber category, no specific list of items can be said to constitute 'normal' operation. Some qualitative aspects of scrubber operation are discussed briefly.

Efficiency of collection of submicron particles increases with increasing pressure drop. For the Four Corners and Dave Johnston plants, the operating pressure drops are 28 inches and 15 inches (water gauge), respectively. Pres-

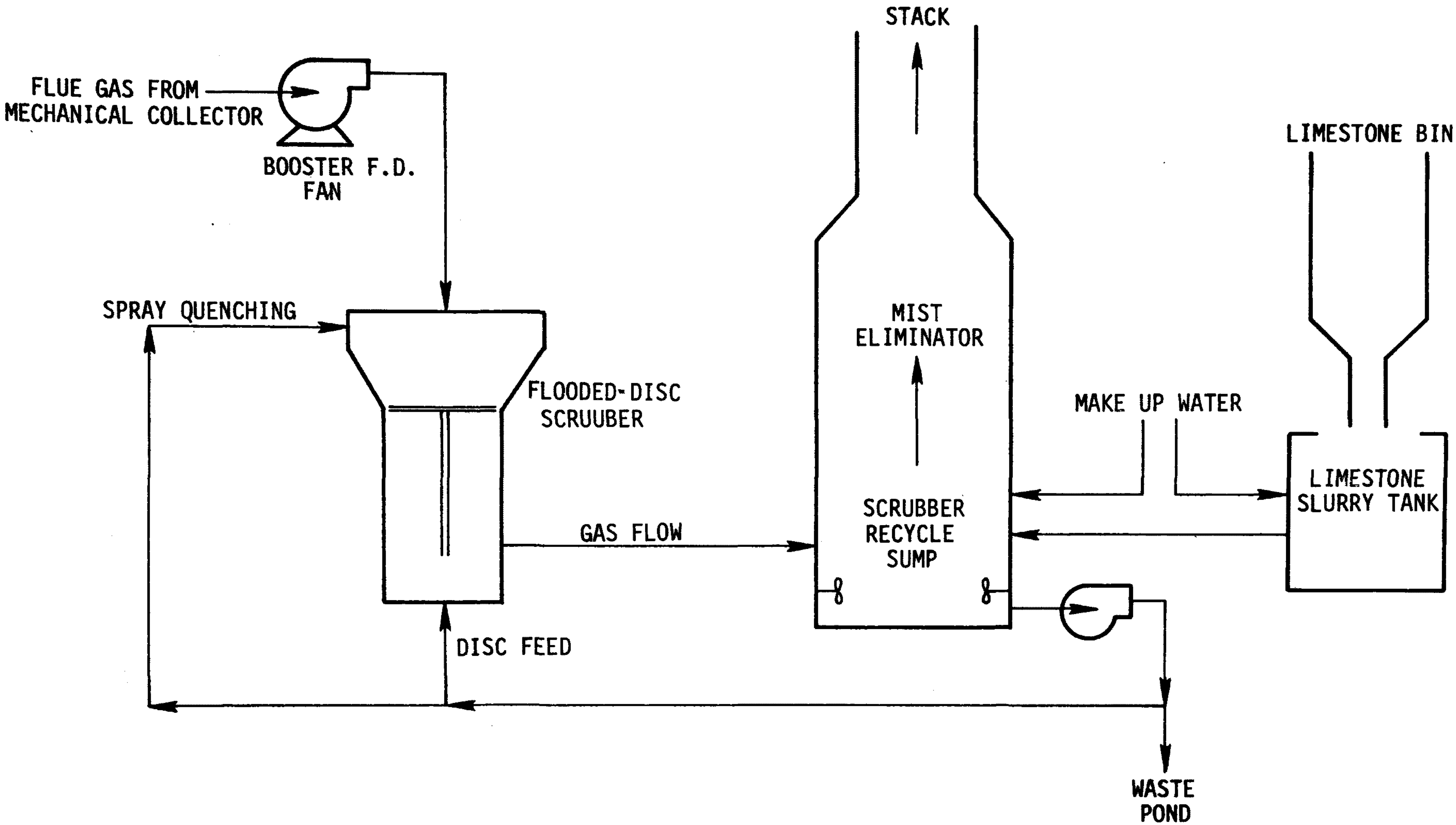

Figure 3-11. Simplified flow diagram of fly ash scrubber, Lewis and Clark plant.[5]

sure drop of the flooded disc scrubber at the Lewis and Clark Station is 12 to 13 inches of water. At system pressure drops of about 20 inches, liquid distribution has an important effect on equipment performance. It can be assumed that efficiency will be somewhat lower in a venturi at low pressure drops when liquor is introduced through a weir rather than through sprays.

Efficiency can be improved by increasing the liquid-to-gas ratio; after a certain point, however, increasing the amount of liquid will not enhance particulate collection efficiency. Furthermore, moisture reentrainment can cause increased emissions. For this reason, mist eliminators are always required.

3.2.1.3 Operational Procedures for Start-up and Shutdown

Preoperational Checks - As with the precipitator systems, it is important that all of the major items of equipment, connecting pipe, and auxiliaries be inspected, cleaned, and tested before startup.

General preoperation practices include checks to ensure that piping is free of debris, oil levels are correct, fans and pumps rotate in the proper direction, and alignments appear proper. More specifically, checkout of the following items should be done in accordance with manufacturer's recommendations:

Utilities

- Power supply
- Instrument air
- Process air

Pumps

- Belt tensions, pump rotation, pump alignment, lubrication, seal water operation, and electrical interlocks.

- Recycle pumps - suction and discharge valves.

- Flush water pumps

- Pneumatic pumps for flooded disc control and liquid level.

- Spare pump availability and operation.

Valves/dampers (stack, isolation, bypass)

- Bypass

- Density control

- Water purge control

- pH elements flush water

- Reagent slurry control

- Pond return

- Fresh water make-up

- Disc control (flooded-disc scrubber)

ID/FD Fan

- Electrical controls
- Fan bearing coolant water
- Lubrication
- Vibration sensors
- Bearing temperature sensors

Process water

- Level detector calibration
- Mist eliminator sump level alarm calibration
- Mist eliminator sump agitator
- Recycle pump

System controls/feedback controls

- Stack gas flow
- Make-up water control
- Reagent feeder rate
- Slurry pH
- Reagent dissolver level
- Slurry density
- Sludge drainoff and disposal

Safety system

- Interlocks
- Alarms for various system components according to design of system.

Start-Up Procedures

Energize motor control center, fan controller, and control panel.

Turn compressed air supplies on (both plant and instrument air). Check to see that domestic water is ready for process, coolant to fan bearings is sufficient, holding tanks are filled, pump is on automatic, and slurry pumps are ready.

Following the manufacturer's instruction manual, close drain valves; ensure that bypass is in operation, and that all process and control lines are clear.

Start Slurry System

This entails activation of process water booster pumps, scrubber flushdown program, slurry circulating pumps, and reagent feeder systems.

Start ID/FD Fan

Check that inlet damper is closed and interlocks are satisfied.

Start Sludge System

Activate sludge-to-thickener controls, sludge pumps, delumper, and all associated equipment.

Shutdown

Stop fan.

Stop reagent feed.

Flush scrubber. This may not be necessary for short outages, in which case some process control flow circuits may be kept operational, i.e. any flow circuits that carry slurry.

Slurry circulating pumps should be on as long as there is slurry in the system.

Shut down reagent feeder, then slaker.

As slurry tank levels become too low for slurry to circulate, dilute tank slurry, drain off to pond, and turn process off.

Flush and drain slurry pumps and close suction and discharge valves on the slurry pumps.

3.2.1.4 Inspection/Maintenance During Normal Operation and Common Malfunction Areas - Many of the items on the preoperation checklist should be checked in routine maintenance. The maintenance performed generally includes unplugging lines, nozzles, pumps, etc.; replacing worn pump parts, erosion/corrosion prevention liners, and instruments (level indicators, pH indicators, etc.); and repairing damaged components when this is practical from the standpoint of labor and materials.

The following checklist is based on problems encountered in scrubber operation. These should be checked routinely and corrected by the manufacturer's recommended procedures.

Check for wear in the throat section. Heavy wear occurs in areas downstream of the acceleration. Silicon carbide brick or replaceable wear liners help to extend throat life.

If abrasion is high inside the scrubber and large particles predominate the size distribution, check operation of the quench chamber.

Check for excessive scaling below disc of flooded disc scrubber. This can be caused by process changes such as changes in temperature, pH, chemical composition of the dust, or chemical composition of the make-up water; reduced liquor recycle rate; increase in the inlet loading; or failure of solids removal system.

Check the nozzle for buildup and/or damage. Repair or replacement may be necessary.

Check for solids buildup in blowdown lines. Cleaning may be effected without system shutdown, and a flush connection may be installed to prevent this condition in the future.

Check for corrosion and leaks in lines and vessels where protective liners may have deteriorated. Replace liners as required.

Check operation of mist eliminator. Formation of droplets can be caused by excessive gas flow rate, plugged drains from the moisture eliminator, or condensation in the outlet duct. Check structural supports and agitator for structural integrity and smooth operation.

Check pumps for wear, seal water, packing, and smooth operation.

Check dampers and damper linkages for proper positioning and wear.

Check fan for lubrication, fan bearing coolant, belt wear and belt tension, and impeller erosion/corrosion.

Inspect all interior surfaces and condition of holding tanks during major outages.

Inspect exterior for leaks in all process and control lines, ductwork, and expansion joints.

Note the condition of all instruments, e.g. level probes, and pH elements, with regard to solids buildup. It is impractical and usually impossible to remove solids buildup from the probes, and the probes must be replaced.

Check the reagent system and associated equipment for proper functioning (lime feeder, slaker, thickener and rake mechanism, and delumper).

Perform a final check for proper operation of pH sensors, density sensors, lime feed rate control, and level elements.

3.2.2 Preformed Spray Impingement Scrubber

3.2.2.1 Description - The scrubbing efficiency of this type of scrubber is dependent on distribution of the liquid in the gas by means other than the gas velocity. Particles or gases are collected on liquid droplets atomized by use of high-pressure spray nozzles. The properties of the nozzle, the liquid to be atomized, and pressure determine the characteristics of the liquid droplets. Spray towers can be used for both mass transfer and particle collection; they represent probably the least expensive method for achieving mass transfer.[16] Particle collection is principally by impaction, but is usually limited by the terminal settling velocity and diameter of the spray droplets.

The Minnesota Power and Light Company operates similar horizontal spray chambers at its Clay Boswell and Aurora plants. Nozzles located in the stainless steel enclosures direct a high-pressure spray against baffles, causing the spray to be finely atomized. Also, the induced turbulence promotes effective scrubbing of particulate.

The flow circuit for the Clay Boswell scrubber is shown in Figure 3-12. As indicated, liquid is pumped from a seal tank at the bottom of the spray chamber to two clarifiers (not provided at the Aurora Station). The overflow is then combined with make-up water and pumped back to feed the spray nozzles.

3.2.2.2 Normal Operation - Again, the operation of a scrubber is very specific to the site and the manufacturer's design.

Particulate removal efficiency depends upon the droplet size and opportunity for intimate contact of particles and liquid. For high efficiencies, nozzle pressures will exceed 200 psig. According to one test,[5] the efficiency can be comparable to that of a venturi and the preformed spray impingement scrubber consumes equivalent energy.

Depending on the particle size distribution, increasing the number of nozzles, liquid rate, or nozzle pressure may provide significant positive effects on scrubber performance.

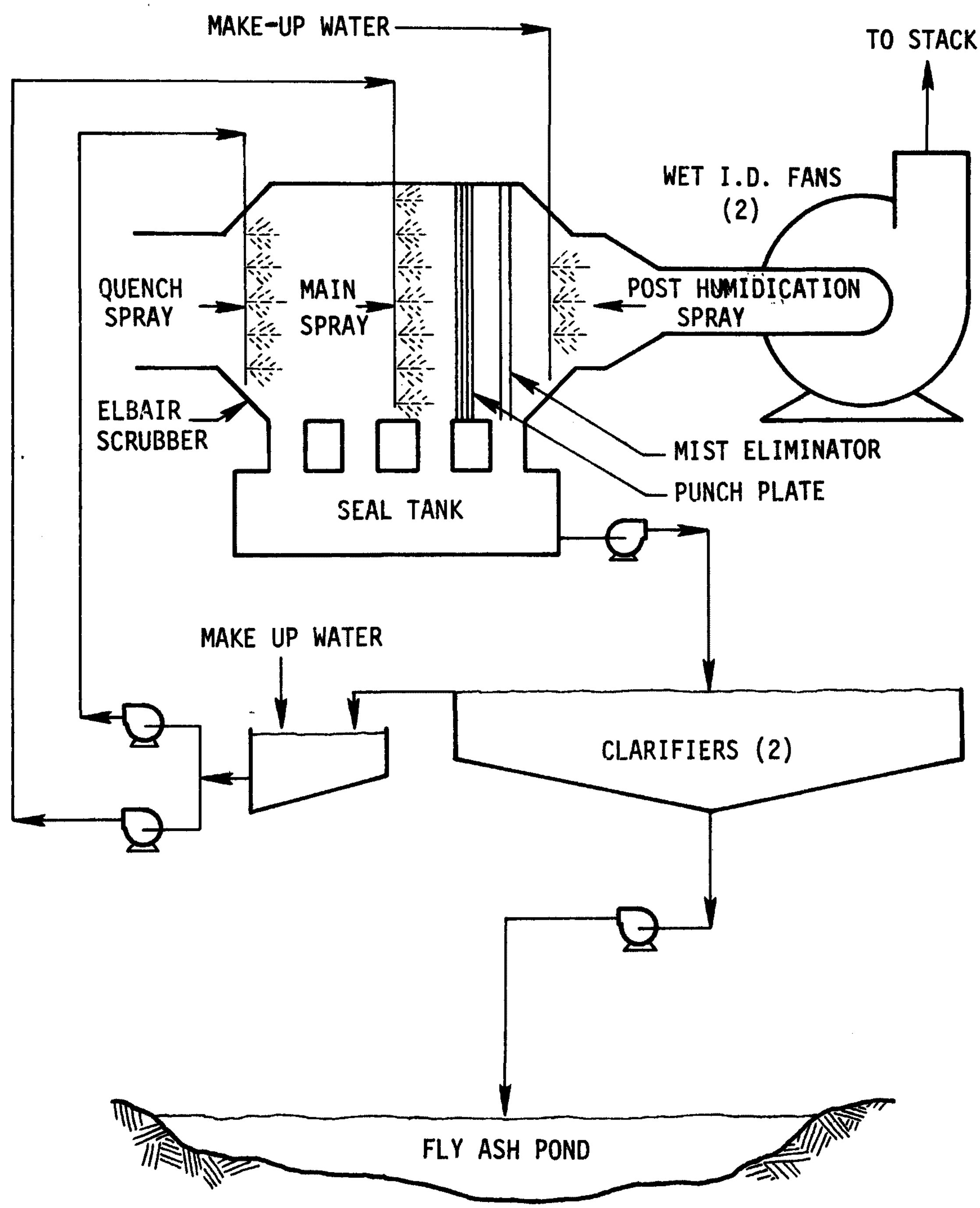

Figure 3-12. Simplified flow diagram for the particulate at the Clay Boswell station.[3]

Gas atomizing and sonic nozzles can produce small droplets, but only at the expense of power consumption.

Collection of fine particulate can be effected, of course, by increasing gas retention time but only at the expense of increased scrubber size.

3.2.2.3 Operational Procedures For Start-up and Shutdown - Preoperational Checks - The instruction manuals provided by equipment manufacturers should supersede any checklist presented here. The items listed for preoperation check of the gas atomized spray scrubber (Section 3.2.1.3) are applicable to spray towers also.

3.2.2.4 Start-Up/Shutdown - Again, follow the manufacturer's instructions for any given unit. Essentially all of the items mentioned in Section 3.2.1.3 apply here.

3.2.2.5 Inspection/Maintenance During Normal Operation and Common Malfunction Areas - The points presented with respect to inspection and maintenance of gas atomized spray scrubbers (Section 3.2.1.4) are applicable. Potential problem areas with high-pressure spray impingement scrubbers that should be checked include the following:

Check for nozzle problems. The high velocity causes potential erosion and the small orifices can be easily plugged.

Check wet induced-draft fan for plugging.

Check for scaling in the scrubber liquid circuit.

Check for stack gas mist carryover in the scrubber and liquid circuit.

3.2.3 Moving-Bed Scrubber

3.2.3.1 Description - Moving-bed scrubbers are designed to provide intimate contact between flue gas and liquid. The gas passes through a zone of mobile packing, which rests on a perforated plate. Liquid is either sprayed up from the bottom through the perforated plate and/or from the top down onto the perforated plate. The recirculation liquid flow rate and gas flow rate must be controlled within specified limits to create proper turbulence of the bed, thereby keeping the packing elements clean. If the gas and liquid flow rates are too high, the spheres will be carried upward and be held in a semistationary state against the underside of the top grid. In this latter condition, liquor can build up above the top grid and a condition known as flooding will develop. Flooding will be indicated by excessive pressure drop across the scrubber. The pressure drop across the scrubber is an indication of scrubbing action. Efficient scrubbing action occurs if the pressure drop is within the specified limits (7 to 12 in. water). The operating temperature of the TCA must not exceed 170° to avoid damage to the rubber lining and plastic spheres.

The only scrubbers of this type applied successfully to utility installations are at the Valmont, Arapahoe, and Cherokee stations of Colorado Public Service. A typical arrangment is shown in Figure 3-13. At the Valmont station, flue gas is treated first with a mechanical collector, then channeled with a booster fan through the scrubber to the chevron mist eliminator, and on to a reheater. The Arapahoe and Cherokee stations use electrostatic precipitators following the mechanical collector and before the scrubber.

3.2.3.2 Normal Operation - Using the Cherokee Station scrubber as an example,[7] the flue gas from the precipitator passes into two parallel induced draft fans. A bypass damper is used to direct the flue gas into either the stack or the scrubber. The flue gas enters the booster fans to offset the pressure drop through the scrubber. In the presaturator, the makeup water is sprayed into the gas to reduce the temperature to approximately 125°F. From the presaturator, the gas enters the scrubber. The scrubber consists of three stages of fluidized beds with 1.5-inch diameter plastic balls arranged into three separated parallel scrubber sections. The two outer sections each handle 20 percent of the flow, while the center section handles the remaining 60 percent. All three sections can operate independently to provide flexibility of operation. The scrubber liquor is then pumped from the bottom of the scrubber to a header equipped with spray nozzles at the top of the packing. Under normal operation, a portion of the

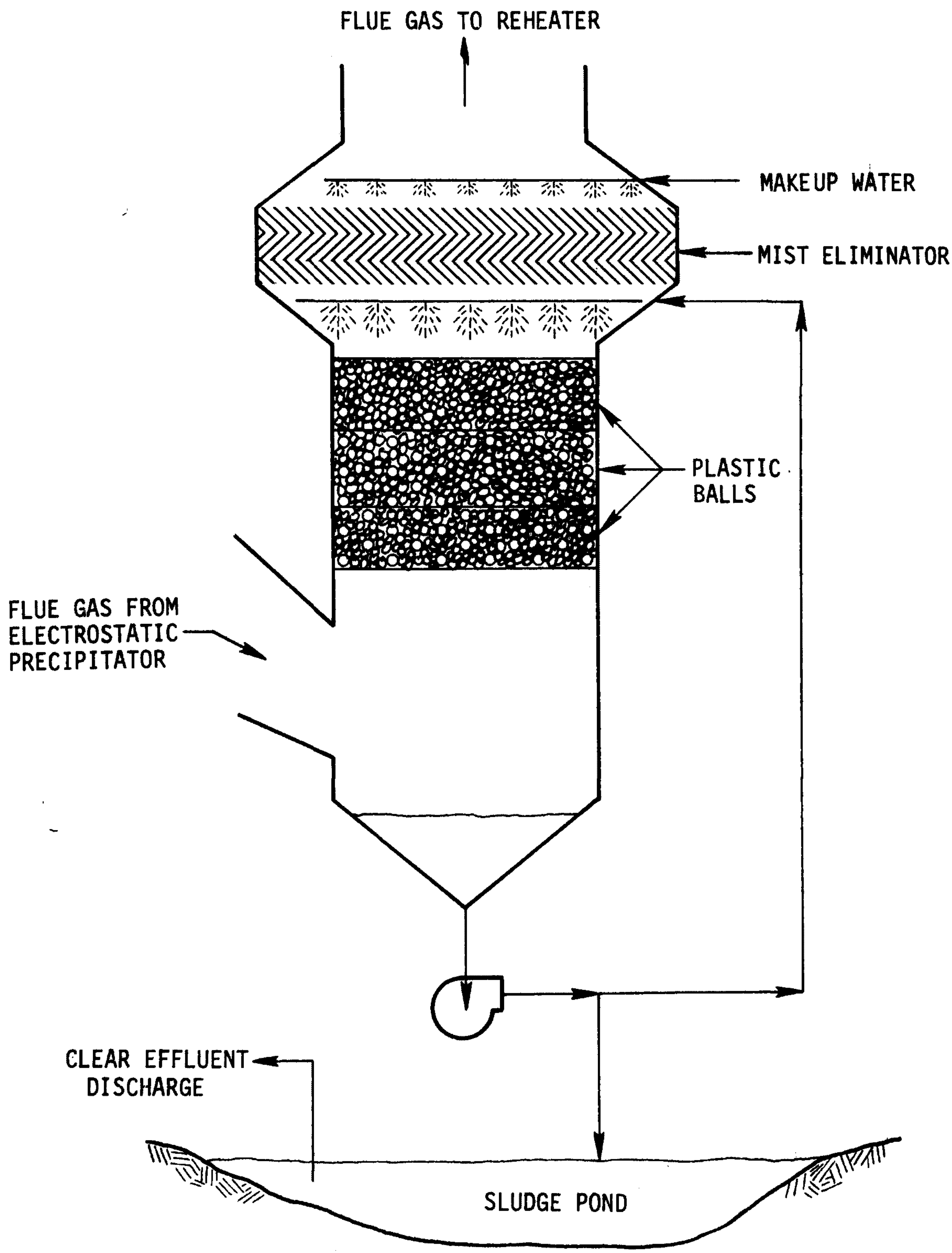

Figure 3-13. Typical scrubber installation at Valmont, Cherokee, and Arapahoe Stations, Public Service Company of Colorado.[3]

slurry is purged from the system to prevent buildup of solids. This slurry is pumped to an ash pond for disposal.

The scrubbed gas passes through a Chevron-type mist eliminator made of fiberglass-reinforced plastic where entrained droplets are removed. The mist eliminators are sprayed from the top once per shift to prevent accumulation of solids.

The gas is then heated by steam coils to 185°F before entering the stack to prevent corrosion of the stack and ductwork and to provide plume buoyancy after discharge into the atmosphere. The steam coils are equipped with two sets of soot blowers to remove fly ash from the heat transfer surfaces.

3.2.3.3 Operational Procedures For Start-Up and Shutdown

Preoperational Checks - Before start-up is initiated, all of the major items of equipment, connecting pipe, and auxiliaries must be inspected, cleaned, and tested. The manufacturer's instruction manuals will specify the checks that apply to the unit. In general, all the preparation checks listed earlier are applicable here, except with regard to the reagent system. In the TCA's discussed above (Colorado Public Service Stations) reagents are not normally used.

In addition, the following equipment should be checked in accordance with the manufacturer's recommendations:

Induced-draft fans

Bypass damper (isolation and stack dampers)

Booster fans (to overcome pressure loss across the scrubber)

Presaturator

Three stages of mobile balls

Scrubber liquor pump

Spray nozzles

Purging apparatus (to remove suspended solids from slurry)

Chevron-type mist eliminators

Steam coils (reheater coils)

Start-Up

Make a final check to insure that all internals have been installed in accordance with the instructions and accompanying drawings.

Carefully review all utility connections and ductwork; inspect all filters for debris; and check all presaturator, recycle liquor, trapout and demister wash nozzles for proper operation.

Set the scrubber inlet high temperature alarm at 150°F.

Start flow to presaturator and demister nozzles at the prescribed rate, and check for proper distribution of water and functioning of nozzles.

When the recirculation liquid in the external recirculation tanks is at the desired level, start the recirculation pumps and adjust flow to the design rate. Check the distribution of the recirculation header to make sure that all nozzles are functioning properly.

Start the fan. If the damper is available to control gas flow, close the damper during start-up of fan. When fan has reached its operating RPM, slowly open the damper until the design gas flow and pressure drop are obtained.

Check the pressure drop and temperature differences across the unit. Compare these values with design values. If a discrepancy appears, check the system for gas flow, gas temperature, gas distribution, liquor flow, and liquor distribution.

Continue to monitor process variables after the scrubber is operating satisfactorily.

Shutdown

Reduce the gas flow through the scrubber by closing the TCA inlet and outlet dampers.

Shut off the fan after damper is completely closed.

Shut off presaturator liquid flow, recirculation liquid flow demister wash flow, and deflector tray wash flow.

3.2.3.4 Inspection/Maintenance During Normal Operation; and Common Malfunction Areas[7]

Routine maintenance suggested by the manufacturer includes the following inspection procedures:

Open access doors and visually inspect the scrubber internals such as grids, spheres, headers, and demister.

Check periodically for proper operation of pressure, temperature, and flow sensors.

Clean scrubber sumps periodically to remove solids which may have built up.

Check periodically to verify proper operation of the recirculation liquid nozzles, deflector tray wash nozzles, demister wash nozzles, and presaturator nozzles.

Check the chevron demister for buildup on the blades. If significant buildup is present, the blades must be cleaned or plugging will occur, causing excessive pressure drop across the demister.

Based on actual operation at Colorado Public Service generating stations, the following items are indicated as problem areas that must be inspected consistently:

Check condition of mobile bed contactors. The basic problem is that, because of the turbulent nature of the system, the spheres wear out prematurely or break apart. In addition, sphere fragments falling through the grids and into the recirculation pumps severely cut the rubber linings. As a further consequence of deterioration of mobile balls, fragments may pass through the pump and plug the nozzles in the recirculatory system. Screens installed to prevent this passage of fragments into the recirculation system must be checked often for plugging. Cleaning of the screens may necessitate system shutdown.

Check vertical partitions for structural integrity and position to prevent migration of mobile-bed contactors. Migration of the spheres because of improper positioning of a vertical partition so that it blocks a portal can allow gas to channel through the empty section and thereby reduce contacting efficiency. Reduction of the pressure drop across the scrubber below 8 inches w.g. would indicate that channeling of the gas is occurring and a shutdown for repair is imminent.

Check guillotine isolation dampers. An ash buildup in the duct may prevent the guillotine damper from closing completely and thereby shear the motor couplings. Leaky dampers cause excessive ash buildup over the drive train motors, gear boxes, and couplings; this will hinder operation and create an unworkable atmosphere for maintenance personnel.

Check recirculation pumps. If V-belts on overhead motors are too tight, they should be readjusted to prevent excessive wear on motor bearings. Adhere to a periodic schedule of lubrication and cleaning of motor parts.

Check reheater section. Check condition of the steam coils for signs of corrosion. Since the service life is a direct function of the performance of the mist eliminators, condensed slurry corrodes and helps plug subcooling coils and fins respectively. This problem may be aggravated by reentrainment of slurry droplets, which is caused by higher-than-design flue gas velocity. The excessive velocity can be caused by backflow at the edges of the mist eliminators caused by duct section that expands at too great an angle.

Check rubber-lined piping. Where rubber lining is designed to protect stainless steel pipes, care should be taken to ensure that the covering is complete and in good condition. Y-sections lined with rubber are particularly vulnerable and should be checked regularly for signs of failure.

Check for buildup in the presaturator. Since the job of the presaturator is to cool the flue gas to near the saturation temperature of the gas with water sprays, buildup of soft solids may occur in the area of the wet-dry interface. These accumulations may fall into the scrubber hopper screens and cause plugging. Correction may require reorientation of the nozzle sprays.

Check mist eliminators for signs of corrosion and erosion and increased pressure drops due to plugging.

Inspect stack damper interlock system to ensure that the system is failsafe and that isolation and stack dampers respond quickly to the interlock system. All dampers should be clean and free-moving.

Check booster fan bearings. Ensure a clean atmosphere around all moving parts by providing soot blowers and following a regular lubrication schedule.

Inspect for weather-related problems. Freezing weather can cause dampers to lock up and can freeze water and slurry lines (process lines). All lines (process and control) should be properly insulated and heat-traced.

In conclusion, although many of the required operation and maintenance procedures are the same, each type of scrubber has its own characteristic problems, which are discussed in the inspection and maintenance sections.

3.3 OPERATION AND MAINTENANCE OF FABRIC FILTERS

Regular maintenance and proper operation of fabric filters are critical to good performance. Although most plant personnel realize the importance of these factors, proper records of operation and maintenance are seldom kept.

The Nucla study conducted by GCA[8] did not include maintenance but was concerned with normal and abnormal operation of the baghouse during testing to determine the effects of operating variables on baghouse performance. These effects were discussed in Section 2.0. An early study on fabric filters by GCA[9] does present detailed maintenance procedures, however, many of which could be applied to fabric filters for collecting fly ash. A more recent study of the Nucla baghouse, sponsored by the Electric Power Research Institute (EPRI), has systematically analyzed maintenance and operation procedures and their effects on performance as well as costs.[9] Results of this study are not yet available. Some data are reported on the Sunbury baghouse operation by the manufacturer (Western Precipitation).[10] Reference 11 and a recent EPA-sponsored study[12] discuss performance and costs of maintenance and operation of the Sunbury baghouse. No information is available on maintenance and operation of the Holtwood baghouse. The available data on the Sunbury facility, and general maintenance procedures applicable to all types of fabric filters are summarized below.

3.3.1 Sunbury Baghouse

The recommended preoperational checks, start-up and shutdown procedures, and maintenance practices used at Sunbury are presented below and are based on information reported in Reference 11 and 12.

3.3.1.1 Preoperational Checks - The following checks are recommended prior to start-up:

- Test control air lines (hydrostatically).
- Check air dryers that supply control air to the bag filters.
- Check ash removal system.
- Inspect collapse air fans for alignment and rotation.
- Check seals at gas inlet, collapse air, and gas outlet damper.
- Check baghouse compartments, remove debris.
- Check filter bags for proper installation and tension.
- Check and sweep thimble floors clean. Dust build-up on floor during operation is a positive indication of a broken bag.
- Calibrate pressure drop recorders and transmitters.
- Check pressure taps for leakage.
- Coat filter bags with fly ash prior to light-off (fly ash coating is required to prevent blinding by fuel oil during start-up).

3.3.1.2 Start-Up - Before a new set of bags is placed in service, each bag is precoated with fly ash remaining in the boiler gas passes to prevent blinding of the bags with the oil used during boiler start-ups. The boiler is brought on the line and the baghouse cleaning cycle is not activated until 1 hour after coal is fired. This allows an additional coating to form on the bags.

3.3.1.3 Shutdown - Approximately 15 to 20 minutes before taking the last mill and exhauster out of service, the collapse air fan is de-energized. This preserves the filter cake on the bags and prevents blinding by the fuel oil residue during the ensuing start-up period. The cleaning cycle controls remain in service during the entire outage to continuously exercise the gas inlet and collapse air dampers.

When a boiler is taken off line for furnace and gas pass cleaning, it may be necessary to restart the collapse air fan during the outage to clean the bags. Pressure drop must be monitored during the shutdown. If it rises to 3 in. H_2O because of dust collected from the gas passes, the collapse air fan will be placed in service for one complete cleaning cycle and then taken out of service. This process may be repeated as necessary. It must be kept in mind, however, that because a fly ash coating on the bags prior to start-up is very desirable, good judgment must be used when cleaning the filter bags during an outage.

3.3.1.4 Maintenance During Normal Operation - It is reported[13] that most maintenance hours at Sunbury have been spent on bag replacement, collapse air fan repairs, and air-operated damper repairs. Although little data are available on maintenance of fabric filters relative to collection of fly ash, many maintenance procedures can be applied to all types of fabric filters.[13] This section summaries some of these procedures.

Inlet Ducting

Common problems such as abrasion, corrosion, sticking or plugging of fly ash, and settling must be dealt with on a routine basis. Abrasion can be reduced with special materials at bends in ducting, for example. Corrosion can be minimized by supplying insulation, especially in long duct runs, which are most susceptible to moisture condensation. Regular inspection will help control plugging and settling problems in ducts.

Blast Gate and Flow Control

Problems with flow control equipment are reported frequently.[13] The blast gate valve is especially vulnerable and should be checked periodically and adjusted. Filter compartment inlet dampers are a high-maintenance item, and spare parts should be stocked.[13] A bad damper seal can shorten the life of bags in a shake-type system, and caking bags, if not replaced, can foul valves on the clean side of the baghouse and cause them to malfunction.

Fans

Fans and blowers are reported to be a large problem area, particularly those located on the dirty side of the baghouse where material can accumulate on the vanes and throw off the balance.[13] Corrosion and abrasion can also cause problems.

Condensation and corrosion in the fan may be alleviated with duct and fan insulation.[13] Most fan housing can be drained, and the drains should be checked on a regular basis.

Air flow and fan speed should be measured periodically and belt condition and tension determined; the fan should also be checked for direction of rotation. These checks can be combined with routine lubrication procedures.[13]

Collapse Fan Repairs

At Sunbury, collapse fan failure is detected from increased differential pressure signals. When a main collapse fan fails, the spare collapse fan is put into service by opening blast-gate (butterfly-type) dampers. The spare fan is normally filled with fly ash caused by leakage past the blast gate dampers, and normally the fan is cleaned out before it is put into service. This takes as much as 2 to 3 hours. Originally, the spare fan was isolated by sliding gate dampers. These dampers provided a tight seal; however, they were difficult to open and close. It took four men with a chain hoist approximately 4 hours. As a temporary measure, the spare fans were pressurized with compressed air to prevent inleakage.

Damper failures can sometimes be detected by observation of the differential pressure chart. As the dampers open and close the differential pressure swings. If a damper fails, the absence of this pressure swing leaves a "gap" on the differential pressure chart. If a high differential pressure alarms, the dampers are routinely checked for proper operation. If not, the operator must go up to the baghouse and visually observe damper operation through the complete cycle (a total of 32 minutes).

Entrance Baffles

Baffles may be added to improve distribution of the gas to each compartment and bag. The baffles should be adjustable, however. Also, they may cause problems by accumulating dust or abrading too rapidly.

Hoppers

Hoppers are a common problem in any fly ash collection system. Ash flow can be facilitated by the use of vibrators and/or heaters (if they work properly); by lining the hoppers with antifriction material; by the use of air-pulsed rubber-lined hoppers; by placing poke holes in the side of the hoppers; or by insulation if condensation is a problem.

Regular inspection (once per shift) of the hopper is mandatory to alleviate problems with the suction removal system or bridging in the hopper before the problems become serious.

Bag Replacement

In most filter systems, the biggest part of the maintenance program is related to fabric upkeep.[13]

At Sunbury, all baghouse compartments are inspected during each annual boiler outage. If an accumulation of dust is found on the compartment floor, each bag in the compartment is inspected for possible failure, and all failed bags are replaced.

To replace a bag with the boiler in service, the associated compartments are isolated by closing the gas inlet and outlet dampers. The lower and upper doors of the compartment are opened to allow ambient air to circulate. The cover is removed from the vent stack, and a portable 7000-cfm fan is set on the vent stack and started to provide forced ventilation. It normally takes 3 to 4 hours to ventilate the compartment sufficiently for men to enter to replace the failed bag, and it is still necessary that they wear masks to prevent inhalation of sulfur dioxide.[12] The entire procedure (isolating and ventilating the compartment, finding the leak, replacing the bag, and returning the compartment to service) takes approximately 6 to 8 hours.

Bag failures are detected by daily observations of the opacity meter charts. When a bag has failed, the opacity meter senses the increased particulate emissions; generally, the stack discharge is not visible. The opacity meter chart will indicate a periodic spike in sequence with the cleaning cycle. There will be a decrease in the reading when the compartment with the failed bag is removed from service, a spike when the compartment is returned to service, and a settling out to a higher-than-normal reading. Some spikes are not easily discernable, and a careful study of each chart is necessary. Also some nonperiodic spikes occur, but these do not indicate an abnormal condition.

When it is determined which compartment has the failed bag, the compartment is taken out of service. The opacity meter readings then return to normal. The compartment is entered, and each of the 90 bags is inspected. An accumulation of fly ash on the compartment floor is a telltale sign of an actual bag failure in the compartment. However, bag failures have been found in compartments with no fly ash accumulations. The bags are inspected by holding a flashlight at the bottom of the bag and shining it up the side of the bag. Any tears are illuminated in this manner. Also, a slight tap on the bag will, if there is a failure, cause a stream of fly ash to flow from the bag, which is illuminated by the light, thus providing an additional check for failures.

The failed bag is replaced, the compartment floor is cleaned, and the compartment is returned to service.

Tension

The amount of bag tension required for best overall performance varies between manufacturers. A bag that is too slack can fold over at the lower cuff and bridge across and wear rapidly.[13] Too much tension can damage the cloth and the fastenings. Correct tension is a function of filter dimensions and cleaning mechanism. Shake cleaning in particular seems to require a unique combination of tension, shake frequency, and bag properties for best results.[13] In any event, the manufacturer's recommendations should be followed and the tension checked periodically, and especially a few hours after installing a new bag.

Spare Stock

It is advisable to have a complete set of filter elements in stock, in case of an emergency. The spare filter elements should be clearly labeled and kept well-separated from used filter elements.[13]

Inspection Frequency

External maintenance inspection of the filter house is usually performed daily, whereas the filter elements themselves are typically inspected once a week to once a month.[13]

Shake Cleaning

The shaking machinery should be checked periodically for wear. If the bags are not being cleaned properly, sometimes a minor adjustment of the shake amplitude of frequency can markedly improve cleaning. If a safe amount of shaking still does not properly clean the cloth, it may be necessary to reduce the filtration velocity for a few hours.[13]

Reverse-Flow Cleaning

With this type of cleaning, the only maintenance requirement is to periodically check the rate of flow (back pressure) and the timing to keep the residual drag at an economical level.

Shake and Reverse-Flow Cleaning

As in the case of shake cleaning, wherever the bag is flexed, the rate of wear is apt to be high. This is especially common near the thimbles, as was the cage at the Nucla plant (section 2.6.10.3). The maintenance procedures outlined for the shale and reverse-flow methods also apply here.

Instrumentation

Proper operation of fail-safe mechanisms and automatic control instrumentation is very important to the safety of the filter cloth.[13] The location of all sensing instruments should be checked to see that the proper temperature, air flow, etc. are being measured. All instruments should be calibrated after installation and rechecked monthly for sensor location, leaks (manometer), sticking, and legibility.[13] The instrument readings covering one complete operating cycle should be recorded for future use in routine checks and trouble shooting. This record should be posted beside each instrument.[13]

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4.0 FRACTIONAL EFFICIENCY RELATIONSHIPS

Up to this point, this report has dealt with the relationship of input variables to control device design and costs for various application areas. Recall that an application area is defined with respect to coal type, boiler type, and overall mass efficiency level. This information along with typical data on fly ash size distribution at the collector inlet was used in developing a computer model that predicts percent penetration (the portion of particulate that escapes the collection devices) versus particle size for electrostatic precipitators. Computer models have also been developed to predict percent penetration as a function of particle size for gas atomized spray (venturi) TCA, and high-pressure spray impingement scrubbers. These models are based on the data described above and also on values for L/G ratio and system pressure drop. In this section, the assumptions and descriptions of the models are presented, along with the results of computer runs. For a 500-MW power output, precipitator costs are calculated for different levels of control for particles in the 0.2 to 0.4 micron range.

In the assessment of fractional and total mass efficiencies of fabric filters, performance data for the Nucla and Sunbury baghouses are presented. Since minimal information is available on percent penetration as a function of particle size below 1 micron, additional fractional efficiency data are presented from a pilot plant fabric filter on an industrial pulverized-coal-fired boiler.

No computer model is presented in this report for predicting the fractional efficiency of fabric filters as a function of particle size. A suitable model is presently not available for predicting the fractional collection efficiency of fabric filters, as applied to this study.

4.1 LIMITATIONS OF CURRENT DATA

Only in the past 4 or 5 years has particle size distribution been measured and recorded with any regularity by control equipment manufacturers, independent testing companies, and consultants; and because of operator error and the inherent technical limitations of some particle-sizing instruments, reliable data are still not readily available. Meaningful evaluation of fine particulate emissions will require development of a reliable and consistent fine-particle measuring technique that can be applied widely. A broadly applicable technique for compliance monitoring of fine-particle sources would have the added advantage enabling the collection of valuable data concerning various coal/boiler applications and operating conditions.

4.2 SUMMARY OF INLET PARTICLE SIZE DISTRIBUTION DATA USED FOR PRECIPITATOR AND SCRUBBER COMPUTER MODELS

Table 4-1 summarizes size distribution data obtained from several sources by different particle-sizing techniques. These data represent measurements at the collector inlet. Because of the high degree of scatter, "standard" statistics have been selected from the literature[1] to characterize only the effect of boiler type on the particle size distribution at the outlet of the boiler. Coal type, of course, also influences particle size distribution, particularly whether the coal is soft or hard and how it is affected by preparation procedures. The data of Table 4-1, however, do not allow differentiation on the basis of coal type. References providing the input for Table 4-1 are listed at the end of Section 4.0.

4.3 ELECTROSTATIC PRECIPITATOR COMPUTER MODEL

The electrostatic precipitator computer model computes size distribution at the precipitator outlet, based on inlet size distribution and overall mass collection efficiency. From the inlet and outlet distributions, fractional efficiencies can be calculated directly.

Table 4-1. SUMMARY OF INLET PARTICLE SIZE DISTRIBUTION DATA

Case	Utility name/station	Location	Coal			Firing method	Inlet particle size distribution characteristics		Particle sizing method
			Type	Sulfur, %	Na_2O, %		$\bar{X}$	σg	
1	TVA/Widows Creek, Unit 5	Bridgeport, TN	Bituminous 30% ash	0.7		PC	13.8	2.26	Brinks cascade impactor
2	Union Electric/ Meramec	St. Louis, MO	Bituminous	2.46		PC	11.0	3.44	Brinks impactor
3	TVA/unidentified	--	Bituminous	1.64		PC	24.3	2.35	Brinks impactor
4	TVA/unidentified	--	Bituminous	1.64		PC	24.0	2.33	Brinks impactor
5	Illinois Power/ Wood River, Unit 4	East Alton, IL	Bituminous	2.82		PC	20.0	3.15	Cascade impactor
6	Col. Ute Elec./Nucla	Nucla, CO	Subbituminous	0.70		STO	18.0	3.16	Anderson Mark III
7	North Dakota Lignite/ unidentified		Lignite (Baukol)	0.96	2.0	PC	5.20	4.04	Bahco
8	North Dakota Lignite/ unidentified		Lignite (Beulah)	0.96	1.0	PC	8.60	2.91	Bahco
9	North Dakota Lignite/ unidentified		Lignite (Beulah)	0.96	6.0	CYC	18.0	5.56	Bahco
10	Iowa Pub. Serv./ George Neal	Sioux City, IA	Subbituminous	0.81		PC	34.0	4.72	Brinks impactor
11	Kansas City Power & Light/Montrose, Unit 1	Ladue, MO	Subbituminous (Amax)	5.52		PC	5.60	3.57	Bahco sub-sieve
12	So. Cal. Ed/Mohave	near Bullhead City, AZ	Subbituminous	0.38		PC	14.0	5.34	Bahco
13	Hot-side utility/ unidentified	--	Subbituminous	--		PC	21.0	2.62	Modified Brinks cascade
14	Ala. Power/Gorgas, Unit 10	Birmingham, AL	Bituminous	1.43		PC	22.5	2.93	Modified Brinks

4.3.1 Design Equations and Assumptions - Electrostatic Precipitators

The following relationships[2] are used in the program to determine particle collection as a function of particle size.

The electrical force on a charged particle in an electric field is given by:

$$F = qE_p \tag{1}$$

where E_p (by the Deutsch model) is the electric field strength at the precipitator collecting electrode. (See Table 4-2 for definition of all terms. Units are m k s system.) The force opposing particle motion through the gas is:

$$F = 3\pi\mu d w_d/C \tag{2}$$

Equating the forces and solving for the migration velocity of particles of size d:

$$w_d = \frac{qE_pC}{3\pi\mu d} \tag{3}$$

C is the Cunningham correction factor given by:

$$C = 1 + 2.5\lambda/d + 0.84\lambda/d \exp(-.435d/\lambda) \tag{4}$$

The particle charge q can be represented by the Cochet equation:

$$q = [(1 + \frac{2\lambda}{d})^2 + \frac{2}{(1 + 2\lambda/d)}] \pi\varepsilon_o E_o d^2 \tag{5}$$

Table 4-2. NOMENCLATURE FOR ELECTROSTATIC PRECIPITATOR COMPUTER MODEL

A	=	precipitator collecting area, m^2
a	=	defined by equation (6), dimensionless
C	=	Cunningham correction factor, dimensionless
d	=	particle diameter, m
$\bar{d}$	=	geometric mean particle diameter, m
E_o	=	effective charging field, (V/m)
E_p	=	effective precipitating field, (V/m)
F	=	force, N
$f_1(d)$	=	inlet particle size distribution function, m^{-1}
g(d)	=	defined by equation (10), m
k	=	defined by equation (9), m^{-1}
Q	=	volumetric gas flow rate, m^3/sec
q	=	particle charge, C
w	=	Deutsch effective migration velocity, m/sec
w_d	=	migration velocity for particle of diameter d, m/sec
ε_o	=	permittivity of free space, 8.86 x 10^{-12} F/m
$\bar{\eta}$	=	overall collection efficiency, dimensionless
η_d	=	collection efficiency for particles of diameter d
λ	=	mean free path of gas molecules, m
μ	=	gas viscosity, kg (m/sec)
σ	=	geometric standard deviation of size distribution, dimensionless

The Cochet equation accounts for particle charging by both field charging and diffusion charging mechanisms. This is important in analyzing the effects of particle size, since the charging mechanism changes from field to diffusion in the submicron range.

Combining (3) and (5) and defining

$$a = [(1 + \frac{2\lambda}{d})^2 + \frac{2}{(1 + 2\lambda/d)}] \quad (6)$$

the particle migration velocity for particles of size d becomes:

$$w_d = (\frac{\varepsilon_o E_o E_p}{3\mu})\ aCd \quad (7)$$

For particles of a single size, d, the Deutsch equation can be applied to calculate collection efficiency:

$$(1 - n_d) = \exp\ [\frac{wdA}{Q}] = \exp\ [-(\frac{\varepsilon_o E_o E_p A}{3\mu Q})\ (aCd] \quad (8)$$

Defining new terms:

$$k = \frac{\varepsilon_o E_o E_p A}{3\mu Q} \quad (9)$$

$$g(d) = aCd \quad (10)$$

the single-size efficiency equation becomes:

$$(1 - n_d) = \exp[-kg(d)] \quad (11)$$

The overall collection efficiency is found by integrating over the inlet size distribution, f_1 (d):

$$(1 - \bar{n}) = \int_o^\infty (1 - n_d)\ f_1\ (d)\ dd \quad (12)$$

Assuming a log normal inlet distribution, this becomes:

$$(1 - \bar{n}) = \frac{1}{2\pi' \ln\sigma} \int_0^\infty \exp[-kg(d) - 0.5 \frac{\ln d/\bar{d}}{\ln\sigma})^2] \, d\ln d \qquad (13)$$

The above procedures can be used to determine outlet size distribution and fractional efficiencies (or percent penetration). An important effect that the program cannot model is that of reentrainment of particles on fractional efficiency. This limitation is discussed in Section 4.3.2. Nomenclature for the above equations is defined in Table 4-2.

4.3.2 Percent Penetration as a Function of Particle Size For Electrostatic Precipitators

Predicted penetration as a function of particle size is presented for electrostatic precipitator applications in Figures 4-1 through 4-3. Use of the computer program shows an important result: a minimum in efficiency in the particle size range of 0.2 to 0.4 micron for pulverized-coal-cyclone-and stoker-fired boilers (Figures 4-1 through 4-3, respectively). This observed minimum is probably caused by the changing particle charging rates from the diffusion and field charging mechanisms. The particle size range between 0.1 and 1.0 micron represents a transition region where particles begin to exhibit actions characteristic of gases. Diffusion charging is related to the motion of negative ions in the gas stream caused by their thermal velocity (Brownian

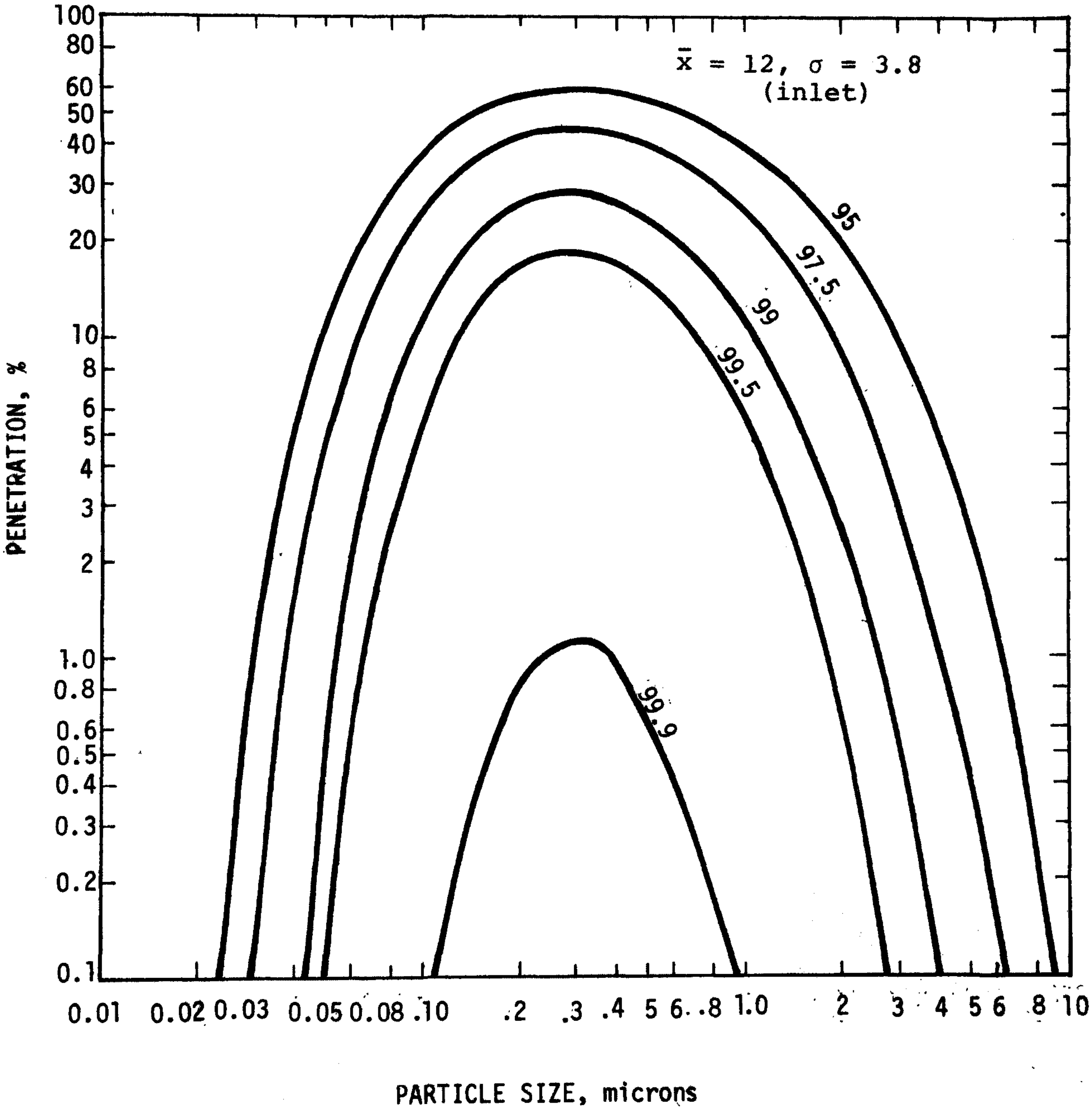

Figure 4-1. Percent penetration, pulverized-coal-fired boiler (cold-side ESP).

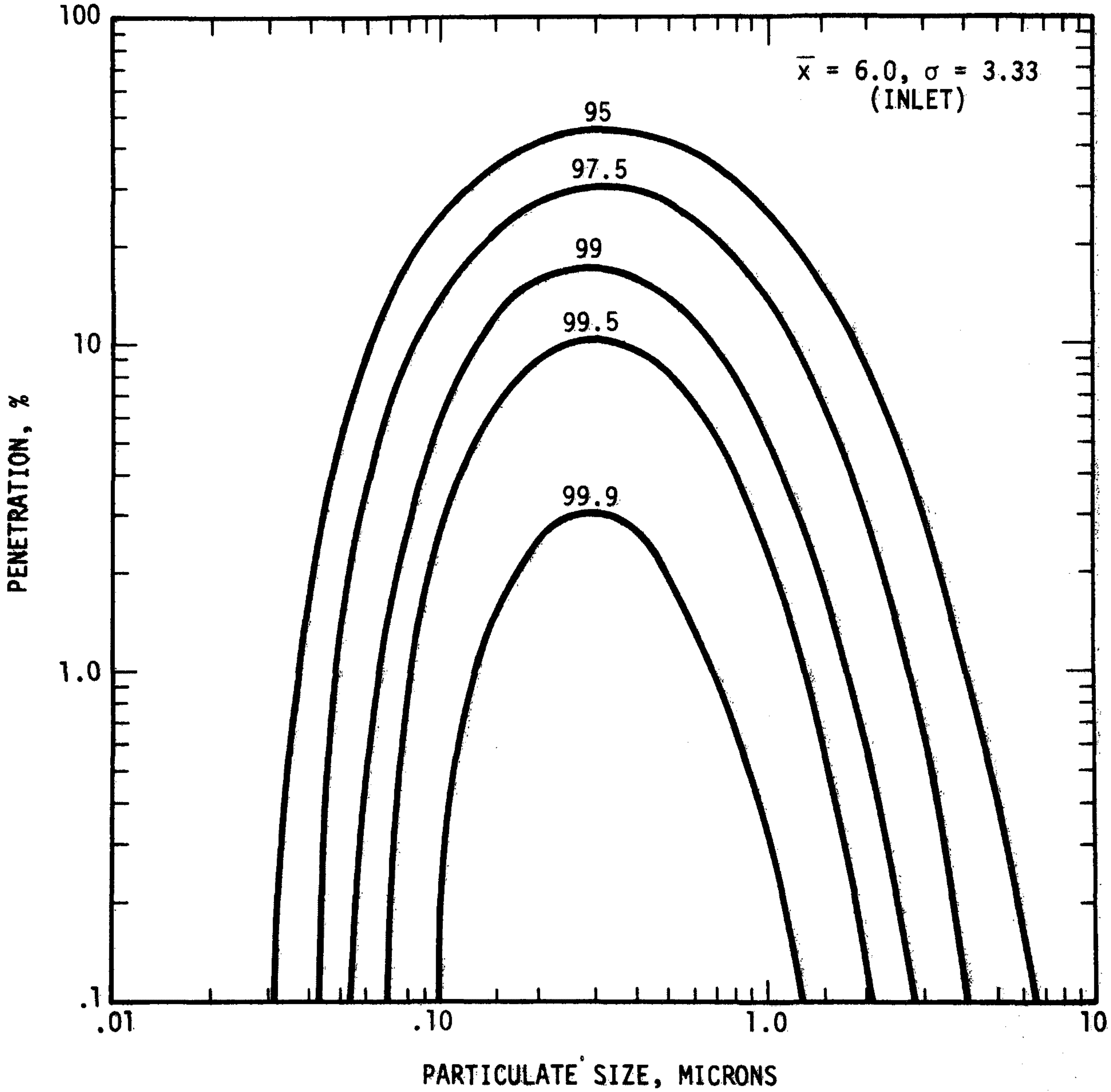

Figure 4-2. Percent penetration, cyclone-fired boiler (cold-side ESP).

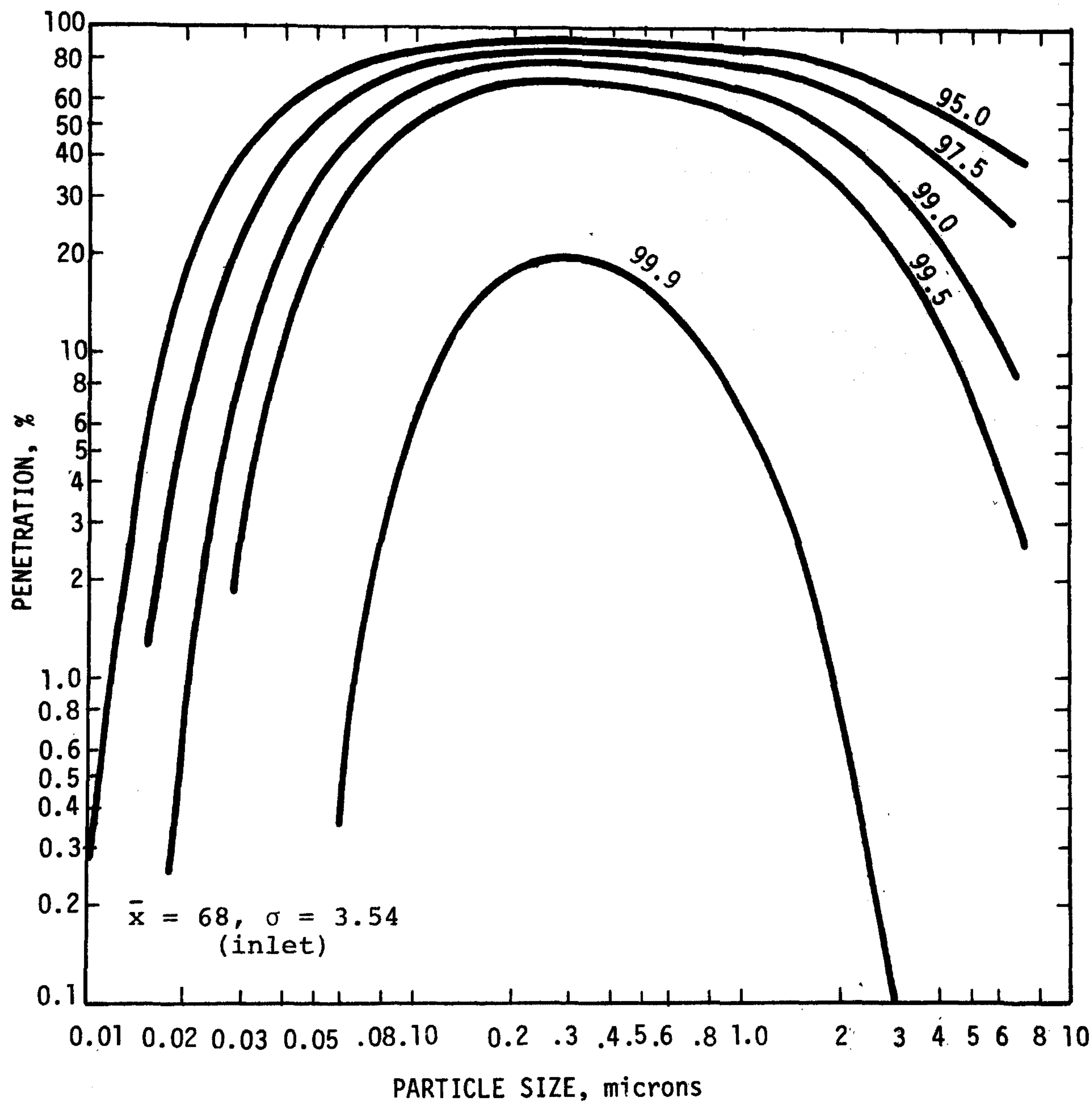

Figure 4-3. Percent penetration, stoker-fired boiler (cold-side ESP).

motion), and field charging results from the flow of negative ions along the direction of the electric field.

Field data on coal-fired boilers confirm this observation. Figures 4-4 through 4-7 present fractional efficiencies obtained in tests of precipitators at the Gorgas Station of Alabama Power Company, the Wood River Station of the Illinois Power Co., an unidentified hot-side installation, and an unidentified western subbituminous-fired boiler, respectively. The Gorgas, Wood River, and hot-side installation are pulverized-coal-fired boilers. The data for the western subbituminous-fired boiler show predicted versus test values on the same graph.

As mentioned earlier, the program cannot model the effect of reentrainment of particles on fractional efficiency. In the process of reentrainment, fine particles form agglomerates on the collecting plates and are reentrained as larger particles. Thus, the measured fractional efficiencies must show a decrease at the larger particle sizes. The data in Figure 4-7 (lignite boiler) show an apparent increase in penetration at a particle size of 6 microns. Note the agreement between computed and measured fractional efficiency at particle sizes below the size range where reentrainment becomes obvious.

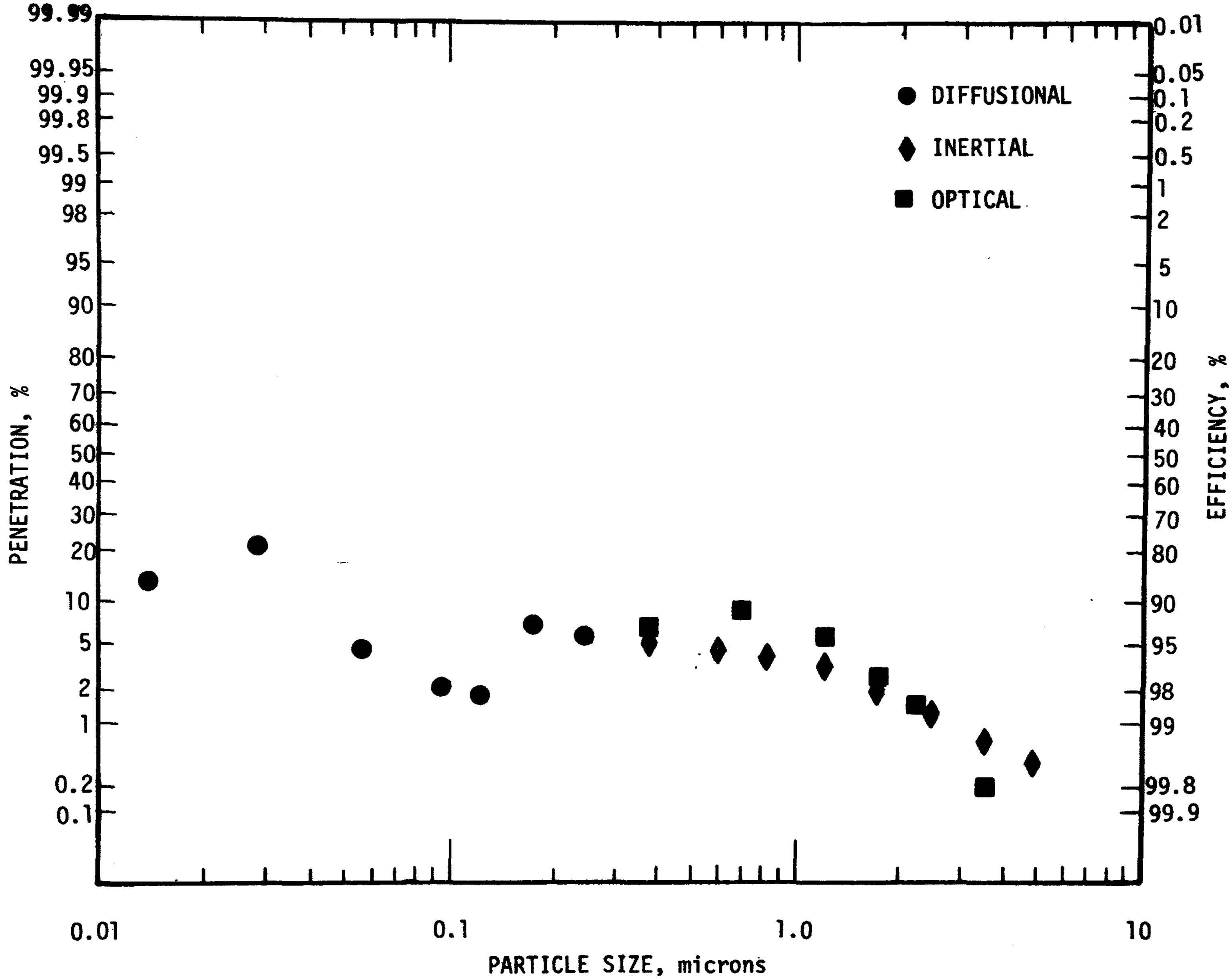

Figure 4-4. Measured efficiency as a function of particle size for Precipitator Installation at the Gorgas Plant of Alabama Power Company.

Source: (Reference 3)

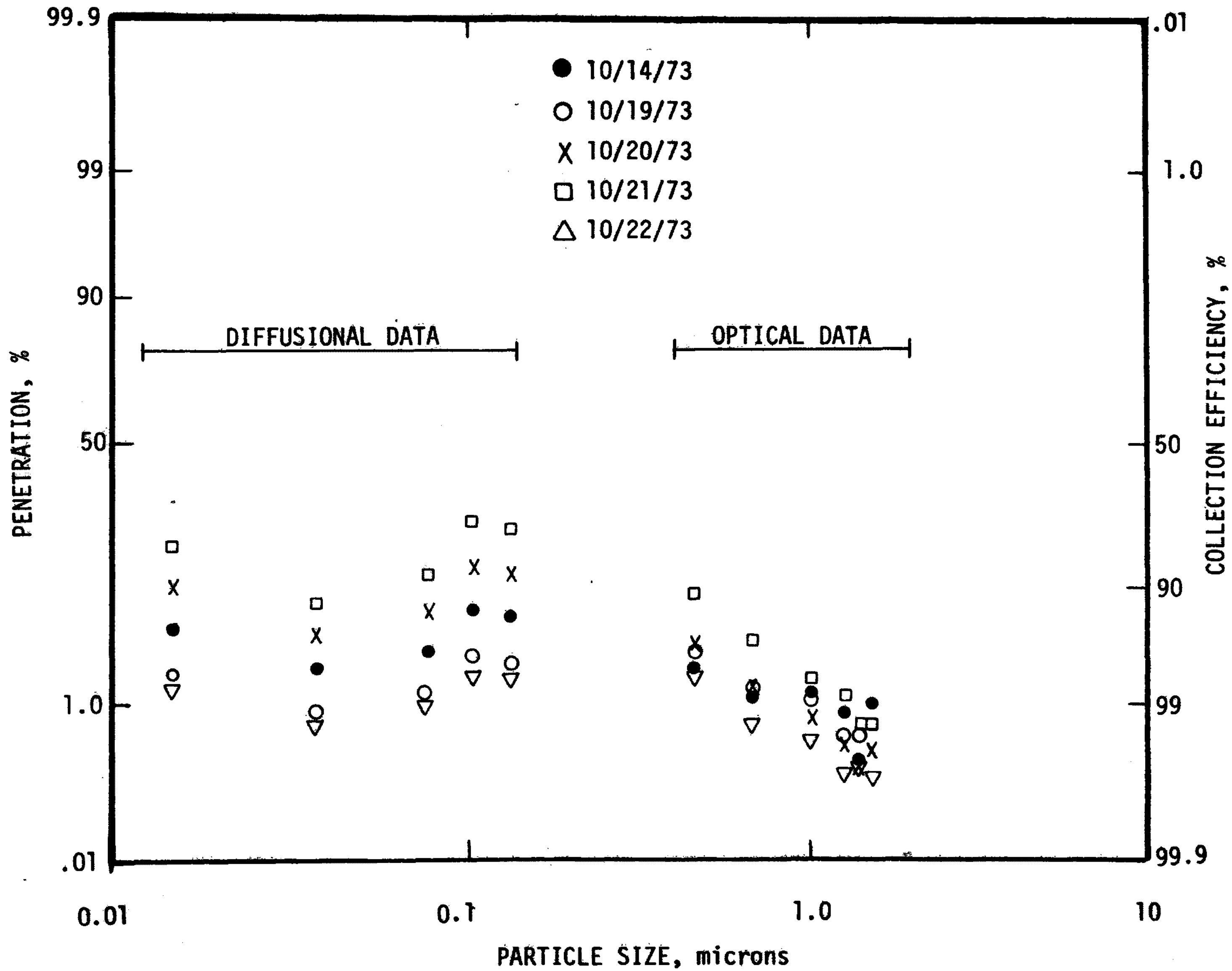

Figure 4-5. Fractional efficiencies for the Wood River Precipitator.

Source: (Reference 4)

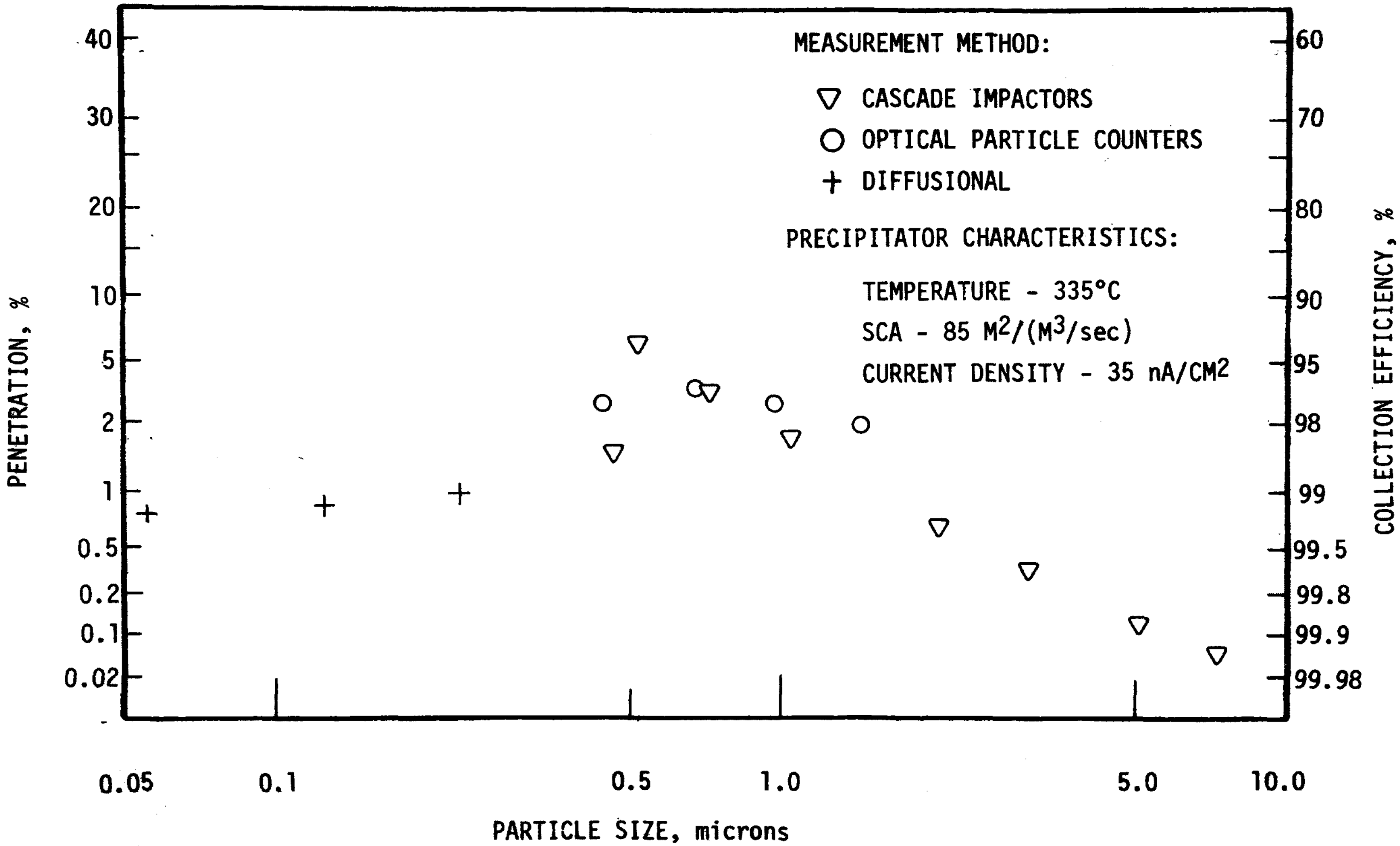

Figure 4-6. Average fractional efficiency for a hot-side ESP installation.

Source: (Reference 3)

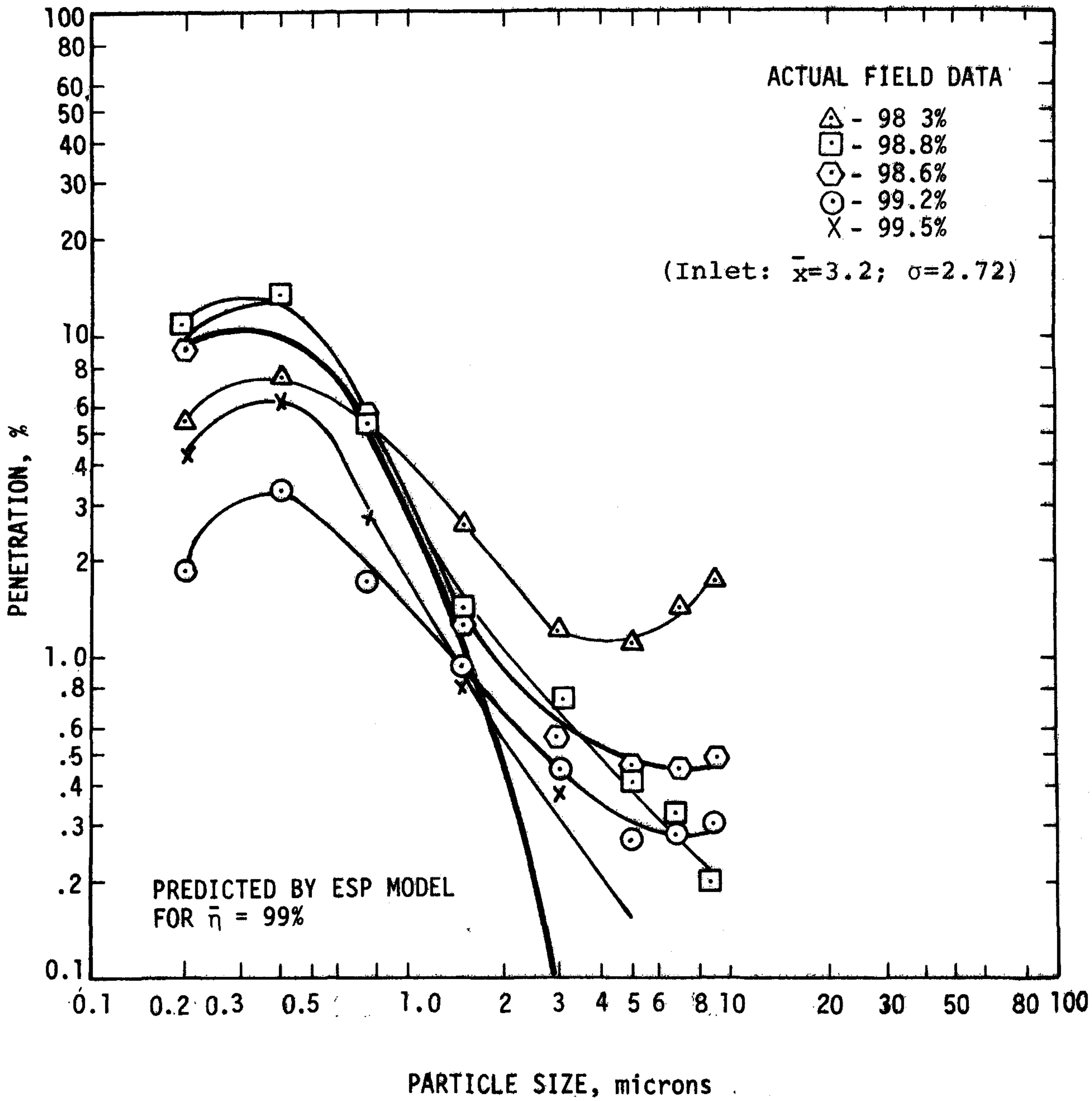

Figure 4-7. Computed versus actual percent penetration for cold-side ESP on a western subbituminous-fired boiler.

4.3.3 Projected Costs of Fine Particulate Control - Electrostatic Precipitators

The projected costs of fine particulate control with cold-side and hot-side electrostatic precipitators are presented in Tables 4-3 and 4-4, respectively. The data are based on assumptions of no particle reentrainment, gas nonisoturbulence, and absence of gas sneakage. Temperatures of 700°F and 300°F are assumed for representative hot-side and cold-side precipitators, respectively.

As mentioned earlier, in the absence of reliable data on inlet fly ash size distribution the influence of coal type on fractional efficiency is not shown. The influence of significant coal characteristics for the various application areas is shown clearly, however. The information presented is intended to support two points: (1) in establishing a fine particulate emissions standard, both fractional efficiency in collection of the most difficult particles to collect (those in the 0.2- to 0.4-micron range) <u>and</u> overall mass efficiency must be considered; and (2) for low-sulfur coal applications, a hot-side precipitator is often a more economically attractive alternative to a cold-side precipitator.

Selected cases from Tables 4-3 and 4-4 are presented in Tables 4-5 and 4-6 respectively and discussed below to illustrate the first point.

Table 4-3. COLD-SIDE ELECTROSTATIC PRECIPITATOR - COST OF FINE PARTICULATE CONTROL

Type boiler	Coal ash characteristics, % of significant constituent	Overall mass eff., %	Frac. eff. on particles in 0.2-0.4μ range, %	SCA required, ft^2/1000 acfm			Cost @ 500 MW: Capital cost, $/kW			Cost @ 500 MW: Ann. oper. cost, mills/kWh		
				Bitum.	Subbit.	Lignite	Bitum.	Subbit.	Lignite	Bitum.	Subbit.	Lignite
PC	0.6 sulfur	95.0	41.0	195	252		6.17	7.71		0.133	0.162	
	3.0 sulfur	95.0	41.0	108	115		3.69	3.90		0.101	0.106	
	0.6 sulfur	97.5	56.0	265	396		8.05	11.43		0.169	0.233	
	3.0 sulfur	97.5	56.0	140	132		4.62	4.39		0.123	0.118	
	0.6 sulfur	99.0	73.0	420	535		12.03	14.85		0.244	0.298	
	3.0 sulfur	99.0	73.0	208	200		6.52	6.30		0.169	0.164	
	0.6 sulfur	99.5	82.0	520	740		14.49	19.70		0.291	0.392	
	3.0 sulfur	99.5	82.0	284	290		8.55	8.71		0.218	0.222	
	0.6 sulfur	99.9	99.0		1050			26.73			0.527	
	1.2 sulfur	99.9	99.0	620			16.89			0.355		
	3.0 sulfur	99.9	99.0	460	455		13.02	12.90		0.329	0.326	
	1.2 Na_2O	95.0	41.0			137			4.54			0.112
	6.0 Na_2O	95.0	41.0			61			2.24			0.067
	1.2 Na_2O	97.5	56.0			207			6.50			0.154
	6.0 Na_2O	97.5	56.0			93			3.24			0.090
	1.2 Na_2O	99.0	73.0			323			9.57			0.221
	6.0 Na_2O	99.0	73.0			144			4.74			0.125
	1.2 Na_2O	99.5	82.0			427			12.20			0.279
	6.0 Na_2O	99.5	82.0			191			6.06			0.157
	1.2 Na_2O	99.9	99.0			726			19.38			0.439
	6.0 Na_2O	99.9	99.0			324			9.59			0.242
CYC	0.6 sulfur	95.0	80.0	265			8.05			0.169		
	3.0 sulfur	95.0	80.0	147			4.82			0.128		
	0.6 sulfur	97.5	88.0	360			10.52			0.216		
	3.0 sulfur	97.5	88.0	191			6.06			0.158		
	0.6 sulfur	99.0	95.0	571			15.72			0.315		
	3.0 sulfur	99.0	95.0	283			8.53			0.218		
	0.6 sulfur	99.5	97.0	707			18.94			0.377		
	3.0 sulfur	99.5	97.0	386			11.18			0.283		
	1.2 sulfur	99.9	97.0	843			22.07			0.461		
	3.0 sulfur	99.9	97.0	626			17.03			0.429		

PC - Pulverized coal; CYC - Cyclone.

Table 4-4. HOT-SIDE ELECTROSTATIC PRECIPITATOR - COST OF FINE PARTICULATE CONTROL

Type boiler	Coal ash characteristics, % of significant constituent	Overall mass eff., %	Frac. eff. on particles in 0.2-0.4μ range, %	SCA required, ft^2/1000 acfm		Cost @ 500 MW			
						Capital cost, $/kW		Ann. oper. cost, mills/kWh	
				Western low-sulfur coals	Eastern low-sulfur coals	Western	Eastern	Western	Eastern
PC	Fe_2O_3=5.0; Na_2O=0.2	95.0	41.0	265		11.66		0.273	
	2.0	95.0	41.0	170		7.92		0.193	
	0.2	97.5	56.0	297		12.88		0.299	
	2.0	97.5	56.0	190		8.73		0.211	
	0.2	99.0	73.0	325		13.93		0.323	
	2.0	99.0	73.0	208		9.45		0.227	
	0.2	99.5	82.0	344		14.64		0.338	
	2.0	99.5	82.0	220		9.92		0.237	
	0.2	99.9	99.0	436		18.00		0.412	
	2.0	99.9	99.0	280		12.24		0.288	
	Fe_2O_3=9.0; Na_2O=0.2	95.0	41.0		234		10.47		0.247
	2.0	95.0	41.0		150		7.11		0.176
	0.2	97.5	56.0		262		11.55		0.270
	2.0	97.5	56.0		168		7.84		0.192
	0.2	99.0	73.0		286		12.47		0.290
	2.0	99.0	73.0		184		8.49		0.206
	0.2	99.5	82.0		303		13.11		0.304
	2.0	99.5	82.0		194		8.89		0.215
	0.2	99.9	99.0		384		16.11		0.370
	2.0	99.9	99.0		247		10.97		0.260
CYC	Fe_2O_3=5.0; Na_2O=0.2	95.0	56.0	361		15.27		0.352	
	2.0	95.0	56.0	232		10.39		0.247	
	0.2	97.5	69.0	404		16.84		0.386	
	2.0	97.5	69.0	259		11.43		0.270	
	0.2	99.0	83.0	442		18.22		0.417	
	2.0	99.0	83.0	283		12.35		0.291	
	0.2	99.5	89.0	468		19.15		0.437	
	2.0	99.5	89.0	300		13.00		0.305	
	0.2	99.9	97.0	593		23.54		0.535	
	2.0	99.9	97.0	381		16.00		0.372	
	Fe_2O_3=9.0; Na_2O=0.2	95.0	56.0		319		13.71		0.318
	2.0	95.0	56.0		204		9.29		0.223
	0.2	97.5	69.0		357		15.12		0.349
	2.0	97.5	69.0		229		10.27		0.245
	0.2	99.0	83.0		389		16.30		0.374
	2.0	99.0	83.0		251		11.13		0.264
	0.2	99.5	89.0		413		17.17		0.394
	2.0	99.5	89.0		264		11.63		0.275
	0.2	99.9	97.0		523		21.09		0.480
	2.0	99.9	97.0		336		14.34		0.335

PC - Pulverized coal; CYC - Cyclone.

Table 4-5. COSTS FOR OVERALL MASS AND FRACTIONAL EFFICIENCIES OF COLD-SIDE ESP ON BOILERS BURNING EASTERN BITUMINOUS LOW-SULFUR (0.6%) COAL

Case	Boiler type	Overall mass efficiency, %	Fractional mass efficiency on particles in 0.2 - 0.4 micron range, %	Capital cost, $/kW
1	PC	99.5	82	14.49
2	CYC	95.0	56	8.05
3	CYC	97.5	69	10.52
4	CYC	99.0	83	15.72
5	CYC	99.5	89	18.94

PC - Pulverized-coal-fired-boiler.
CYC - Cyclone-fired-boiler.

Table 4-6. COSTS FOR OVERALL MASS AND FRACTIONAL EFFICIENCIES OF HOT-SIDE ESP ON BOILERS BURNING WESTERN SUBBITUMINOUS LOW-SULFUR (0.6%) COAL

Case	Boiler type	Overall mass efficiency, %	Fractional mass efficiency on particles in 0.2 - 0.4 micron range, %	Capital cost, $/kW
1	PC	99.5	82	14.64
2	CYC	95.0	56	15.27
3	CYC	97.5	69	16.84
4	CYC	99.0	83	18.22
5	CYC	99.5	89	19.15

Table 4-5 indicates that the cost of maintaining a fractional efficiency level of 82 percent for collection of 0.2- to 0.4-micron particles from a pulverized-coal-fired boiler burning Eastern bituminous coal (0.6% S) is only slightly higher than the cost of maintaining an 83 percent fractional efficiency level for the same size particles with a cyclone-fired boiler (refer to Cases 1 and 2). However, the overall mass efficiency must also be considered. When both the fractional efficiency and the overall efficiency criteria are considered (comparison of Case 1 with Case 5), the capital costs show the cyclone to be 31 percent more expensive than for the pulverized boiler. The cyclone boiler, however, does show a higher collection efficiency in the 0.2 to 0.4 micron range (89%). If both criteria are satisfied with a hot-side electrostatic precipitator (Table 4-6 - Western subbituminous coal) the cost of the cyclone-firing application (Case 5) is approximately 30 percent higher than that of the pulverized-coal-firing application (Case 1), but again is more efficient in collecting fine particles.

The differences in size distribution characteristics of fly ash from the boilers in question are responsible for differences in fractional efficiency at a given overall mass efficiency level. Coal type also affects the size distribution of particles at the outlet of the boiler. For example, size distribution data obtained from burning of a pulverized hard coal may show larger mean and standard deviations than those obtained from firing a pulverized soft coal. Also, there is some evidence that fine particles often agglomerate to some extent when passing through the air preheater. Therefore, the fly ash size distribution at the inlet of a hot-side precipitator may be different from that entering a cold-side precipitator. The problem of quantifying the particle size distribution and precipitator fractional efficiency becomes even more complex and difficult when the nonidealities of gas nonisoturbulence, gas sneakage, and particle reentrainment are considered. It is not surprising, therefore, that reliable data are not easily obtainable. In any event, it is clear that both fractional and overall efficiencies must be carefully weighed in the establishment of a fine particulate emissions standard.

The economic advantage of hot-side electrostatic precipitators is illustrated for a variety of cases in Table 4-7 and Table 4-8.

The percentage of Na_2O in the coal affects the cost for hot-side precipitators. Cases 2 and 4 in Table 4-7 and Case 2 in Table 4-8 show that hot-side electrostatic precipitators have an economic advantage over cold-side precipitators given the assumptions previously stated. Data on cyclone-firing or Western subbituminous coal were not available.

Table 4-7. COMPARISON OF COLD- AND HOT-SIDE ESP'S ON BOILERS BURNING EASTERN BITUMINOUS LOW-SULFUR (0.6%) COAL

Case	Boiler type	ESP type	Overall mass eff., %	Fractional mass efficiency on particles in 0.2-0.4 micron range, %	Capital cost @ 500 MW, $/kW	
					% Na_2O=0.2	% Na_2O=2.0
1	PC	cold	99.5	82	14.49	14.49
2	PC	hot	99.5	82	13.11	8.89
3	CYC	cold	99.5	89	18.94	18.94
4	CYC	hot	99.5	89	17.17	11.63

Table 4-8. COMPARISON OF COLD- AND HOT-SIDE ESP'S ON PC BOILERS BURNING WESTERN SUBBITUMINOUS LOW-SULFUR (0.6%) COAL

Case	Boiler type	ESP type	Overall mass eff., %	Fractional mass efficiency on particles in 0.2-0.4 micron range, %	Capital cost @ 500 MW, $/kW	
					% Na_2O=0.2	% Na_2O=2.0
1	PC	cold	99.5	82	19.70	19.70
2	PC	hot	99.5	82	14.64	9.92

4.4 WET SCRUBBER COMPUTER MODELS

Thirty commercial-size scrubber modules operating in the Western United States were installed specifically for particulate removal.[6] Selection of scrubbers over electrostatic precipitators in the past was motivated by the poor performance of the precipitators on boilers firing low-sulfur Western coals. These installations include the following three classes of scrubbers:

1. Gas-Atomized Spray (Venturi) Scrubbers
2. Three-Stage TCA
3. High-Pressure Spray Scrubber

Available operating data have been summarized by Sondreal.[5] In spite of some of the problems[6] that have become apparent with the use of scrubbers over the last 5 or 6 years, it is still of interest to estimate the scrubber capabilities in removing fine particles.

Design equations and the assumptions for formulation of the models to predict fractional efficiency performance are included in the following paragraphs.

4.4.1 Design Equations and Assumptions - Venturi Scrubber Computer Model

Venturi scrubbers are well described in the available literature.[7,8] The particle collection process depends mainly upon the acceleration of the gas to provide impaction and intimate contact between the particles and fine liquid droplets generated as a result of gas atomization. The condensation effect also plays an important role in the effectiveness of the venturi scrubber. If the gas in the reduced pressure region in the throat is fully saturated, condensation will occur on the particles in the higher pressure region of the diffuser. This is known as heterogeneous nucleation; it helps particle growth and also causes agglomeration, which tends to enhance collection. Particle collection mechanisms in the venturi scrubber have been investigated by many researchers.[8,9,10]

The venturi model used in this study is based on inertial impaction. It is assumed that the particles do not grow during the collection process as a result of heterogeneous nucleation and condensation effects. The general form of the expression for collection efficiency for particle size i can be written as:

$$E_i = 1 - \exp(-K(L/G)\ \Psi_i) \qquad (1)$$

where E_i = Removal efficiency, fractional

K = Impaction correlational parameter (system parameter)

L/G = Outlet liquid-to-gas ratio, (gal/1000 actual ft^3)

Ψ_i = Inertial impaction parameter of particle size grade, i

Available experimental data have been used to develop a correlation for inlet throat velocity, V_t in ft/sec, based on ΔP (in. H_2O) and outlet L/G measurements.

$$V_t = \left[\frac{\Delta P}{5.23 \times 10^{-6} (L/G + 105)}\right]^{1/2} \qquad (2)$$

Knowing the inlet throat velocity and measured outlet L/G, the droplet diameter in microns can be calculated from a modified form of an equation developed by Nukiyama and Tanasawa.[11]

$$D_c = \frac{16050}{V_t} + 1.41 (L/G)^{1.5} \qquad (3)$$

The system parameter K is determined by an iterative procedure based on comparison of the actual measured overall mass collection efficiency and that calculated from summing the individual fractional efficiencies. For a given particle size the inertial impaction parameter is defined below:

$$\Psi_i = \frac{0.85 (C) (\rho_p) (D_p)^2}{\mu} \frac{V_t}{D_c} \qquad (4)$$

where C = Cunningham correction coefficient

ρ_p = Particle specific gravity, (grams/cm^3)

D_p = Particle diameter, (microns)

μ = Dynamic gas viscosity, (poise x 10^4)

D_c = Droplet diameter, (microns)

and $$C = 1 + \frac{2\lambda}{D_p}\ 1.23 + 0.41 \exp(-0.44 \frac{D_p}{\lambda}) \quad (5)$$

where λ = Mean free path of gas molecules, (microns)

The value of K is modified during the course of iteration to yield a closer match between measured and calculated overall mass collection efficiencies for given input values of L/G and ΔP. When the "optimum" value of K has been found, it is inserted into the above equations to generate the outlet particle size distribution and finally the fractional penetration for the various particle sizes. It should be noted that this is really an averaged system parameter since it is not a function of any specific particle size.

4.4.2 Design Equations and Assumptions - UOP Three-Stage TCA Scrubber

The design details of this moving-bed scrubber are given in the literature.[9,10] Inertial impaction and interception are the primary collection mechanisms. The UOP design uses lightweight hollow plastic spheres, which exhibit random motion with the formation of a turbulent layer above the spheres as a result of the gas flow.

Based upon the theory of moving-bed scrubbers and experimental data, Calvert[8] recommends a semi-empirical design equation of the form

$$E_i = 1 - \exp\ [-2.45E6(U_L)^{3.3}(U_G)^{.36}K\ \frac{Z}{d}] \qquad (6)$$

where U_L = Superficial liquid velocity, cm/sec

U_G = Superficial gas velocity, cm/sec

Z = Stage height, cm

d = Packing diameter (spherical, hollow balls), cm

K = Inertial parameter

$$= \frac{U_G D^2}{9\mu d} \qquad (7)$$

where μ = Dynamic gas viscosity, poise

D = Particle diameter, cm

Unfortunately, the values for U_G and U_L could not be obtained from the available operating data. Therefore, an alternative approach was elected and is described in the following paragraphs.

An alternative method of determining the fractional efficiency of the TCA scrubber is to perform empirical correlations of the form

$$E_i = f(\Delta p,\ L,\ D) \qquad (8)$$

Statnick and Drehmel[12] have published data on measured fractional efficiency for a TCA scrubber under different operating conditions. Regression analysis performed on those data yields a best fit of the form

$$E_i = 1 - K\ \exp\ [-0.0222(L)^{.6}(\Delta p)^{.85}(D)^{1.5}] \qquad (9)$$

where Δp = Total pressure drop, in. H_2O

D = Particle diameter, microns

K = System parameter

4.4.3 Design Equations and Assumptions - Krebs-Elbair High-Pressure Spray Impingement Scrubber

In this design, liquid is atomized by some means other than energy transferred from the gas being cleaned. Therefore, these scrubbers are also called preformed spray scrubbers. High-pressure spray nozzles are used to generate high-velocity water droplets in the size range of 200 to 600 microns. In this particular design, droplets flow initially in a concurrent fashion acting as a spray column, then hit against a membrane to form a rebound zone at the membrane surface. At the membrane the gas is suddenly accelerated, the membrane itself simulating many linear venturi tubes, which do further scrubbing.

Inertial impaction is the predominant mechanism of particulate collection. Calculation of the collection efficiency of the device is based on the following assumptions:

a) Nozzle type and Δp across the nozzle

b) Opening of nozzle orifice, droplet size, and droplet velocity

c) Opening area of the membrane

d) Percent (fraction) of the droplets actually rebounding from the membrane, their size, and velocity

e) Percent (fraction) of the droplets actually passing through the membrane

f) Percent (fraction) of the droplets actually lost at the membrane surface.

With the above assumptions, the Krebs-Elbair high-pressure spray system could be looked upon as a hybrid scrubber for which particulate collection can be split into three components:

(1) Collection resulting from concurrent spray

(2) Collection resulting from countercurrent spray

(3) Collection resulting from the venturi effect

Mathematically, the total collection of particle size grade i could be written as:

$$E_i = 1 - \exp\left[-K_1 L \Psi_{1i}^{0.5} - 0.1 K_1 L \Psi_{1i}^{0.5} - 0.1 K_2 L \Psi_{2i}^{0.5}\right] \quad (10)$$

where the first two terms under the exponential indicate penetration resulting from the concurrent spray zone and the countercurrent rebound zone, respectively. The last term represents the contribution resulting from the venturi effect simulated by the membrane surface. The various assumptions used in developing Equation (10) are as follows:

(i) The system parameters K_1 and K_2 (K_1 for the concurrent spray zone and K_2 for the counter current (rebound) spray zone) are assumed to be the same. This further implies that during the process of rebounding there is no change in droplet size.

(ii) In estimating the impaction parameter Ψ_{2i}, knowledge of the droplet velocity relative to that of the gas is essential. It is assumed that the droplets rebound with the same velocity as that of the oncoming gas.

(iii) It is further assumed that only 10 percent of the spray rebounds.

(iv) It is assumed that the opening area of the membrane is 10 percent of the effective scrubber cross section and that the water flow rate through the membrane is 10 percent of the total water flow. For computational purposes, the value of both system parameters (K_1 and K_2) is assumed to be 0.1, which is typical for most venturi scrubbers.

The process parameters for the Krebs-Elbair high-pressure spray scrubber are assumed and are given below.

(i) Average gas velocity before the membrane = 10 fps

(ii) Spray nozzle type - whirljet nozzle

(iii) Spray nozzle pressure = 200 psi

(iv) Average droplet size = 280 μm

(v) Water flow rate per nozzle = 6.52 gpm

(vi) Droplet velocity (assuming 1/8-inch orifice) = 170 fps

The above values and a typical inlet particle size distribution from a pulverized-coal-fired boiler are used to determine fractional efficiency values for specific L/G measurements.

4.4.4 Percent Penetration As a Function of Particle Size For Wet Scrubbers

Tables 4-9 through 4-12 show performances of the four types of wet scrubbers for collection of particulate from coal-fired utility boilers as predicted by mathematical models, and Figures 4-8 through 4-11 graphically show these performances. Table 4-13 summarizes the relative predicted performance of all scrubbers considered at particle sizes of 0.2, 0.5, and 1.0 micron. All particle sizes given with reference to scrubbers are in terms of aerodynamic diameter unless specifically noted.

Inlet particle size distribution information only was available for the Montana-Dakota Flooded Disc, venturi scrubber, and the Cherokee TCA scrubber. An inlet particle size distribution ($\bar{x}$ = 12 μm, σ = 3.8 μm) was assumed for all of the scrubbers evaluated except for the Montana-Dakota installation. Section 4.4.4.3 includes reasons for not using particle size distribution from the Cherokee station in the computer model predictions. Three other power stations (Arapahoe, Mohave, and Reid Gardner) were preceded by a mechanical collector, precipitator, or both (see Table 2-9 for details), but no particle size data were available. Thus, because of a lack in accurate particle size data, precise comparison of the predicted scrubber fractional efficiencies is not possible.

The results of the model predictions within each scrubber category are discussed in the next sections.

Table 4-9. PREDICTED PERFORMANCE OF CHEMICO VENTURI SCRUBBERS IN COLLECTION OF FINE PARTICLES

System parameters \ Utility and station	Arizona Public Service (Four Corners)		Pacific Power and Light (Dave Johnston plant)	
$\bar{\eta}$, %	99.2		99.0	
Δp, in. H_2O	28		15	
L/G, gal/1000 acf	9		13	
	Penetration, %		Penetration, %	
Particle size, microns	Calvert Model	Research-Cottrell Model	Calvert Model	Research-Cottrell Model
0.2	81.6	60.20	86.1	63.80
0.6	21.5	28.60	30.0	33.00
0.9	4.8	16.40	7.5	20.10
1.5	0.17	5.37	0.33	7.52
3.0	0.0	0.33	0.0	0.64
7.0	0.0	0.0	0.0	0.0

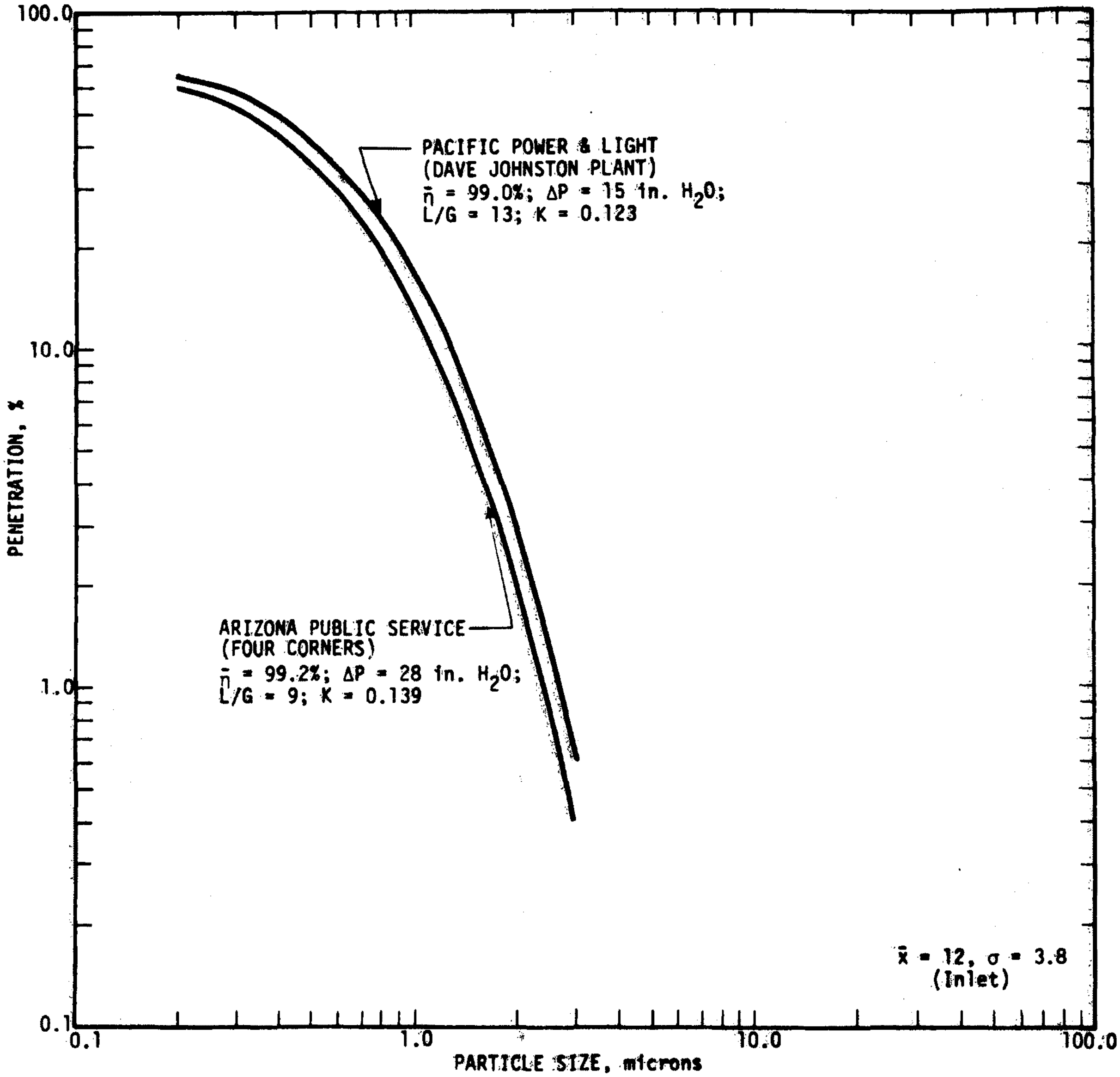

Figure 4-8. Predicted performance of venturi scrubbers in removal of fine particulate.

Table 4-10. PREDICTED PERFORMANCE OF RESEARCH-COTTRELL FLOODED DISC SCRUBBER IN COLLECTION OF FINE PARTICULATE

System parameters \ Utility and station	Montana-Dakota Utilities (Lewis and Clark station, Unit 1)	
$\bar{\eta}$, %	96.0	
ΔP, in. H_2O	12.3	
L/G, gal/1000 acf	11.8	
Particle size, microns	Penetration, %	
	Calvert Model	Research-Cottrell Model
0.2	89.0	67.40
0.6	44.0	37.80
0.9	24.5	24.50
1.5	1.65	10.4
3.0	0.0	1.20
7.0	0.0	0.004

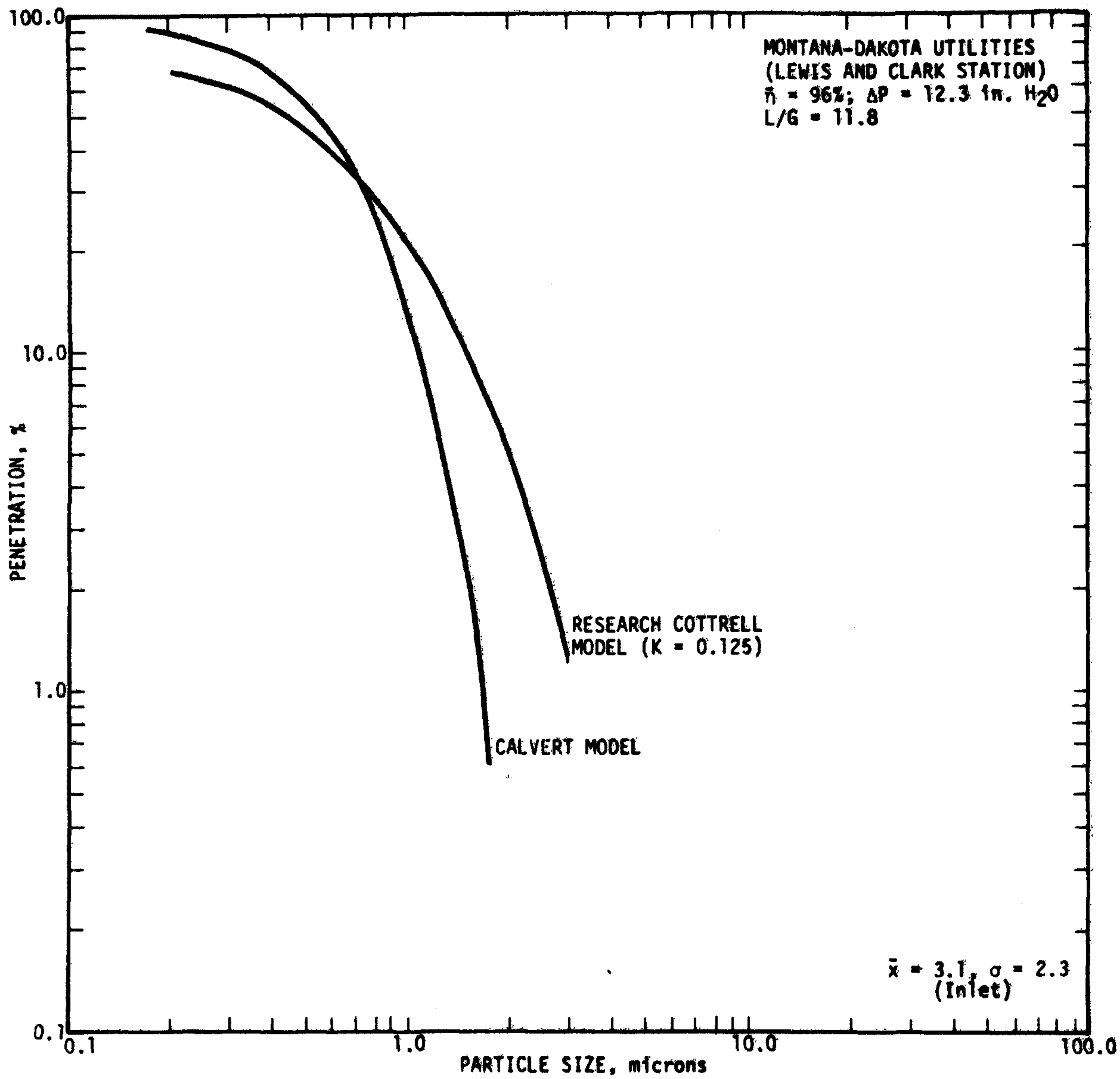

Figure 4-9. Predicted fine particulate performance of flooded-disc scrubber at Montana-Dakota Utilities Lewis and Clark Station.

Table 4-11. PREDICTED PERFORMANCE OF UOP TCA SCRUBBERS IN COLLECTION OF FINE PARTICULATE

System parameters \ Utility and station	Public Service of Colorado (Cherokee station)		Public Service of Colorado (Arapahoe station)	
$\overline{\eta}$, % ΔP, in. H_2O L/G, gal/1000 acf	95 - 97.5[a] 10 - 15 (10)[b] 50 (40)[c]		97.5[a] 10 - 15 (12)[b] 50 (40)[c]	
Particle size, microns	Fractional efficiency, %	Penetration, %	Fractional efficiency, %	Penetration, %
0.2	12.07	87.93	14.88	85.12
0.6	48.73	51.27	56.70	43.30
0.9	70.69	29.30	78.52	21.48
1.5	92.87	7.13	96.35	3.65
3.0	99.94	0.06	99.91	0.09
7.0	100.00	0.00	100.00	0.00

[a] Calculated overall mass efficiencies for the Cherokee and Arapahoe Stations are 98.71 and 99.0 percent, respectively.

[b] Values in parentheses were selected from the ranges given for system pressure drop. (See note c).

[c] Scrubber model utilizes an iterative procedure to determine the calculated overall mass efficiency and the model is sensitive only to L/G, ΔP, and $\overline{\eta}$. The values for L/G and ΔP were selected so as to give close agreement of the computed $\overline{\eta}$ to the actual $\overline{\eta}$. The value "K" (iterative parameter) is selected based on the scrubber system, ranging between 0.3 and 1.0 for the different scrubbers.

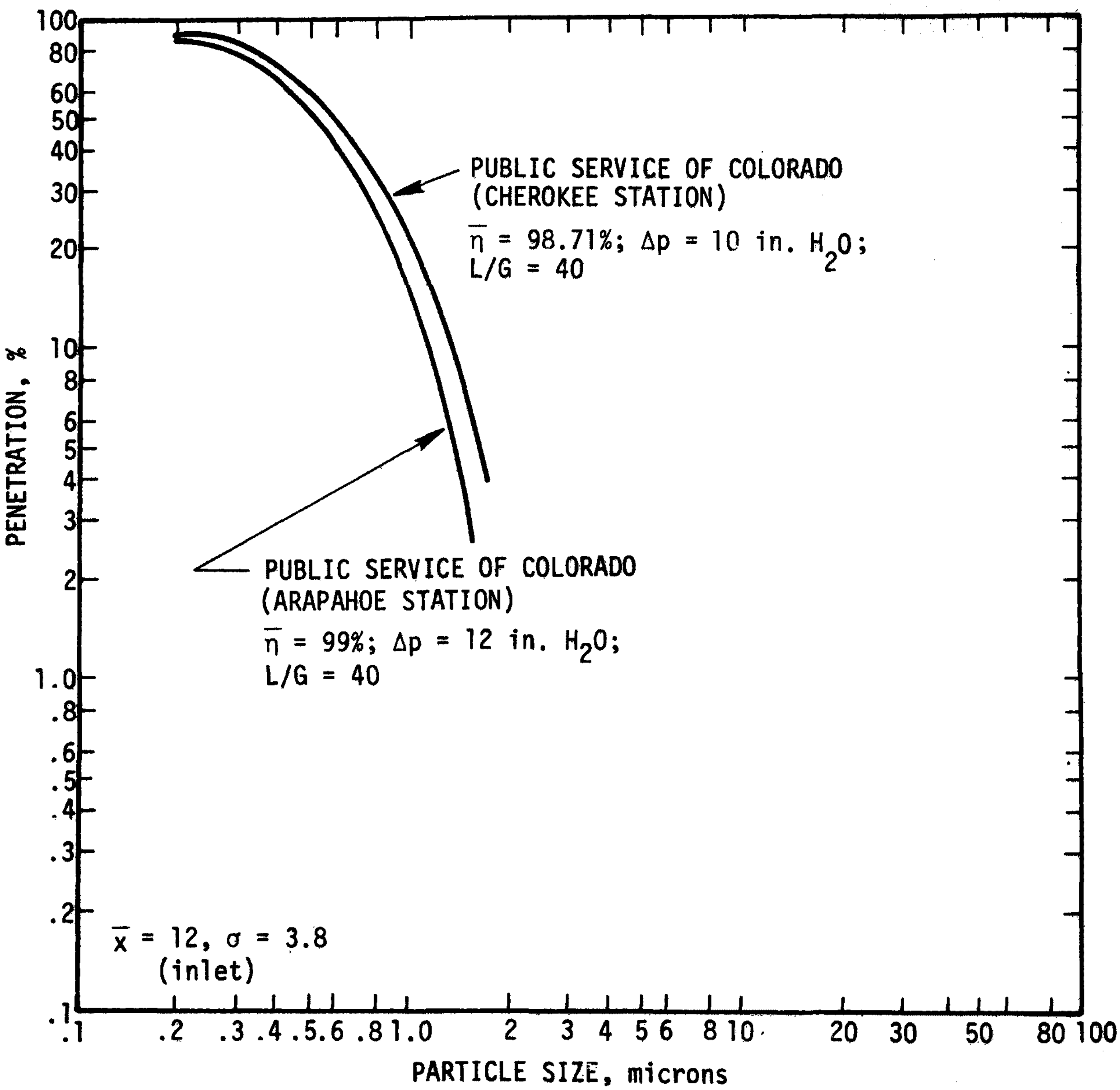

Figure 4-10. Predicted performance of TCA scrubbers on fine particulate.

Table 4-12. PREDICTED PERFORMANCE OF KREBS-ELBAIR HIGH-PRESSURE SPRAY SCRUBBER IN COLLECTION OF FINE PARTICULATE

System parameters \ Utility and station	Minnesota Power and Light (Clay Boswell plant)		Minnesota Power and Light (Aurora plant)	
$\overline{\eta}$, %	99.0		98.0	
ΔP, in. H_2O	4		4	
L/G, gal/1000 acf	8		8	
Particle size, microns	Fractional efficiency, %	Penetration, %	Fractional efficiency, %	Penetration, %
0.2	29.98	70.02	24.14	75.86
0.6	65.67	34.33	56.35	43.65
0.9	79.89	20.11	71.16	28.84
1.5	93.09	6.91	87.41	12.59
3.0	99.52	0.48	98.42	1.58
7.0	100.00	0.00	99.99	0.01

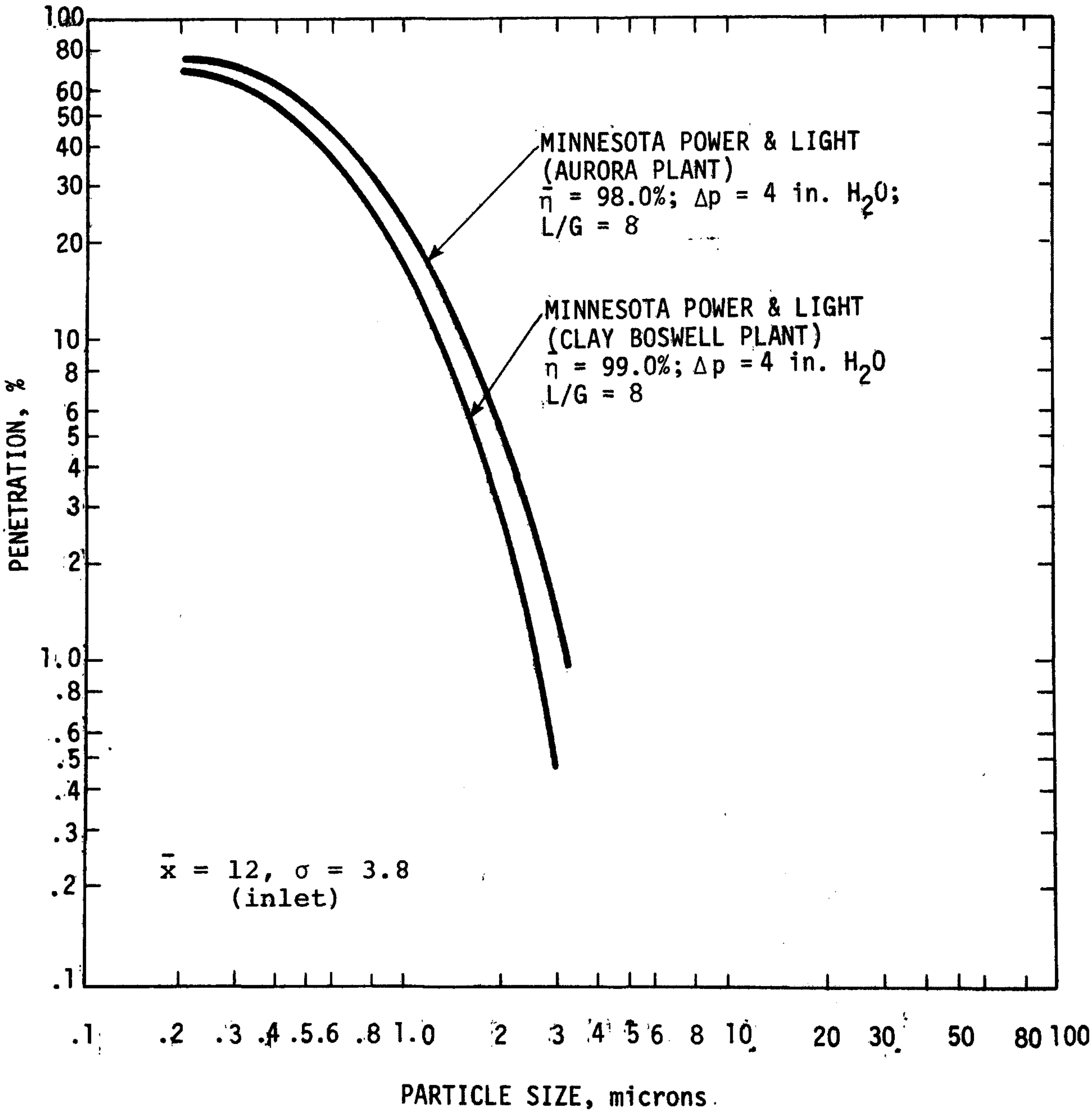

Figure 4-11. Predicted performance of high-pressure spray scrubbers in removal of fine particulate.

Table 4-13. PREDICTED PERFORMANCE OF WET SCRUBBERS IN COLLECTION OF FINE PARTICULATE FROM COAL-FIRED UTILITY BOILERS

Scrubber type	Penetration, %		
Gas-atomized spray scrubbers	0.2 μm	0.5 μm	1.0 μm
Research-Cottrell flood disc			
Montana-Dakota Utilities (Calvert Model)	89	55	13
(Lewis and Clark station) (RC Model)	67.4	44	22
Chemico venturi			
Pacific Power & Light (Calvert Model)	86.1	42	4.8
(Dave Johnston plant) (RC Model)	64	42	17
Arizona Public Service (Calvert Model)	81.6	33	3
(Four Corners plant) (RC Model)	60	36	13
High-pressure spray impingement scrubbers			
Krebs-Elbair high-pressure spray			
Minnesota Power & Light (Aurora plant)	75	52	23.5
Minnesota Power & Light (Clay Boswell plant)	70	44	17
Moving-bed scrubbers			
UOP, three-stage TCA scrubber			
Public Service of Colorado (Cherokee station)	90	60	22.5
Public Service of Colorado (Arapahoe station)	85	52	16

4.4.4.1 Gas Atomized Spray Scrubbers - Figure 4-8 presents Research Cottrell's (RC) predicted penetration vs. particle size for the conventional venturi scrubbers at the Dave Johnston and Four Corners Station and Figure 9 presents the flooded disc venturi scrubber at the Montana-Dakota station. These predictions were compared with Calvert's Model,[8] which is also plotted in Figure 4-9 for comparison with the RC model.

The cut diameter particle sizes* obtained for the three scrubbers mentioned above are slightly higher using the Calvert Model than for the RC Model. The Calvert Model also shows 1) a sharper rise in penetration for particle sizes below the cut diameter size, and 2) a more rapid decrease in penetration for particle sizes above the cut diameter size, as compared to the RC Model.

Variations in the RC and Calvert models could result from the following: 1) use of an average correlational impaction value, K, as an iterative value as opposed to the use of an "F" factor as an iterative parameter in the Calvert model (the "F" factor relates the nonuniformity of the atomized liquid resulting in a difference in the liquid and gas velocities, particle diameter, and the nature of the particles), 2) use of the Nukiyama and Tanasawa droplet

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* Particle size at which penetration is 50 percent.

diameter in the RC model as opposed to the Sauter mean droplet diameter in the Calvert model, and 3) use of a greater number of particle size intervals for the Calvert model than for the RC model for the comparisons made in this report. The greater the number of size intervals used, the more precise the penetration will be when plotted on a graph.

The Chemico venturi scrubber shows little improvement in collection as a result of increased pressure drop (Figure 4-8). Increasing the pressure drop from 15 inches of water at Dave Johnston to 28 inches of water at Four Corners contributes relatively little to the overall collection. The water requirements, however, decrease by about 70 percent.

The cut diameter predictions for the Dave Johnston Station are approximately 0.40 micron with the RC Model and 0.44 micron with the Calvert Model (ΔP = 15 in. H_2O). For the Four Corners Station the cut diameter predictions are approximately 0.36 micron with the RC Model and 0.39 micron with the Calvert Model (ΔP = 28 in. H_2O). As would be expected from the venturi scrubber models, the flooded-disc venturi scrubber at the Lewis and Clark Station, because of its lower pressure drop, shows a higher cut diameter (0.42 micron at ΔP of 12.3 in H_2O using the RC model) than the other conventional venturi scrubbers. Use of the Calvert

Model for the Lewis and Clark Station yields a cut diameter of approximately 0.54 micron.

4.4.4.2 High Pressure Spray Scrubber - Operating data on the Krebs-Elbair high-pressure spray impingement scrubber indicate different degrees of collection for the same system pressure drop and L/G values (Figure 4-11). The computer model accounts for this variation by adjusting the system parameter K_1 in equation (10). Various assumptions were required in formulating the model for this scrubber, as indicated in the design equations.

4.4.4.3 TCA Scrubbers - The predicted performance of the TCA scrubber at the Valmont Station of the Public Service of Colorado appeared to be the best among the scrubbers under study. However, its pressure drop of 15 in. water lies outside of the limit for which the model was developed (ΔP = 12 in. H_2O). Therefore, no conclusions were drawn from this data.

The predicted performance of the TCA scrubbers at the Cherokee and Arapahoe stations is shown in Figure 4-10. Both the Cherokee and Arapahoe scrubbers were preceded by a mechanical collector and a precipitator. The effect of these preceding devices on the particle size distribution was not evaluated in the model. Scrubber model values for the Cherokee and Arapahoe stations indicate that the fractional efficiencies in collection of submicron particles are extremely sensitive to system pressure drop and L/G values. It is apparent that high rates of water circulation are necessary to achieve greater collection of submicron particles.

The TCA scrubber models perform an iterative procedure by selecting a value of the system parameter, K_1 to reflect the particular features of the system. The input overall mass efficiency is compared to that calculated from L/G and Δp values. Since the model is sensitive only to those parameters, and since both the Cherokee and Arapahoe stations have identical L/G and Δp values but different overall mass efficiency levels, it is clear that some modification of the input variables is required. To minimize the discrepancy between the actual and calculated values of overall mass efficiency, the values of L/G and Δp were modified slightly, as shown in Table 4-11.

An attempt was also made to base predicted performance of the Cherokee scrubber on actual test data for Δp, L/G, and particle size distribution as measured in two separate tests on the Cherokee scrubber in 1974[13] and 1975.[15] However, it was not possible to match the actual collection efficiencies and the calculated efficiencies from the model within the limits, of the system parameter, K_1. This means that for the Cherokee scrubber, the data upon which the model is based do not agree with actual TCA scrubber results as measured in the above tests.

4.4.5 Comparison of Wet Scrubber Test Data and the Computer Models

The validity of the assumptions underlying the performance prediction models for the particulate wet scrubbers can be determined only after testing the models against experimental data under various operating conditions.

Data are available on a number of coal-fired boilers utilizing venturi and TCA wet scrubbers for particulate control.[12,13,14,15] Unfortunately, in only one case, (Cherokee Station) are predicted and actual results available for the same scrubber.

Table 4-14 summarizes pertinent fractional efficiency test data for two venturi and three TCA scrubbers on a number of coal-fired boilers. Without making direct comparisons it can be seen that the test data demonstrate what the scrubber models predict: a sharp rise in penetration below a particle size of about 2 microns.

Figure 4-12 presents the test results of two venturi scrubbers and one TCA scrubber from Table 4-14. The TVA-Shawnee-TCA scrubber fractional efficiencies plotted in Figure 4-12 show much lower penetrations through all size ranges than the TVA-Shawnee or unidentified Chemico venturi scrubber. At particle sizes between 0.3 and 1.0 micron, the

Table 4-14. SUMMARY OF FRACTIONAL EFFICIENCY TEST DATA FOR WET SCRUBBERS OPERATING ON COAL-FIRED BOILERS

Location/Company	Type of scrubber	Particle size, microns	Percent penetration	Source
1. TVA-Shawnee	UOP-TCA	0.11	5.4	Reference 12
		0.29	5.0	
		0.65	7.1	
		0.99	1.5	
		1.73	0.4	
2. TVA-Shawnee	Chemico venturi	0.11	100	Reference 12
		0.29	71	
		0.65	19	
		0.99	8	
		1.73	6	
3. Coal-fired boiler (360,000 acfm)	Chemico venturi	0.3	93	Reference 14
		0.5	53	
		1.0	10	
		2.0	<1	
4. Public Service of Colorado-Cherokee Station (1974)	UOP-TCA	0.3	90	Reference 14
		0.5	30	
		1.0	10	
		2.0	2.0	
5. Public Service of Colorado - Cherokee Station (1974)	UOP-TCA[a]	0.1	5	Based on data from Reference 15
		0.3	63	
		0.5	70	
		0.8	54	
		1.0	44	
		2.0	15	

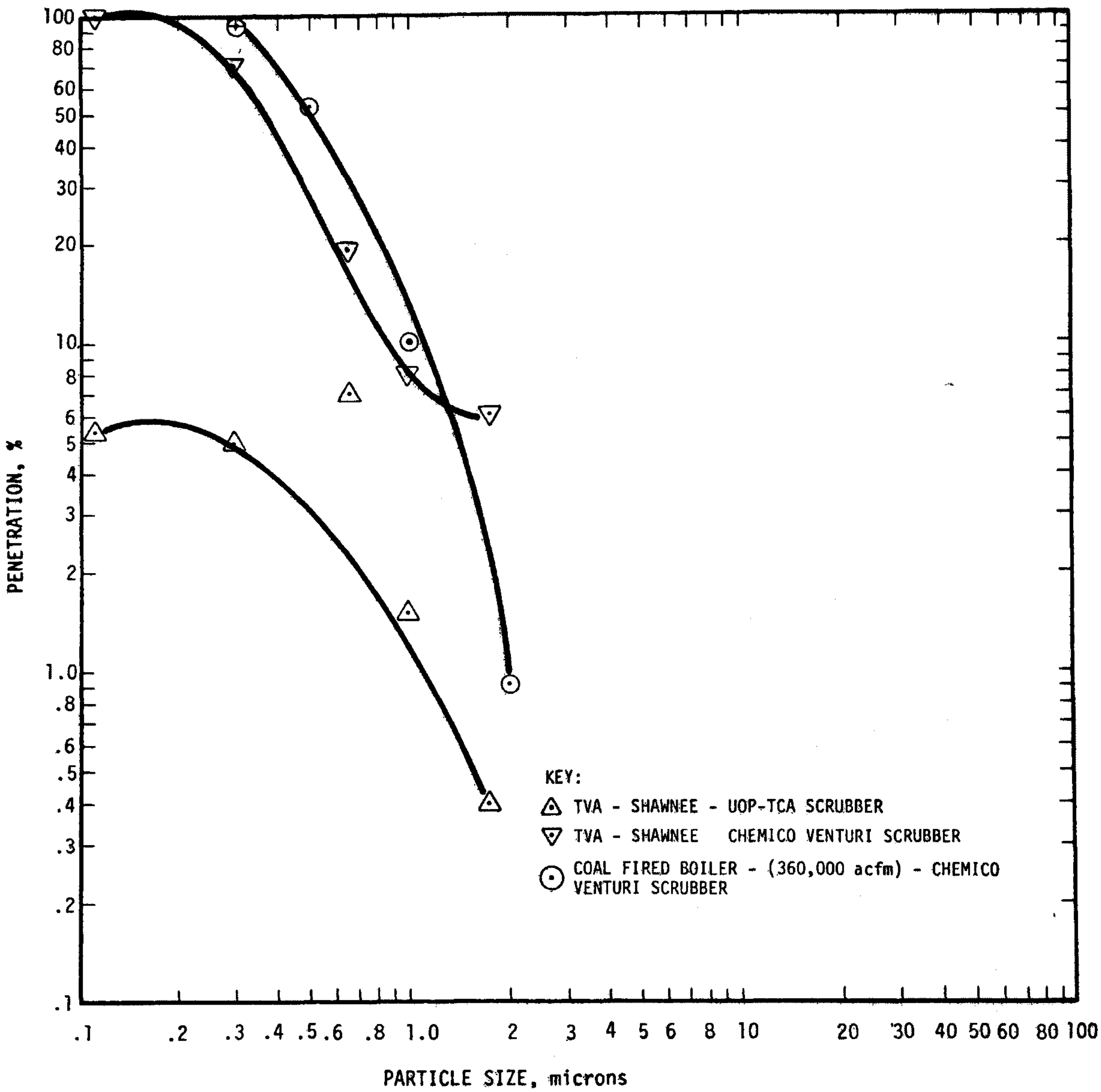

Figure 4-12. Wet scrubber fractional efficiency test data from various coal-fired boilers.

TVA-Shawnee Chemico venturi scrubber shows the next lowest penetration, followed by the unidentified venturi scrubber. Thus, these data do not demonstrate the expected greater performance of the venturi type scrubber. This does not mean that the computer models are invalid. The computer model predictions are based on assumed inlet particle size distribution. The 360,000-acfm venturi scrubber is the only test result in Figure 4-12 for which a particle size distribution is available ($\bar{x}$ = 38, σ = 5). It is highly probable that the size distributions occurring in the other two tests are different from the ones assumed in the scrubber models. Furthermore, when the scrubbers are designed as a part of a hybrid system (i.e. in conjunction with mechanical collectors and electrostatic precipitators), assumed values for inlet particle size distribution may unfavorably bias the predicted results for any one of the scrubbers.

Test data for the same Cherokee station TCA scrubber are available from both a 1974[13] and a 1975[15] study. The penetrations determined in the 1975 study are significantly higher than the 1974 test data, and higher than the penetrations determined in the TVA-TCA scrubber study (Statnick and Drehmel),[14] as shown in Figure 4-12. Cascade impactor results from the 1974 and 1975 Cherokee scrubber studies, plus diffusion battery results from the 1975 Cherokee data, are presented in Figure 4-13. The predicted performance of the TCA scrubber for the Cherokee station (from Figure 4-10), is also shown in Figure 4-13 for comparison with the test results. It can be seen that the predicted performance for the Cherokee station falls between the 1974 and 1975 test results. As mentioned in section 4.4.4.3 the predicted performance is not based on actual operating conditions because of the limits of the system parameter, K_1.

In comparing the 1974 and 1975 test data one would expect that the smaller particle size distribution measured in the 1974 data would shift the entire curve to the right in relation to the 1975 data. However, the higher Δp of the 1974 data combined with a higher overall efficiency apparently more than offsets the effect of the smaller particle size distribution and results in lower penetrations for the 1974 data.

The 1975 Cherokee results in Figure 4-13 include diffusion battery data and show a maximum penetration in the 0.2 to 0.5 micron range, similar to the fractional efficiency relationship of precipitators; this is because of a transition region between collection by inertial impaction, which begins to lose its effect around 0.5 micron, and collection by Brownian diffusion, which would account for the decrease in penetration below the 0.2 to 0.5 micron range.

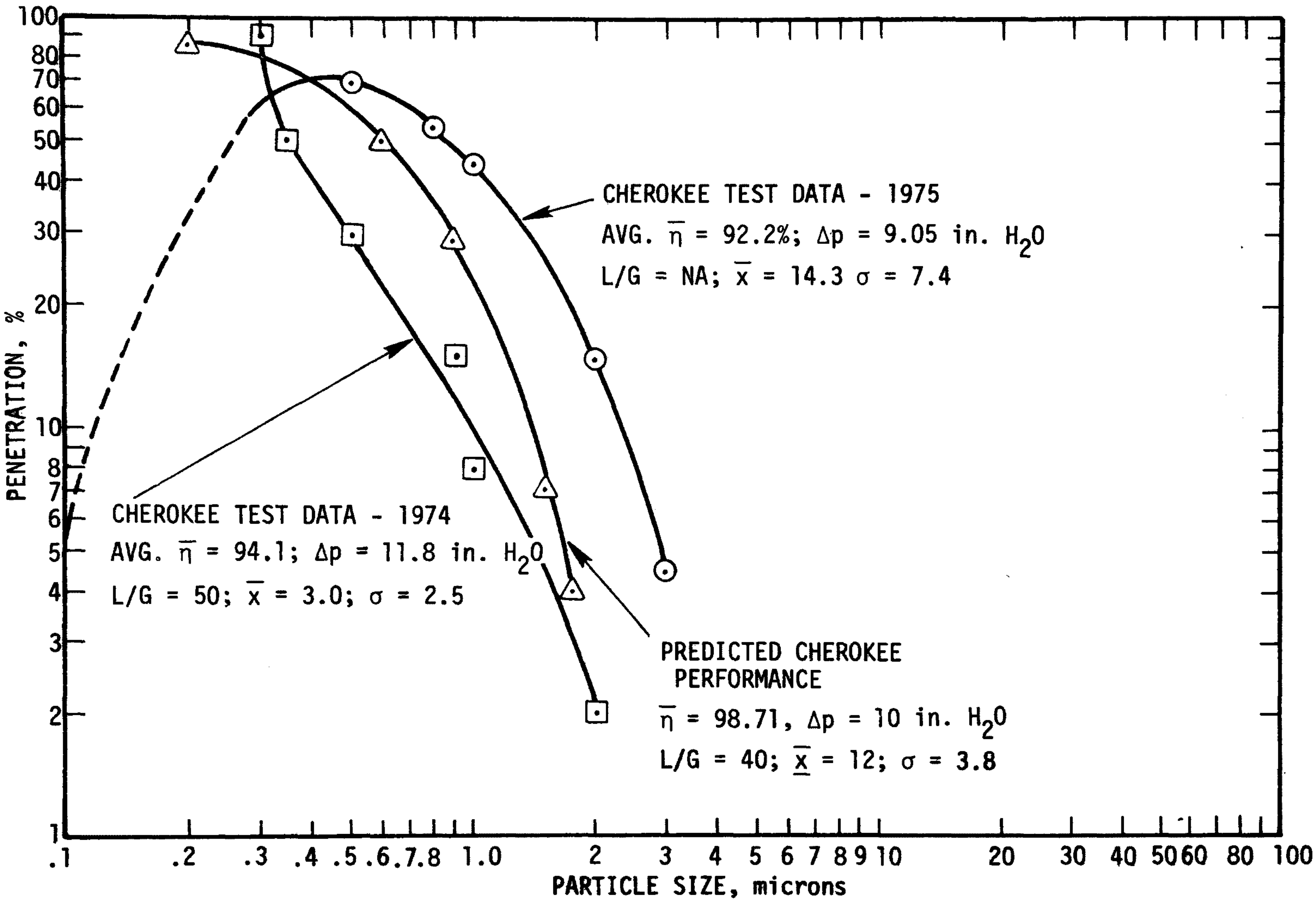

Figure 4-13. Comparison of predicted and actual test results for the Cherokee scrubber.

Test data are not available for any of the other power stations for which predictions were made.

In conclusion it is realized that because of a lack of accurate particle size data, precise comparison of the wet scrubber fractional efficiency prediction models is not possible. However, in general the wet scrubber computer models, show the performance of the venturi-type gas-atomized spray scrubbers in fine-particle collection to be better than that of the high-pressure spray impingement or the three-stage TCA scrubber. Although presently available test data on TCA and venturi scrubbers generally confirm the scrubber computer models, the expected superior performance of the venturi scrubbers is not confirmed in all cases.

4.5 FRACTIONAL/TOTAL MASS EFFICIENCY FOR FABRIC FILTERS

Efficiency data are available for fabric filters in operation at two of the three utility plants. Fractional and mass efficiency and mean particle size data are reported in detail for the Nucla baghouse and for the Sunbury baghouse.[15,16,17] Apparently no performance tests have been conducted on the Holtwood baghouse.[18] The available data on particle size, collection efficiency, and the effects of operating variables on penetration are presented for the Nucla and Sunbury installations. Experimental data on various types of fabric used at a pilot plant baghouse operation are also presented. A suitable theoretical model is not available for prediction of fractional efficiencies for fabric filters.

4.5.1. Nucla Baghouse

A total of 22 tests were run at the Nucla facility.[16] The baghouse operating conditions and the measured inlet/outlet mass loadings are shown in Table 4-15.[16] Mass efficiency was calculated by use of the inlet and outlet mass loadings determined by Method 5. Because the outlet mass loading for run 22 was not obtained, no mass efficiency value was determined but the particle size information from that run was included in the sizing analysis.[16]

The mean mass efficiency for all runs was 99.84 percent with a standard deviation of 0.11.[16] Results of two particular tests are noteworthy. Run 8 shows a mass efficiency of over 99.98 percent, the highest reported for all runs. This high collection efficiency is explained by the very high inlet loadings observed that day. Combustion conditions in the boiler were very poor for part of the run, and the problem is attributed to the combustion system rather than the fuel because the coal properties did not appear to be atypical.[16] The observation that the baghouse could operate under such adverse conditions and still allow a penetration of only 0.0016 gr/dscf is important.

TABLE 4-15.

RESULTS OF PARTICULATE SAMPLING AT NUCLA[16]

Date	Run	Inlet Mass Loading, gr/dscf			Outlet Mass Loading, gr/dscf			Mass Efficiency, %	Baghouse Operation
		Method 5	Andersen A[a]	Andersen B[a]	Method 5	Andersen North[a]	Andersen West[a]		
9/21/74	1	2.0759	0.4984	-	0.0044	0.0101	0.0031	99.7880	Normal
9/22/74	2	2.1712	1.5078	1.4610	0.0049	0.0069	0.0034	99.7743	Normal
9/23/74	3	1.9753	1.4014	1.7176	0.0045	0.0034	0.0028	99.7722	Normal
9/24/74	4	1.7021	1.7092	1.1793	0.0063	0.0043	0.0021	99.6299	Normal
9/25/74	5	1.6768	1.4819	1.4382	0.0042	0.0031	0.0030	99.7495	Cont. cleaning
9/26/74	6	1.7995	1.3426	1.1600	0.0047	0.0048	0.0051	99.7388	Cont. cleaning
9/27/74	7	1.8516	1.3144	1.9251	0.0045	0.0033	0.0025	99.7570	Normal
9/28/74	8	11.4446	1.6248	2.0818	0.0016	0.0053	0.0015	99.9860	Long repressure
9/30/74	9	2.3878	1.6636	1.9608	0.0016	0.0021	0.0020	99.9330	Long repressure
10/1/74	10	1.6873	1.4206	1.3540	0.0010	0.0021	0.0034	99.9407	Normal
10/2/74	11	1.7422	1.0294	1.4893	0.0015	0.0035	0.0046	99.9139	No cleaning
10/3/74	12	2.1112	1.5900	1.3091	0.0092	0.0563	0.0796	99.5642	No cleaning
10/4/74	13	2.2693	1.8991	2.0574	0.0040	0.0034	0.0035	99.8237	Normal
10/5/74	14	1.7751	1.6593	1.4318	0.0029	0.0047	0.0154	99.8366	No repressure
10/6/74	15	1.3572	2.4579	1.6854	0.0007	0.0039	0.0036	99.9484	No repressure
10/7/74	16	2.1779	2.3232	1.5909	0.0019	0.0042	0.0037	99.9128	Normal
10/22/74	17	2.1098	1.8337	-	0.0022	0.0025	0.0025	99.8957	Normal
10/23/74	18	2.0669	1.5351	1.6651	0.0010	0.0024	0.0022	99.9516	Long repressure
10/24/74	19	1.9828	1.8120	1.7094	0.0015	0.0030	0.0021	99.9244	Normal
10/25/74	20	1.7791	2.9943	1.6683	0.0017	0.0025	0.0025	99.9045	No shaking
10/26/74	21	1.9502	1.5053	1.3352	0.0015	0.0028	0.0023	99.9231	No shaking
10/27/74	22	2.0572	1.9528	1.7008	-	0.0036	0.0035	-	Normal

[a] Duplicate samplers for both inlet and outlet.

Results of run 12 are interesting in that they show the lowest efficiency and highest outlet loading of all tests. Seven bags were replaced in the baghouse on that day, and one might expect performance to improve with the removal of failed bags. The bags that were replaced during run 12, however, were in particularly bad shape, some having tears several feet long. As a result, large amounts of fly ash were deposited on the floor of the baghouse and were not removed when the bags were replaced. It is theorized that when that compartment came back on line the fly ash was gradually reentrained and swept up the stack, causing the extraordinarily high outlet concentrations.[16]

Results of cascade impactor measurements show a mean mass median diameter at the inlet of 18.4 microns, with a standard deviation of 5.2; at the outlet of the baghouse the mean mass median diameter was 8.8 microns, with a standard deviation of 4.1.[16] The outlet value of 8.8 microns appears large for the reported mean mass efficiency of 99.84 percent and suggests a possible leak in the system. This has not been verified. A summary of the mass median diameter data is shown in Table 4-16.[16]

TABLE 4-16.

RESULTS OF PARTICLE SIZING AT NUCLA[16]

Date	Inlet		Outlet	
	Andersen A,[a] mmd, μm	Andersen B,[a] mmd, μm	Andersen North[a] mmd, μm	Andersen West[a] mmd, μm
9/21/74	37	-	10.8	12.9
9/22/74	17.6	28	8.8	21
9/23/74	21	20.5	18.1	13.5
9/24/74	16.5	21.5	14.9	9.4
9/25/74	20	23.4	15.3	8.0
9/26/74	16.5	20.8	10.1	11.0
9/27/74	17.1	18.3	8.6	9.5
9/28/74	16.2	15.5	-	4.55
9/30/74	18.2	11.6	9.7	4.45
10/1/74	19.0	15.5	6.1	13.4
10/2/74	16.5	16.0	7.2	7.6
10/3/74	18.1	14.2	0.80	-
10/4/74	12.5	27	14.6	7.0
10/5/74	18.6	20.7	10.2	-
10/6/74	1.2	16.0	9.5	8.7
10/7/74	21.0	16.0	7.7	6.3
10/22/74	17.3	-	4.1	6.2
10/23/74	18.8	15.3	7.0	5.4
10/24/74	15.8	17.2	4.4	5.2
10/25/74	-	18.0	6.3	5.5
10/26/74	22.0	18.0	5.8	5.4
10/27/74	19.5	21.7	7.4	7.4

[a] Duplicate samplers for both inlet and outlet.

The fractional efficiency values for each run were calculated from differential size distribution plots.[16] The differential particle size distributions were constructed in Reference 16 in the manner described by Smith et al.[19] The concentrations of each of six particle diameters were averaged for the two impactor runs at the inlet and outlet, and the efficiency value calculated for each size. These fractional efficiency or fractional penetration curves show the performance of the baghouse as a function of particle size. The results of all 22 fractional efficiency curves have been combined in Figure 4-14 to give the median efficiency/penetration over the range of 1 to 10 microns.[16] The result is a fairly smooth curve that tends toward higher collection efficiencies for the larger particles and toward higher penetration for the smaller particle sizes. Also shown in Figure 4-14 is the range of observed efficiency/penetration values for each size, but excluding the extreme observations (highest and lowest). The wide bar indicates the range of that half of the values nearest the median; the narrow bar indicates the range of that half of the values farthest from the median.[16]

The effect of boiler load (air-to-cloth ratio) on particulate penetration is reported for the Nucla facility in a more recent report,[15] as illustrated in Figure 4-15.

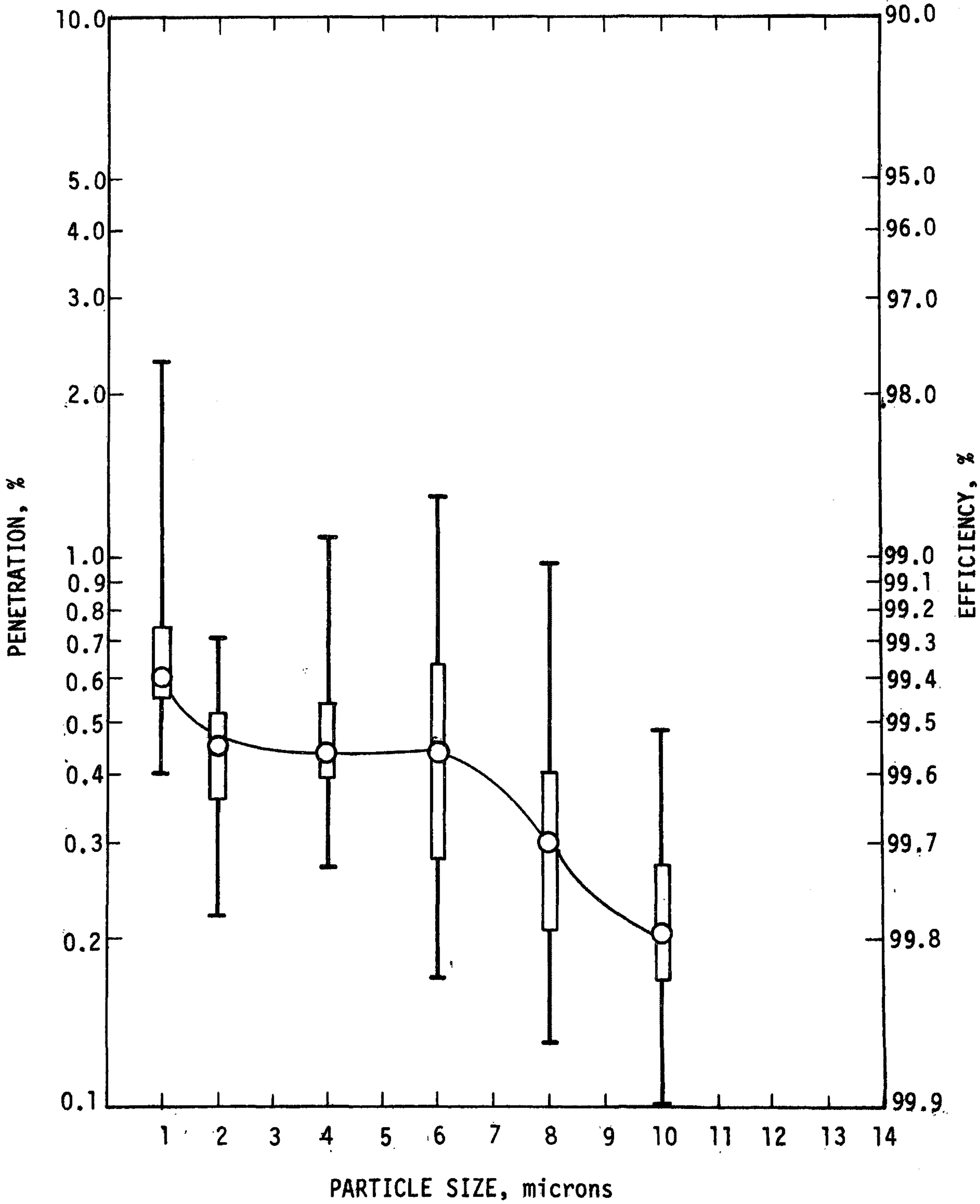

Figure 4-14. Median fractional efficiency for 22 tests on Nucla baghouse.[16]

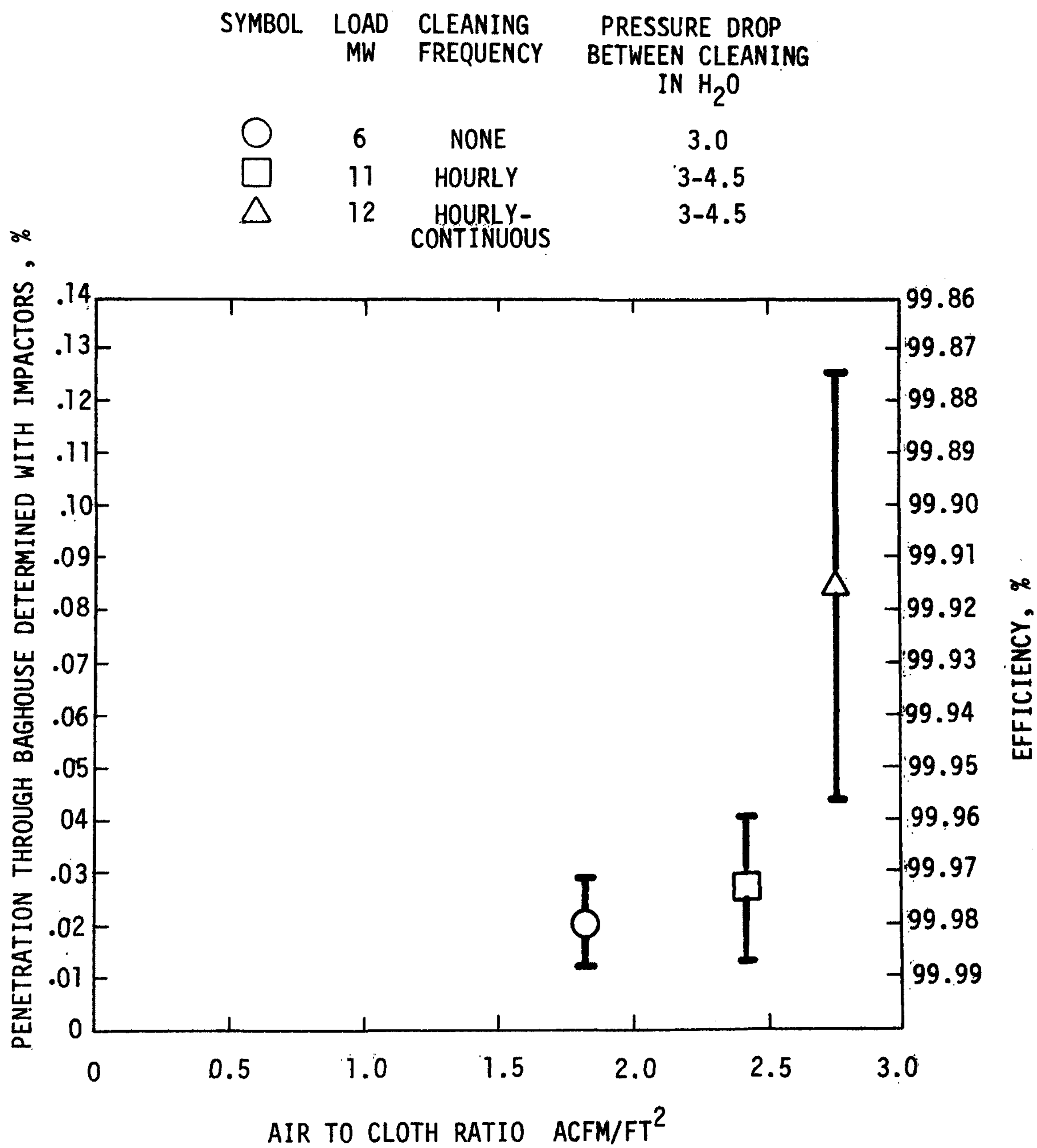

Figure 4-15. Penetration as a function of air-to-cloth ratio with one standard deviation limit, Nucla baghouse.[15]

With increasing load the baghouse cleaning cycle increased in frequency; the pressure drop also increased. As indicated at 6 MW, the baghouse operated during a full-day test period without requiring cleaning, and the pressure drop was nearly constant at 3 in. H_2O.[15] As load increased, cleaning became more frequent. The large variation in the 12-MW data is believed to be related to bag cleaning and to condition of the filter cake.[15]

Reference 15 also presents penetration data for particle sizes from 0.1 to 10 microns. Measurement in the size range of 0.01 to 1 micron were done with an Electrical Aerosol Size Analyzer (EASA), in the range 0.5 to 10 microns, with cascade impactors. Results for an 11-MW load are shown in Figure 4-16. The submicron tests were conducted between bag cleaning cycles, whereas the impactor tests included at least three cleaning cycles. The difference between the EASA penetration curve and impactor penetration curve is probably because of increase in emissions during cleaning.[15]

The flat penetration of particles greater than 1.5 microns in Figure 4-16 is illustrative of particle "seepage" through the bags. This "seepage" occurs after the baghouse is cleaned and is a result of particles sifting through the newly cleaned bag until a cake again forms and aids filtration.[15] The increased penetration of the 0.01 micron par-

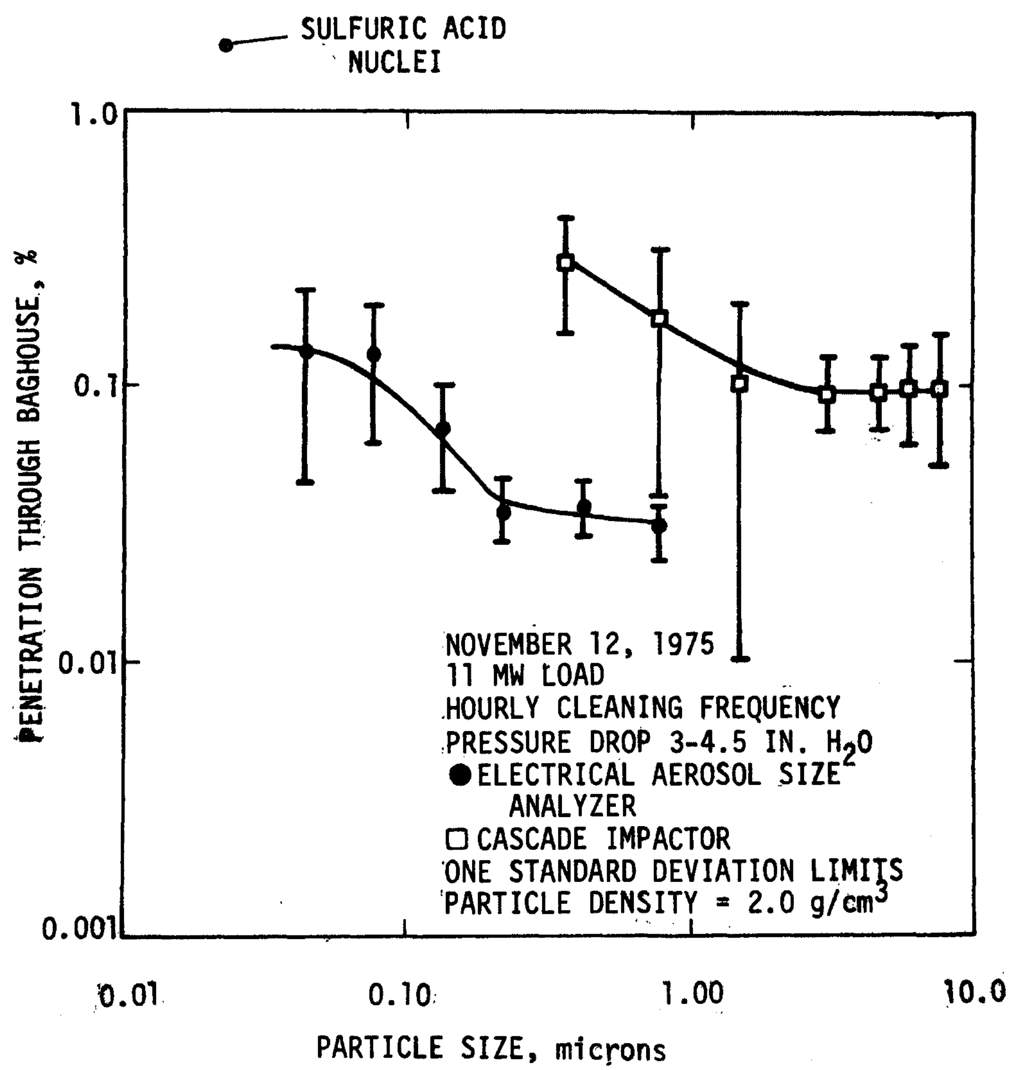

Figure 4-16. Fractional penetration through Nucla baghouse (11-MW load).[16]

ticle is believed to be the result of the formation of sulfuric acid nuclei.[15] The stack temperature was at 210°F, which is below the acid dew point.

The penetration values obtained with cascade impactors by Bradway and Cass[16] (Figure 4-14) for the same baghouse are about 10 times greater than those shown in Figure 4-16. It is suspected that the former data were strongly influenced by bag leakage.[15]

The particle diameter fractional penetration for the half-load of 6 MW is shown in Figure 4-17. During the test day, the bags were not cleaned. The good match of the EASA and cascade impactor penetrations was because of the lack of bag cleaning cycles.

The earlier Nucla study[16] also reports the effect of several variables on particulate penetration. The list of variables analyzed is shown in Table 4-17. Among these variables, numbers 6, 7, 9, and 10 relate to baghouse operation. Variable 6, number of shakes per cycle, was varied only for two tests when the shaking part of the cleaning cycle was eliminated.[16] Variable 7 is a somewhat qualitative assignment in that it attempts to account for the excessive frequency of bag failures. The baghouse was inspected periodically for broken bags, and nearly every inspection resulted in some bag replacement.[16] Because it

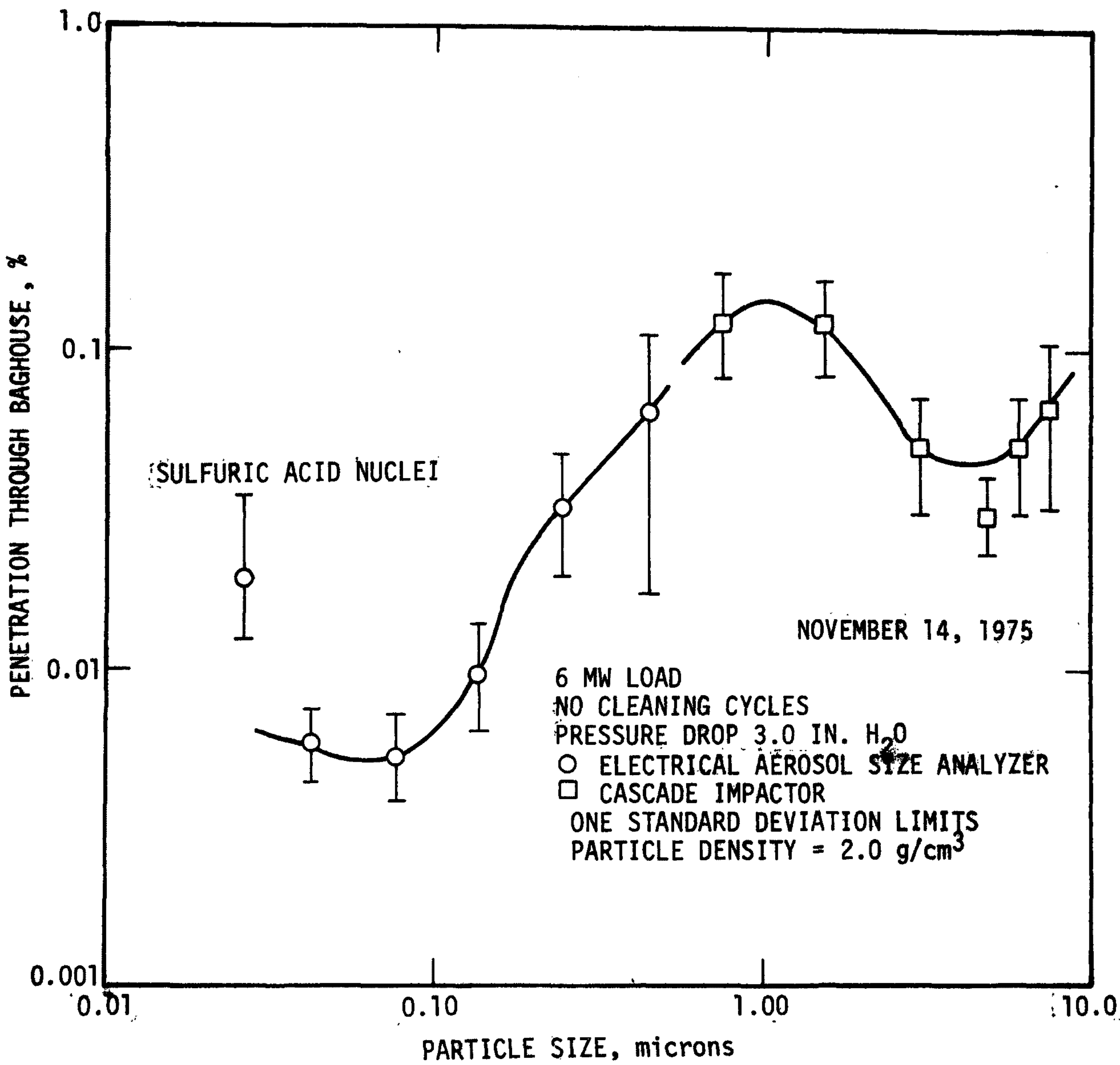

Figure 4-17. Fractional penetration through Nucla baghouse (6-MW load).[16]

Table 4-17. LIST OF VARIABLES ANALYZED IN NUCLA STUDY[16]

1.	Inlet grain loading, gr/ft^3
2.	Outlet grain loading, gr/ft^3
3.	Coal moisture, %
4.	Coal ash, %
5.	Coal sulfur, %
6.	Bag shakes per cleaning cycle
7.	Days since baghouse inspection
8.	Boiler steam load, 1000 lb/hr
9.	Repressure time, sec
10.	Cleaning cycles per test
11.	Efficiency, %
12.	Penetration, %

was impossible to determine when the bag failure had actually occurred, each day was assigned the number equal to the number of days since a baghouse inspection resulted in bag replacement.[16]

Variable 9, length of reverse flow, was normally 15 seconds. In three tests it was extended to 60 seconds, and in two tests it was eliminated. Variable 10, number of cleaning cycles during the test, was included because the frequency of cleaning cannot be closely controlled. The cleaning cycle is actuated when pressure drop across the bag reaches 4 in. of water and hence is dependent upon the quality of the coal, the quality of combustion in the boiler, the flue gas flow rate, and other factors. In addition, two tests were run in which the pressure transducer was bypassed so that no cleaning took place; thus each compartment was active for the entire 6-hour sampling period.[16]

In two other tests the baghouse was forced to clean continuously. As a result, 14 cleaning cycles occurred during the test period and each compartment was active during only 5 of the 6 hours of testing.

Multiple regression analysis of the variables in Table 4-17 shows that changes in the cleaning cycle had no statistically significant effect on particle collection efficiency and only the time since last replacement of failed bags had a significant effect on penetration.[16]

4.5.2 Sunbury Baghouse

A total of 31 tests were run at the Sunbury installation. Table 4-18 shows the inlet and outlet particulate mass concentrations determined by total mass and cascade impactor sampling techniques.[17] The particulate mass penetration and emission rate for each run are also shown.[17] Mass penetration and the total mass sample outlet concentration statistics for all 31 runs are presented in Table 4-19.[17] These data show that the average particulate penetration and mean outlet concentrations with new bags were 1.7 times and 1.45 times greater, respectively, than with used fabric.

Inlet and outlet mass median diameters (mmd) were also measured using impactors for each run. Table 4-20 presents the inlet and outlet mmd summaries for all 31 runs.[17] These data show that the mmd values for the filter effluents are on the average lower than those for the inlet dust. Excluding the two questionable mmd values, the average outlet mmd is roughly 19 percent lower than that at the filter inlet.

Fractional efficiency curves down to 1 micron for used and new bags at Sunbury are also reported.[17] These plots are shown in Figures 4-18 and 4-19. The fractional efficiencies of the new bags are slightly higher than those of the used bags. This is not what would be expected based

Table 4-18. RESULTS OF PARTICULATE SAMPLING AT SUNBURY STEAM ELECTRIC STATION[17]

Run no.	Baghouse inlet concentration, grains/dscf				Baghouse outlet concentration, grains/dscf			Mass penetration,[a] percent	Emission rate, lbs/10^6 Btu
	Total mass sampler	Impactor run A	Impactor run B	Impactor run C	Total mass sampler	Impactor A	Impactor B		
1	3.6296	2.6154	-	-	0.0022	0.0046	0.0051	0.06	0.0047
2	2.6596	2.2244	1.3184	-	E	0.0272	0.0146	-	-
3	2.8082	2.0680	2.2677	-	E	0.0075	0.0084	-	-
4	4.1235	1.0839	3.5096	-	0.0013	0.0059	0.0064	0.03	0.0028
5	2.6851	2.5708	1.3776	-	0.0017	0.0028[D]	0.0025[D]	0.06	0.0039
6	2.5243	1.6296	2.8180	-	0.0014	0.0077	0.0060	0.06	0.0031
7	3.1661	2.0869	2.1190	-	0.0014	0.0029[D]	P	0.04	0.0031
8	2.2977	2.5095	1.3616	-	0.0014	0.0024[D]	0.0019[D]	0.06	0.0031
9	2.4280	1.9984	1.9855	-	0.0015	0.0020[D]	0.0029[D]	0.06	0.0035
10	3.2936	2.0085	2.0120	-	0.0016	0.0014[D]	S	0.05	0.0041
11	2.6678	2.5278	2.1174	-	0.0033	S	L[W]	0.12	0.0101
12	2.0891	1.5471	2.0761	-	0.0017	0.0018[D]	L[W]	0.08	0.0044
13	2.6020	1.9184	2.5280	-	0.0020	0.0040[D]	0.0010[W]	0.08	0.0047
14	2.8845	1.4442	3.3717	-	0.0015	0.0018[D]	0.0021[W]	0.05	0.0035
15	2.6728	1.3356	1.3409	-	0.0016	S	0.0004[W]	0.06	0.0037
16	2.4403	2.8056	1.0743	-	0.0013	S	0.0019[W]	0.05	0.0033
17	2.5058	1.9631	1.9043	-	0.0016	0.0026[D]	P[D]	0.06	0.0038
18	1.8291	1.2430	2.0925	-	0.0013	0.0019[D]	P[D]	0.07	0.0031
19	2.8942	1.2809	1.9564	-	0.0016	0.0020[D]	0.0002[W]	0.06	0.0037
20	2.2016	1.3857	1.8968	-	0.0018	0.0024[D]	P[D]	0.08	0.0044
21	1.6694	2.2743	1.3782	-	0.0019	0.0032[D]	0.0011[W]	0.11	0.0044
22	1.3822	2.3328	1.7426	1.9390	0.0031	0.0016[W]	0.0029[D]	0.22	0.0074
23	3.2646	1.7175	1.4863	1.8851	0.0028	0.0014[W]	0.0037[D]	0.09	0.0063
24	2.0503	2.0914	2.2034	2.7331	0.0029	0.0015[W]	0.0035[D]	0.14	0.0058
25	3.0946	1.6780	1.6408	2.4440	0.0025	0.0019[W]	0.0029[D]	0.08	0.0056
26	2.3859	1.8363	1.8807	1.6942	0.0022	0.0033[W]	0.0035[D]	0.09	0.0047
27	1.3477	1.8289	1.8489	1.8929	0.0022	0.0002[W]	0.0029[D]	0.16	0.0051
28	3.0022	1.3270	1.8423	1.1209	0.0022	0.0009[W]	0.0016[D]	0.07	0.0049
29	2.0174	1.6922	1.8105	2.1041	0.0023	0.0012[W]	0.0024[D]	0.11	0.0054
30	2.0843	1.7849	1.9178	1.5965	0.0020	0.0010[W]	0.0026[D]	0.10	0.0044
31	2.2181	2.5772	2.3989	2.8530	0.0022	0.0011[W]	0.0020[D]	0.10	0.0047

[a] Calculated from the inlet and outlet total mass sampler concentrations.

Note: E - Excluded because of apparent vacuuming of the duct floor during sample collection.
D - Double substrates per stage.
P - Impactor with prefilter.
S - Substrates stuck together.
L - Substrates lost weight.
W - University of Washington impactor.

Table 4-19. PENETRATION AND OUTLET CONCENTRATION[17]

Runs	Penetration, percent		Outlet concentration, grains/dscf	
	Mean	Standard deviation	Mean	Standard deviation
All, normal and abnormal; new and used bags[a]	0.08276	0.03963	0.00195	0.00056
Normal with used bags[a]	0.06889	0.03018	0.00181	0.00063
Normal with new bags	0.11667	0.05610	0.00262	0.00038

[a] Does not include Runs 2 and 3, which were discounted because of apparent vacuuming of the outlet duct floor.

Table 4-20. INLET AND OUTLET MASS MEDIAN DIAMETERS[17]

Runs	Inlet mmd, μm		Outlet mmd, μm	
	Mean	Standard deviation	Mean	Standard deviation
All, normal and abnormal; new and used bags	6.9	2.5	6.3, (5.6[a])	4.3, (2.5[a])
Normal with used bags	7.1	2.7	5.7	1.8
Normal with new bags	7.0	2.3	6.4, (4.9[b])	5.9, (2.2[b])

[a]Impactor A data for runs 25 and 26 excluded.

[b]Impactor A data for run 25 excluded.

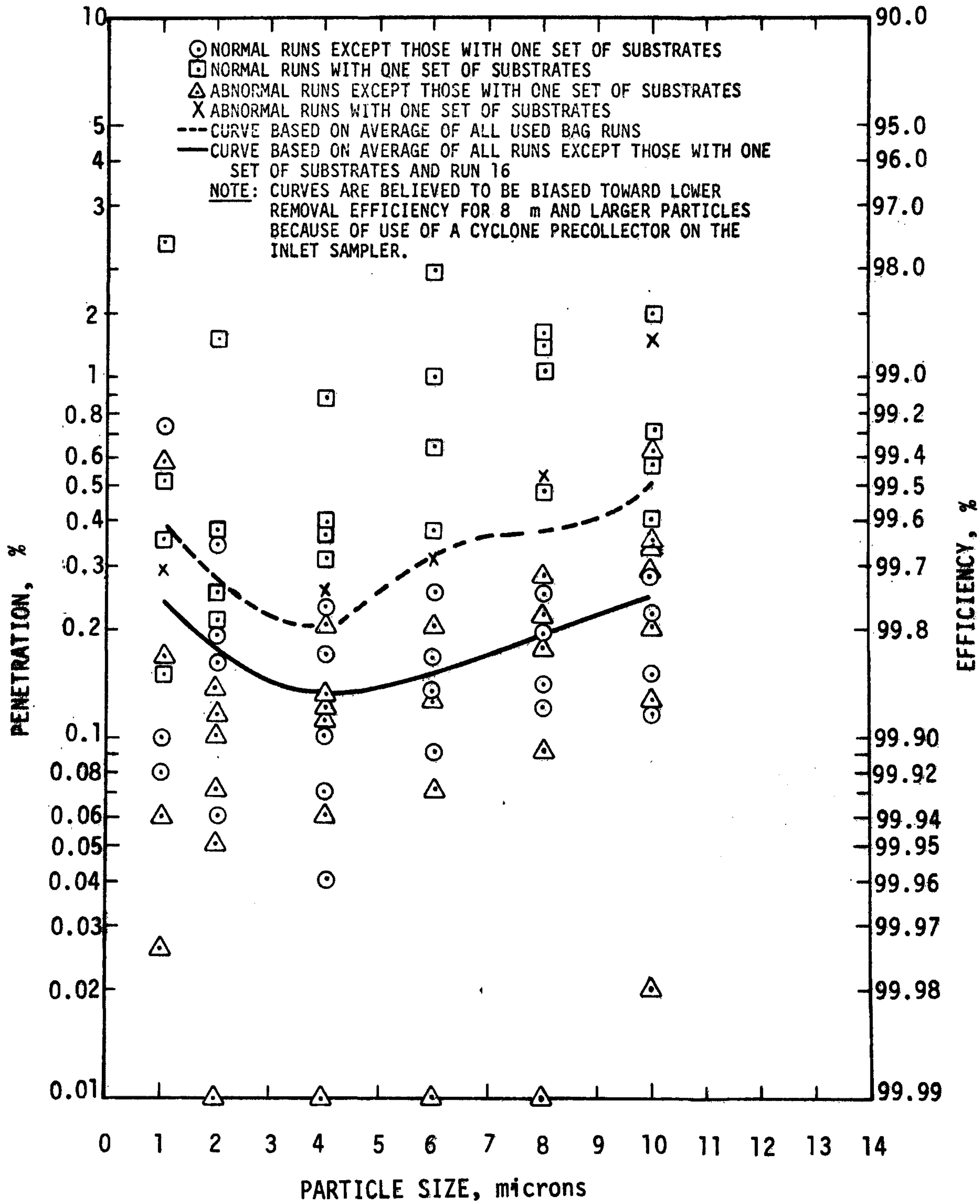

Figure 4-18. Removal efficiency as a function of particle size for runs with used bags, Sunbury baghouse.

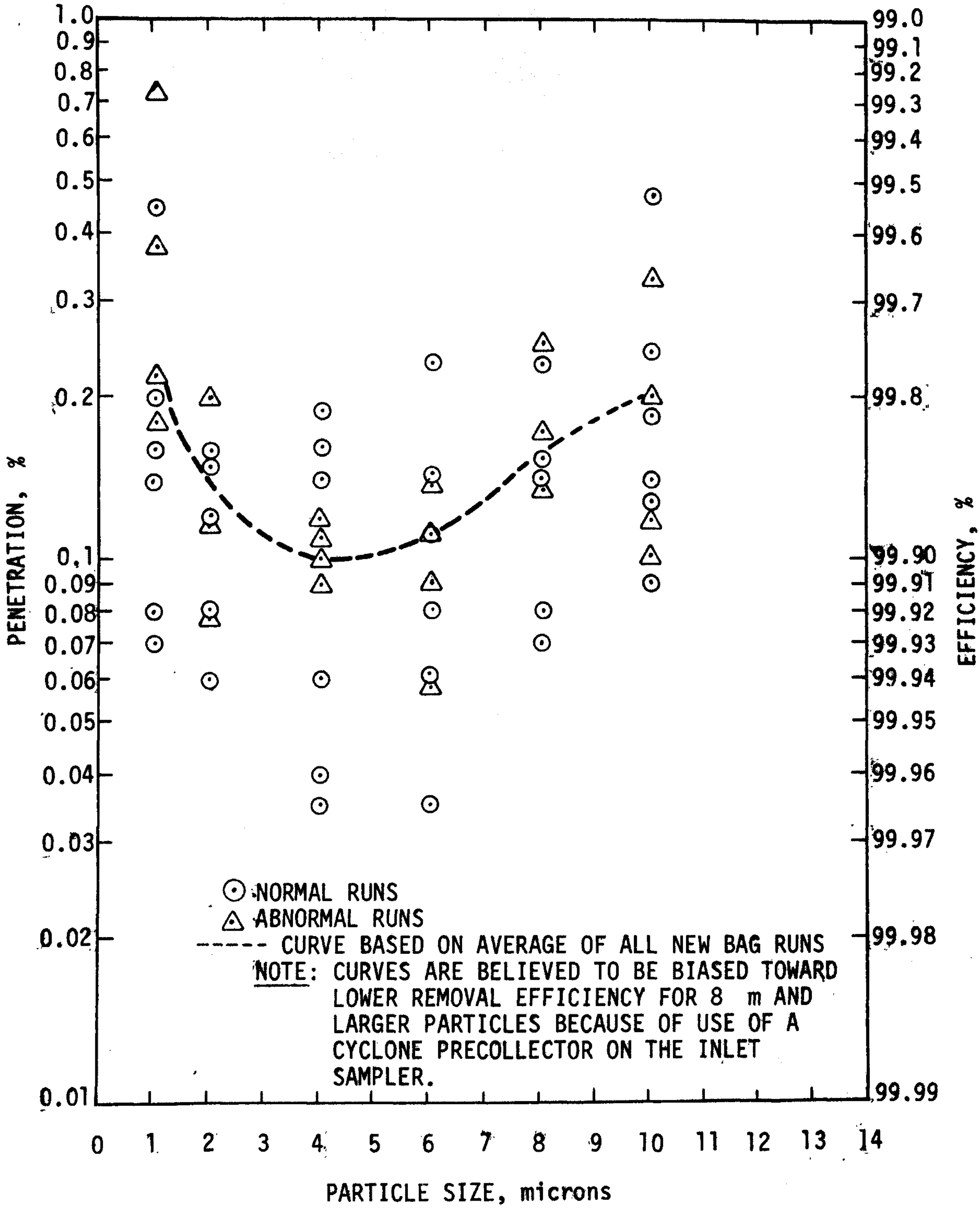

Figure 4-19. Removal efficiency as a function of particle size for runs with new bags, Sunbury baghouse.

upon the higher mass efficiencies determined for used bags. Reference 17 indicates that this difference might have been caused by problems with the Andersen impactor substrate. Furthermore, it is reported that the curves in Figure 4-18 and 4-19 are somewhat distorted for the larger particle sizes because of the use of the Andersen cyclone precollector at the baghouse inlet.

Apparent collection efficiency by particle size for the size range 0.1 to 10 microns is shown in Figure 4-20. This figure shows a nearly uniform, high reduction of particles entering the system. All sizes in the impactor range are collected with better than 99 percent efficiency.

The Sunbury study also investigated the effects on particle penetration or outlet mass concentration of altering such operating parameters as ash and sulfur content of coal, boiler steam flow, and number of compartments in service. Tests on used bags showed no significant effect of these parameters. Significant differences were observed, however, when results obtained with new bags were compared with those from used bags. With new bags, particulate penetration and outlet mass concentration were most dependent upon inlet mass concentration and pressure drop across the baghouse. With used bags, moisture content of the fuel and the baghouse face velocity had the most significant effects.[17]

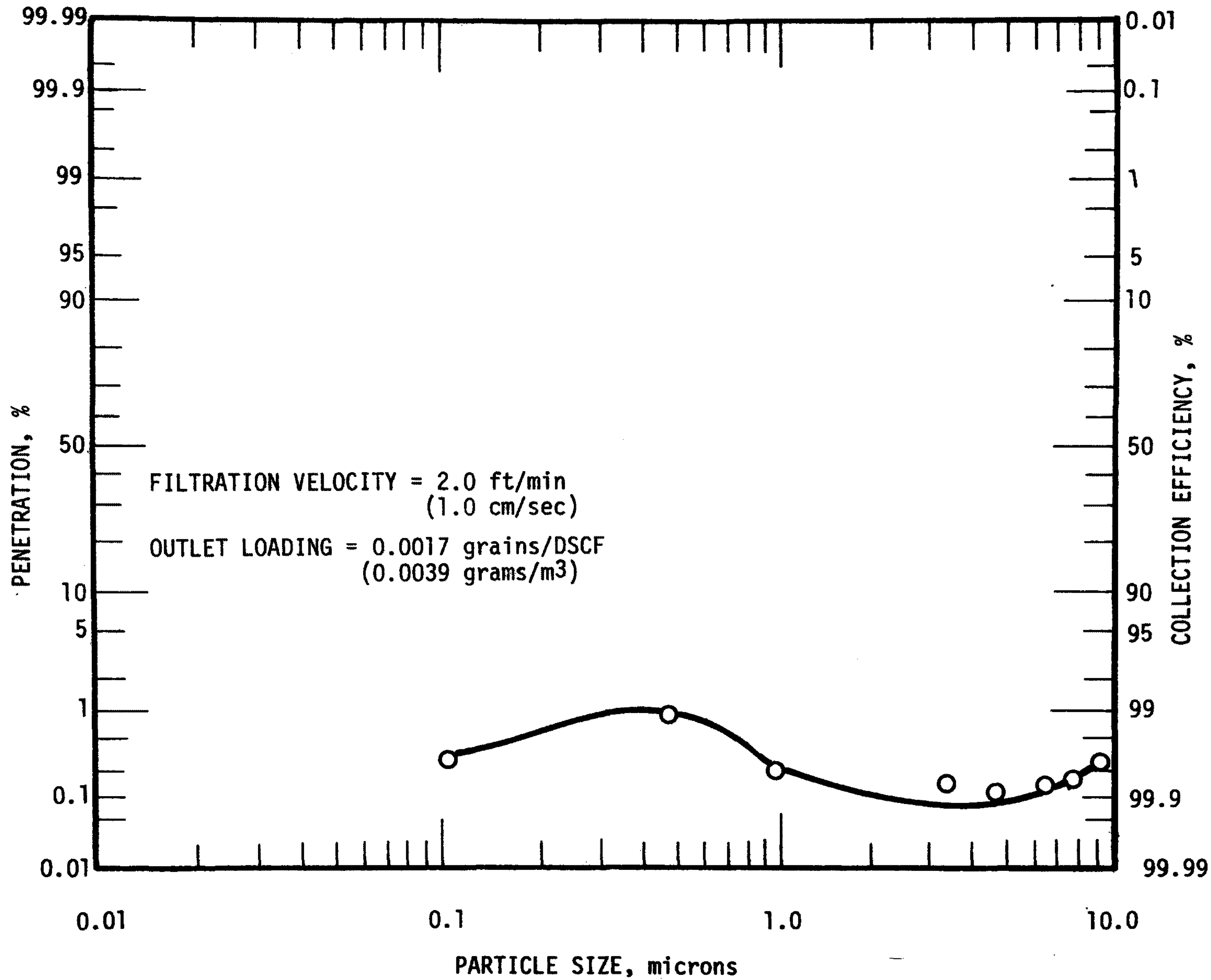

Figure 4-20. Baghouse performance at Sunbury Steam Electric Station.[17]

4.5.3 Pilot Scale Investigation of Fractional Efficiency of Fabric Filters on Coal-Fired Industrial Boilers

The fractional efficiency of five different fabrics was determined on a coal-fired boiler at Kerr Industries by McKenna et al.[20] The fabrics tested were Nomex felt, Teflon felt, Gore-Tex, and Dralon-T. Fractional efficiency was determined using an Andersen inertial impactor for the four filter media at three air/cloth ratios.

Although data of this type are interesting, the results are experimental and should not be compared with actual fabric filter efficiency under normal operating conditions of a utility coal-fired boiler. Bags used on utility boilers are made of fiberglass; none of the bags tested here are of fiberglass construction. In addition, many of the air/cloth ratios used in the pilot plant tests are considerably higher than those used on the fabric filters now in use on coal-fired utility boilers. One of the fabrics (Gore-Tex) has a different filtration mechanism than other fabrics, called laminate filtration.

It should also be noted that penetration figures for the pilot plant are much higher than Sunbury or Nucla, partly because inlet loading is much lower.

Teflon Felt - Style 2663

Figure 4-21 presents collection efficiency versus particle size for Teflon felt - Style 2663. The curves at

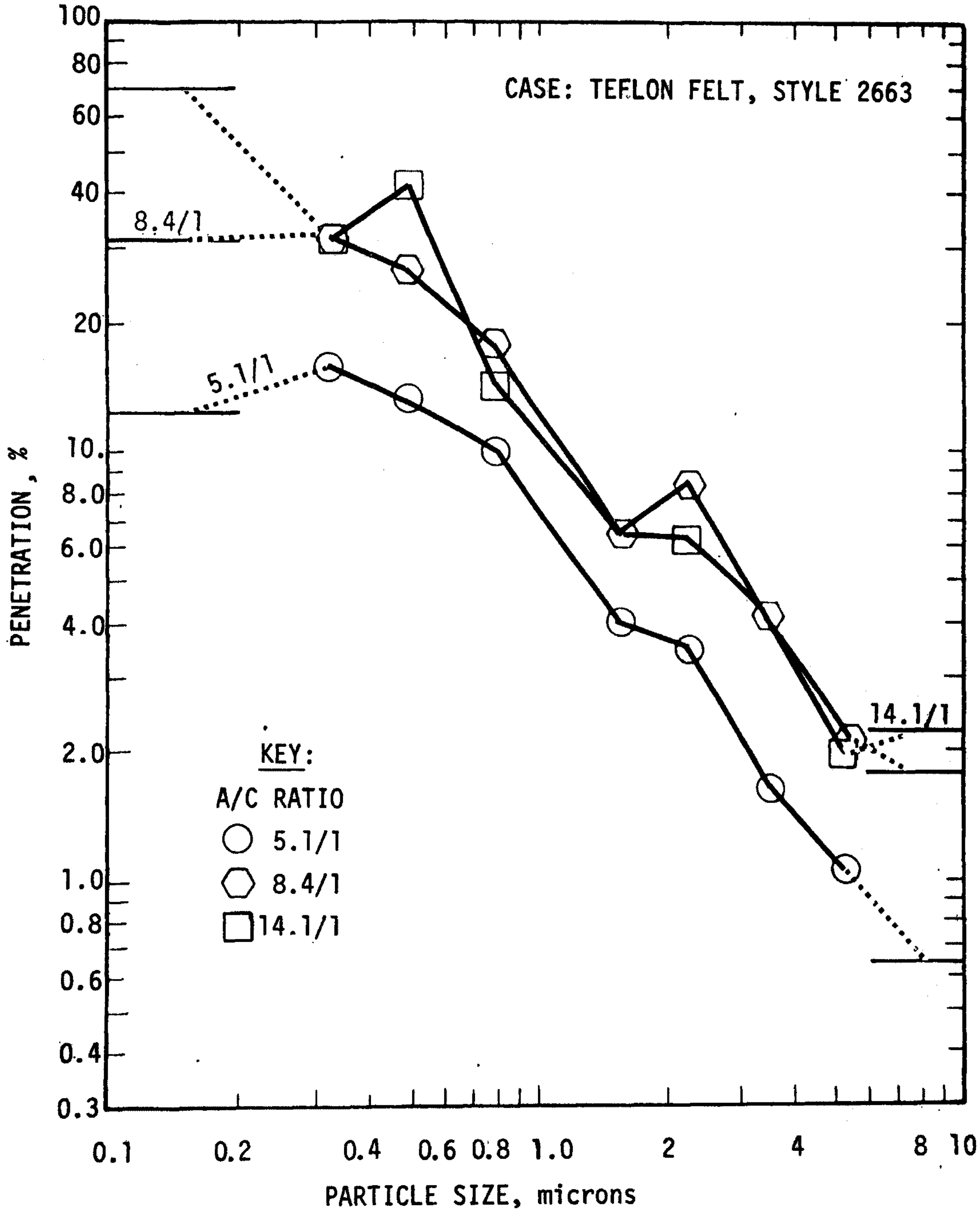

Figure 4-21. Penetration vs. particle diameter, Teflon felt style 2663.[20]

each A/C ratio all show the same general trend, with the curve sloping downward to the right indicating less penetration of the larger particles. Two of the curves indicate some leveling or decrease of penetration for the very small fractions. This improved collection of the finest fractions is also present and, in some cases, even more pronounced in the data for the other media. For the Teflon, an increase in A/C ratio generally resulted in an increase in outlet loadings. For the smaller size fractions, the curve does appear to flatten above an A/C ratio of about 8.

Gore-Tex/Nomex

Figure 4-22 illustrates collection efficiency versus particle size for Gore-Tex/Nomex. These curves indicate an increase in penetration as the fractions decrease from 10 to 0.5 micron. Below 0.5 micron, there is a sharp decrease in penetration for all three A/C ratios. The performance of Gore-Tex on submicron particles seems essentially the same at all three A/C levels. As with the Teflon felt, the largest particle size fraction, i.e. the total of all sizes greater than 9.35 μm, is most sensitive to increases in A/C ratio, and an increase in velocity results in an increase in the outlet concentration. One unresolved problem with the Gore-Tex bags, however, was that of durability.

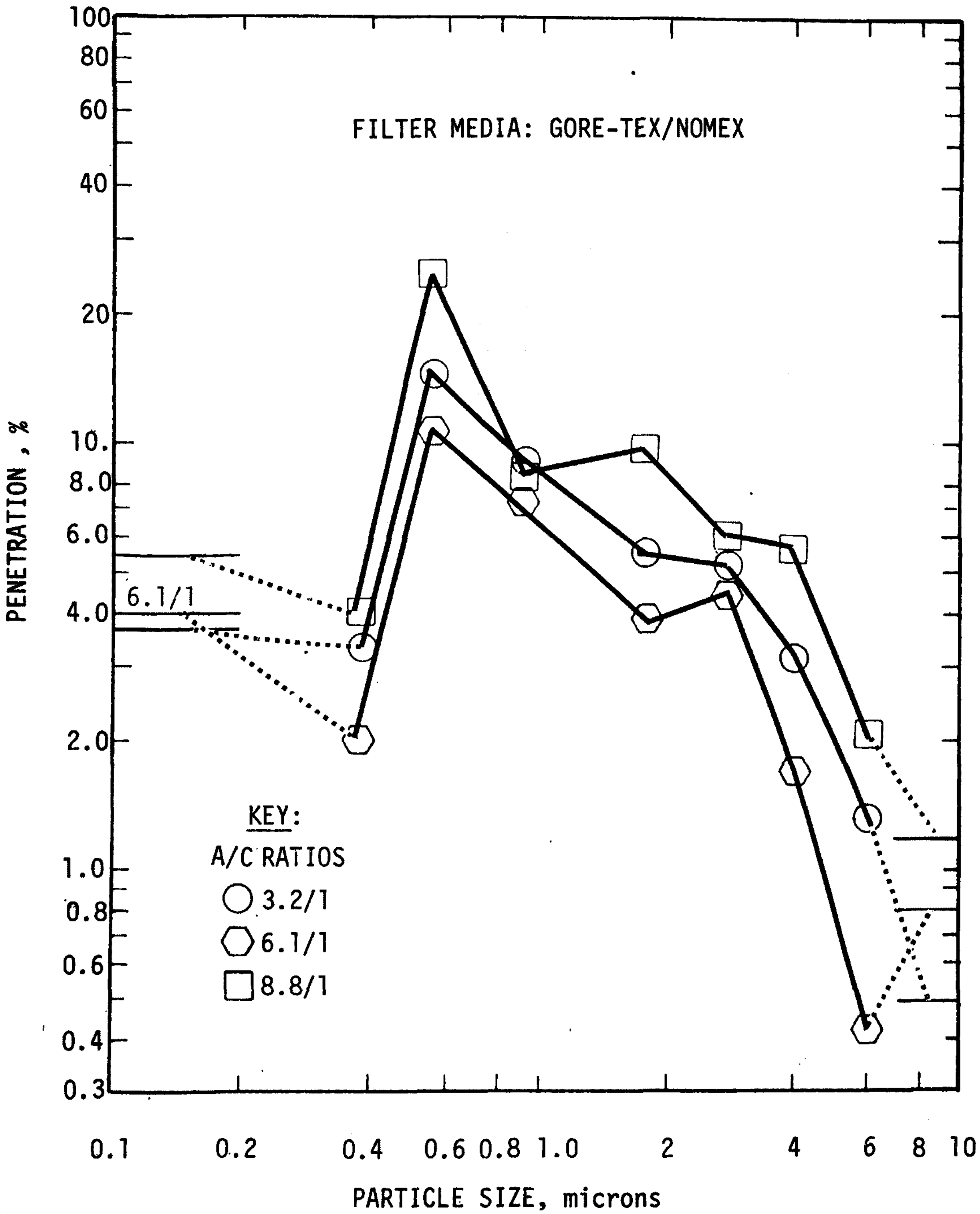

Figure 4-22. Penetration vs. particle diameter, Gore-Tex/Nomex.[20]

Dralon-T

The collection efficiency versus particle size for Dralon-T is illustrated in Figure 4-23. Dralon-T was found to exhibit greater filtering capabilities as the A/C ratio was increased.

Nomex Felt

The efficiency of Nomex felt vs. particle size is shown in Figure 4-24. Again, these curves show a higher efficiency for the larger particles and indicate a significant decrease in penetration of the two smallest fractions. When compared with the other bag materials, Nomex was considered to provide the best filtering efficiency.

McKenna et al. also studied the effect of duration and volume of cleaning air on particle size efficiency, clean-down, and pressure drop, using Nomex felt as the filter medium. They found that higher collection efficiencies were possible when the reverse air fan was not employed and that varying the volume of reverse air (once in operation) has little effect on overall efficiency. They also found that A/C ratio is the key parameter in predicting baghouse efficiency. Their data showed an increase in outlet loading with increasing velocity for the three larger fractions, while the outlet loading for the smallest fraction did not seem to increase above an A/C ratio of 6.

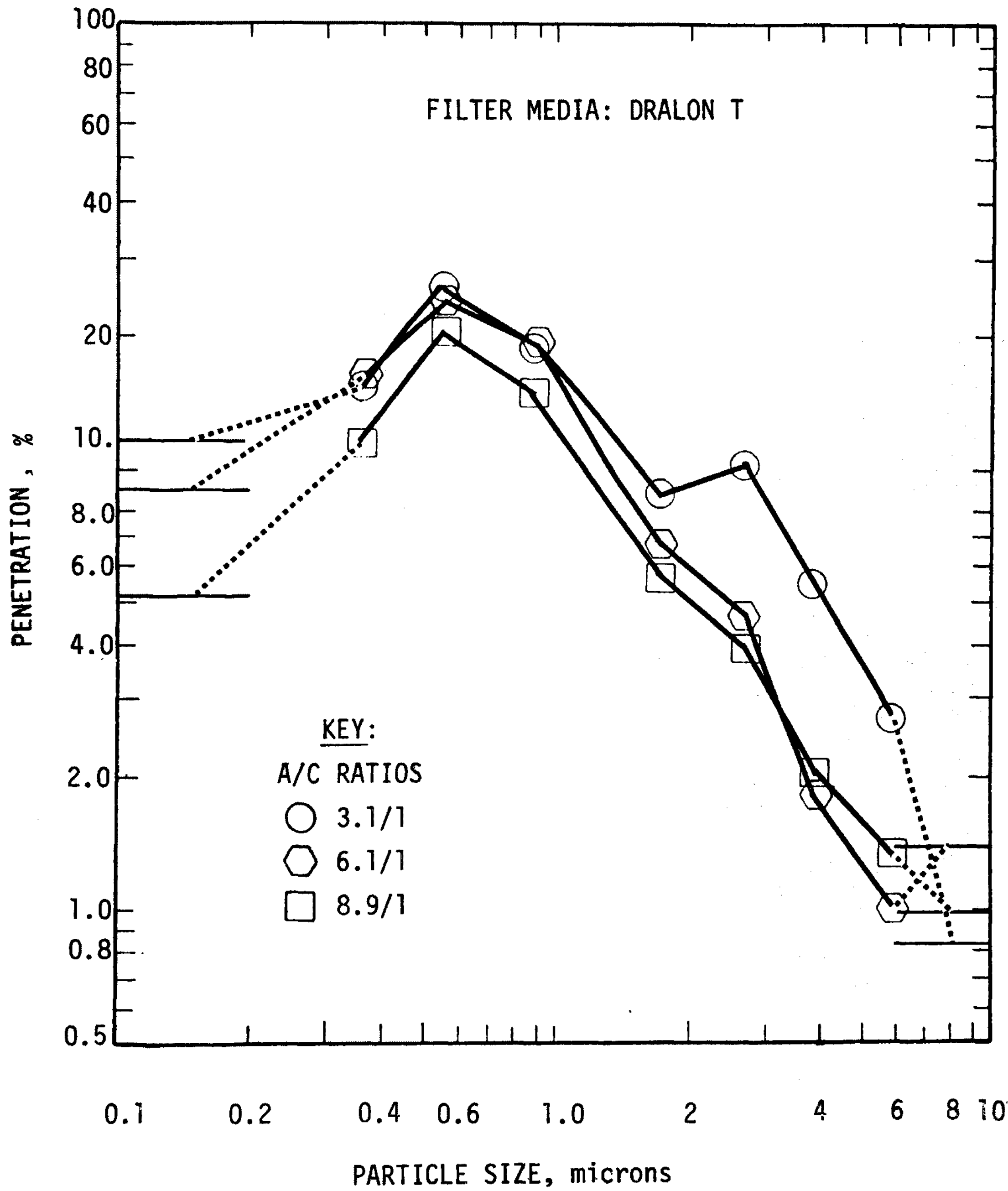

Figure 4-23. Penetration vs. particle diameter, Dralon-T.[20]

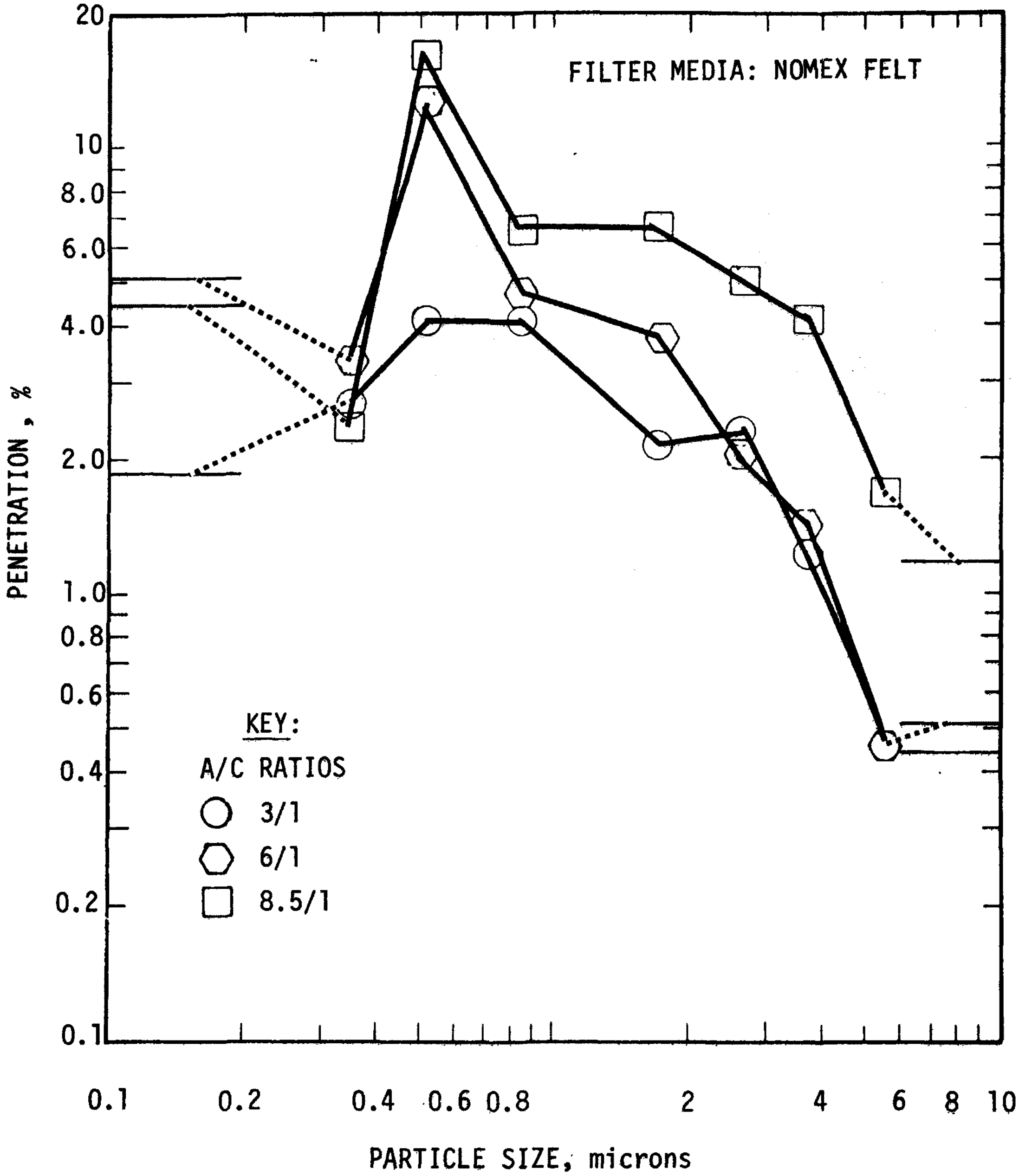

Figure 4-24. Penetration vs. particle diameter, Nomex felt.[20]

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Case

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4 Private Communication

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7 Private Report, Research-Cottrell, Inc.

8 Ref. 7

9 Ref. 7

10 Iowa Public Service/George Neal (Different source from Ref. 7).

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5.0 CONCLUSIONS

Particulate emissions from coal-fired utility boilers have historically been controlled by electrostatic precipitators, but wet scrubbers and fabric filters have also recently been utilized for this purpose. Some advantages and disadvantages of each type of control device are summarized in Tables 5-1 through 5-3.

It is likely that precipitators will remain the predominant device for controlling particulate emissions from coal-fired utility boilers because, when well-designed, they offer high reliability and low operating costs. However, each application must be reviewed on a case-by-case basis. Low-sulfur coal, which presents the greatest design problems for precipitators, will be consumed to a much greater extent in the future; and when this occurs, utilities will most likely consider a wet scrubber or fabric filter since these control devices are less sensitive to low-sulfur coal.

5.1 DESIGN PRACTICES

The design of precipitators has been refined considerably in the past few years to meet increasingly stringent particulate emission regulations. Using the current design

Table 5-1. ADVANTAGES AND DISADVANTAGES OF USING PRECIPITATORS ON COAL-FIRED UTILITY BOILERS

Control device	Advantages	Disadvantages
Electrostatic precipitator	1) Can be designed to provide high collection efficiency for all sizes of particles from submicron to the largest present; new designs can meet stringent particulate regulations. 2) Economical in operation because of low internal power requirements and inherently low draft loss; high reliability. 3) Flexible in gas temperature used, ranging from as low as 200°F to as high as 800°F. 4) Long useful life, if properly maintained. 5) No water pollution potential. 6) Extensive history of application.	1) High resistivity of low-sulfur coal fly ash degrades performance of cold precipitator not designed for this type of fuel. 2) Discharge wire breakage, ash hopper plugging are potential maintenance problems. 3) Efficiency is sensitive to change in ash characteristics. 4) Potential explosion and fire problems during start-up because of high voltage sparking. 5) High-voltage hazards to personnel.

Table 5-2. ADVANTAGES AND DISADVANTAGES OF USING WET SCRUBBERS ON COAL-FIRED UTILITY BOILERS

Control device	Advantages	Disadvantages
Wet scrubber	1) Smaller space requirements than precipitator or fabric filter. 2) Not affected by high resistivity associated with low-sulfur coal fly ash; relatively insensitive to coal chemical composition and variations in gas temperature. 3) No high-voltage hazard.	1) Collection efficiency decreases rapidly with decreasing particle size. 2) Maintenance costs are higher than for precipitators and fabric filters. (Corrosion, scaling, plugging) 3) Water pollution control required for scrubber effluent. 4) Greater pressure drop and resulting higher power demand needed for high efficiency.

Table 5-3. ADVANTAGES AND DISADVANTAGES OF USING FABRIC FILTERS ON COAL-FIRED UTILITY BOILERS

Control device	Advantages	Disadvantages
Fabric filter	1) Collection efficiency essentially independent of sulfur content in coal. 2) High overall mass and fractional efficiency. (99 + %) 3) Collection efficiency and pressure drop are relatively unaffected by changes in inlet grain loadings for continuously cleaned filters. 4) No water pollution potential. 5) Corrosion is not a problem, with bags 6) No high-voltage hazard, thus simplifying repairs.	1) Higher pressure drop than ESP resulting in higher energy consumption. 2) Fabric life is difficult to estimate; may be shortened in the presence of acid or alkaline particles. 3) Low air-to-cloth ratios require large amounts of space (70 ft^2/MW), at A/C ratio of 2.5. However, as coal sulfur content decreases, sizes of fabric filters and precipitators begin to equalize. 4) Condensation of moisture may cause crusty deposits or plugging of the fabric or require special additives.

practices discussed in Section 2.0, a precipitator can be more precisely tailored to its specific application. The use of the Matts-Öhnfeldt modified migration velocity (w_k), is an improvement over the conventional Deutsch Anderson migration velocity (w), which is no longer adequate to meet current demands for efficiencies well in excess of 98 percent. Once the particle size distribution for a given application is known, w_k can be treated as a constant; w cannot be treated as such. American and foreign manufacturers have used the w_k concept in sizing precipitators. The Jim Bridger Power Station in Wyoming is a recent example where the w_k concept was used successfully to help size a precipitator for use with low-sulfur coal.

Increased use of other procedures such as combustor tests and pilot scale precipitators also help in the sizing of precipitators, especially where low-sulfur coal is to be used.

Increased sectionalization, i.e., a greater number of independent electrical sections in modern precipitators, is another major design improvement since it substantially improves on-stream reliability. Automatic controls for power input also assist in assuring reliable performance.

Reported operating data from Sondreal and Tute[1] on particulate scrubbers in the western U.S. have shown overall mass collection efficiencies, ranging from 70 to 99.75 percent, although Green[2] reports lower overall mass efficiencies on some of the same installations as reference 1. No clear trend, however, emerges from available test data as to which type of scrubber is the best for use in the collection of fly ash. Applications of scrubbers for collection of fly ash have been limited for the most part to low sulfur coal, sometimes in conjunction with an SO_2 scrubber. To date, operation and maintenance costs of particulate scrubbers have been higher than precipitators or fabric filters, and utilities have placed less emphasis on their use for particulate control. The high maintenance costs are caused by corrosion, scaling, and plugging of equipment.

The design of fabric filters for utility use does not represent a breakthrough in technology, but rather a refinement of the basic design procedures used in other industries. Existing fabric filters on utility boilers have shown excellent overall mass collection efficiencies.

The present size of fabric filters required for installation on large coal-fired utility boilers (approximately 70 ft^2 area/MW) may present a problem, where space is at a premium. This size could be reduced if air-to-cloth ratios in the baghouses were increased. Innovations such as pulse-jet cleaning (cleaning with periodic bursts of compressed air) may allow this increase in the air-to-cloth-ratio in baghouses. Also, changes in baghouse construction such as utilizing suspended bags attached to a tube sheet will allow changing entire sets of bags without entering the chamber. This type of modification will reduce the number of internal walkways and total area requirements for the baghouse.

Another design problem that requires attention is the vena contracta effect which occurs when fly ash enters the filter through a hole in the cell plate. The vena contracta effect impacts fly ash at relatively high velocity against the filter surface and rapidly abrades it immediately following the mouth of the filter. One utility that operates a baghouse solved this design problem by installing gas straighteners, called "thimbles", at the inlet of the bags. Improved filtration media are also being developed to supplement fiberglass bags.

Thus, it appears that design improvements and modifications to make fabric filters smaller, more reliable, and easier to maintain are occurring fairly rapidly.

5.2 OPERATION AND MAINTENANCE

The collection efficiency of particulate control systems degrades rapidly, especially in the fine-particle range, when strict maintenance and operating procedures are not followed. However, more study is needed on the quantitative relationship between malfunctions resulting from neglect or improper maintenance and the degradation in efficiency of the control device. For particulate scrubbers and fabric filters especially, a detailed handbook of maintenance procedures and troubleshooting tips would be useful for utility operators who are responsible for maintaining these control devices.

5.3 FRACTIONAL EFFICIENCY RELATIONSHIPS

Precipitators and fabric filters are highly efficient collectors of submicron particles, while the collection efficiency of scrubbers decreases rapidly with decreasing particles size.

More fractional collection efficiency test data are available for precipitators and scrubbers than for fabric filters, and the tested data generally confirm predicted efficiencies of computer models for precipitators and scrubbers. Test data show that precipitators can effectively remove fine particles under favorable conditions. Overall collection efficiencies can be greater than 99.5 percent, and the efficiency for any particle size can be greater than 90 percent. Particles smaller than 0.1 micron can be collected with efficiencies greater than 99 percent. Test data for particulate scrubbers on coal fired boilers usually show a sharp decrease in efficiency below a a particle size of micron, but the magnitude of the efficiency drop varies greatly, (from approximately 5% to 94%) as shown in section 4.4.5, Table 4-13. Existing fabric filter systems operating at an air-to-cloth ratio of 1 to 2 or less can collect 99+ percent of the particles from less than 0.1 micron to 10 microns in size.

Precipitators show a minimum in collection efficiency in the particle size range of 0.2 to 0.4 micron, while available data for fabric filters show a more uniform collection efficiency in the submicron particle size range. The collection efficiency of scrubbers declines to about the 0.2 to 0.5 micron range, the limit of collection by inertial impaction. Below the 0.2 to 0.5 micron range, the efficiency usually increases because of diffusion effects. However, scrubbers are least effective in the collection of submicron particles.

The limited and scattered available particle size data point out a need for a reliable, consistent, and widely used technique for measuring particle size distribution. This would enable valuable data to be collected for different coal/boiler applications and different operating conditions.

5.4 COSTS

Installation costs for precipitators, scrubbers, and fabric filters applied to a model plant have not been estimated; the results would present a biased cost picture that depends largely on the selected boiler and fuel. Thus a few selected model cost estimates would present a less-than-accurate overall picture of cost comparison. In addition, variable site-specific conditions can greatly affect installation costs of control systems.

Limited cost data were available from two scrubber installations and two fabric filter installations.

Using the costs presented for precipitators, it is evident that both the total mass and fractional collection efficiencies of a control device must be considered. For example, a comparison of precipitators for cyclone and pulverized-coal-fired boilers with roughly equal efficiencies in the range of 0.2 to 0.4 micron (83% cyclone vs. 82% pulverized coal), shows the cyclone boiler precipitator to be only slightly more expensive than that for a similar sized pulverized-coal boiler. The corresponding overall mass collection efficiency of the precipitator for the cyclone boiler, however, is less than that of the precipitator for the pulverized-coal boiler (99% vs. 99.5%). When the overall mass collection efficiencies of the two control systems are both 99.5 percent, the cyclone boiler precipitator becomes about 31 percent more expensive than the precipitator for the pulverized-coal unit. In this instance, however, the fractional efficiency of the cyclone boiler in the 0.2 to 0.4 micron range does increase considerably (83% to 89%). A similar comparison should be made when determining the cost of installing any type of control device on a coal-fired utility boiler; i.e. the fractional control efficiency should be studied in addition to the overall control efficiency.

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APPENDIX A

LIST OF U.S. POWER PLANTS WITH ELECTROSTATIC PRECIPITATORS HAVING EFFICIENCIES OF 95 PERCENT OR GREATER

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = AB

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
TVA	COLBERT	05	PRIDE	AB	11	65	550	CB		11032		3.5	4.2	12.3	75	PE		99.7			PI	TV	
ALABAMA PWR	GORGAS	10	GORGAS	AB		72	700	CB	O	11751	7.1	.6	3.7	16.0	72	PE	BU	98.0					SS
ALABAMA PWR	BARRY	05	BUCKS	AB		71	712	CB	O	11815	7.7	.9	3.2	14.4	73	PE	BU	98.5					
ALABAMA PWR	BARRY	04	BUCKS	AB		69	350	CB	O	11815	7.7	.9	3.2	14.4	73	PE	BU	98.5					
ALABAMA PWR	GASTON E.C.	02	WILSONVILLE	AB	06	60	250	CB		11509	7.5	.7	2.6	14.7	73	HP	BU	99.3					SS
ALABAMA PWR	GREENE COUNTY	02	DEMOPOLIS	AB		69	250	CB	O	11757	6.6	1.0	1.8	14.9	73	HP	RC	99.1					
ALABAMA PWR	GREENE COUNTY	01	DEMOPOLIS	AB		65	250	CB	O	11757	6.6	1.0	1.8	14.9	73	HP	RC	99.1					
ALABAMA PWR	GASTON E.C.	01	WILSONVILLE	AB	03	60	250	CB		11509	7.5	.7	2.6	14.7	73	HP	RC	99.3					SS
ALABAMA PWR	GASTON E.C.	04	WILSONVILLE	AB	04	62	250	C		11509	7.5	.7	2.6	14.7	72	HP	RC	99.3					SS
ALABAMA PWR	GASTON E.C.	03	WILSONVILLE	AB	04	61	250	CB		11509	7.5	.7	2.6	14.7	73	HP	RC	99.4					SS
ALABAMA PWR	BARRY	03	BUCKS	AB	06	59	225	CB	O	11815	7.7	.9	3.2	14.4	73	HP	WA	99.0					
ALABAMA PWR	BARRY	02	BUCKS	AB	06	56	125	CB	O	11815	7.7	.9	3.2	14.4	73	HP	WA	99.0					
ALABAMA PWR	BARRY	01	BUCKS	AB	02	54	125	CB	O	11815	7.7	.9	3.2	14.4	73	HP	WA	99.0					
ALABAMA PWR	GASTON E.C.	05	WILSONVILLE	AB		74	880	C		11509	7.5	.7	2.6	14.7	71	PE	WP	98.0					SS
ALABAMA PWR	GORGAS	09	GORGAS	AB	05	58	165	CB	O	11751	7.1	.6	3.7	16.0		PE	WP	99.5					SS

	ALL UNITS UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	15	5,332	15	5,332						

DATE RUN 12/24/75

ELECTRIC UTILITY DATA

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = AZ

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
SALT RIVER PROJ	NAVAJO	01	PAGE	AZ		74	770	CS		11070		.4	1.3			PE	WP	99.5			PI		BE
SALT RIVER PROJ	NAVAJO	02	PAGE	AZ		75	770	CS		11070		.4	1.3			PE	WP	99.5			PI		BE

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	2	1,540	2	1,540						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = CL

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
COLORADO UTE ELEC.	HAYDEN	01	HAYDEN	CL		65	185	CS		10770	11.1	.4	.4	10.2	73	HP	BU	99.6					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	1	185	1	185						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = CN

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
UNITED ILLUM.CO.	BRIDGEPORT HBR	01	BRIDGEPORT	CN		51	75	CS	O			1.5	1.5			PE	RC	97.5					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	1	75	1	75						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = DC

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	TYPE	MFR	PCT EFY	R Y	SO2 YR	TYPE	MFR	CON SLT
POTOMAC ELEC PWR	BENNING	14	WASHINGTON	DC		52	28	CB	12985	5.1	.6	1.0	10.1		ME	AT	97.9					
POTOMAC ELEC PWR	BENNING	13	WASHINGTON	DC		47	55	CB	12985	5.1	.6	1.0	10.1		PE	RC	96.0					

	ALL UNITS	MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	2	83	2	83						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = DE

UTILITY CO. NAME	PLANT NAME	UN IT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE R Y	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
DELMARVA PWR & LT	DELAWARE CITY	03	DELAWARE CITY	DE		61	66	C	G	14019	7	7.2	7.2	3		ME	RC	97.5					
DELMARVA PWR & LT	INDIAN RIVER	01	MILLSBORO	DE		56	75	C	O	12231	5.8	.1	3.2	12.6	75	ME	RC	99.5					GA
DELMARVA PWR & LT	INDIAN RIVER	02	MILLSBORO	DE		56	75	C	O	12231	5.8	.1	3.2	12.6	75	ME	RC	99.5					
DELMARVA PWR & LT	INDIAN RIVER	03	MILLSBORO	DE		70	167	C	O	12231	5.8	.1	3.2	12.6	70	PE	UP	98.0					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	4	383	4	383						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = FL

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
TAMPA EL.CO.	FRANCIS J. GANN	04	TAMPA	FL		63	180	C	11325	9.7	1.4	3.2	12.3		PE	AS	98.0					
GULF POWER CO	CRIST	06	PENSACOLA	FL		70	323	CB	12179	8.1	2.0	4.6	12.1	70	PE	BU	98.0					SS
GULF POWER CO	CRIST	07	PENSACOLA	FL		73	505	CB	12179	12.1	2.0	4.6	8.1	73	PE	BU	98.0					SS
GULF POWER CO	LANSING SMITH	01	PANAMA CTY	FL		65	125	C	11522		2.1	3.5	8.3	74	HP	BU	99.1					
GULF POWER CO	LANSING SMITH	02	PANAMA CTY	FL		67	180	C	11522		2.1	3.5	8.3	74	HP	BU	99.1					
GULF POWER CO	CRIST	05	PENSACOLA	FL		61	75	CB	12179	8.1	2.0	4.6	12.1	74	HP	BU	99.1					SS
GULF POWER CO	CRIST	04	PENSACOLA	FL		59	75	CB	12179	8.1	2.0	4.6	12.1	74	HP	BU	99.1					SS
GULF POWER CO	SCHOLZ	02	CHATTAHOOCHEE	FL		53	40	CB	12298	5.6	.1	3.8	7.8	73	PE	BU	99.5					
GULF POWER CO	SCHOLZ	01	CHATTAHOOCHEE	FL		53	40	CB	12298	5.6	.1	3.8	7.8	73	PE	BU	99.5					
TAMPA EL.CO.	FRANCIS J. GANN	05	TAMPA	FL		65	240	C	11325	9.7	1.4	3.2	12.3	72	PE	RC	99.0					SW
TAMPA EL.CO.	FRANCIS J. GANN	06	TAMPA	FL		67	325	C	11325	9.7	1.4	3.2	12.3	72	PE	RC	99.8					
TAMPA EL.CO.	BIG BEND	01		FL		70	350	CB	11366	9.8	3.0	9.6	12.1	72	PE	WP	98.5					
TAMPA EL.CO.	BIG BEND	02		FL	1	73	300	CB	11366	9.8	3.0	9.6	12.1	73	PE	WP	98.5					SW

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	13	2,758	13	2,758						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = GA

UTILITY CO. NAME	PLANT NAME	UN IT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
GEORGIA PWR.CO.	MC DONOUGH JACK	01	SMYRNA	GA	07	63	245	C		11983		.6	1.3	14.2		PE	BU	98.0					
GEORGIA PWR.CO.	MC DONOUGH JACK	02	SMYRNA	GA	05	64	245	C		11983		.6	1.3	14.2		PE	BU	98.0					
GEORGIA PWR.CO.	HAMMOND	04	COOSA	GA		70	505	C		12236		.3	3.4	12.6	67	PE	BU	98.0					SS
GEORGIA PWR.CO.	HARLLEE BRANCH	04	MILLEDGEVILLE	GA	06	69	490	C	O	11748		.7	2.2	20.0		PE	BU	98.3					
GEORGIA PWR.CO.	YATES	05	NEWMAN	GA	05	58	125	C		12390		1.0	2.9	16.8		PE	BU	98.3					
GEORGIA PWR.CO.	YATES	04	NEWMAN	GA	06	57	125	C		12390		1.0	2.9	16.8		PE	BU	98.3					
GEORGIA PWR.CO.	YATES	03	NEWMAN	GA	08	52	100	C		12390		1.0	2.9	16.8		PE	BU	98.3					
GEORGIA PWR.CO.	YATES	02	NEWMAN	GA	11	50	100	C		12390		1.0	2.9	16.8		PE	BU	98.3					
GEORGIA PWR.CO.	HAMMOND	01	COOSA	GA	06	54	100	C		12236		.3	3.4	12.6		PE	BU	98.7					
GEORGIA PWR.CO.	YATES	06	NEWMAN	GA		74	350	C		12390		1.0	2.9	16.6	71	PE	BU	99.0					UE
GEORGIA PWR.CO.	YATES	07	NEWMAN	GA		74	350	C		12390		1.0	2.9	16.8	71	PE	BU	99.0					UE
GEORGIA PWR.CO.	MITCHELL	03	ALBANY	GA	04	46	125	C	O	11337		.7	3.0	12.0	73	PE	BU	99.0					
GEORGIA PWR.CO.	YATES	01	NEWMAN	GA	09	50	100	C		12390		1.0	2.9	16.8	71	PE	BU	99.1					
GEORGIA PWR.CO.	MITCHELL	02	ALBANY	GA	03	49	23	C	O	11337		.7	3.0	12.0		PE	RC	96.0					
GEORGIA PWR.CO.	MITCHELL	01	ALBANY	GA	11	48	23	C	O	11337		.7	3.0	12.0		PE	RC	96.0					
GEORGIA PWR.CO.	BOWEN	04	TAYLORSVILLE	GA		75	876	C				2.5	2.5		72	PE	RC	98.0					SS
GEORGIA PWR.CO.	ARKWRIGHT	03	MACON	GA	09	43	40	C		11285		.7	4.0	12.0		PE	RC	98.0					
GEORGIA PWR.CO.	BOWEN	02	TAYLORSVILLE	GA		72	712	C		11595		.9	3.1	12.7	68	PE	RC	98.0					SS
GEORGIA PWR.CO.	BOWEN	01	TAYLORSVILLE	GA		71	712	C		11595		.9	3.1	12.7	68	PE	RC	98.0					SS
GEORGIA PWR.CO.	HARLLEE BRANCH	03	MILLEDGEVILLE	GA	06	68	481	C	O	11748		.7	2.2	20.0		PE	RC	98.5					
GEORGIA PWR.CO.	BOWEN	03	TAYLORSVILLE	GA		74	876	C				2.5	2.5		72	PE	RC	99.0					OW
GEORGIA PWR.CO.	HAMMOND	03	COOSA	GA	06	55	100	C		12236		.3	3.4	12.6		PE	WP	96.0					
GEORGIA PWR.CO.	HAMMOND	02	COOSA	GA	09	54	100	C		12236		.3	3.4	12.6		PE	WP	98.0					
GEORGIA PWR.CO.	ARKWRIGHT	01	MACON	GA	06	41	40	C	G	11285		.7	4.0	12.0	73	PE	WP	99.0					
GEORGIA PWR.CO.	ARKWRIGHT	02	MACON	GA	05	42	40	C	G	11285		.7	4.0	12.0	73	PE	WP	99.0					
GEORGIA PWR.CO.	ARKWRIGHT	04	MACON	GA	11	48	40	C		11285		.7	4.0	12.0	73	PE	WP	99.0					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	26	7,023	26	7,023						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = IL

UTILITY CO. NAME	PLANT NAME	UN IT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
CENTRAL ILL.LT.	WALLACE R.S.	07	E. PEORIA	IL		58	100	C		10623	17.3	2.6	2.8	9.5		PE		95.0					
COMMONWEALTH EDISON	WAUKEGAN	05		IL		31	130	CS	G	11042	16.1	.3	3.6	12.6		01		95.0					
COMMONWEALTH EDISON	WILL COUNTY	01	JOLIET	IL		55	188	CS		10114		.3	4.0	15.8		SC		99.0			FS	BW	
ELECTRIC ENERGY	JOPPA	03	MASSAC CTY	IL			174	C		3115	10.8	2.2	2.2	25.1		PE		98.9					
ELECTRIC ENERGY	JOPPA	04	MASSAC CTY	IL			174	C		3115	10.8	2.2	2.2	25.1		PE		98.9					
ELECTRIC ENERGY	JOPPA	01	MASSAC CTY	IL			174	C		3115	10.8	2.2	2.2	25.1		PE		98.9					
ELECTRIC ENERGY	JOPPA	02	MASSAC CTY	IL			174	C		3115	10.8	2.2	2.2	25.1		PE		98.9					
SPRINGFIELD WT.LT&PW	DALLMAN	01	SPRINGFIELD	IL		68	80	C		10375		2.6	4.4			PE		97.5					BM
SPRINGFIELD WT.LT&PW	LAKESIDE	04	SPRINGFIELD	IL		50	20	C		10375		2.6	4.3			PE		97.5					
SO ILLINOIS PWR COOP	MARION	01	MARION	IL	6	63	33	C			14.0	1.0	1.0	45.1	73	PE	AS	96.0					
SO ILLINOIS PWR COOP	MARION	03	MARION	IL	9	63	33	C			14.0	1.0	1.0	45.1	73	PE	AS	96.0					
SO ILLINOIS PWR COOP	MARION	02	MARION	IL	8	63	33	C			14.0	1.0	1.0	45.1	73	PE	AS	96.0					
CENTRAL ILL. P S	COFFEEN	02	COFFEEN	IL	3	72	600	CB		10000	15.0	3.6	4.5	15.0	72	PE	BU	99.0					SL
ILLINOIS PWR.	WOOD RIVER	05	EAST ALTON	IL		64	369	C	G	10964	11.9	.4	3.0	10.6	70	PE	BU	99.0					
ILLINOIS PWR.	VERMILION	01	OAKWOOD	IL		52	77	C		10831	13.8	1.1	3.1	10.9	72	PE	BU	99.5					
ILLINOIS PWR.	HENNEPIN	02	HENNEPIN	IL		59	235	C	G	11017	11.0	2.8	4.3	12.9	72	PE	BU	99.5					
ILLINOIS PWR.	HENNEPIN	01	HENNEPIN	IL		50	76	C	G	11017	11.0	2.8	4.3	12.9	72	PE	BU	99.5					SL
CENTRAL ILL. P S	MEREDOSIA	03	MEREDOSIA	IL		60	237	C		10880	15.8	2.8	3.6	9.7	70	PE	KC	97.0					
COMMONWEALTH EDISON	JOLIET	06	JOLIET	IL		59	360	C		1029						PE	KC	97.0					
COMMONWEALTH EDISON	WAUKEGAN	08		IL		62	355	CS	G	11042	16.1	.3	3.6	12.6		PE	KC	98.0					
CENTRAL ILL. P S	GRAND TOWER	04	GRAND TOWER	IL		58	194	C		10833	10.8	2.3	3.4	16.2	71	PE	RC	97.1					
COMMONWEALTH EDISON	KINCAID	02	KINCAID	IL		68	660	C		9706	15.5	4.2	4.2	15.3		PE	RC	98.0					
COMMONWEALTH EDISON	CRAWFORD	08	CHICAGO	IL		61	358	CS	G	9124	24.0	.3	4.0	8.4		PE	RC	98.0					
COMMONWEALTH EDISON	JOLIET	07	JOLIET	IL		65	660	CS	G	10570	13.3	.6	4.0	14.0		PE	RC	98.0					
COMMONWEALTH EDISON	FISK	19	CHICAGO	IL		59	374	CS	G	9124	23.9	.3	.6	8.4		PE	RC	98.0					
COMMONWEALTH EDISON	JOLIET	08	JOLIET	IL		66	660	CS	G	10570	13.3	.6	4.0	14.0		PE	RC	98.0					
COMMONWEALTH EDISON	WILL COUNTY	04	JOLIET	IL		63	598	CS		10114		.3	4.0	15.8		PE	RC	98.0					
COMMONWEALTH EDISON	CRAWFORD	07	CHICAGO	IL		58	239	CS	G	9124	24.0	.3	4.0	8.4		PE	RC	98.0					
COMMONWEALTH EDISON	JOLIET	05	JOLIET	IL		50	107	C		1029					71	PE	RC	98.0					
COMMONWEALTH EDISON	WAUKEGAN	06		IL		52	121	CS	G	11042	16.1	.3	3.6	12.6	71	PE	RC	98.0					
COMMONWEALTH EDISON	WILL COUNTY	03	JOLIET	IL		57	299	CS		10114		.3	4.0	15.8	73	HP	RC	98.5					
COMMONWEALTH EDISON	KINCAID	01	KINCAID	IL		67	660	C8		9646	15.5	3.9	3.9	15.8		PE	RC	99.0					
COMMONWEALTH EDISON	WILL COUNTY	02	JOLIET	IL		55	184	CS		10114		.3	4.0	15.8	72	PE	RC	99.0					
COMMONWEALTH EDISON	+ 2 DEFERRED IN	05	PEKIN	IL	4	72	840	CS		10583	14.9	.3	3.6	7.9	71	PE	RC	99.5					SL

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
ILLINOIS PWR.	BALDWIN	03	BALDWIN	IL	6	75	632	C		10574	11.3	2.8	3.3	14.3	72	PE	RC	99.5					SL
ILLINOIS PWR.	WOOD RIVER	04	EAST ALTON	IL		60	103	C	G	10964	11.9	.4	3.0	10.6		PE	RC	99.6			DE	MS	
COMMONWEALTH EDISON	WAUKEGAN	07		IL		58	326	CS	G	11042	16.1	.3	3.6	12.6	74	HP	WA	99.1					SL
CENTRAL ILL. P S	GRAND TOWER	03	GRAND TOWER	IL		50	73	C		10833	10.8	2.3	3.4	16.2	69	PE	WP	97.1					
CENTRAL ILL. P S	MEREDOSIA	02	MEREDOSIA	IL		47	65	C		10880	15.8	2.8	3.6	9.7	71	PE	WP	98.0					
CENTRAL ILL. P S	MEREDOSIA	01	MEREDOSIA	IL		46	65	C		10880	15.8	2.8	3.6	9.7	71	PE	WP	98.0					
CENTRAL ILL. P S	HUTSONVILLE	04	HUTSONVILLE	IL		54	78	C		11214	13.2	1.6	4.0	11.3	71	PE	WP	99.0					
CENTRAL ILL. P S	HUTSONVILLE	03	HUTSONVILLE	IL		54	78	C		11214	13.2	1.6	4.0	11.3	71	PE	WP	99.0					
CENTRAL ILL.LT.	EDWARDS, E.D.	02	BARTONVILLE	IL		68	250	C		10600	17.7	2.6	2.8	8.1		PE	WP	99.0					
CENTRAL ILL. P S	COFFEEN	01	COFFEEN	IL		65	365	CB		9297	15.2	3.6	4.5	20.5	72	PE	WP	99.0					
CENTRAL ILL.LT.	EDWARDS, E.D.	03	BARTONVILLE	IL	4	72	350	C		10600	17.7	1.4	3.2	8.1		PE	WP	99.0		79	FS		CA
ILLINOIS PWR.	BALDWIN	02	BALDWIN	IL	3	73	604	C		10574		2.8	3.3	11.4	73	PE	WP	99.0					SL
ILLINOIS PWR.	BALDWIN	01	BALDWIN	IL		70	626	C		10574	11.4	2.8	3.3	9.8	70	PE	WP	99.0					SL
ILLINOIS PWR.	VERMILION	02	OAKWOOD	IL		56	109	C		10831	13.8	1.1	3.1	10.9	72	PE	WP	99.5					SL

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	48	13,320	48	13,320						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = IN

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
INDIANAPOLIS PWR.&LT	PERRY W	07	INDIANAPOLIS	IN		32	11	C		11124	13.1	3.2	3.2	11.6		PE		99.0					
NORTHERN INDIANA PS	BAILLY	08	DUNE ACRES	IN		68	422	C	G	11215	12.0	3.0	4.0	10.0		PE		98.0					
NORTHERN INDIANA PS	BAILLY	07	DUNE ACRES	IN		64	194	C	G	11215	12.0	3.0	4.0	10.0		PE		98.0					
NORTHERN INDIANA PS	MITCHELL D.H.	05	GARY	IN		61	138	C	G	11103	11.7	2.7	3.6	10.4	69	PE	AS	98.0					
NORTHERN INDIANA PS	MITCHELL D.H.	04	GARY	IN		58	138	C	G	11103	11.7	2.7	3.6	10.4	69	PE	AS	98.0					
NORTHERN INDIANA PS	MITCHELL D.H.	06	GARY	IN		64	138	C	G	11103	11.7	2.7	3.6	10.4	69	PE	AS	98.0					
INDIANAPOLIS PWR.&LT	STOUT ELMER W.	06	INDIANAPOLIS	IN		61	100	C		11467	12.4	1.3	5.3	9.4	71	ME	BU	99.0					
INDIANAPOLIS PWR.&LT	PRITCHARD H.T.	06	MARTINSVILLE	IN		54	100	C		11047	14.2	.9	3.5	11.2	71	PE	BU	99.0					
INDIANAPOLIS PWR.&LT	STOUT ELMER W.	07	INDIANAPOLIS	IN	3	73	450	C		11467	12.4	1.3	5.3	9.4	73	PE	BU	99.5					SW
P.S. OF INDIANA	EDWARDSPORT	02	EDWARDSPORT	IN		46	45	C		10947	13.5	1.0	2.9	10.3	72	PE	BU	98.0					
P.S. OF INDIANA	EDWARDSPORT	03	EDWARDSPORT	IN		50	75	C		10947	13.5	1.0	2.9	10.3	72	PE	BU	98.0					
NORTHERN INDIANA PS	MICHIGAN CTY	12	MICHIGAN CTY	IN	2	74	520	C	G	10891	13.7	1.0	4.0	10.0	72	PE	KC	99.5					SL
S. INDIANA G&E	CULLEY, F.B.	03	NEWBURGH	IN		73	265	C		10476	3.2	3.0	4.5	15.8	71	PE	LC	98.0					BR
INDIANA-MICH.EL.	BREED	01	SULLIVAN	IN		60	450	CS		10901		.3	6.0	28.0			PE	98.3					SR
COMMONWEALTH EDISON	DIXON	05		IN		53	69	C	G	9646	14.2	1.3	4.0	15.8		PE	RC	96.3					
COMMONWEALTH EDISON	STATE LINE	04	HAMMOND	IN		62	389	CS	G	9855	18.0	.3	3.7	13.0		PE	RC	98.0					
INDIANAPOLIS PWR.&LT	STOUT ELMER W.	05	INDIANAPOLIS	IN		58	100	C		11467	12.4	1.3	5.3	9.4	69	MC	RC	99.0					
INDIANA-MICH.EL.	TANNERS CREEK	04	LAWRENCEBURG	IN		64	580	CB		10688		.8	4.4		75	PE	RC	99.1					
INDIANA-MICH.EL.	TANNERS CREEK	03	LAWRENCEBURG	IN		54	213	CB		10688		.8	4.4		74	ME	RC	99.7					
INDIANA-MICH.EL.	TANNERS CREEK	02	LAWRENCEBURG	IN		52	153	CB		10688		.8	4.4		74	PE	RC	99.7					
INDIANA-MICH.EL.	TANNERS CREEK	01	LAWRENCEBURG	IN		51	153	CB		10589		.8	4.4		74	PE	RC	99.7					
P.S. OF INDIANA	WABASH RVR.	06	W. TERRE HAUTE	IN		66	360	C		11004	12.9	2.5	2.9	10.4	68	PE	RC	98.0					
P.S. OF INDIANA	WABASH RVR.	04	W. TERRE HAUTE	IN		54	100	C		11004	12.9	2.5	2.9	10.4	69	PE	RC	98.5					
P.S. OF INDIANA	WABASH RVR.	01	W. TERRE HAUTE	IN		48	99	C		11034	12.9	2.5	2.9	10.4	71	PE	RC	98.5					
P.S. OF INDIANA	WABASH RVR.	03	W. TERRE HAUTE	IN		53	99	C		11004	12.9	2.5	2.9	10.4	71	PE	RC	98.5					
P.S. OF INDIANA	WABASH RVR.	05	W. TERRE HAUTE	IN		56	122	C		11004	12.9	2.5	2.9	10.4	69	PE	RC	98.5					
P.S. OF INDIANA	WABASH RVR.	02	W. TERRE HAUTE	IN		51	100	C		11004	12.9	2.5	2.9	10.4	70	PE	RC	98.5					
INDIANAPOLIS PWR.&LT	PETERSBURG	01	PETERSBURG	IN		67	220	C		10915	13.4	1.0	6.0	12.0	72	PE	UP	99.5					

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE R Y	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
INDIANA-KENTUCKY EL	CLIFTY CREEK ST	06	MADISON	IN		55	266	C	B	10886		.3	6.0	12.0	75	PE	WP	99.4					SP
INDIANAPOLIS PWR.&LT	PETERSBURG	02	PETERSBURG	IN		69	420	C		10915	13.4	1.0	6.0	12.0	69	PE	WP	99.0					GH
P.S. OF INDIANA	NOBLESVILLE	02	NOBLESVILLE	IN		44	53	C		11498	11.4	2.9	2.9	8.9	72	PE	WP	98.0					
P.S. OF INDIANA	NOBLESVILLE	01	NOBLESVILLE	IN		40	53	C		11498	11.4	2.9	2.9	8.9	72	PE	WP	98.0					
P.S. OF INDIANA	GALLAGHER R.A.	02	NEW ALBANY	IN		58	159	C		11267	11.6	3.1	4.1	10.3	68	PE	WP	99.0					
P.S. OF INDIANA	GIBSON	02	PLAINFIELD	IN	3	75	650	C				1.5	1.5		75	PE	WP	99.0					SL
P.S. OF INDIANA	GALLAGHER R.A.	01	NEW ALBANY	IN		58	159	C		11267	11.6	3.1	4.1	10.3	68	PE	WP	99.0					
P.S. OF INDIANA	GALLAGHER R.A.	04	NEW ALBANY	IN		61	159	C		11267	11.6	3.1	4.1	10.3	68	PE	WP	99.0					
P.S. OF INDIANA	CAYUGA	01	CAYUGA	IN		70	500	C		10335	14.3	2.3	2.3	13.0	70	PE	WP	99.0					SL
P.S. OF INDIANA	GALLAGHER R.A.	03	NEW ALBANY	IN		60	159	C		11267	11.6	3.1	4.1	10.3	68	PE	WP	99.0					
P.S. OF INDIANA	CAYUGA	02	CAYUGA	IN		72	500	C		10335	14.3	2.3	2.3	13.0	71	PE	WP	99.0					SL
S. INDIANA G&E	CULLEY, F.B.	02	NEWBURGH	IN		67	96	C		10476	3.2	3.0	4.5	15.8	71	MC	WP	99.3					
S. INDIANA G&E	CULLEY, F.B.	01	NEWBURGH	IN		60	40	C		10476	3.2	3.0	4.5	15.8	72	MC	WP	99.3					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	41	9,017	41	9,017						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = IO

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
IOWA-ILLINOIS G&E	RIVERSIDE	04	BETTENDORF	IO		56	43	C	G	10465	16.6	1.7	2.7	9.7	72	PE	BU	99.1					
INTERSTATE PWR.	LANSING	02	LANSING	IO		46	11	CB		11302	11.3	1.0	3.5	10.5	73	PE	RC	99.0					SL
INTERSTATE PWR.	KAPP M.L.	01	CLINTON	IO			15	CB	G	11030	14.5	2.6	3.4	10.9	73	PE	RC	99.0					
INTERSTATE PWR.	LANSING	01	LANSING	IO		39	15	CB		11302	11.3	1.0	3.5	10.5	73	PE	RC	99.0					SL
IOWA P.S. CO.	GEORGE NEAL	01	SIOUX CITY	IO		64	147	CB	G	12700		2.9	2.9	11.5	72	PE	RC	99.0					
IOWA P.S. CO.	GEORGE NEAL	02	SIOUX CITY	IO		72	540	C	G	10071		.4	1.2	13.2		HP	RC	99.6					EB
IOWA ELEC. LT.&PWR.	PRAIRIE CREEK 3	03	CEDAR RAPIDS	IO		61	50	C		10306	16.9	1.9	2.4	10.3	70	PE	UP	99.0					
IOWA ELEC. LT.&PWR.	PRAIRIE CREEK 4	04	CEDAR RAPIDS	IO		67	140	C		10367	16.9	.6	2.7		75	PE	UP	99.0					
IOWA ELEC. LT.&PWR.	SIXTH STREET	04	CEDAR RAPIDS	IO		51	20	CB		10257	16.9	1.9	1.9	37.1	73	PE	UP	99.0					
IOWA ELEC. LT.&PWR.	SIXTH STREET	02	CEDAR RAPIDS	IO		49	4	CB		10257	16.9	1.9	1.9	37.1	73	PE	UP	99.0					
IOWA ELEC. LT.&PWR.	SIXTH STREET	01	CEDAR RAPIDS	IO		49	10	CB	G	10257	16.9	1.9	3.7	10.3	73	PE	UP	99.0					
IOWA PWR.&LT.	COUNCIL BLUFFS	02	COUNCIL BLUFFS	IO		58	82	CS	G	10638	13.2	.9	1.5	8.8	72	HP	UP	99.3					BV
IOWA SOUTHERN UTIL	BURLINGTON	01	BURLINGTON	IO		68	212	CB	O	10219	18.9	2.5	3.0	9.1	67	PE	UP	98.0					
INTERSTATE PWR.	DUBUQUE	03	DUBUQUE	IO		50	25	CB	G	11326	11.3	2.9	3.1	10.9	73	PE	WP	99.0					
INTERSTATE PWR.	LANSING	03	LANSING	IO		61	33	CB		11302	11.3	3.0	3.0	10.5	73	PE	WP	99.0					
IOWA P.S. CO.	MAYNARD	07	WATERLOO	IO		50	54	CB	G	10728		2.9	3.5		72	HP	WP	99.0					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	16	1,401	16	1,401						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = KY

UTILITY CO. NAME	PLANT NAME	UN IT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
LOUISVILLE G&E	CANE RUN	04	LOUISVILLE	KY		62	138	CB	G	11267		3.3	3.8	13.7		PE		98.5				AM	
OWENSBORO	SMITH E.	02	OWENSBORO	KY		74	265	C		10663	12.7	3.2	3.2	12.0		PE		99.5					BV
E. KENTUCKY RR EL.	DALE W.C.	04	FORD	KY	8	60	72	C		11956	7.6	.8	1.5	16.4	72	PE	AS	96.0					
E. KENTUCKY RR EL.	DALE W.C.	03	FORD	KY	8	57	72	C		11956	7.6	.8	1.5	16.4	72	PE	AS	96.0					
E. KENTUCKY RR EL.	COOPER J.S.	01	BURNSIDE	KY	2	65	114	C		11332	5.7	1.5	3.3		71	PE	AS	98.0					
E. KENTUCKY RR EL.	COOPER J.S.	02	BURNSIDE	KY		69	221	C		11332	5.7	1.5	3.3		71	PE	AS	98.0					
KENTUCKY UTIL.	PINEVILLE	03	FOUR MILE	KY		38	32	CB		12336	5.6	.9	6.8	15.6	73	PE	BU	98.5					
KENTUCKY UTIL.	BROWN E.W.	01	BURGIN	KY		57	105	CB		11879	5.9	.8	3.1	13.1	71	ME	BU	98.5					SL
KENTUCKY UTIL.	GREEN RIVER	03	CENTRAL CITY	KY		52	72	CB		11276	11.5	.6	3.5	10.9	73	PE	BU	98.5				AM	
KENTUCKY UTIL.	GREEN RIVER	04	CENTRAL CITY	KY		59	105	CB		11276	11.5	.6	3.5	10.9	73	PE	BU	99.0					
KENTUCKY UTIL.	BROWN E.W.	02	BURGIN	KY		63	165	CB		11879	5.9	.8	3.1	13.1	73	PE	BU	99.0					
KENTUCKY PWR.	BIG SANDY	01	LAURENCE	KY		63	265	CB		11139		.7	3.2		69	PE	KC	98.5					
BIG RIVERS CO-OP	COLEMAN	02	HANESVILLE	KY		70	185	C		11117		2.8	3.6	12.2	70	PE	RC	99.0					RP
BIG RIVERS CO-OP	COLEMAN	01	HANESVILLE	KY		69	185	C		11117		2.8	3.6	12.2	69	PE	RC	99.0					
KENTUCKY PWR.	BIG SANDY	02	LAURENCE	KY		69	800	CB		11139		.7	3.2		69	PE	RC	98.5					
KENTUCKY UTIL.	BROWN E.W.	03	BURGIN	KY		71	427	CB		11879	5.9	.8	3.1	13.1	74	PE	RC	99.0					SL
LOUISVILLE G&E	CANE RUN	03	LOUISVILLE	KY		58	137	CB	G	11267		3.3	3.8	13.7		PE	RC	97.5					
LOUISVILLE G&E	CANE RUN	05	LOUISVILLE	KY		66	183	CB	G	11267		3.3	3.8	13.7		PE	RC	98.5		75	FS	CE	
TVA	SHAWNEE	06	PADUCAH	KY	11	54	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
TVA	SHAWNEE	07	PADUCAH	KY	12	54	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
TVA	SHAWNEE	05	PADUCAH	KY	10	54	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
TVA	SHAWNEE	10	PADUCAH	KY	10	56	175	CB		10850		2.1	4.4		69	ME	RC	98.0			FS	BE	
TVA	SHAWNEE	04	PADUCAH	KY	01	54	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
TVA	SHAWNEE	03	PADUCAH	KY	10	53	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
TVA	SHAWNEE	02	PADUCAH	KY	06	53	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
TVA	SHAWNEE	08	PADUCAH	KY	03	55	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
TVA	SHAWNEE	01	PADUCAH	KY	04	53	175	CB		10850		2.1	4.4		69	ME	RC	98.0					BW
TVA	SHAWNEE	09	PADUCAH	KY	07	55	175	CB		10850		2.1	4.4		69	ME	RC	98.0					
KENTUCKY UTIL.	GHENT	01	GHENT	KY		74	500	CB		10800		2.7	3.8	12.2		PE	WP	98.0					SL
LOUISVILLE G&E	MILL CREEK	01	KOSMOSDALE	KY	5	72	330	CB	G	11400		3.2	3.7	14.2	69	PE	WP	99.4					PI
LOUISVILLE G&E	MILL CREEK	02	KOSMOSDALE	KY	5	74	330	CB	G			3.2	3.2	14.2	70	PE	WP	99.4				--	PI

	ALL UNITS		COAL		OIL		GAS		NUCLEAR	
	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW
SUBTOTAL	31	6,453	31	6,453						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE

STATE = MC

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
CONSUMERS PWR	WEADOCK J.C.	08	BAY CITY	MC		58	156	C		12096	7.5	.4	3.7	14.7		PE		99.0					CA
CONSUMERS PWR	WEADOCK J.C.	07	BAY CITY	MC		55	156	C		12096	7.5	.4	3.7	14.7		PE		99.0					CA
LANSING BD WT & LT.	ERICKSON	01	LANSING	MC		73	150	CB		12255		2.0	3.9	11.5				95.0					SE
LANSING BD WT & LT.	OTTAWA	05	LANSING	MC		49	3	C		12132	6.0	2.5	2.5	12.6		PE		97.5					
LANSING BD WT & LT.	OTTAWA	03	LANSING	MC		48	25	C		12132	6.0	2.5	2.5	12.6		PE		97.5					
LANSING BD WT & LT.	OTTAWA	02	LANSING	MC		41	25	C		12132	6.0	2.5	2.5	12.6		PE		97.5					
LANSING BD WT & LT.	OTTAWA	01	LANSING	MC		38	25	C		12132	6.0	2.5	2.5	12.6		PE		97.5					
LANSING BD WT & LT.	OTTAWA	04	LANSING	MC		49	4	C		12132	6.0	2.5	2.5	12.6		PE		97.5					
CONSUMERS PWR	KARN D.E.	01	ESSEXVILLE	MC		59	265	C		12096	8.7	.6	3.7	14.7		PE	AS	95.0					CA
CONSUMERS PWR	KARN D.E.	02	ESSEXVILLE	MC		61	265	C		12096	8.7	.6	3.7	14.7		PE	AS	95.0					CA
CONSUMERS PWR	WHITING J.R.	01	ERIE	MC		52	100	C		11682	7.1	.7	4.4	14.3	72	PE	AS	99.0					CA
CONSUMERS PWR	WHITING J.R.	03	ERIE	MC		54	125	C		11682	7.1	.7	4.4	14.3	72	PE	AS	99.0					CA
CONSUMERS PWR	WHITING J.R.	02	ERIE	MC		52	100	C		11682	7.1	.7	4.4	14.3	72	PE	AS	99.0					CA
CONSUMERS PWR	CAMPBELL J.H.	01	WEST OLIVE	MC		62	265	C		11203	8.2	.8	3.3	17.9	74	PE	BU	97.0					
CONSUMERS PWR	CAMPBELL J.H.	02	WEST OLIVE	MC		67	385	C		11203	8.2	.8	3.3	14.5	67	PE	BU	98.0					
UPPER PENINSULA PWR.	PRESQUE ISLE	05	MARQUETTE	MC	6	74	79	CS		12540	5.3	1.5	2.8	11.2	73	PE	BU	99.0					SW
DETROIT EDISON	RIVER ROUGE	03	RIVER ROUGE	MC		58	322	C	O	12397	5.8	.5	3.8	14.7	58	PE	RC	97.8			PI	BE	
DETROIT EDISON	MARYVILLE	07	MARYVILLE	MC			75	C	G	12030	5.8	1.6	4.6	14.0	69	PE	RC	99.4					
DETROIT EDISON	MARYVILLE	08	MARYVILLE	MC			75	C	G	12030	5.8	1.6	4.6	14.0	69	PE	RC	99.4					
DETROIT EDISON	MONROE	02	MONROE	MC	3	73	790	C	O	12948	3.1	2.7	3.7	12.0	73	PE	RC	99.6					OW
DETROIT EDISON	MONROE	01	MONROE	MC	4	71	790	C	O	12948	3.1	2.7	3.7	12.0	73	PE	RC	99.6					OW
DETROIT EDISON	MONROE	03	MONROE	MC	3	73	790	C	O	12948	3.1	2.7	3.7	12.0		PE	RC	99.6					OW
DETROIT EDISON	MONROE	04	MONROE	MC	3	74	800	C	O	12948	3.1	2.7	3.7	12.0	72	PE	RC	99.6					OW
LANSING BD WT & LT.	ECKERT, O.E.	05	LANSING	MC		65	80	CB		12382	5.5	2.3	3.1	11.5	73	PE	RC	97.4					
LANSING BD WT & LT.	ECKERT, O.E.	06	LANSING	MC		68	75	CB		12382	5.5	2.3	3.1	11.5	73	PE	RC	97.4					
LANSING BD WT & LT.	ECKERT, O.E.	04	LANSING	MC		62	80	CB		12382	5.5	2.3	3.1	11.5	73	PE	RC	97.4					
LANSING BD WT & LT.	ECKERT, O.E.	02	LANSING	MC		56	44	CB		12382	5.5	.8	3.1	11.5	75	PE	RC	98.4					OW
LANSING BD WT & LT.	ECKERT, O.E.	03	LANSING	MC		59	47	CB		12382	5.5	.8	3.1	11.5	75	PE	RC	98.4					OW
LANSING BD WT & LT.	ECKERT, O.E.	01	LANSING	MC		50	44	CB		12382	5.5	.8	3.1	11.5	75	PE	RC	98.4					OW
DETROIT EDISON	ST. CLAIR	01	BELLE RIVE	MC		54	156	C	O	12066	7.2	1.6	4.6	14.0	74	ME	WH	99.6					
DETROIT EDISON	ST. CLAIR	04	BELLE RIVE	MC		54	156	C	O	12066	7.2	1.6	4.6	14.0	74	ME	WH	99.6					
DETROIT EDISON	ST. CLAIR	03	BELLE RIVE	MC		54	156	C	O	12066	7.2	1.6	4.6	14.0	74	ME	WH	99.6					
DETROIT EDISON	ST. CLAIR	02	BELLE RIVE	MC		54	156	C	O	12066	7.2	1.6	4.6	14.0	74	ME	WH	99.6					

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
CONSUMERS PWR	COBB B.C.	05	MUSKEGON	MC		57	156	C		11592	10.9	1.5	4.6	9.2		PE	WP	99.0					CA
CONSUMERS PWR	COBB B.C.	04	MUSKEGON	MC		56	156	C		11592	10.9	1.5	4.6	9.2		PE	WP	99.0					CA
CONSUMERS PWR	COBB B.C.	03	MUSKEGON	MC		50	66	C		11592	10.9	1.5	4.6	9.2	69	PE	WP	99.0					CA
CONSUMERS PWR	COBB B.C.	01	MUSKEGON	MC		48	66	C		11592	10.9	1.5	4.6	9.2		PE	WP	99.0					CA
CONSUMERS PWR	COBB B.C.	02	MUSKEGON	MC		48	66	C		11592	10.9	1.5	4.6	9.2		PE	WP	99.0					CA

	ALL UNITS		COAL		OIL		GAS		NUCLEAR	
		MW	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW
SUBTOTAL	38	7,274	38	7,274						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = MD

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
POTOMAC EDISON	SMITH R.PAUL	04	WILLIAMSPORT	MD		49	75	CB		11686	6.2	.6	2.5	15.3	71	PE	8U	99.0					
POTOMAC ELEC PWR	DICKERSON	02	=4 DEFERRED	MD		60	190	CB	O	11622	7.2	.9	3.3	15.9		PE	RC	97.5					
POTOMAC ELEC PWR	DICKERSON	03	=4 DEFERRED	MD		62	190	CB	O	11622	7.2	.9	3.3	15.9		PE	RC	97.5				CH	
POTOMAC ELEC PWR	DICKERSON	01	=4 DEFERRED	MD		59	190	CB	O	11622	7.2	.9	3.3	15.9		PE	RC	97.5					
POTOMAC ELEC PWR	CHALK POINT	02	PR.GEO.CO.	MD		65	365	C	G	12091	5.8	.7	2.2	14.6		PE	RC	97.5					UE
POTOMAC ELEC PWR	MORGANTOWN	01	CHARLES CTY	MD		70	556	CB	O	12160	4.1	.4	2.5	16.3	70	PE	RC	99.5					
POTOMAC ELEC PWR	MORGANTOWN	02	CHARLES CTY	MD		71	558	CB	O	12160	4.1	.4	2.5	16.3		PE	RC	99.5					BR

	ALL UNITS		COAL		OIL		GAS		NUCLEAR	
	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW
SUBTOTAL	7	2,124	7	2,124						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = MI

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
MINNESOTA PWR & LT	BOSWELL C.	03	COHASSETT	MI		73	350	CB	O	8620	25.8	.8	1.0	9.7		SC	OH	99.0					EB
MINNESOTA PWR & LT	AURORA	02	AURORA	MI		57	58	CB	O	8271	27.2	.9	1.1	10.2		SC	OH	99.0					
MINNESOTA PWR & LT	AURORA	01	AURORA	MI		52	58	CB	O	8271	27.2	.9	1.1	10.2		SC	OH	99.0					CC
NRN STATES PWR	HIGH BRIDGE	03	ST. PAUL	MI		42	62	CS	G	8532	10.4	.5	3.3	8.2		PE	RC	96.0					
NRN STATES PWR	RIVERSIDE	06	MINNEAPOLIS	MI		49	67	CS		11000		.6	4.4	8.0		PE	RC	96.0					
NRN STATES PWR	RIVERSIDE	08	MINNEAPOLIS	MI		64	223	CS		11000		.6	4.4	8.0		PE	RC	97.5					
NRN STATES PWR	HIGH BRIDGE	04	ST. PAUL	MI		44	62	CS	G	8532	10.4	.5	3.3	8.2		PE	RC	97.5					
NRN STATES PWR	HIGH BRIDGE	05	ST. PAUL	MI		56	116	CS	G	8532	10.4	.5	3.3	8.2		PE	RC	99.0					
NRN STATES PWR	KING ALLEN S.	01	BAYPORT	MI		68	598	CS		13970	12.1	.8	4.2	10.8	68	PE	RC	99.0					
NRN STATES PWR	HIGH BRIDGE	06	ST. PAUL	MI		59	166	CS	G	10722	10.4	.5	3.3	8.2		PE	RC	99.0					
OTTER TAIL PWR.	HOOT LAKE	02	FERGUS FALLS	MI		59	53	CL		7094	34.7	.7	1.1	6.2	71	PE	RC	99.0					
OTTER TAIL PWR.	HOOT LAKE	03	FERGUS FALLS	MI		64	66	CL		7094	34.7	.6	1.1	6.2	71	PE	RC	99.0					
NRN STATES PWR	MINNESOTA VALLE	03	GRANITE FALLS	MI		53	49	CS	G	8742	14.0	.8	3.7	10.7	72	PE	UP	97.0					

	ALL UNITS		COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
	UNITS	MW								
SUBTOTAL	13	1,928	13	1,928						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = MO

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
KANSAS CTY. PWR.&LT.	HAWTHORN	05	KANSAS CITY	MO		69	493	CB	G	10409	14.4	.6	3.0	8.2	69	PE	BU	99.0					
UNION ELEC.	RUSH ISLE	01	CRYSTAL CITY	MO	10	75	590	C		10400	9.7	1.2	1.2	18.7	72	PE	LC	99.5					BE
UNION ELEC.	MERAMEC	01	SE ST. LOUIS	MO	05	53	125	C	G	12175		.8	3.1	11.7		PE	RC	97.5			FS	CE	
UNION ELEC.	MERAMEC	02	SE ST. LOUIS	MO	07	54	125	C	G	12175		.8	3.1	11.7		PE	RC	97.5					
UNION ELEC.	MERAMEC	03	SE ST. LOUIS	MO	01	59	250	C	G	12175		.8	3.1	11.7		PE	RC	97.5					
UNION ELEC.	LABADIE	03	LABADIE	MO	5	72	580	C		11200	11.3	2.9	3.2	9.9	72	PE	RC	99.5					BE
UNION ELEC.	LABADIE	04	LABADIE	MO	5	73	580	C		11200	11.3	2.9	3.2	9.9	73	PE	RC	99.5					BE
UNION ELEC.	LABADIE	02	LABADIE	MO		71	600	C		11200	11.3	2.9	3.2	9.9	71	PE	RC	99.5					BE
UNION ELEC.	LABADIE	01	LABADIE	MO		70	600	C		11200	11.3	2.9	3.2	9.9	70	PE	RC	99.5					BE
UNION ELEC.	SIOUX	02	PRTGE DES SIOUX	MO	05	68	488	C		10975		2.7	3.7	12.8	74	PE	RC	99.6					
UNION ELEC.	SIOUX	01	PRTGE DES SIOUX	MO	05	67	488	C		10975		2.7	3.7	12.8	74	PE	RC	99.6					
ASSOC ELEC COOP	NEW MADRID	01	NEW MADRID	MO	4	72	600	C		12066		4.8	5.0			PE	UP	97.5					BM
MISSOURI P.S.	SIBLEY	01	SIBLEY	MO		55	50	CB		12041		3.7	3.9	10.7	72	PE	UP	99.0					
MISSOURI P.S.	SIBLEY	02	SIBLEY	MO		62	50	CB		12041		3.7	3.9	10.7	72	PE	UP	99.0					
SPRINGFIELD CTY U.	JAMES RVR.	05	KISSICK	MO		70	112	C	G						75	PE	UP	99.0					BM
UNION ELEC.	MERAMEC	04	SE ST. LOUIS	MO	07	61	300	C	G	12175		.8	3.1	11.7		PE	WP	97.5					

	ALL UNITS		COAL		OIL		GAS		NUCLEAR	
	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW
SUBTOTAL	16	6,031	16	6,031						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = MP

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
MISSISSIPPI PWR.	WATSON JACK	04	GULFPORT	MP	05	68	250	C		11809		2.9	2.9		68	PE	WP	98.0					
MISSISSIPPI PWR.	WATSON JACK	05	GULFPORT	MP		73	505	C		11809		2.9	2.9			PE	WP	99.0					SS

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	2	755	2	755						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE .= MT

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
MONTANA PWR.	CORETTE J.E.	01	BILLINGS	MT		68	173	CS		8643	25.2	.7	.7	8.4	68	PE		95.0					

	ALL UNITS	ALL MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	1	173	1	173						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = NB

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
OMAHA PUB. PWR.	N. OMAHA	04	OMAHA	NB		61	102	C	G	10300	12.0	.3	.9	6.0	74	PE	BU	99.4					
OMAHA PUB. PWR.	N. OMAHA	05	OMAHA	NB		68	235	C	G	10300	12.0	.3	.9	6.0	74	PE	BU	99.4					
OMAHA PUB. PWR.	N. OMAHA	01	OMAHA	NB		54	102	C	G	10300	12.0	.3	.9	6.0	74	PE	BU	99.4					
OMAHA PUB. PWR.	N. OMAHA	03	OMAHA	NB		59	102	C	G	10300	12.0	.3	.9	6.0	74	PE	BU	99.4					
OMAHA PUB. PWR.	N. OMAHA	02	OMAHA	NB		57	102	C	G	10300	12.0	.3	.9	6.0	74	PE	BU	99.4					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	5	643	5	643						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = NC

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
CAROLINA PWR & LT	LEE H.F.	02	GOLDSBORO	NC		51	66	CB	O	12753	5.8	.8	2.2	8.6	73	ME		99.2					
DUKE POWER CO.	MARSHALL	02	TERRELL	NC		66	386	CB	O	11657	7.4	.8	3.0	16.3	70	ME	AT	99.0					
CAROLINA PWR & LT	WEATHERSPOON	02	LUMBERTON	NC		49	44	CB	O	12641	5.6	.7	1.3	13.0	73	ME	BU	99.3					EB
CAROLINA PWR & LT	WEATHERSPOON	01	LUMBERTON	NC		49	44	CB	O	12641	5.6	.7	1.3	13.0	73	ME	BU	99.3					EB
CAROLINA PWR & LT	CAPE FEAR	06	MONCURE	NC		58	156	C		12185	5.5	.7	1.5	16.0	73	ME	BU	99.5					
CAROLINA PWR & LT	SUTTON LOUIS V.	02	WILMINGTON	NC		54	99	C	O	12133	7.0	.7	1.4	12.1	73	HP	BU	99.5					
CAROLINA PWR & LT	ROXBORO	02	ROXBORO	NC		68	630	CB		12268	4.6	1.0	2.5	12.0	72	PE	BU	99.6					
CAROLINA PWR & LT	ROXBORO	01	ROXBORO	NC		66	379	CB		12268	4.6	1.0	2.5	12.0	72	PE	BU	99.6					
DUKE POWER CO.	RIVERBEND	05	MT. HOLLY	NC		52	109	CB		12050	5.9	.6	3.2	17.5		PE	BU	99.0					
DUKE POWER CO.	RIVERBEND	07	MT. HOLLY	NC		54	143	CB		12050	5.9	.6	3.2	17.5		PE	BU	99.0					
DUKE POWER CO.	RIVERBEND	06	MT. HOLLY	NC		54	143	CB		12050	5.9	.6	3.2	17.5		PE	BU	99.0					
DUKE POWER CO.	BUCK	03	SPENCER	NC		41	76	C		12206	7.4	.6	1.5	11.9		PE	BU	99.0					
DUKE POWER CO.	BUCK	04	SPENCER	NC		42	38	C		12206	7.4	.6	1.5	11.9		PE	BU	99.0					
DUKE POWER CO.	RIVERBEND	04	MT. HOLLY	NC		52	109	CB		12050	5.9	.6	3.2	17.5		PE	BU	99.0					
DUKE POWER CO.	BUCK	06	SPENCER	NC		53	137	C		12206	7.4	.6	1.5	11.9		PE	BU	99.0					
DUKE POWER CO.	CLIFFSIDE	02	CLIFFSIDE	NC		40	38	CB		12530	6.4	.6	1.6	14.2		PE	BU	99.0					
DUKE POWER CO.	CLIFFSIDE	01	CLIFFSIDE	NC		40	38	CB		12530	6.4	.6	1.6	14.2		PE	BU	99.0					
DUKE POWER CO.	BUCK	05	SPENCER	NC		53	138	C		12206	7.4	.6	1.5	11.9		PE	BU	99.0					
CAROLINA PWR & LT	ASHEVILLE	02	SKYLAND	NC		71	193	CB	O	11820	7.2	.6	2.4	12.3	71	PE	RC	99.0					BR
CAROLINA PWR & LT	LEE H.F.	01	GOLDSBORO	NC		52	63	CB	O	12753	5.8	.8	2.2	8.6	73	ME	RC	99.3					
CAROLINA PWR & LT	WEATHERSPOON	03	LUMBERTON	NC		52	63	CB	O	12641	5.6	.7	1.3	10.0	73	ME	RC	99.3					
CAROLINA PWR & LT	LEE H.F.	03	GOLDSBORO	NC		62	220	CB		12753	4.0	.8	2.2	14.0	73	ME	RC	99.4					
CAROLINA PWR & LT	SUTTON LOUIS V.	01	WILMINGTON	NC		54	114	C	O	12133	7.0	.7	1.4	12.1	72	HP	RC	99.5					
DUKE POWER CO.	ALLEN	05	BELMONT	NC		61	290	CB		12161	6.8	.7	1.0	11.8		HP	RC	99.0					
DUKE POWER CO.	ALLEN	01	BELMONT	NC		57	169	CB		12161	6.8	.7	1.0	11.8		ME	RC	99.0					
DUKE POWER CO.	ALLEN	04	BELMONT	NC		59	287	CB		12161	6.8	.7	1.0	11.8		HP	RC	99.0					
DUKE POWER CO.	DAN RIVER	02	DRAPER	NC		49	76	CB		12263	7.0	.6	1.5	16.3		HP	RC	99.0					
DUKE POWER CO.	DAN RIVER	01	DRAPER	NC		49	76	CB		12263	7.0	.6	1.5	16.3		HP	RC	99.0					
DUKE POWER CO.	CLIFFSIDE	03	CLIFFSIDE	NC		48	66	CB		12530	6.4	.6	1.6	14.2		HP	RC	99.0					
DUKE POWER CO.	CLIFFSIDE	04	CLIFFSIDE	NC		48	66	CB		12530	6.4	.6	1.6	14.2		HP	RC	99.0					
DUKE POWER CO.	ALLEN	03	BELMONT	NC		59	288	CB		12161	6.8	.7	1.0	11.8		HP	RC	99.0					
DUKE POWER CO.	ALLEN	02	BELMONT	NC		57	170	CB		12161	6.8	.7	1.0	11.8		ME	RC	99.0					
DUKE POWER CO.	MARSHALL	04	TERRELL	NC		70	671	CB	O	11657	7.4	.8	3.0	16.3	70	PE	RC	99.5					
DUKE POWER CO.	MARSHALL	03	TERRELL	NC		69	650	CB	O	11657	7.4	.8	3.0	16.3	69	PE	RC	99.5					
DUKE POWER CO.	CLIFFSIDE	05	CLIFFSIDE	NC		72	575	CB		12530	6.4	.6	1.6	14.2		PE	RC	99.5					BE
DUKE POWER CO.	BELEWS CREEK	02	WINSTON-SALEM	NC		75	1144	C				.8	.8		73	PE	RC	99.7					OI

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CONSLT
DUKE POWER CO.	BELEWS CREEK	01	WINSTON-SALEM	NC		74	1144	C				.8	.8		73	PE	RC	99.7					OW
CAROLINA PWR & LT	SUTTON LOUIS V.	03	WILMINGTON	NC		72	420	C	O	12133	7.0	.7	1.4	12.1	73	PE	UP	99.0					BR
CAROLINA PWR & LT	ROXBORO	03	ROXBORO	NC	3	73	720	CB		12268	4.6	1.0	2.5	12.0	73	PE	UP	99.0					BR

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	39	10,238	39	10,238						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = ND

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
BASIN EL PWR CO-OP	LELAND OLDS	01	STANTON	ND		62	216	CL		6661	37.6	.7	.8	12.1	73	PE	RC	99.5					BO
MINNKOTA COOP	YOUNG, MILTON R	01	CENTER	ND		70	235	CL	O	6370	38.5	.5	1.3	8.5	73	PE	RC	99.0					SP
MONTANA-DAKOTA UTIL.	HESKETT R.M.	01	MANDAN	ND		50	25	CL	G	6975	36.1	.3	1.4	6.7	73	ME	RC	99.5					SR
MONTANA-DAKOTA UTIL.	HESKETT R.M.	02	MANDAN	ND		63	75	CL		6975	36.1	.3	1.4	6.7	73	ME	RC	99.5					SR
UNITED POWER ASSOC	STANTON	01	STANTON	ND		67	150	CL		7032		.4	.9	6.9	74	PE	RC	98.0					BV
BASIN EL PWR CO-OP	LELAND OLDS	02	STANTON	ND	10	75	450	CL							73	PE	WP	99.5					BO

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	6	1,151	6	1,151						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = NJ

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
ATLANTIC CTY ELEC	ENGLAND B.L.	01	BEESLEYS PT.	NJ		62	125	CB	O	12064	3.5	2.0	5.0	15.0		PE		98.0					
ATLANTIC CTY ELEC	ENGLAND B.L.	02	BEESLEYS PT.	NJ		64	150	CB	O	12064	3.5	2.0	5.0	15.0		PE		99.5					
ATLANTIC CTY ELEC	MISSOURI AVE	07	ATLANTIC CITY	NJ		46	25	C		13653	5.7	.5	.5	6.8	46	PE	RC	95.0					
ATLANTIC CTY ELEC	MISSOURI AVE	06	ATLANTIC CITY	NJ		41	25	C		13653	5.7	.5	.5	6.8	41	PE	RC	95.0					
PUBLIC SERV. E&G	MERCER	02	HAMILTON TWP	NJ		59	320	CB	O	12837	5.7	.9	2.4	11.6	69	PE	RC	99.0					
PUBLIC SERV. E&G	MERCER	01	HAMILTON TWP	NJ		58	320	CB	O	12837	5.7	.9	2.4	11.6	69	PE	RC	99.0					
PUBLIC SERV. E&G	HUDSON	02	JERSEY CITY	NJ		69	600	C	O	12156		.9	2.1	12.1	68	PE	RC	99.5					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	7	1,565	7	1,565						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = NM

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CONSLT
P.S. OF NEW MEXICO	SAN JUAN	02	WATERFLOW	NM		73	340	CS		9887		.8	.8	22.0		PE	WP	99.5			FS	DP	BR

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	1	340	1	340						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = NV

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CONSLT
SOUTHERN CAL ED.	MOHAVE	01		NV		71	790	CS	G	10774		.4	.8	10.9	70	PE	RC	98.6				OW	BE
SOUTHERN CAL ED.	MOHAVE	02		NV		71	790	CS	G	10774		.4	.8	10.9	71	PE	RC	98.6				OW	BE

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	2	1,580	2	1,580						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = NY

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	TYPE 1	TYPE 2	FUEL HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	TYPE	MFR	PCT EFY	RY	SO2 YR	TYPE	MFR	CON SLT
N.Y. STATE EL.&G.	GOUDY	05	JOHNSON CTY	NY		35	12	C		12038	4.8	1.7	4.1	18.7		PE		99.8					
N.Y. STATE EL.&G.	GREENIDGE	02	DRESDEN	NY		43	20	C		11930	6.0	.7	3.6	25.0	74	ME	KC	98.5					
N.Y. STATE EL.&G.	GREENIDGE	03	DRESDEN	NY		48	40	C		11930	6.0	.7	3.6	25.0	74	ME	KC	98.5					
N.Y. STATE EL.&G.	MILLIKEN	02	LUDLOWVILLE	NY		58	135	C		11654	6.4	1.2	4.1	35.1		PE	RC	98.0					
N.Y. STATE EL.&G.	GREENIDGE	04	DRESDEN	NY		52	80	C		11930	6.0	.7	3.6	25.0	71	PE	RC	98.5					
ORANGE ROCKLAND UTIL	LOVETT	04	TOMKINS COVE	NY		66	199	CB	O	12420	5.0	1.8	3.8	12.4		PE	RC	95.0					
ORANGE ROCKLAND UTIL	LOVETT	05	TOMKINS COVE	NY		69	202	CB	O	12420	5.0	1.8	3.8	12.4		PE	RC	99.0					
N.Y. STATE EL.&G.	GOUDY	06	JOHNSON CTY	NY		39	30	C		12038	4.8	1.7	4.1	18.7	73	PE	WP	99.8					
N.Y. STATE EL.&G.	GOUDY	07	JOHNSON CTY	NY		47	44	C		12038	4.8	1.7	4.1	18.7	73	PE	WP	99.8					
N.Y. STATE EL.&G.	GOUDY	08	JOHNSON CTY	NY		50	60	C		12038	4.8	1.7	4.1	18.7	73	PE	WP	99.8					
NIAGARA MOHAWK PWR.	DUNKIRK	01	DUNKIRK	NY		50	109	C		12875		.8	6.5	14.1	73	ME	WP	99.6					OW
NIAGARA MOHAWK PWR.	DUNKIRK	03	DUNKIRK	NY		59	228	C		12875		.8	6.5	14.1		ME	WP	99.6					OW
NIAGARA MOHAWK PWR.	HUNTLEY C.R.	68	BUFFALO	NY		58	230	C		12848		.8	5.4	11.8	73	ME	WP	99.6					OW
NIAGARA MOHAWK PWR.	DUNKIRK	04	DUNKIRK	NY		60	228	C		12875		.8	6.5	14.1		ME	WP	99.6					OW
NIAGARA MOHAWK PWR.	HUNTLEY C.R.	67	BUFFALO	NY		57	230	C		12848		.8	5.4	11.8	73	ME	WP	99.6					OW
NIAGARA MOHAWK PWR.	HUNTLEY C.R.	65	BUFFALO	NY		53	109	C		12848		.8	5.4	11.8	73	ME	WP	99.6					OW
NIAGARA MOHAWK PWR.	DUNKIRK	02	DUNKIRK	NY		50	111	C		12875		.8	6.5	14.1	73	ME	WP	99.6					OW
NIAGARA MOHAWK PWR.	HUNTLEY C.R.	66	BUFFALO	NY		54	108	C		12848		.8	5.4	11.8	73	ME	WP	99.6					OW

	ALL UNITS		COAL		OIL		GAS		NUCLEAR	
	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW	UNITS	MW
SUBTOTAL	18	2,175	18	2,175						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = OH

UTILITY CO. NAME	PLANT NAME	UN IT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
OHIO POWER	PHILO	06	PHILO	OH		57	125	C		10679		1.8	5.7			PE		98.3					
OHIO POWER	PHILO	04	PHILO	OH		42	65	C		10679		1.8	5.7			PE		99.0					
OHIO POWER	PHILO	05	PHILO	OH		42	65	C		10679		1.8	5.7			PE		99.0					
OHIO EDISON	BURGER R.E.	01	SHADYSIDE	OH		44	63	C		11700	7.5	1.2	4.3	16.2	71	PE		99.0					
OHIO POWER	TIDD	02	BRILLIANT	OH		48	111	C		11635		2.6	3.3			PE		99.4					
OHIO POWER	TIDD	01	BRILLIANT	OH		45	105	C		11635		2.6	3.3			PE		99.4			PI	RC	
OHIO EDISON	SAMMIS W.H.	05	STRATTON	OH		67	318	C		11563	7.1	.7	4.0	17.7		PE	AS	99.0					
CINCINNATI G&E	BECKJORD W.C.	05	NEW RICHMOND	OH		62	246	C		10687	8.8	1.0	5.5	17.7	74	PE	BU	98.0					
CINCINNATI G&E	STUART J.M.	04	ABERDEEN	OH		74	580	C		11206		.6	.6	50.1	72	PE	BU	98.0					EB
CINCINNATI G&E	MIAMI FORT	05	NORTH BEND	OH		56	90	C		11272	9.5	1.0	4.6	13.9	75	PE	BU	99.5					SL
COLUMBUS & S. OHIO E	STUART J.M.	02	ABERDEEN	OH		70	580	C		11206	7.5	.6	5.0	15.4	72	PE	BU	98.0					EB
COLUMBUS & S. OHIO E	STUART J.M.	03	ABERDEEN	OH	03	72	580	C		11206	7.5	.6	5.0	15.4	72	PE	BU	98.0					EB
COLUMBUS & S. OHIO E	STUART J.M.	01	ABERDEEN	OH		71	580	C		11206	7.5	.6	5.0	15.4	72	PE	BU	98.0					EB
OHIO EDISON	SAMMIS W.H.	04	STRATTON	OH		62	185	C		11563	7.1	.7	4.0	17.7		PE	BU	97.0					
OHIO EDISON	SAMMIS W.H.	03	STRATTON	OH		61	185	C		11563	7.1	.7	4.0	17.7		PE	BU	97.0					
OHIO EDISON	SAMMIS W.H.	02	STRATTON	OH		60	185	C		11563	7.1	.7	4.0	17.7		PE	BU	97.0					
OHIO EDISON	SAMMIS W.H.	01	STRATTON	OH		59	185	C		11563	7.1	.7	4.0	17.7		PE	BU	97.0					
OHIO EDISON	TORONTO	05	TORONTO	OH		40	44	C		10515	8.1	1.8	3.5	18.0	70	PE	BU	99.0					
OHIO EDISON	TORONTO	06	TORONTO	OH		49	66	C		10515	8.1	1.8	3.5	18.0	70	PE	BU	99.0					
OHIO EDISON	TORONTO	07	TORONTO	OH		49	66	C		10515	8.1	1.8	3.5	18.0	70	PE	BU	99.0					
OHIO POWER	GAVIN	01	GALLIOPOLIS	OH	10	74	1380	C				1.0	3.0	20.0	72	PE	KC	99.7					AP
OHIO POWER	GAVIN	02	GALLIOPOLIS	OH	10	75	1380	C				1.0	3.0	20.0	72	PE	KC	99.7					AP
CINCINNATI G&E	BECKJORD W.C.	02	NEW RICHMOND	OH		52	101	C		10687	8.8	1.0	5.5	17.7	72	PE	RC	99.0					
CINCINNATI G&E	BECKJORD W.C.	01	NEW RICHMOND	OH		49	98	C		10687	8.8	1.0	5.5	17.7	72	PE	RC	99.0					
CINCINNATI G&E	BECKJORD W.C.	03	NEW RICHMOND	OH		55	128	C		10687	8.8	1.0	5.5	17.7	72	PE	RC	99.5					
CLEVELAND ELEC ILLUM	EAST LAKE	04	EAST LAKE	OH		56	208	C	O	11921	7.0	.5	4.2	13.9		ME	RC	95.0					
CLEVELAND ELEC ILLUM	EASTLAKE	05	EASTLAKE	OH	8	72	625	C		11921	7.0	.5	7.1	13.9		PE	RC	99.5					GA
COLUMBUS & S. OHIO E	CONESVILLE	04	CONESVILLE	OH	1	73	744	C		10822		3.0	5.1			PE	RC	99.3					BV
DAYTON PWR & LT	HUTCHINGS O.H.	05	MIAMISBURG	OH			70	CB		12360	5.9	.6	1.0	9.9	73	HP	RC	99.5					
DAYTON PWR & LT	HUTCHINGS O.H.	06	MIAMISBURG	OH			70	CB		12360	5.9	.6	1.0	9.9	73	HP	RC	99.5					
DAYTON PWR & LT	TAIT F.M.	04	DAYTON	OH		58	136	CB		11915	6.9	.7	2.3	11.9	73	HP	RC	99.5					
DAYTON PWR & LT	HUTCHINGS O.H.	04	MIAMISBURG	OH			70	CB		12360	5.9	.6	1.0	9.9	73	HP	RC	99.5					
DAYTON PWR & LT	HUTCHINGS O.H.	03	MIAMISBURG	OH			70	CB		12360	5.9	.6	1.0	9.9	73	HP	RC	99.5					
DAYTON PWR & LT	HUTCHINGS O.H.	02	MIAMISBURG	OH			63	CB		12360	5.9	.6	1.0	9.9	73	HP	RC	99.5					

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	TYPE 1 2	FUEL HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	TY PE	MFR	PCT EFY	R Y	SO2 YR	TY PE	MFR	CON SLT
DAYTON PWR & LT	HUTCHINGS O.H.	01	MIAMISBURG	OH			63	CB	12360	5.9	.6	1.0	9.9	73	HP	RC	99.5					
DAYTON PWR & LT	TAIT F.M.	05	DAYTON	OH		59	145	CB	11915	6.9	.7	2.3	11.9	73	HP	RC	99.5					
COLUMBUS & S. OHIO E	POSTON	04	ATHENS	OH			71	CB	11178	9.5	2.1	4.2	12.2	75	ME	UP	99.0					
COLUMBUS & S. OHIO E	POSTON	03	ATHENS	OH			71	CB	11178	9.5	2.1	4.2	12.2	75	ME	UP	99.0					
COLUMBUS & S. OHIO E	POSTON	02	ATHENS	OH			45	CB	11178	9.5	2.1	4.2	12.2	75	ME	UP	99.0					
COLUMBUS & S. OHIO E	CONESVILLE	02	CONESVILLE	OH		58	137	CB	10822	7.9	3.8	5.0	15.9	75	ME	UP	99.0					
COLUMBUS & S. OHIO E	CONESVILLE	03	CONESVILLE	OH		62	178	CB	10822	7.9	3.8	5.0	15.9	75	ME	UP	99.0					
COLUMBUS & S. OHIO E	POSTON	01	ATHENS	OH			45	CB	11178	9.5	2.1	4.2	12.2	75	ME	UP	99.0					
COLUMBUS & S. OHIO E	CONESVILLE	01	CONESVILLE	OH		59	137	CB	10822	7.9	3.8	5.0	15.9	75	ME	UP	99.0					
COLUMBUS & S. OHIO E	PICWAY	05	COLUMBUS	OH		49	95	CB	11279	8.2	2.9	5.2	17.9	75	PE	UP	99.0					
OHIO EDISON	BURGER R.E.	05	SHADYSIDE	OH		55	160	C	11700	7.5	1.2	4.3	16.2	71	ME	WP	97.0					
OHIO EDISON	BURGER R.E.	04	SHADYSIDE	OH		55	160	C	11700	7.5	1.2	4.3	16.2	71	ME	WP	97.0					
OHIO EDISON	GORGE	06	AKRON	OH		43	44	C	10912	7.1	1.6	4.2	18.9	69	PE	WP	98.0					
OHIO EDISON	GORGE	07	AKRON	OH		48	44	C	10912	7.1	1.6	4.2	18.9	69	PE	WP	98.0					
OHIO EDISON	EDGEWATER	04	LORAIN	OH		57	105	C	12122	6.1	1.3	4.2	16.8		PE	WP	98.0					
OHIO POWER	MUSKINGUM RIVER	04	BEVERLY	OH		58	225	C	10531		1.4	5.8		70	PE	WP	98.5					
OHIO POWER	MUSKINGUM RIVER	03	BEVERLY	OH		57	225	C	10531		1.4	5.8		70	PE	WP	98.5					
OHIO EDISON	BURGER R.E.	02	SHADYSIDE	OH		47	63	C	11700	7.5	1.2	4.3	16.2	71	PE	WP	99.0					
OHIO EDISON	EDGEWATER	03	LORAIN	OH		49	63	C	12122	6.1	1.3	4.2	16.8	70	PE	WP	99.0					
OHIO EDISON	EDGEWATER	02	LORAIN	CH		23	7	C	12122	6.1	1.3	4.2	16.8	70	PE	WP	99.0					
OHIO EDISON	BURGER R.E.	03	SHADYSIDE	OH		50	100	C	11700	7.5	1.2	4.3	16.2	71	PE	WP	99.0					
OHIO EDISON	SAMMIS W.H.	06	STRATTON	OH		69	623	C	11563	7.1	.7	4.0	17.7	69	PE	WP	99.0					
OHIO EDISON	SAMMIS	07		OH		71	625	C	11012		.5	4.1	15.4	71	PE	WP	99.0					CA
OHIO POWER	CARDINAL	02	BRILLIANT	OH		67	590	CB	11867		.3	3.6	15.0	67	PE	WP	99.4					SL
OHIO POWER	MUSKINGUM RIVER	05	BEVERLY	OH		68	591	C	10531		1.4	5.8		68	PE	WP	99.4					
OHIO POWER	CARDINAL	01	BRILLIANT	OH		66	590	CB	11867		.3	3.6	15.0	67	PE	WP	99.4					SL
OHIO POWER	MUSKINGUM RIVER	02	BEVERLY	OH		54	213	C	10531		1.4	5.8		70	PE	WP	99.5					
OHIO POWER	MUSKINGUM RIVER	01	BEVERLY	OH		53	213	C	10531		1.4	5.8		70	PE	WP	99.5					
INCINNATI G&E	MIAMI FORT	07	NORTH BEND	OH		75	500	C						71	PE	WP	99.5					SL

	ALL UNITS	MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	63	15,735	63	15,735						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = PA

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TY PE	PARTICULATE MFR	PARTICULATE PCT EFY	R Y	SO2 YR	SO2 TY PE	SO2 MFR	CON SLT
DUQUESNE LT.	ELRAMA	03	ELRAMA	PA		53	100	CB		11041	5.8	1.1	3.5	19.3		SC		99.0					
METROPOLITAN ED	TITUS	03	READING	PA		54	75	C	O	12023	6.7	.5	2.9	13.5		PE		96.7					
METROPOLITAN ED	TITUS	02	READING	PA		49	75	C	O	12023	6.7	.5	2.9	13.5		PE		96.7					
METROPOLITAN ED	TITUS	01	READING	PA		45	75	C	O	12023	6.7	.5	2.9	13.5		PE		96.7					
PA. ELEC.CO.	SEWARD	03		PA		35	28	C		12124	3.9	2.4	3.0	17.3		ME		98.0					
PA. ELEC.CO.	WARREN	02	WARREN	PA		53	40	C		12255	4.2	1.7	5.4	15.9	74	PE		98.7					
PA. ELEC.CO.	WARREN	01	WARREN	PA		49	38	C		12255	4.2	1.7	5.4	15.9	74	PE		98.7					
PA. PWR.&LT.	HOLTWOOD	01	HOLTWOOD	PA		49	100	CA		9596	15.2	.7	.7	30.5	70	ME		99.0					
PA. PWR.&LT.	SUNBURY	02	SHAMOKIN DAM	PA		47	75	CB		11038	8.6	.7	5.4	34.9		ME		99.6					
PA. PWR.&LT.	SUNBURY	01	SHAMOKIN DAM	PA		42	75	CB		11038	8.6	.7	5.4	34.9		ME		99.6					
PHILADELPHIA ELEC	EDDYSTONE	02	EDDYSTONE	PA		60	365	CB		13123		.8	2.9	10.3		ME		99.0					
PHILADELPHIA ELEC	EDDYSTONE	01	EDDYSTONE	PA		60	361	CB		13123		.8	2.9	10.3		ME		99.0			FS	EN	
PHILADELPHIA ELEC	CROMBY	02	PHOENIXVILLE	PA		55	220	CS		13141	5.3	1.0	3.3	9.5		ME		99.0					
PHILADELPHIA ELEC	CROMBY	01	PHOENIXVILLE	PA		54	168	CS		13141	5.3	1.0	3.3	9.5		ME		99.0			DE	CC	
WEST PENN PWR.	MITCHELL	03	COURTNEY	PA		63	299	C		12620	5.5	1.2	2.9	10.9		PE	AS	95.0					
METROPOLITAN ED	PORTLAND	01	PORTLAND	PA		58	213	C	O	12044	6.2	.7	3.6	14.3	58		BU	97.0					
METROPOLITAN ED	PORTLAND	02	PORTLAND	PA		62	213	C	O	12044	6.2	.7	3.6	14.3	62		BU	97.0					
N.Y. STATE EL.&G.	HOMER CITY	02	HOMER CITY	PA		70	640	C		11659	4.1	.9	2.5	20.1	70	PE	BU	99.5					GA
N.Y. STATE EL.&G.	HOMER CITY	01	HOMER CITY	PA		69	640	C		11659	4.1	.9	2.5	20.1	69	PE	BU	99.5					GA
PA. ELEC.CO.	SHAWVILLE	03	SHAWVILLE	PA		59	183	C		12428	5.1	1.4	2.8	13.4	74	PE	BU	98.5					
PA. ELEC.CO.	SHAWVILLE	04	SHAWVILLE	PA		60	183	C		12428	5.1	1.4	2.8	13.4	74	PE	BU	98.5					
PA. PWR.&LT.	CONEMAUGH	02	NEW FLORENCE	PA		71	900	C	O	11394	5.3	.9	4.6	20.3		PE	BU	99.5					GA
PA. PWR.&LT.	CONEMAUGH	01	NEW FLORENCE	PA		70	900	C	O	11394	5.3	.9	4.6	20.3	70	PE	BU	99.5					GA
PA. PWR.&LT.	SUNBURY	04	SHAMOKIN DAM	PA		53	125	CB		11038	8.6	.7	5.4	34.9	74	ME	BU	99.6					
PA. PWR.&LT.	SUNBURY	03	SHAMOKIN DAM	PA		51	125	CB		11038	8.6	.7	5.4	34.9	74	ME	BU	99.6					
WEST PENN PWR.	SPRINGDALE	08	SPRINGDALE	PA		21	141	C		13330	4.5	1.5	2.1	6.0	68	PE	BU	98.0					
DUQUESNE LT.	ELRAMA	02	ELRAMA	PA		52	80	CB		11041	5.8	1.1	3.5	19.3		SC	CH	99.0					
DUQUESNE LT.	ELRAMA	01	ELRAMA	PA		51	80	CB		11041	5.8	1.1	3.5	19.3		SC	CH	99.0					
PA. PWR. CO.	NEW CASTLE	01	W. PITTSBURG	PA		39	42	C		11982	6.5	1.7	7.0	20.3	75	PE	LC	99.6					CA
PA. PWR. CO.	NEW CASTLE	02	W. PITTSBURG	PA		47	42	C		11982	6.5	1.7	7.0	20.3	75	PE	LC	99.6					CA
PA. PWR. CO.	NEW CASTLE	03	W. PITTSBURG	PA		52	103	C		11982	6.5	1.7	7.0	20.3	75	PE	LC	99.6					CA
PA. PWR. CO.	NEW CASTLE	05	W. PITTSBURG	PA		65	132	C		11982	6.5	1.7	7.0	20.3	75	PE	LC	99.6					CA
PA. PWR. CO.	NEW CASTLE	04	W. PITTSBURG	PA		58	105	C		11982	6.5	1.7	7.0	20.3	75	PE	LC	99.6					CA

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
DUQUESNE LT.	CHESWICK	01	SPRINGDALE	PA		70	570	CB		10950	5.7	1.2	4.4	20.6	73	PE	RC	99.5					SW
PA. ELEC.CO.	SEWARD	04		PA		37	29	C		12124	3.9	2.4	3.0	17.3		ME	RC	97.0					GA
PA. ELEC.CO.	FRONT ST.	07	ERIE	PA		40	17	CB		12143	4.8	1.1	3.9	12.4	74	PE	RC	98.0					
PA. ELEC.CO.	SEWARD	05		PA		57	137	C		12124	3.9	2.4	3.0	17.3		ME	RC	98.0					
PA. PWR.&LT.	BRUNNER ISLAND	02	YORK HAVEN	PA		65	390	CB	O	12501	4.5	1.5	3.6	20.1	65	PE	RC	97.3					
PA. PWR.&LT.	BRUNNER ISLAND	01	YORK HAVEN	PA		61	330	CB	O	12501	4.5	1.5	3.6	20.1	61	PE	RC	98.7					
PA. PWR.&LT.	BRUNNER ISLAND	03	YORK HAVEN	PA		69	750	CB	O	12501	4.5	1.5	3.6	20.1	69	PE	RC	99.5					
PUBLIC SERV. E&G	KEYSTONE	02	SHELOCTA	PA	68	68	444	C	O	11956	2.8	1.3	3.1	18.5	68	PE	RC	99.5					GA
PUBLIC SERV. E&G	KEYSTONE	01	SHELOCTA	PA	67	67	444	C	O	11956	2.8	1.3	3.1	18.4	67	PE	RC	99.5					GA
WEST PENN PWR.	HATFIELDS FERRY	01	MASONTOWN	PA		69	540	C		12445	4.0	1.1	3.0	13.8	69	PE	RC	99.0					UE
WEST PENN PWR.	HATFIELDS FERRY	02	MASONTOWN	PA		70	540	C		12445	4.0	1.1	3.0	13.8		PE	RC	99.0					UE
WEST PENN PWR.	HATFIELDS FERRY	03	MASONTOWN	PA		71	540	C		12445	4.0	1.1	3.0	13.8		PE	RC	99.0					UE
WEST PENN PWR.	ARMSTRONG	01	REESEDALE	PA		58	163	C		11686	4.0	1.6	4.1	16.7	73	PE	UP	99.5					
WEST PENN PWR.	ARMSTRONG	02	REESEDALE	PA		59	163	C		11686	4.0	1.6	4.1	16.7	73	PE	UP	99.5					
DUQUESNE LT.	ELRAMA	04	ELRAMA	PA		58	165	CB		11041	5.8	1.1	3.5	19.3		SC	WP	99.0					
PA. PWR.&LT.	MONTOUR	02	DERRY TWP	PA		.73	750	C		12405	5.0	1.1	5.4	13.4		PE	WP	99.5					EB
PA. PWR.&LT.	MONTOUR	01	DERRY TWP	PA	3	72	750	C		12405	5.0	1.1	5.4	13.4		PE	WP	99.5					EB

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	50	13,663	50	13,663						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = SC

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CONSLT
CAROLINA PWR & LT	ROBINSON H.B.	01	HARTSVILLE	SC		60	185	CB	O	12550	5.0	.7	2.3	16.0	73	ME	BU	99.4					
DUKE POWER CO.	LEE	03	PELZER	SC		58	169	CB	G	11742	7.0	.6	1.6	15.0		ME	BU	99.0					
DUKE POWER CO.	LEE	02	PELZER	SC		51	104	CB	G	11742	7.0	.6	1.6	15.0		HP	RC	99.0					
DUKE POWER CO.	LEE	01	PELZER	SC		51	103	CB	G	11742	7.0	.6	1.6	15.0		HP	RC	99.0					
SOUTH CAROLINA E&G	CANADYS	01	CANADYS	SC		62	127	CB	G	12470	4.5	.9	3.3	11.3	68	PE	RC	99.0					
SOUTH CAROLINA E&G	URQUHART	03	BEECH ISLAND	SC		56	100	CB	G	12573	4.9	.6	2.7	15.9	69	PE	RC	99.0					
SOUTH CAROLINA E&G	MC MEEKIN	02	IRMO	SC		58	125	CB	G	12476	4.8	1.5	2.8	15.0	68	PE	RC	99.0					
SOUTH CAROLINA E&G	URQUHART	02	BEECH ISLAND	SC		53	75	CB	G	12573	4.9	.6	2.7	15.9	69	PE	RC	99.0					
SOUTH CAROLINA E&G	CANADYS	02	CANADYS	SC		64	127	CB	G	12470	4.5	.9	3.3	11.3	68	PE	RC	99.0					
SOUTH CAROLINA E&G	CANADYS	03	CANADYS	SC		67	200	CB	G	12470	4.5	.9	3.3	11.3	68	PE	RC	99.0					
SOUTH CAROLINA E&G	URQUHART	01	BEECH ISLAND	SC		53	75	CB	G	12573	4.9	.6	2.7	15.9	67	PE	RC	99.0					
SOUTH CAROLINA E&G	WATEREE	01	WATEREE	SC		70	375	CB	O	12521	4.6	1.2	5.7	11.5	70	PE	RC	99.3					CM
SOUTH CAROLINA E&G	WATEREE	02	WATEREE	SC		71	385	CB	O	12521	4.6	1.2	5.7	11.5	71	PE	RC	99.3					CM
SOUTH CAROLINA E&G	MC MEEKIN	01	IRMO	SC		58	125	CB	G	12476	4.8	1.5	2.8	15.0	68	PE	RC	99.9					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	14	2,275	14	2,275						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = SD

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CONSLT
BLACK HILLS PWR & LT	KIRK	01	LEAD	SD		32	5	CS		8045		.3	.4	8.5	75	PE	RC	97.5					
BLACK HILLS PWR & LT	KIRK	03	LEAD	SD		39	5	CS		8045		.3	.4	8.5	75	PE	RC	97.5					
BLACK HILLS PWR & LT	KIRK	02	LEAD	SD		36	5	CS		8045		.3	.4	8.5	75	PE	RC	97.5					
BLACK HILLS PWR & LT	KIRK	04	LEAD	SD		40	17	CS		8045		.3	.4	8.5	75	ME	RC	97.5					
OTTER TAIL PWR.	BIG STONE	01	BIG STONE	SD	4	75	440	CL		6200	42.0	.4	.9	6.5	72	PE	WH	98.6					BE

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	5	472	5	472						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = TN

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
TVA	GALLATIN	04	GALLATIN	TN	08	59	328	CB		10965		2.6	4.6	15.5	70	ME	AS	98.5					
TVA	GALLATIN	03	GALLATIN	TN	05	59	328	CB		10965		2.6	4.6	15.5	70	ME	AS	98.5					
TVA	CUMBERLAND	02	CUMBERLAND CITY	TN		73	1275	CB		10640		3.5	4.5		73	PE	AS	99.0					TV
TVA	CUMBERLAND	01	CUMBERLAND CITY	TN		73	1275	CB		10640		3.5	4.5		72	PE	AS	99.0					TV
TVA	GALLATIN	01	GALLATIN	TN	11	56	300	CB		10965		2.6	4.6	15.5	70	ME	BU	98.5					
TVA	GALLATIN	02	GALLATIN	TN	06	57	300	CB		10965		2.6	4.6	15.5	70	ME	BU	98.5					
TVA	BULL RUN	01	CLINTON	TN	06	67	950	CB		11197		.9	1.9	14.8	75	PE	CA	99.0					
TVA	JOHNSONVILLE	08	NEW JOHNSONVILL	TN	01	59	173	CB		10909		3.4	4.2	13.4	75	ME	LC	98.5					
TVA	JOHNSONVILLE	09	NEW JOHNSONVILL	TN	06	59	173	CB		10909		3.4	4.2	13.4	75	ME	LC	98.5					
TVA	SEVIER JOHN	04	ROGERSVILLE	TN	10	57	200	CB		11849		.9	3.4	16.1	74	ME	LC	98.5					
TVA	SEVIER JOHN	02	ROGERSVILLE	TN	09	55	200	CB	9	11849		.9	3.4	16.1	74	ME	LC	98.5					
TVA	SEVIER JOHN	01	ROGERSVILLE	TN	07	55	223	CB	9	11849		.9	3.5	16.1	74	ME	LC	98.5					
TVA	SEVIER JOHN	03	ROGERSVILLE	TN	02	56	200	CB	9	11849		.9	3.5	16.1	74	ME	LC	98.5					
TVA	JOHNSONVILLE	10	NEW JOHNSONVILL	TN	08	59	173	CB		10909		3.4	4.2	13.4	76	ME	LC	98.5					
TVA	WATTS BAR	03	WATTS BAR DAM	TN	02	43	60	C		11617		1.3	4.2		69	PE	RC	95.0					
TVA	WATTS BAR	02	WATTS BAR DAM	TN	02	42	60	C		11617		1.3	4.2		69	PE	RC	95.0					
TVA	WATTS BAR	01	WATTS BAR DAM	TN	03	42	60	C		11617		1.3	4.2		69	PE	RC	95.0					
TVA	WATTS BAR	04	WATTS BAR DAM	TN	04	45	60	C		11617		1.3	4.2		69	PE	RC	95.0					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	18	6,338	18	6,338						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = TX

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
DALLAS PWR & LT	BIG BROWN	02	FAIRFIELD	TX	12	72	576	CL	G	7000	30.8	.6	.6	10.4	71	PE	RC	98.0					EB
DALLAS PWR & LT	BIG BROWN	01	FAIRFIELD	TX	12	71	576	CL	G	7000	30.8	.6	.6	10.4	71	PE	RC	98.0					EB

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	2	1,152	2	1,152						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = UT

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
UTAH PWR.&LT.	CARBON	02	CASTLE GATE	UT		57	100	CS		12165		.5	.6		75	ME	BE	97.0					
UTAH PWR.&LT.	CARBON	01	CASTLE GATE	UT		48	66	CS		12165		.5	.6		73	ME	BE	97.0					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	2	166	2	166						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = VA

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
APPALACHIAN PWR	GLEN LYN	05	GLEN LYN	VA		44	111	CB		12232		.5	2.7		72	PE	AS	99.4					
APPALACHIAN PWR	GLEN LYN	06	GLEN LYN	VA		57	225	CB		12232		.5	2.7		72	PE	AS	99.4					
APPALACHIAN PWR	CLINCH RIVER	01	CLEVELAND	VA		58	223	CB		11839		.5	2.6		72	PE	KC	99.7					
APPALACHIAN PWR	CLINCH RIVER	03	CLEVELAND	VA		58	223	CB		11839		.5	2.6		72	PE	KC	99.7					
APPALACHIAN PWR	CLINCH RIVER	02	CLEVELAND	VA		58	223	CB		11839		.5	2.6		72	PE	KC	99.7					
POTOMAC ELEC PWR	POTOMAC RIVER	01	ALEXANDRIA	VA		49	95	CB	O	13099	4.8	.6	1.3	17.5		ME	WP	99.3					BE
POTOMAC ELEC PWR	POTOMAC RIVER	02	ALEXANDRIA	VA		50	95	CB	O	13099	4.8	.6	1.3	17.5		ME	WP	99.3					BE
POTOMAC ELEC PWR	POTOMAC RIVER	03	ALEXANDRIA	VA		54	108	CB	O	13099	4.8	.6	1.3	17.5	75	ME	WP	99.7					BE
POTOMAC ELEC PWR	POTOMAC RIVER	04	ALEXANDRIA	VA		56	108	CB	O	13099	4.8	.6	1.3	17.5	75	ME	WP	99.7					BE
POTOMAC ELEC PWR	POTOMAC RIVER	05	ALEXANDRIA	VA		57	108	CB	O	13099	4.8	.6	1.3	17.5	75	ME	WP	99.7					BE
VIRGINIA EL.&PWR.	BREMO	04	BREMO BLUFF	VA		58	170	C	O	12728		.7	2.2		71	PE	WP	99.3					
VIRGINIA EL.&PWR.	BREMO	03	BREMO BLUFF	VA		52	60	C	O	12728		.7	2.2		71	PE	WP	99.3					

	ALL UNITS UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	12	1,749	12	1,749						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = WA

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
PACIFIC PWR & LT	CENTRALIA	01	CENTRALIA	WA		73	700	CS		8100		.4	.7		73	PE	LC	99.0					BE
PACIFIC PWR & LT	CENTRALIA	02	CENTRALIA	WA		73	700	CS		8100		.4	.7		73	PE	LC	99.0					BE

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	2	1,400	2	1,400						

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LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = WI

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
WISCONSIN EL.PWR	PORT WASHINGTON	01	P. WASHINGTON	WI		35	80	C		12990	7.9	1.9	4.4	10.9		PE		98.8					
WISCONSIN EL.PWR	PORT WASHINGTON	05	P. WASHINGTON	WI		35	80	C		12990		1.9	4.4	11.9		PE		99.0					
WISCONSIN EL.PWR	PORT WASHINGTON	02	P. WASHINGTON	WI		35	80	C		12990		1.9	4.4	11.9		PE		99.1					
WISCONSIN EL.PWR	PORT WASHINGTON	04	P. WASHINGTON	WI		35	80	C		12990		1.9	4.4	11.9		PE		99.1					
WISCONSIN EL.PWR	PORT WASHINGTON	03	P. WASHINGTON	WI		35	80	C		12990		1.9	4.4	11.9		PE		99.2					
WISCONSIN PWR. & LT.	EDGEWATER	04	SHEBOYGAN	WI		69	225	C		10763		1.6	4.6	9.0	69	PE	BU	98.0					
MADISON G&E	BLOUNT ST.	07	MADISON	WI		70	50	C	O	11669		1.3	4.2	8.4	74	PE	RC	97.3					PI
WISCONSIN EL.PWR	S.OAK CREEK	03	OAK CREEK	WI	.	55	360	CB		11639		.3	3.9	11.2	66	PE	RC	99.0					
WISCONSIN EL.PWR	VALLEY	02	MILWAUKEE	WI		69	140	C	G	11949	8.5	1.3	3.7	11.5	69	PE	RC	99.0			PI	SW	
WISCONSIN EL.PWR	S.OAK CREEK	06	OAK CREEK	WI		67	336	C		11639		.3	3.9	11.2	67	PE	RC	99.0					
WISCONSIN EL.PWR	S.OAK CREEK	05	OAK CREEK	WI		59	275	C	O	11639		.3	3.9	11.2	59	PE	RC	99.0					
WISCONSIN EL.PWR	VALLEY	01	MILWAUKEE	WI		68	140	C	G	11949	8.5	1.3	3.7	11.5	68	PE	RC	99.2					
WISCONSIN EL.PWR	N. OAK CREEK	02	OAK CREEK	WI		52	120	CB	O	11639	11.0	.3	3.9	11.2	70	PE	RC	99.5					
WISCONSIN EL.PWR	N. OAK CREEK	01	OAK CREEK	WI		52	120	CB	C	11639	11.0	.3	3.9	11.2	70	PE	RC	99.5					
WISCONSIN P.S.	PULLIAM	06	GREEN BAY	WI		54	63	C	G	11819	7.7	.9	4.1	12.6	72	PE	RC	98.0					PI
WISCONSIN P.S.	PULLIAM	05	GREEN BAY	WI		49	50	C	G	11819	7.7	.9	4.1	12.6	72	PE	RC	98.0					PI
WISCONSIN P.S.	PULLIAM	04	GREEN BAY	WI		44	30	C	G	11819	7.7	.9	4.1	12.6	72	PE	RC	98.0					PI
WISCONSIN P.S.	PULLIAM	03	GREEN BAY	WI		39	30	C	G	11819	7.7	.9	4.1	12.6	72	PE	RC	98.0					PI
WISCONSIN PWR. & LT.	ROCK RIVER	02	BELOIT	WI		55	75	C		11447		1.0	4.4	9.0	72	PE	RC	99.5					
WISCONSIN PWR. & LT.	ROCK RIVER	01	BELOIT	WI		54	75	C		11447		1.0	4.4	9.0	71	PE	RC	99.5					
WISCONSIN PWR. & LT.	NELSON DEWEY	02	CASSVILLE	WI		62	100	C		10637	26.5	1.0	4.1	10.0	72	HP	RC	99.5					
WISCONSIN PWR. & LT.	NELSON DEWEY	01	CASSVILLE	WI		59	100	C		10837	26.5	1.0	4.1	10.0	72	PE	RC	99.5					
WISCONSIN PWR. & LT.	COLUMBIA	01	PORTAGE	WI	6	75	486	C				.5	2.9	9.0	74	HP	RC	99.5					SL
WISCONSIN PWR. & LT.	EDGEWATER	03	SHEBOYGAN	WI		51	60	C		10763		1.6	4.6	9.0	72	PE	RC	99.5					
WISCONSIN EL.PWR	S.OAK CREEK	07	OAK CREEK	WI		65	313	C		11639		.3	3.9	11.2	71	PE	WP	99.5					
WISCONSIN EL.PWR	S.OAK CREEK	06	OAK CREEK	WI		61	275	C		11639		.3	3.9	11.2	71	PE	WP	99.5					
WISCONSIN P.S.	WESTON	02	ROTHSCHILD	WI		49	75	C	G	11585		2.1	8.0		71	PE	WP	99.0					
WISCONSIN P.S.	WESTON	01	ROTHSCHILD	WI		40	60	C	G	11585		2.1	8.0		71	PE	WP	99.0					

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	28	3,958	28	3,958						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = WV

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	HEAT BTU	PCT MOIS	SULF-PCT MIN	SULF-PCT MAX	PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	RY	SO2 YR	SO2 TYPE	SO2 MFR	CON SLT
MONONGAHELA PWR.	RIVESVILLE	05	RIVESVILLE	WV		42	48	C		12440	4.1	1.6	4.4	12.8	73	PE		99.5					
MONONGAHELA PWR.	RIVESVILLE	06	RIVESVILLE	WV		49	94	C		12440	4.1	1.6	4.4	12.8	73	PE		99.5					
WEST PENN PWR.	HARRISON	02	HAYWOOD	WV		73	650	C		12200		.9	4.0			PE	AS	99.5					GH
WEST PENN PWR.	HARRISON	01	HAYWOOD	WV		72	650	C		12200		.9	4.0			PE	AS	99.5					GH
WEST PENN PWR.	HARRISON	03	HAYWOOD	WV	1	75	650	C				4.0	4.0			PE	AS	99.5					GH
APPALACHIAN PWR	KANAWHA RIVER	02	MONTGOMERY	WV		53	213	C		11486		.6	1.7		69	PE	BU	99.5					
APPALACHIAN PWR	KANAWHA RIVER	01	MONTGOMERY	WV		53	213	C		11486		.6	1.7		69	PE	BU	99.5					
MONONGAHELA PWR.	WILLOW ISLAND	01	WILLOW ISLAND	WV		52	50	C		10897	4.8	1.0	5.4	11.0	73	PE	BU	99.5					
MONONGAHELA PWR.	WILLOW ISLAND	02	WILLOW ISLAND	WV		60	165	C		10897	4.8	1.0	5.4	11.0	73	PE	BU	99.5					
MONONGAHELA PWR.	ALBRIGHT	02	ALBRIGHT	WV		48	69	C		11041	5.7	.7	3.8	21.6	73	PE	BU	99.5					
MONONGAHELA PWR.	ALBRIGHT	03	ALBRIGHT	WV		57	140	C		11041	5.7	.7	3.8	21.6	73	PE	BU	99.5					
APPALACHIAN PWR	SPORN PHILIP	03	NEW HAVEN	WV		53	153	CB				.8	3.0		74	PE	KC	99.7					
APPALACHIAN PWR	SPORN PHILIP	01	NEW HAVEN	WV		50	153	CB				.8	3.0		74	PE	KC	99.7					
OHIO POWER	AMOS	03	ST ALBANS	WV		73	1300	C		12017		.6	1.5		73	PE	KC	99.5					AP
OHIO POWER	SPORN PHILIP	05	NEW HAVEN	WV		60	450	CB				1.0	6.0		74	PE	KC	99.7					
OHIO POWER	SPORN PHILIP	04	NEW HAVEN	WV		52	153	CB				1.0	6.0		74	ME	KC	99.7					
OHIO POWER	SPORN PHILIP	02	NEW HAVEN	WV		50	153	CB				1.0	6.0		74	ME	KC	99.7					
APPALACHIAN PWR	AMOS J.E.	02	SCARY	WV	3	72	800	C		12017		.4	3.8		72	PE	RC	99.7					AP
APPALACHIAN PWR	AMOS J.E.	01	SCARY	WV		71	800	C		12017		.4	3.8		71	PE	RC	99.7					AP
OHIO POWER	MITCHELL	02	MOUNDSVILLE	WV		71	800	C		11731		1.2	4.3		70	PE	RC	98.5					AP
OHIO POWER	KAMMER	03	CAPTINA	WV		59	225	CB		12101		1.0	6.0		75	ME	RC	99.4					SR
OHIO POWER	KAMMER	02	CAPTINA	WV		58	225	CB		12101		1.0	6.0		75	ME	RC	99.4					SR
OHIO POWER	KAMMER	01	CAPTINA	WV		58	225	CB		12101		1.0	6.0		75	ME	RC	99.4					SR
OHIO POWER	MITCHELL	01	MOUNDSVILLE	WV		70	800	C		11731		1.2	4.3		70	PE	RC	99.7					AP
VIRGINIA EL.&PWR.	MT. STORM	01	MT. STORM	WV		65	570	C	O	11137		.7	2.0	25.5	71	PE	RC	99.5					
VIRGINIA EL.&PWR.	MT. STORM	02	MT. STORM	WV		66	570	C	O	11137		.7	2.0	25.5	71	PE	RC	99.5					
VIRGINIA EL.&PWR.	MT. STORM	03	MT. STORM	WV	6	73	560	C	O	11137		.7	2.0	25.5	69	PE	RC	99.7					SW

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	27	10,879	27	10,879						

LIST OF UNITS INSTALLED THROUGH 1975 BY STATE
STATE = WY

UTILITY CO. NAME	PLANT NAME	UNIT	LOCATION CITY	LOCATION ST	MO	YR	UNIT SIZE MW	FUEL TYPE 1	FUEL TYPE 2	FUEL HEAT BTU	FUEL PCT MOIS	FUEL SULF-PCT MIN	FUEL SULF-PCT MAX	FUEL PCT ASH	PARTICULATE YR	PARTICULATE TYPE	PARTICULATE MFR	PARTICULATE PCT EFY	PARTICULATE RY	SO2 YR	SO2 TYPE	SO2 MFR	CONSLT
PACIFIC PWR & LT	JOHNSTON D.	04	GLENROCK	WY		72	330	C		7583		.8	.8	9.3		SC		99.7			FS	CH	EB
UTAH PWR.&LT.	NAUGHTON	03	KEMMERER	WY		71	330	CS	O	9413		.5	.5	4.7		PE		98.0					SR
UTAH PWR.&LT.	NAUGHTON	01	KEMMERER	WY		63	163	CS	O	9413		.5	.5	4.7	72	ME	LC	99.1					
PACIFIC PWR & LT	BRIDGER JIM	01	ROCK SPRINGS	WY		74	500	C							74	PE	SF	99.3					8E

	ALL UNITS	ALL UNITS MW	COAL UNITS	COAL MW	OIL UNITS	OIL MW	GAS UNITS	GAS MW	NUCLEAR UNITS	NUCLEAR MW
SUBTOTAL	4	1,323	4	1,323						
GRAND TOTAL	582	142,657	582	142,657						

APPENDIX B

GRAPHICAL CORRELATIONS OF CAPITAL AND ANNUALIZED OPERATING COSTS, AS A FUNCTION OF PLANT POWER OUTPUT FOR ELECTROSTATIC PRECIPITATORS

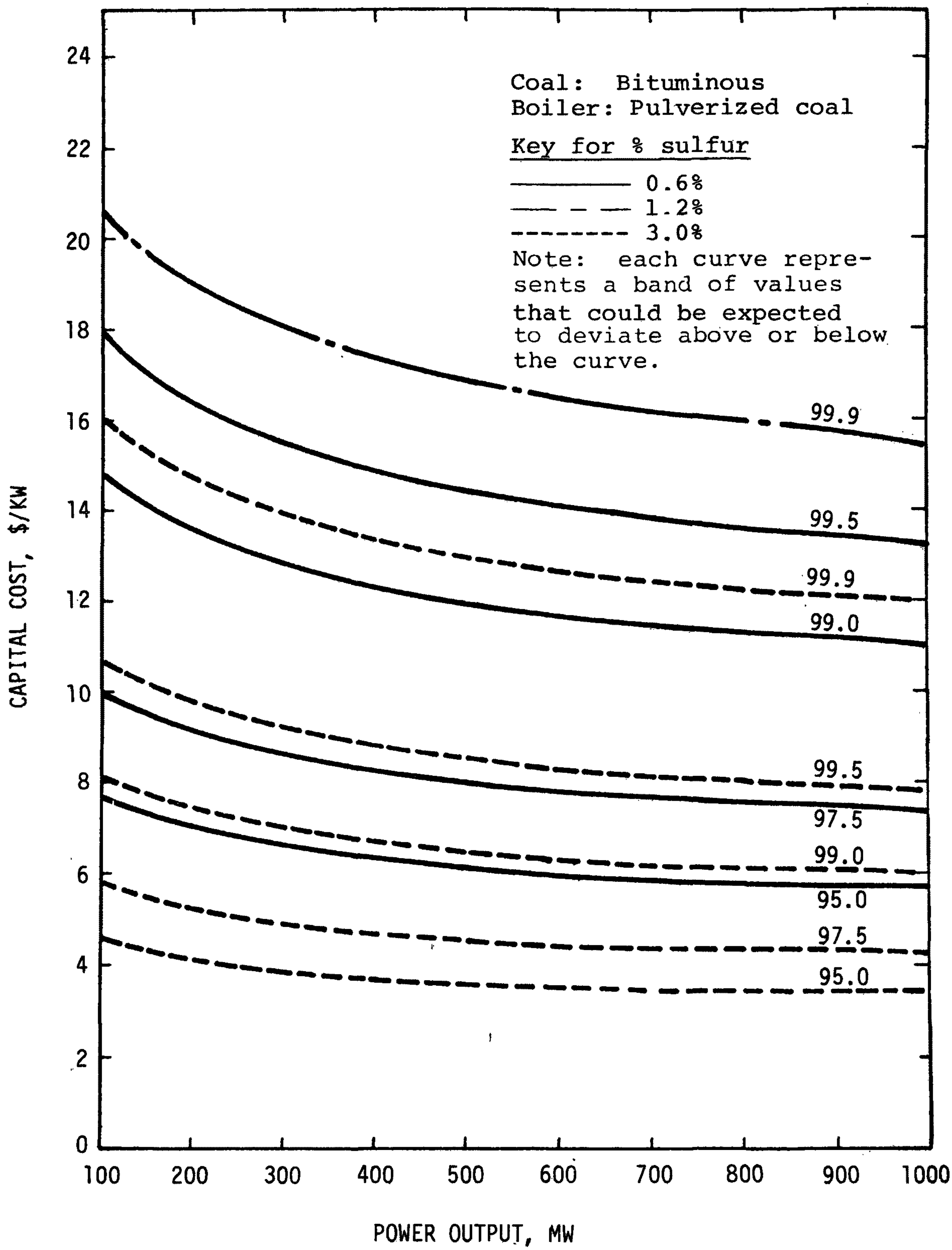

Figure B-1. Capital cost: cold-side ESP, pulverized bituminous.

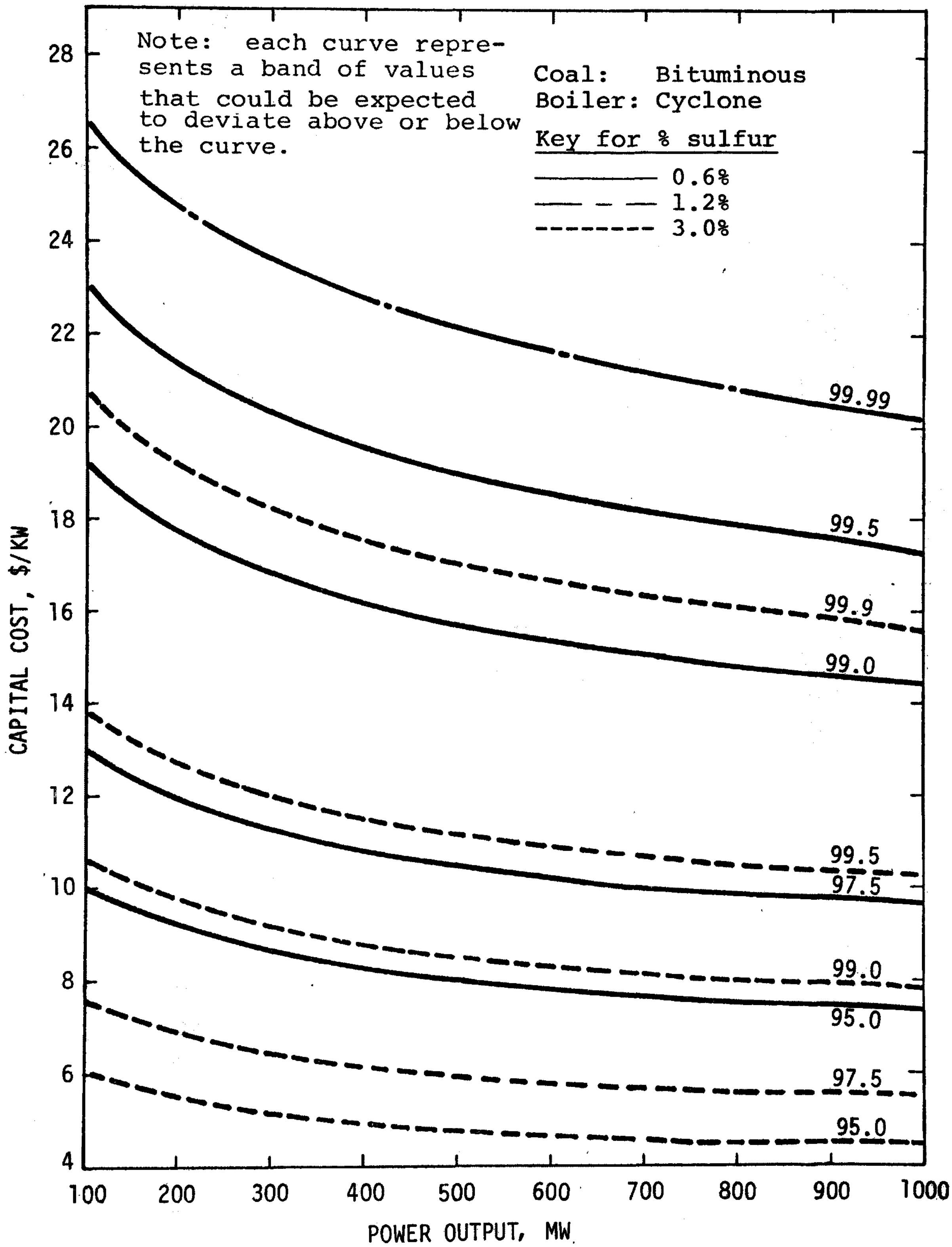

Figure B-2. Capital cost: cold-side ESP, cyclone-fired bituminous.

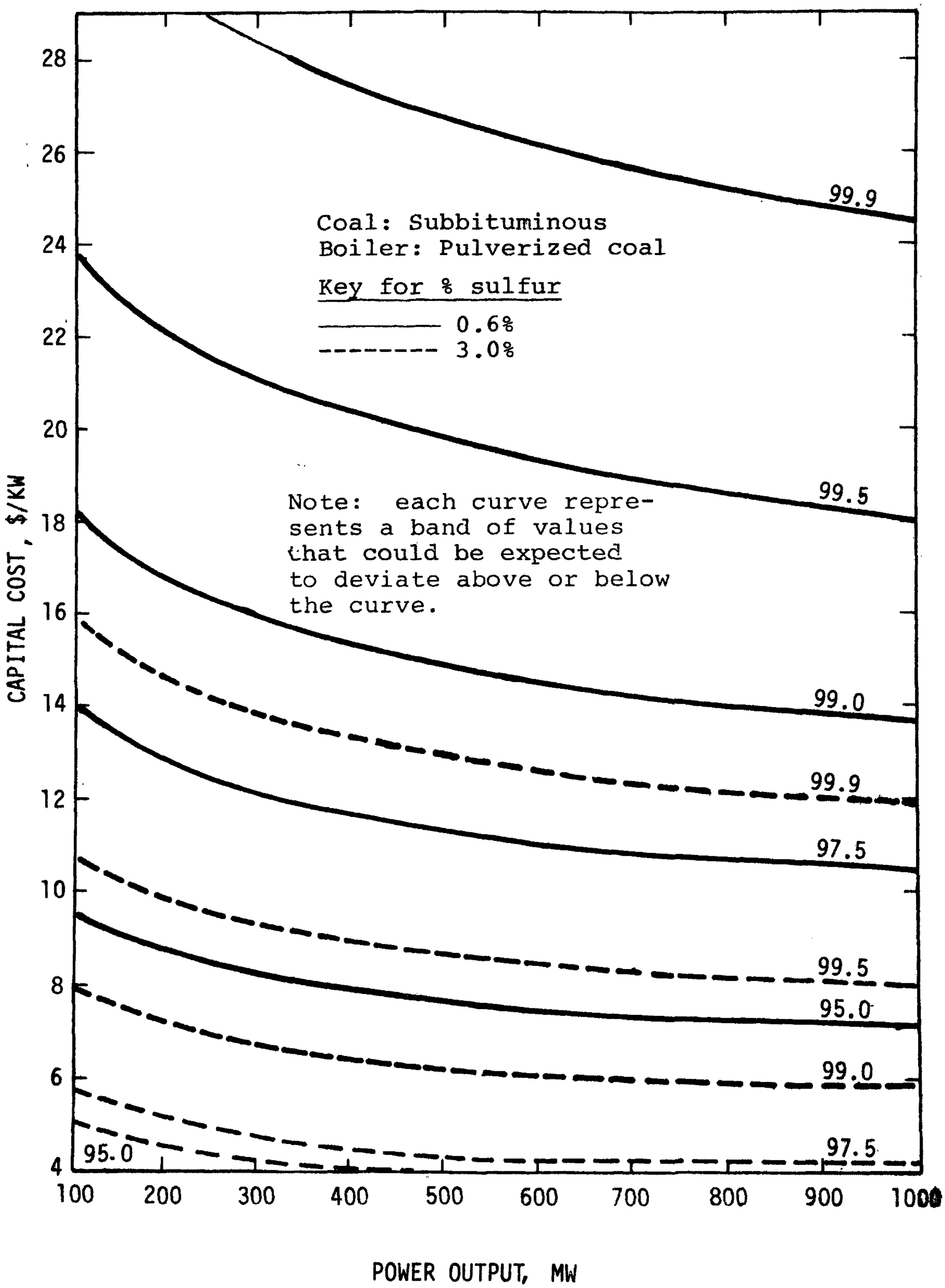

Figure B-3. Capital cost: cold-side ESP, pulverized subbituminous.

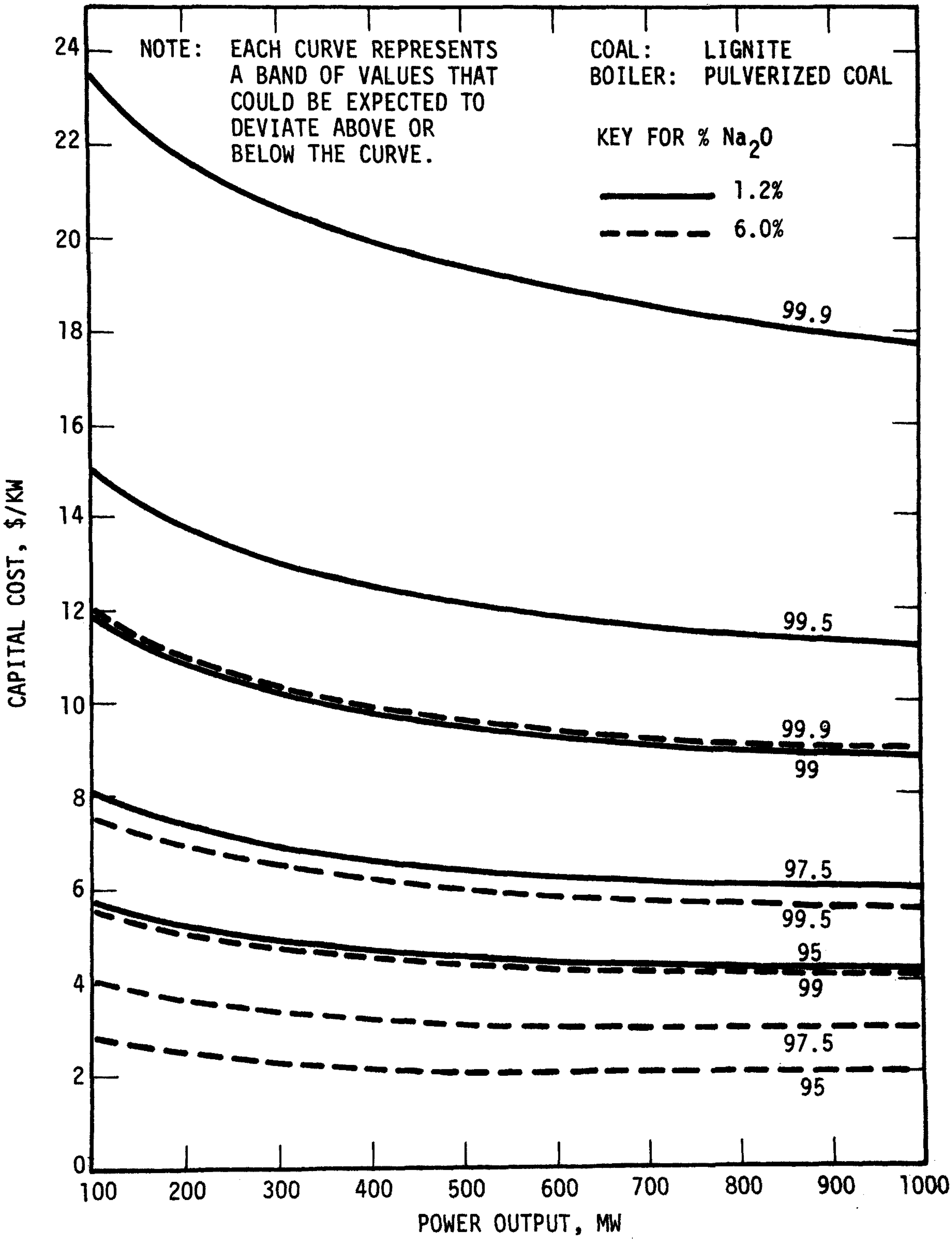

Figure B-4. Capital cost: cold-side ESP, pulverized lignite.

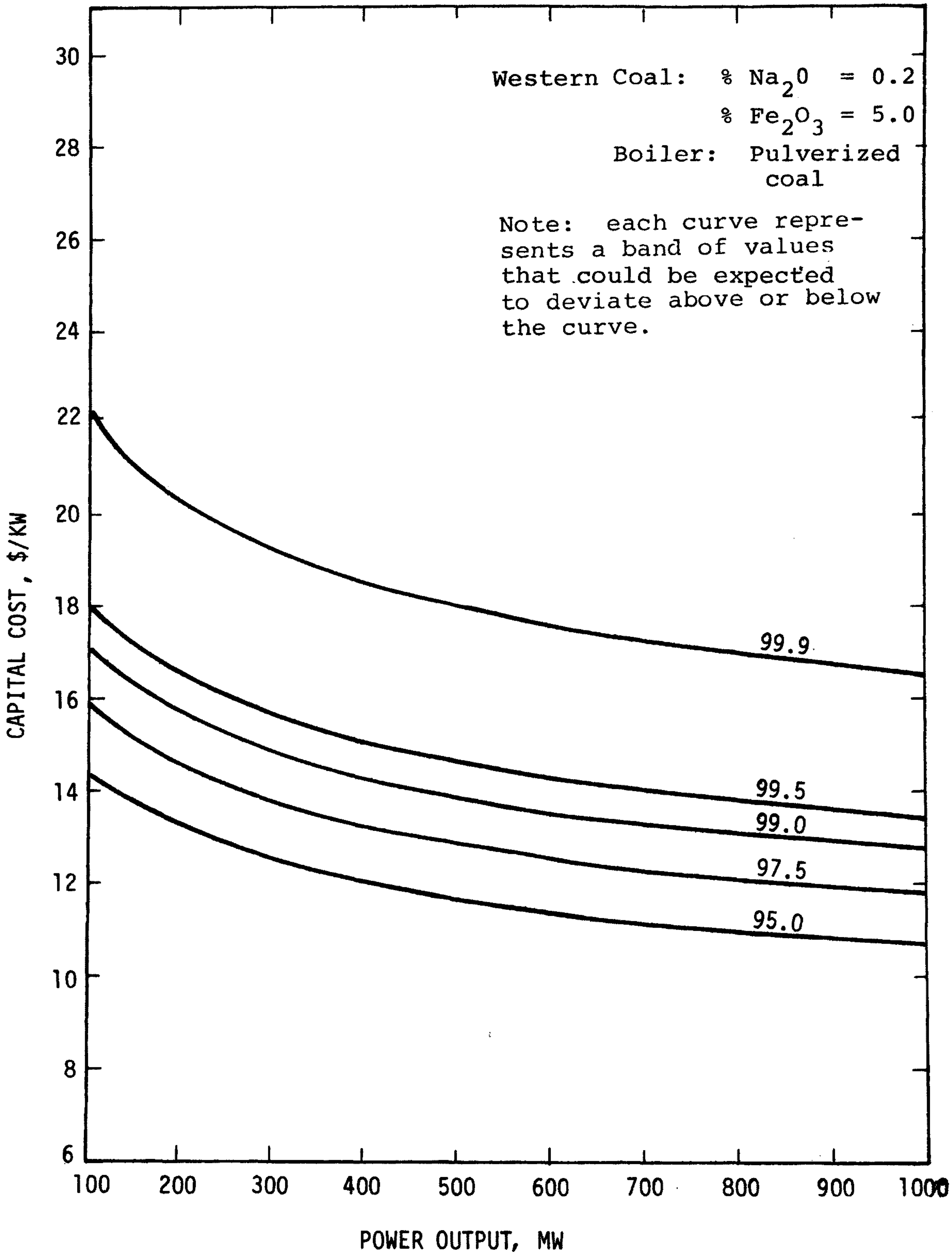

Figure B-5. Capital cost: hot-side ESP, pulverized low-sodium western coal.

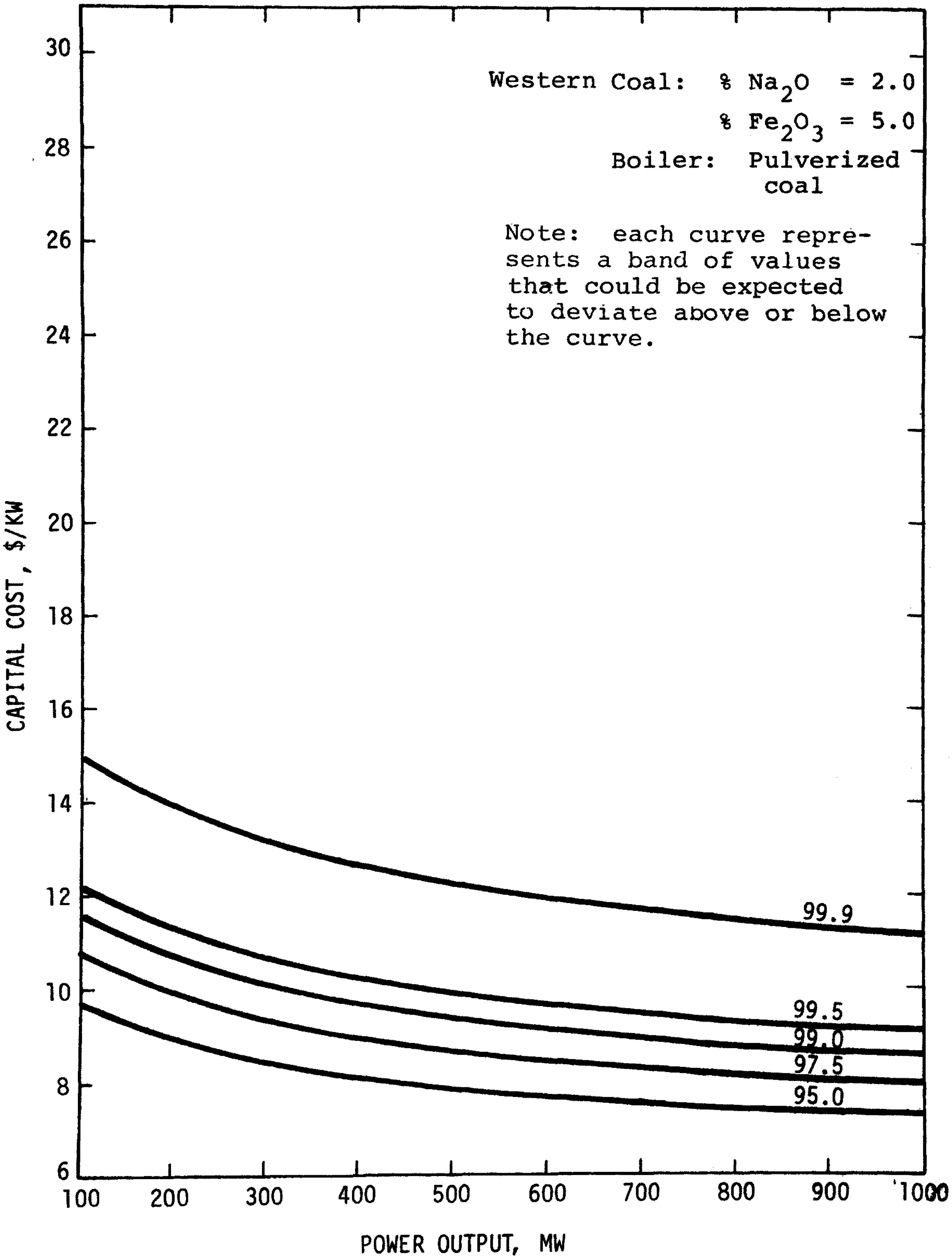

Figure B-6. Capital cost: hot-side ESP, pulverized western coal.

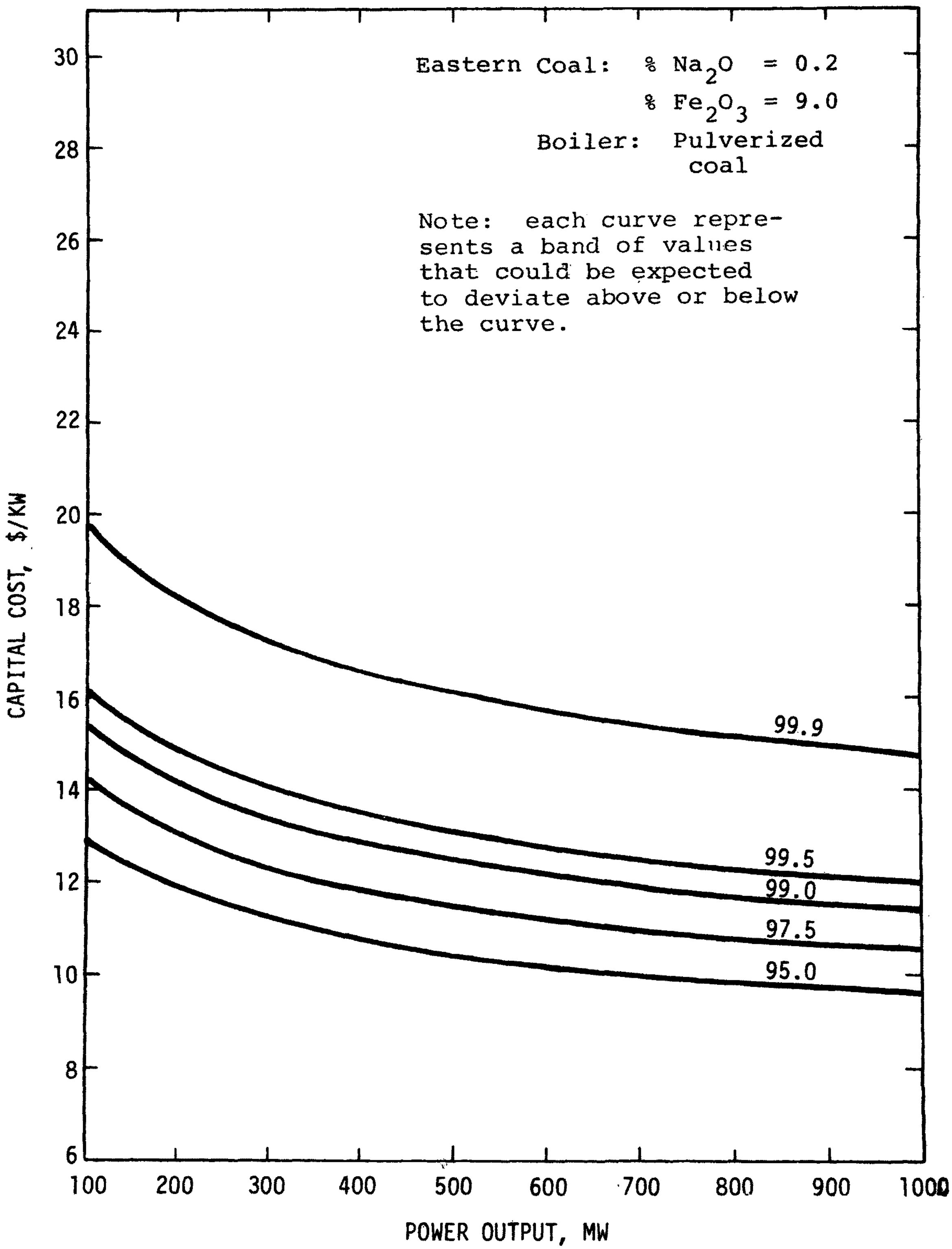

Figure B-7. Capital cost: hot-side ESP, pulverized low-sodium eastern coal.

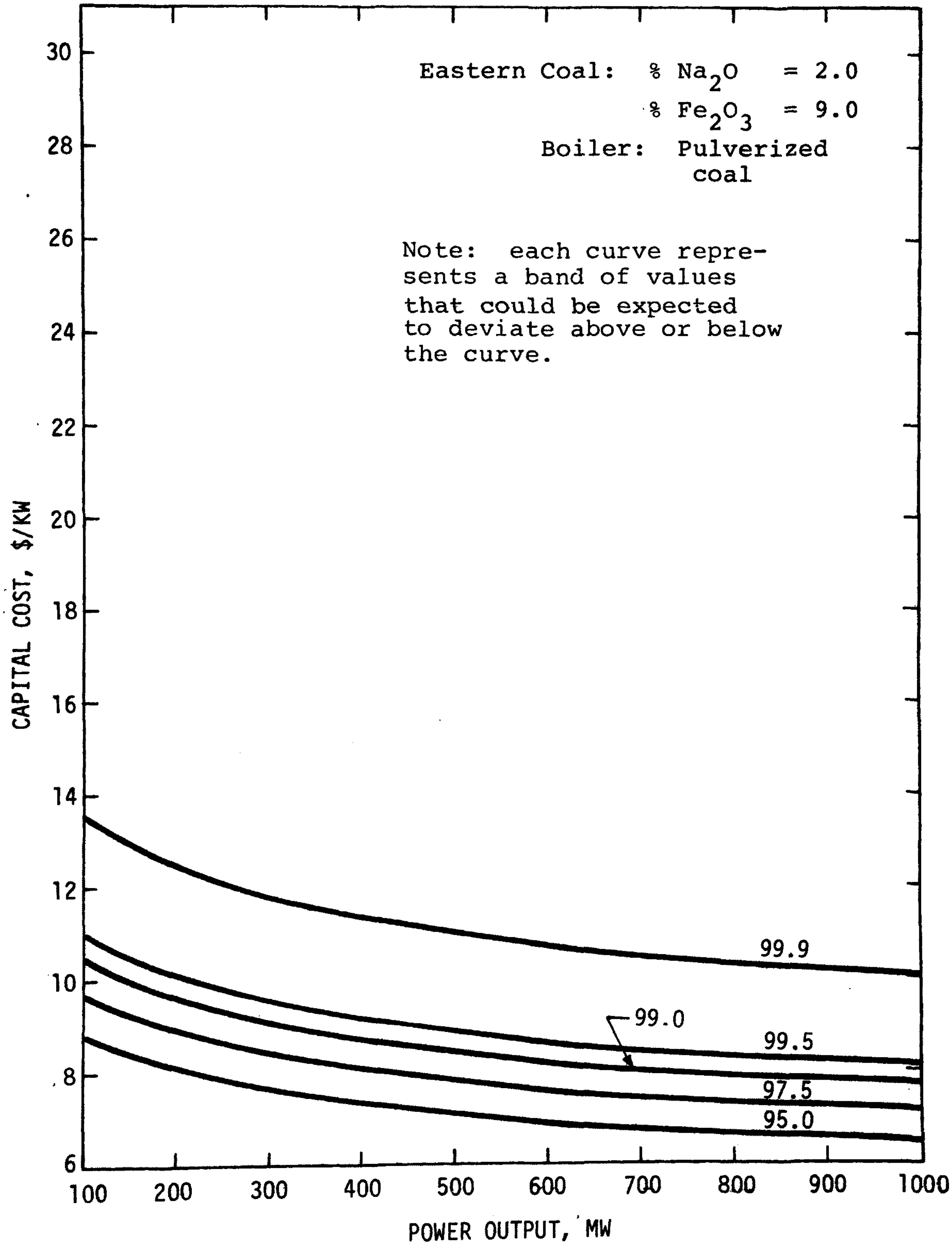

Figure B-8. Capital cost: hot-side ESP, pulverized eastern coal.

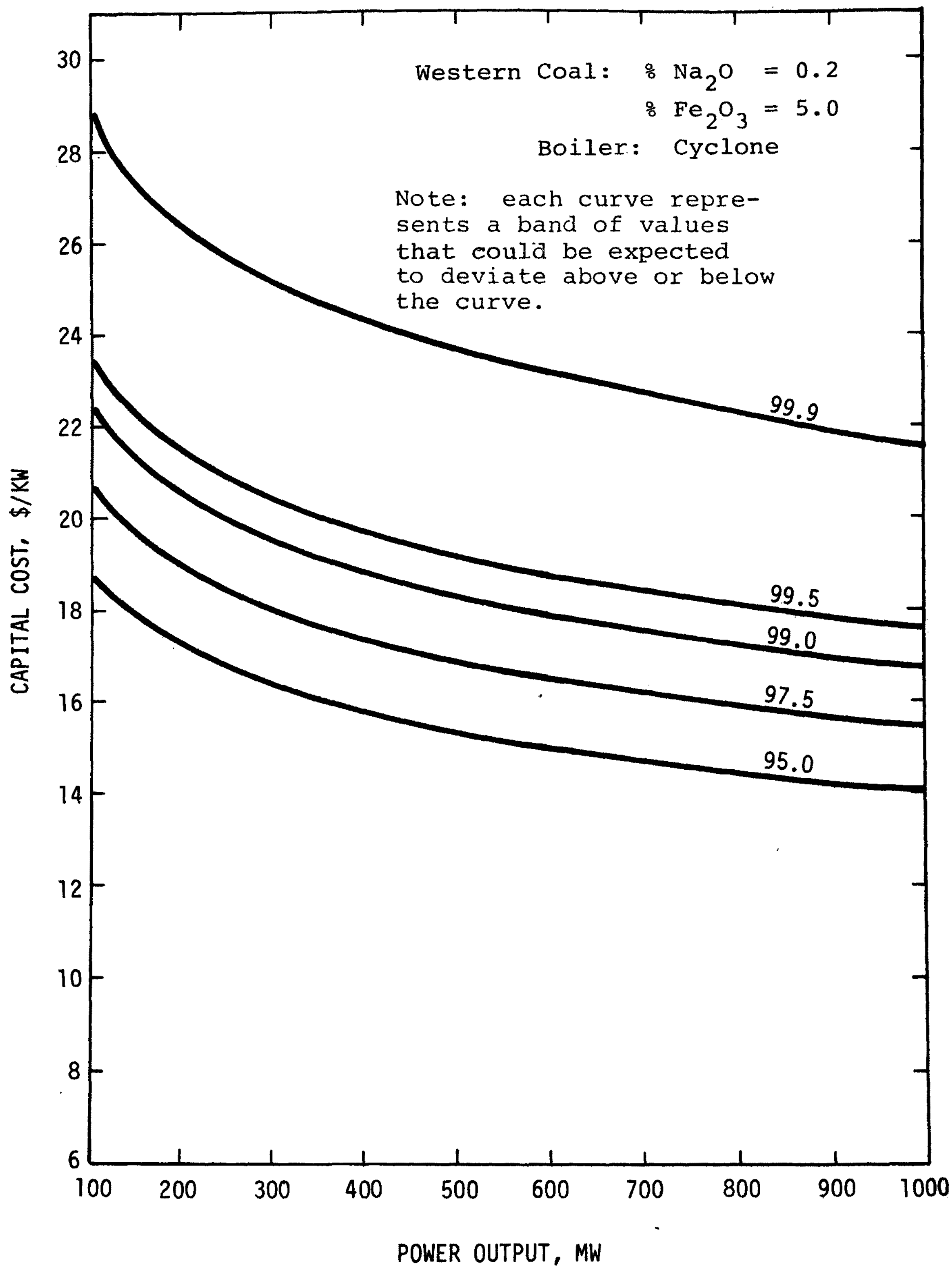

Figure B-9. Capital cost: hot-side ESP, cyclone-fired low-sodium western coal.

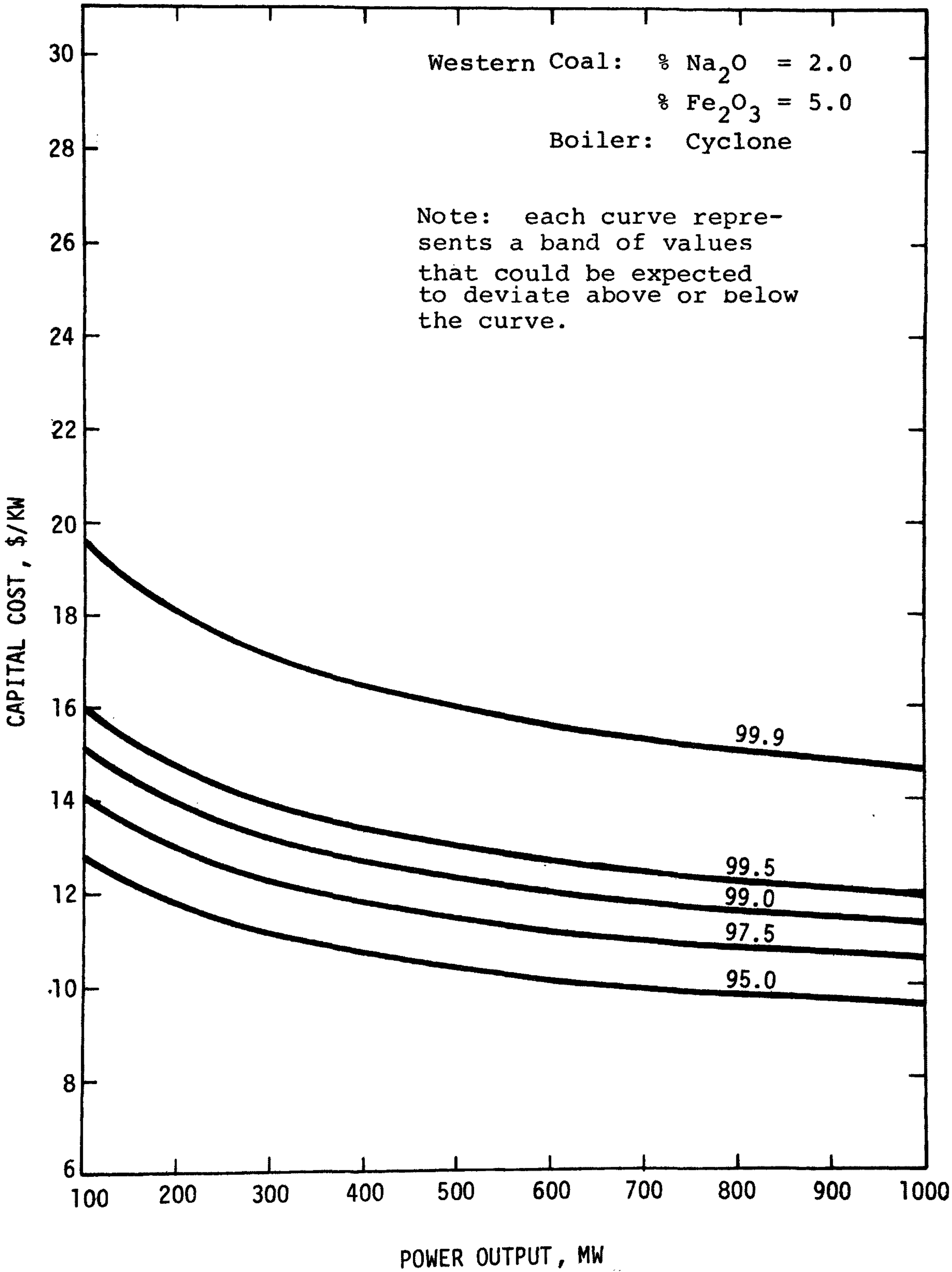

Figure B-10. Capital cost: hot-side ESP, cyclone-fired western coal.

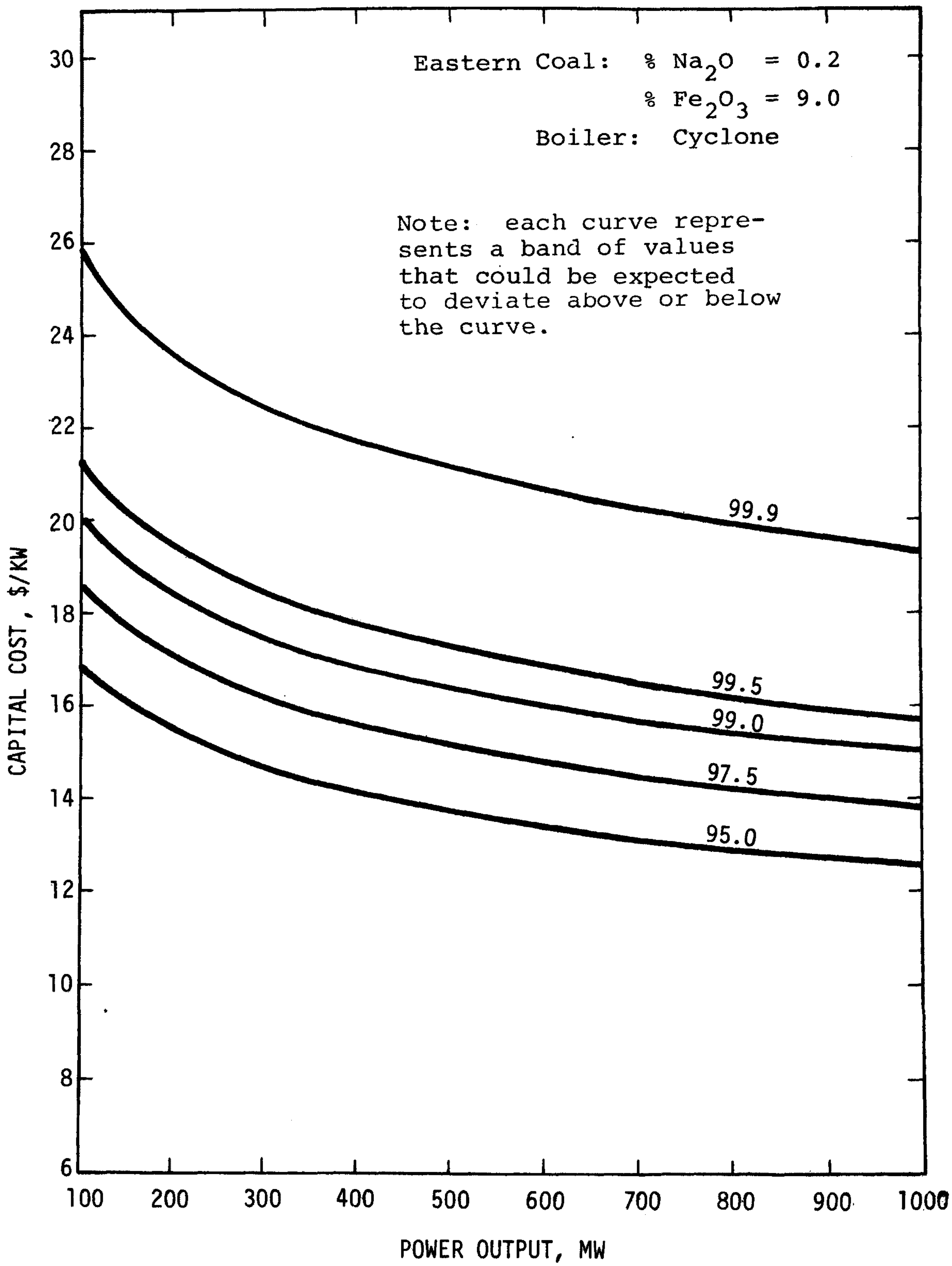

Figure B-11. Capital cost: hot-side ESP, cyclone-fired low-sodium eastern coal.

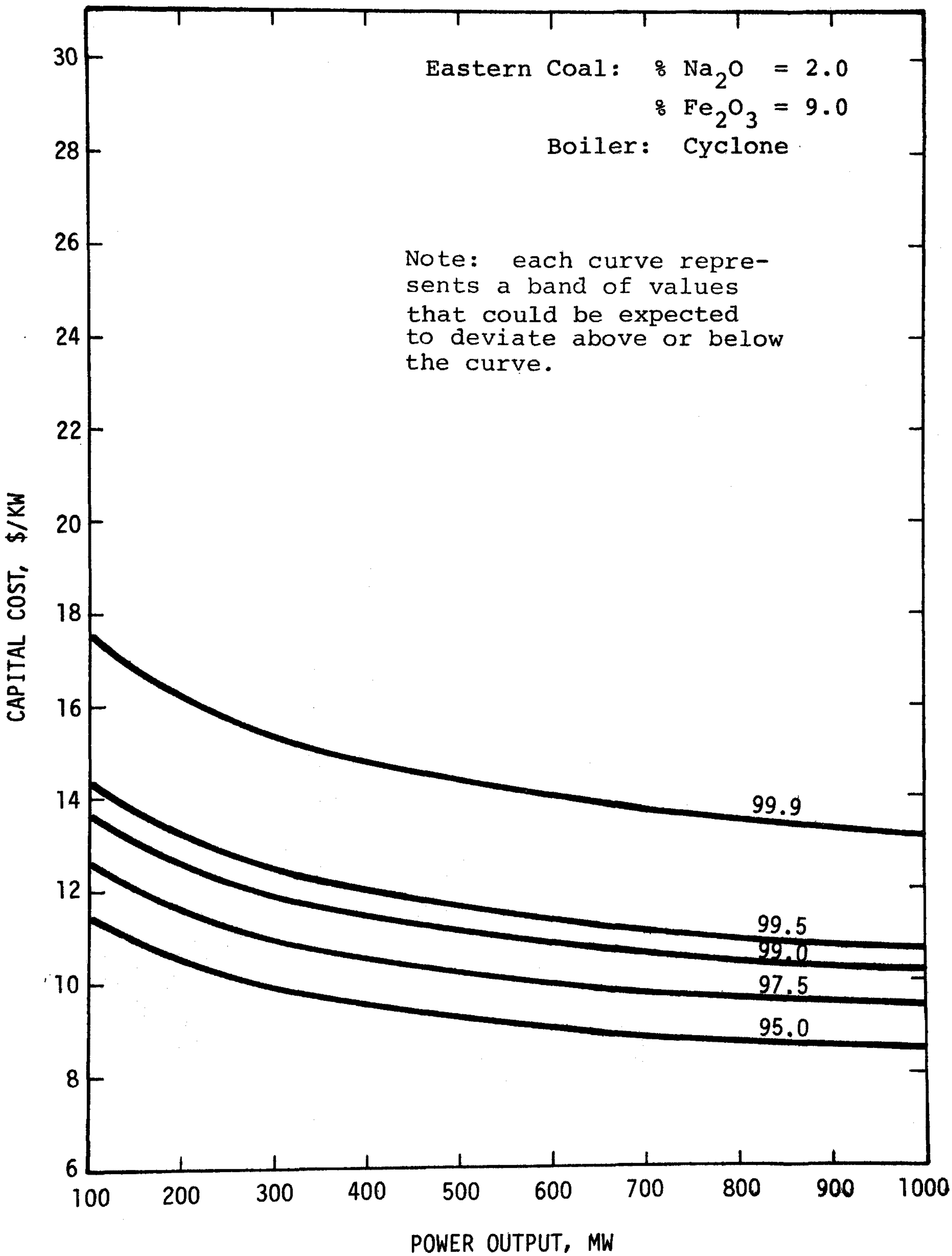

Figure B-12. Capital cost: hot-side ESP, cyclone-fired eastern coal.

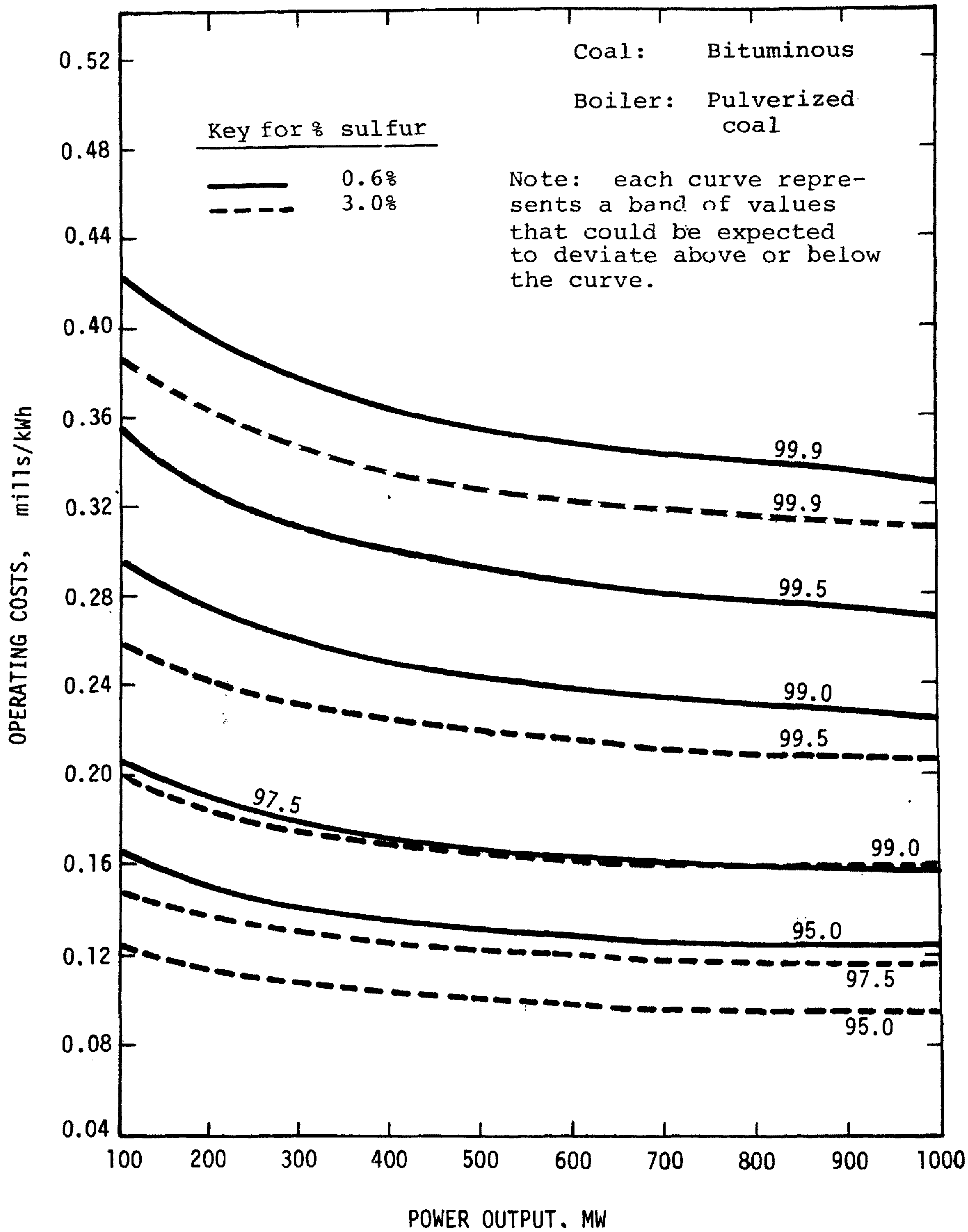

Figure B-13. Operating cost: cold-side ESP, pulverized bituminous

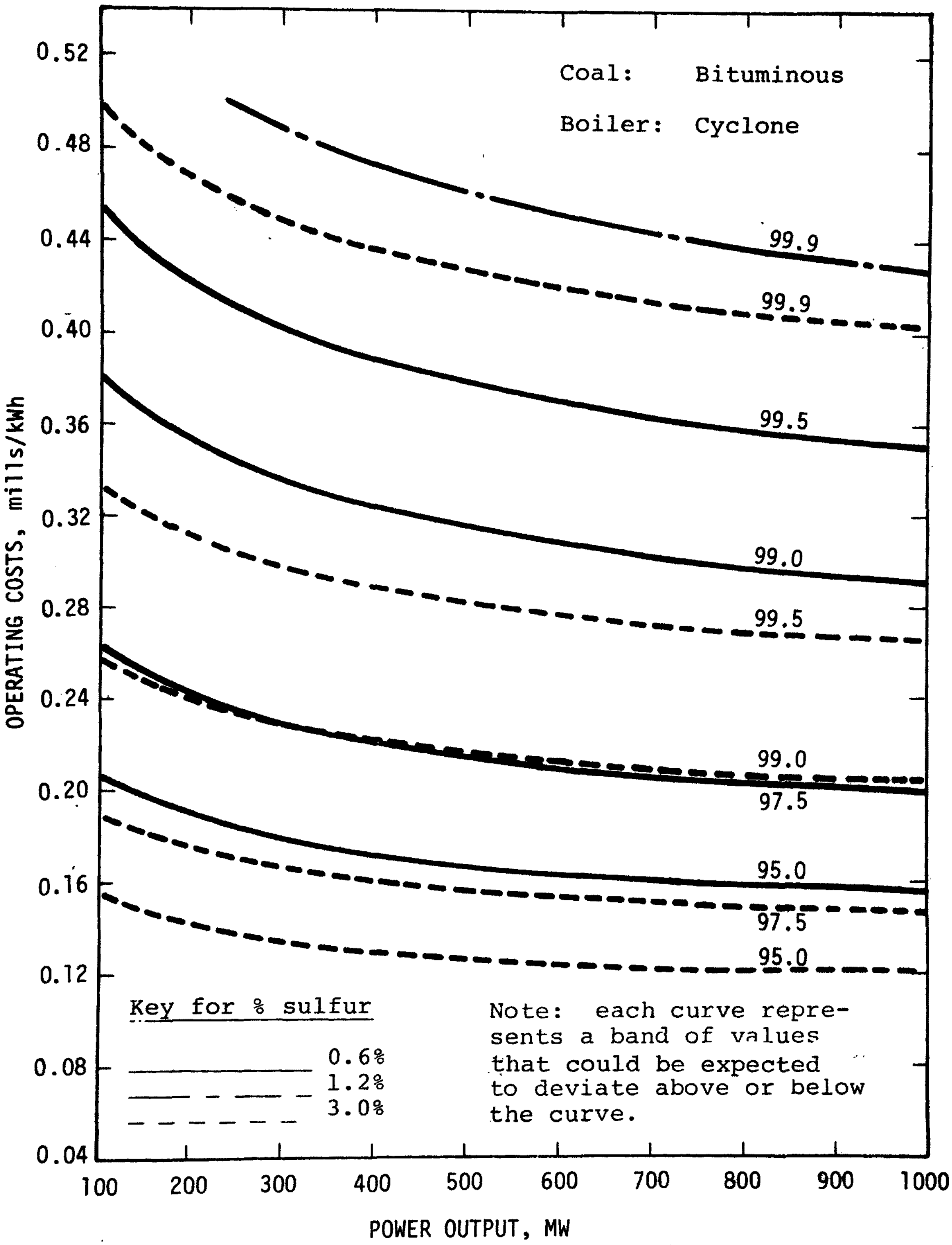

Figure B-14. Operating cost: cold-side ESP, cyclone-fired bituminous.

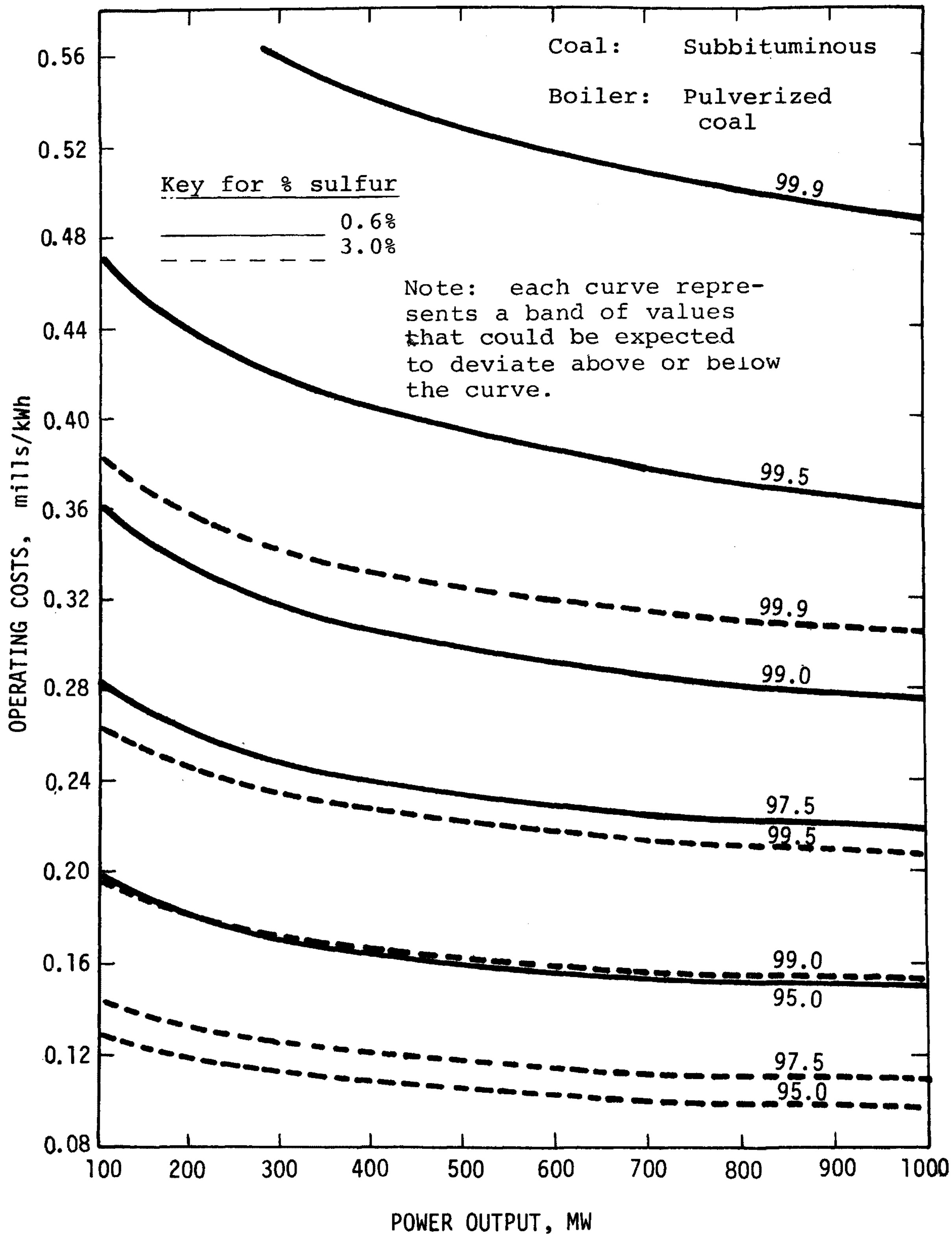

Figure B-15. Operating cost: cold-side ESP, pulverized subbituminous.

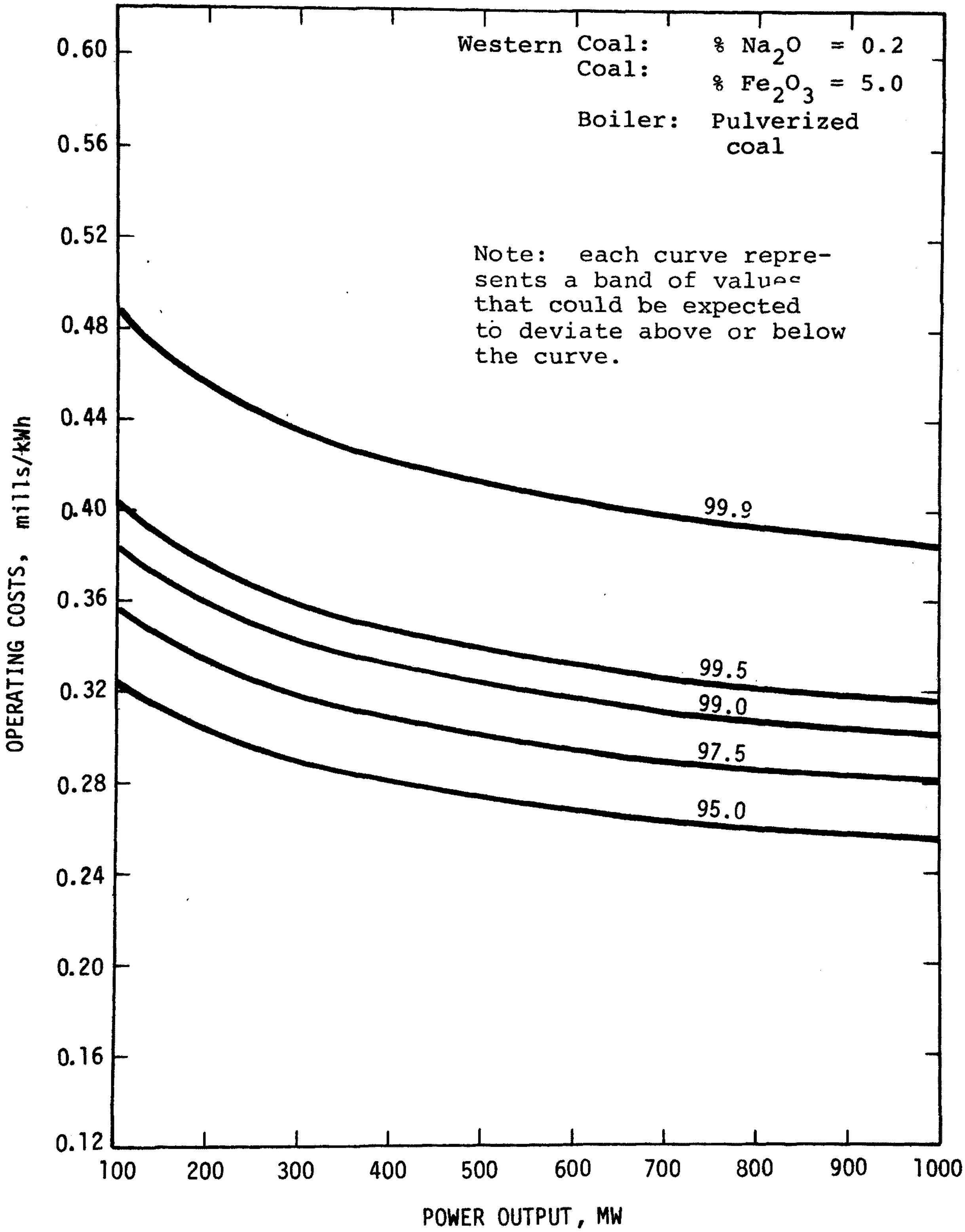

Figure B-16. Operating cost: hot-side ESP, pulverized low-sodium western coal.

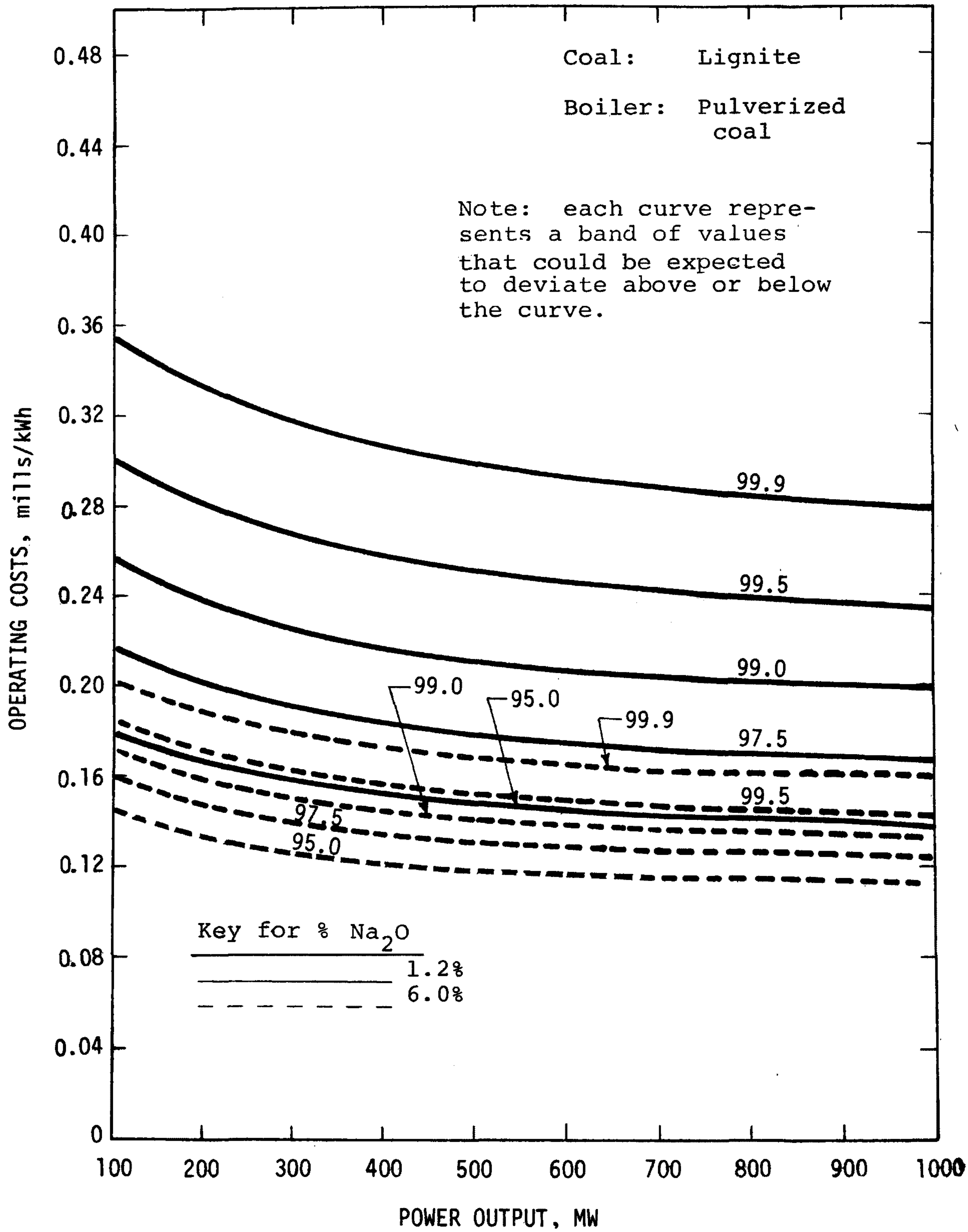

Figure B-17. Operating cost: cold-side ESP, pulverized lignite.

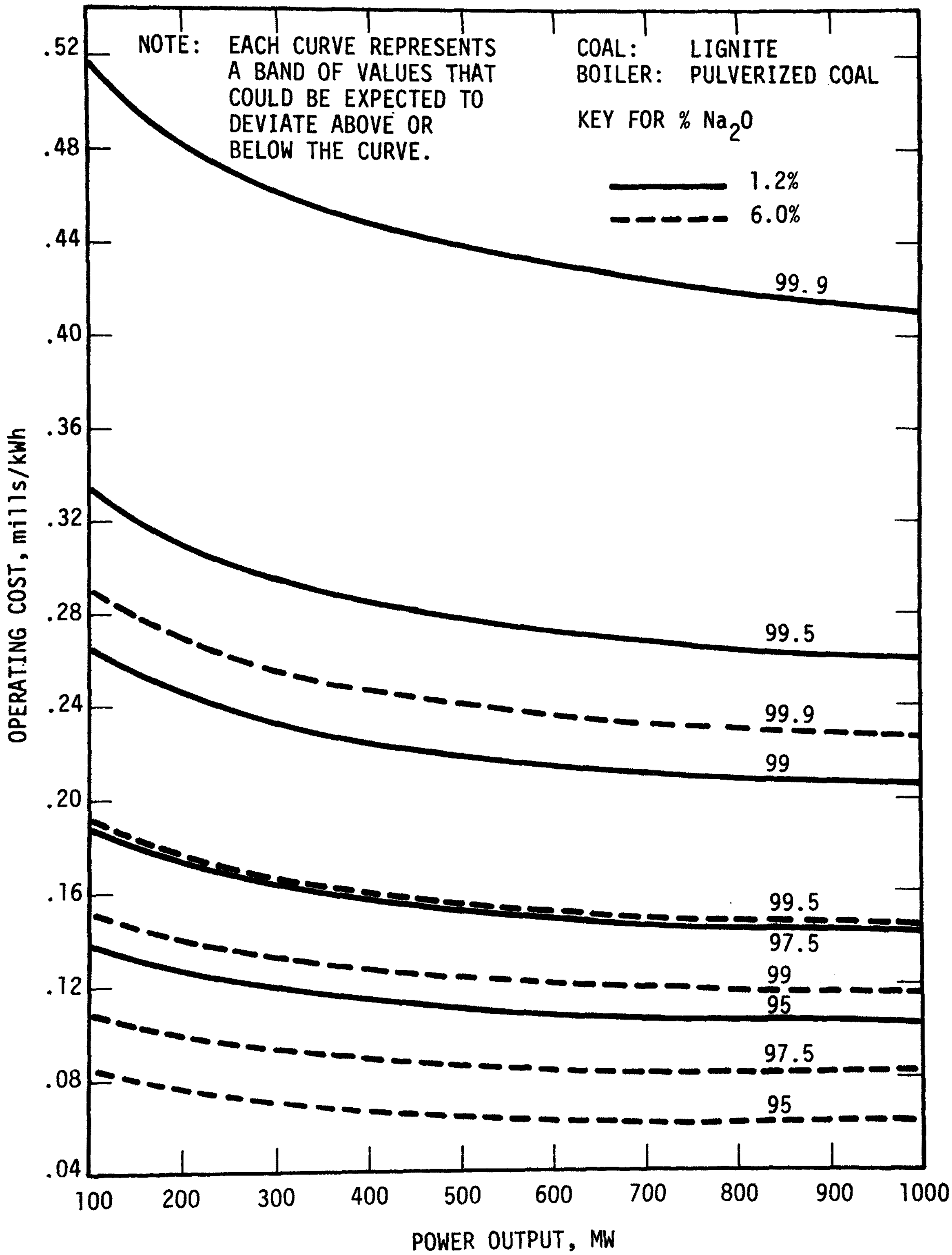

Figure B-18. Operating cost: hot-side ESP, pulverized western coal.

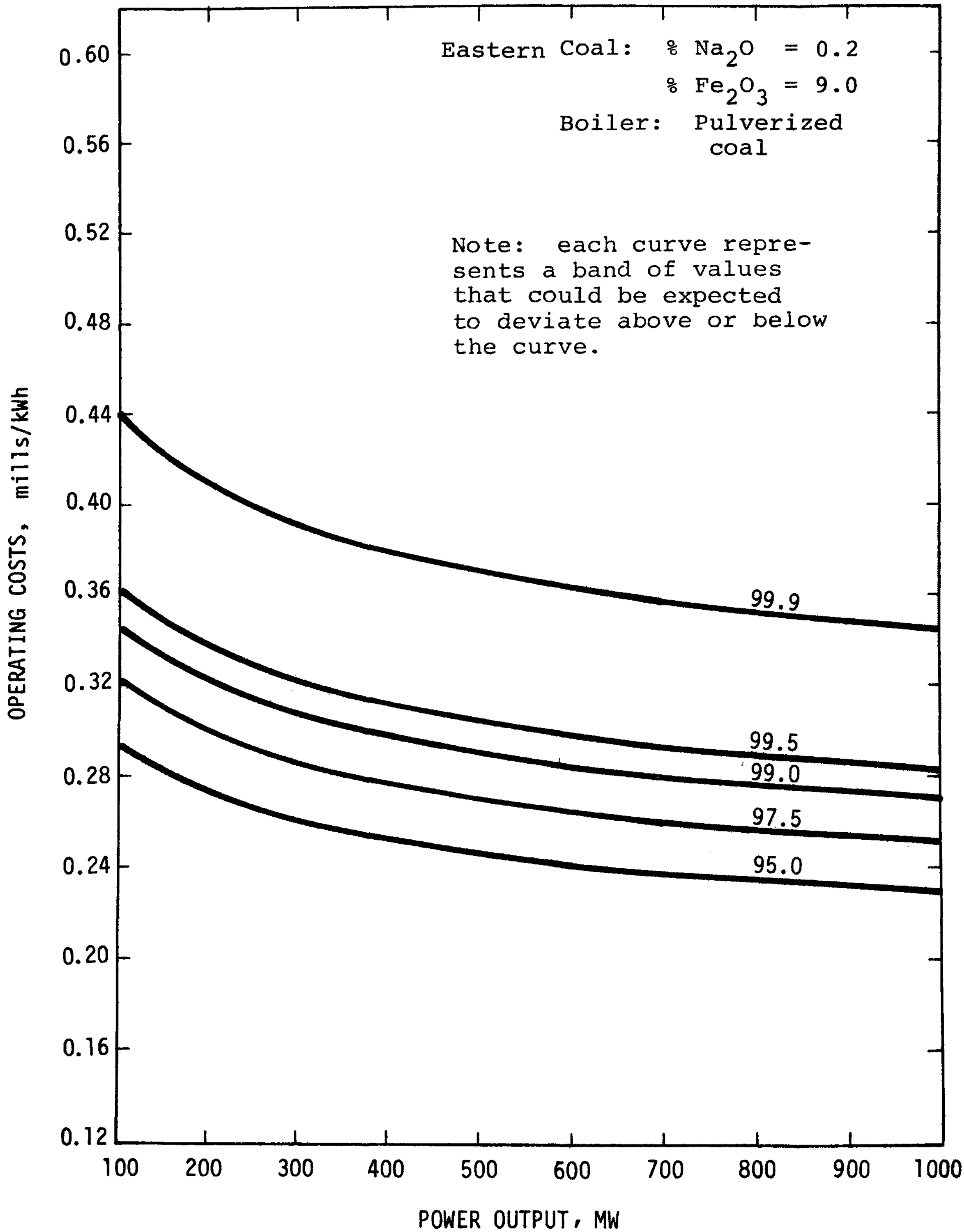

Figure B-19. Operating cost: hot-side ESP, pulverized low-sodium eastern coal.

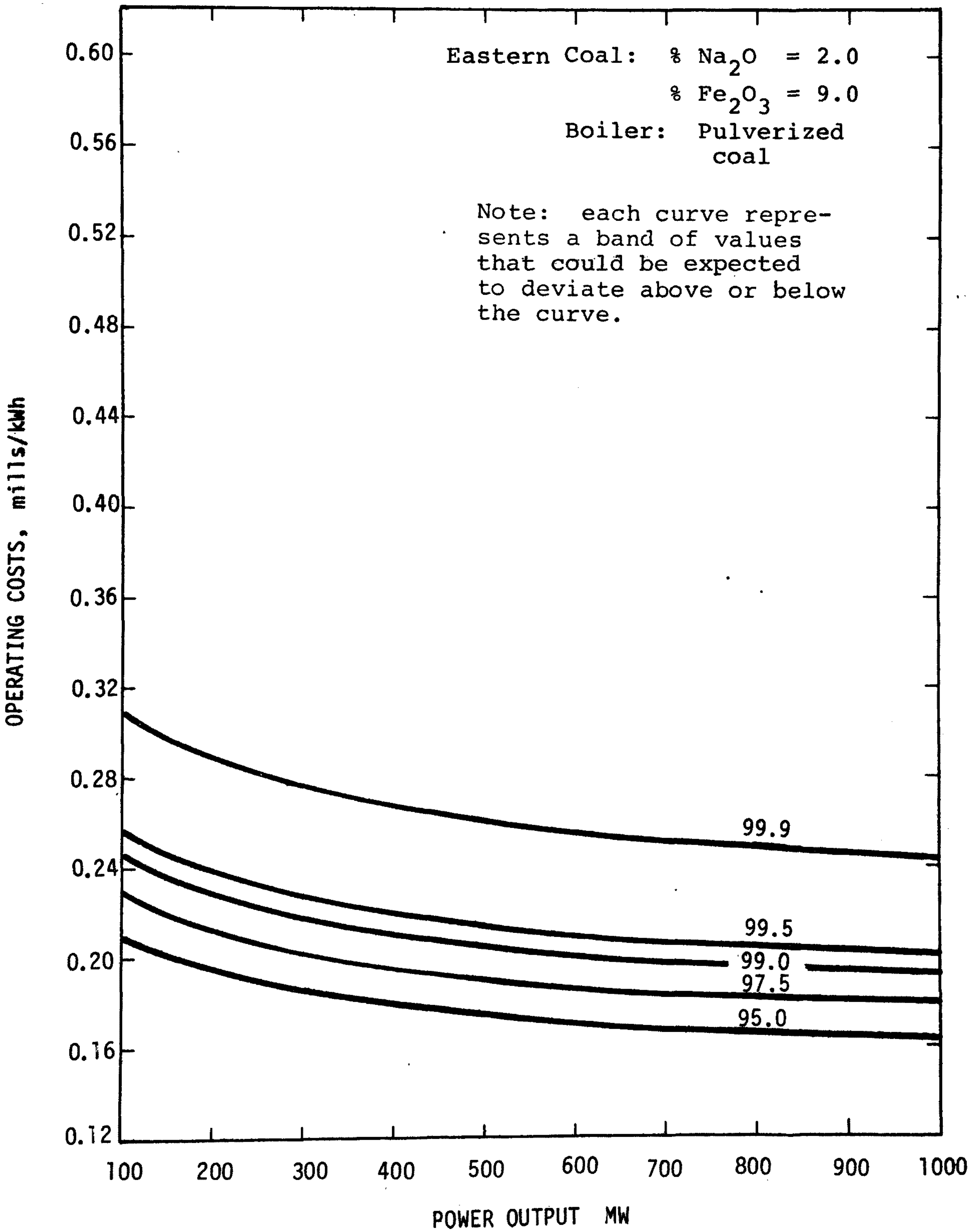

Figure B-20. Operating cost: hot-side ESP, pulverized eastern coal.

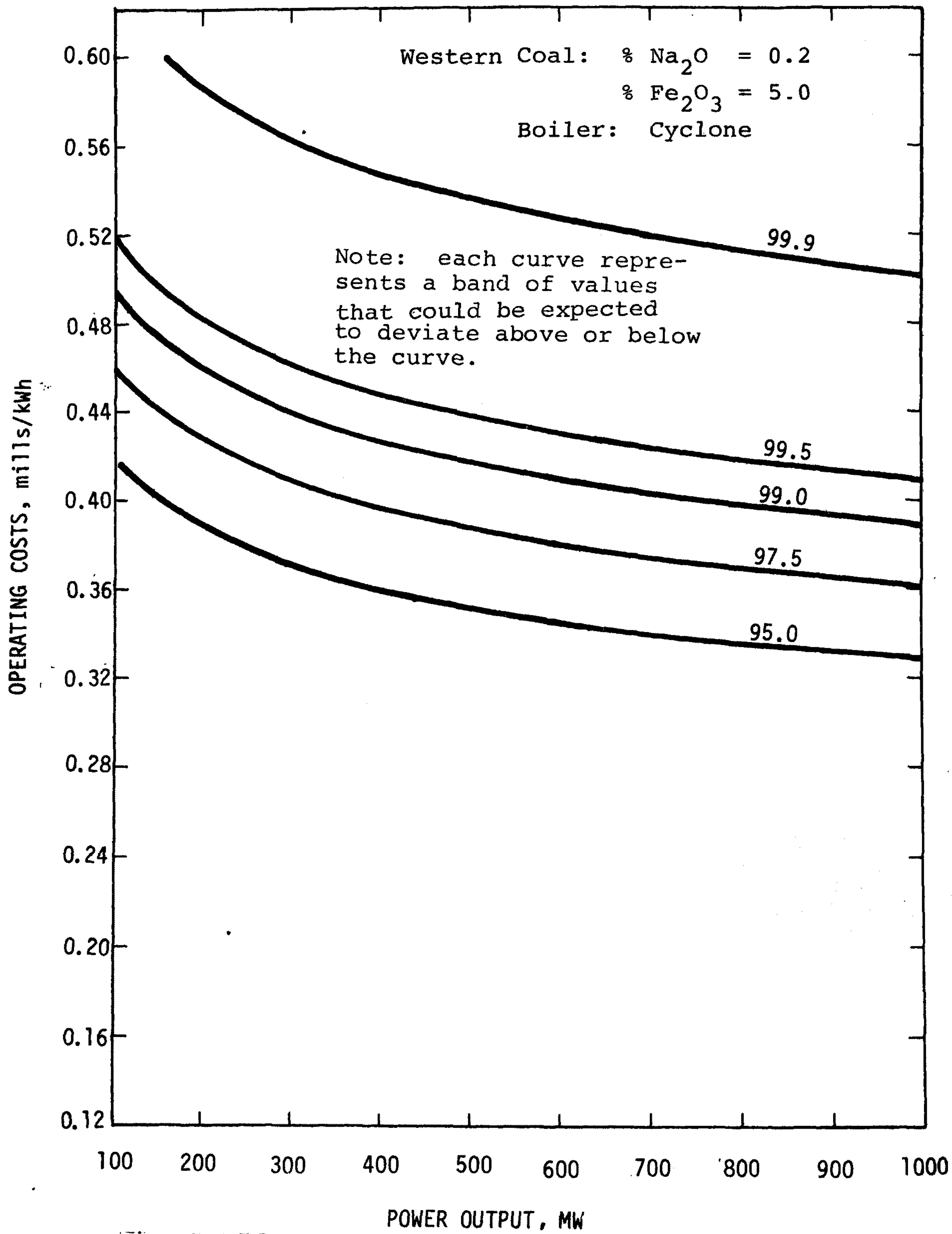

Figure B-21. Operating cost: hot-side ESP, cyclone-fired low-sodium western coal.

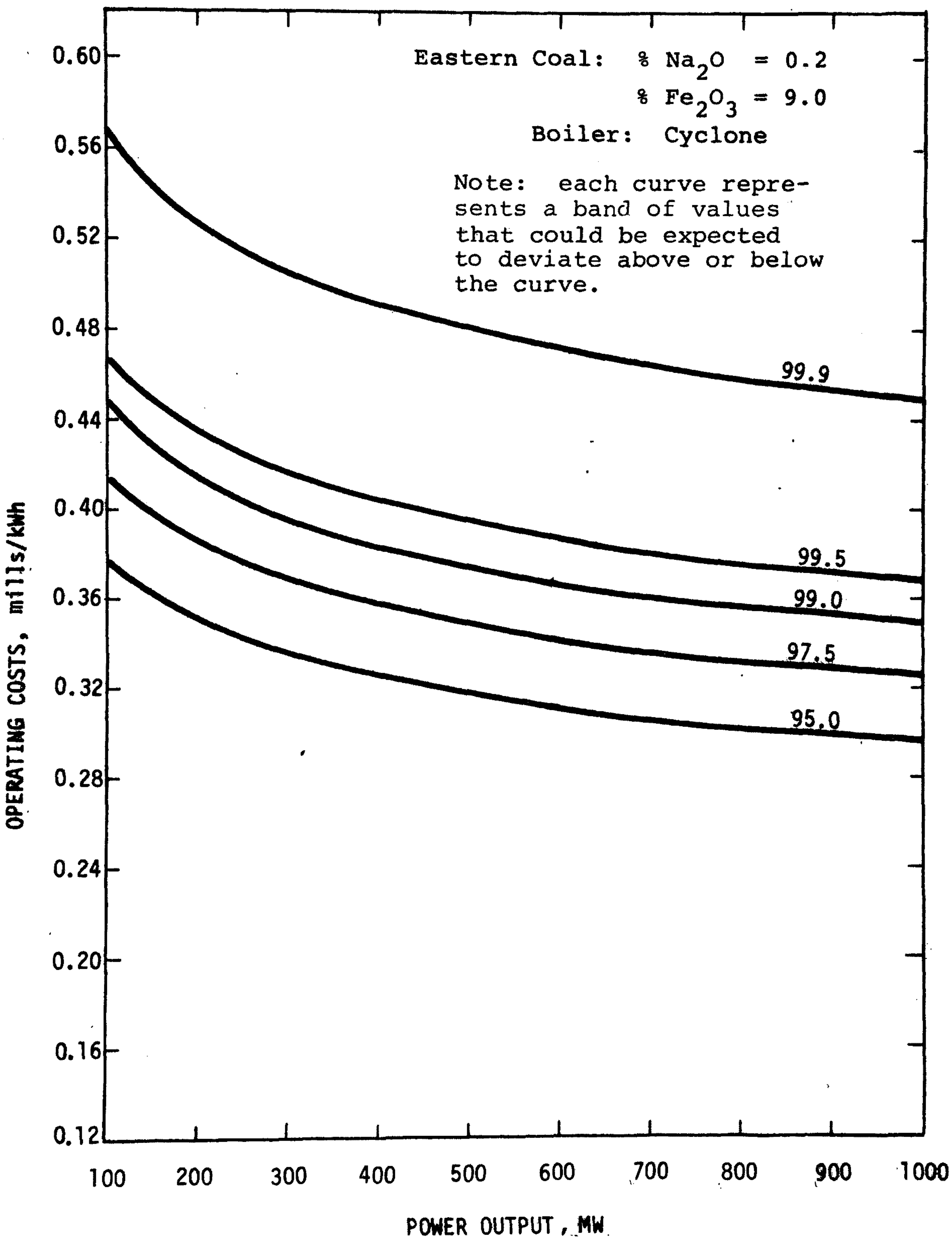

Figure B-22. Operating cost: hot-side ESP, cyclone-fired low-sodium eastern coal.

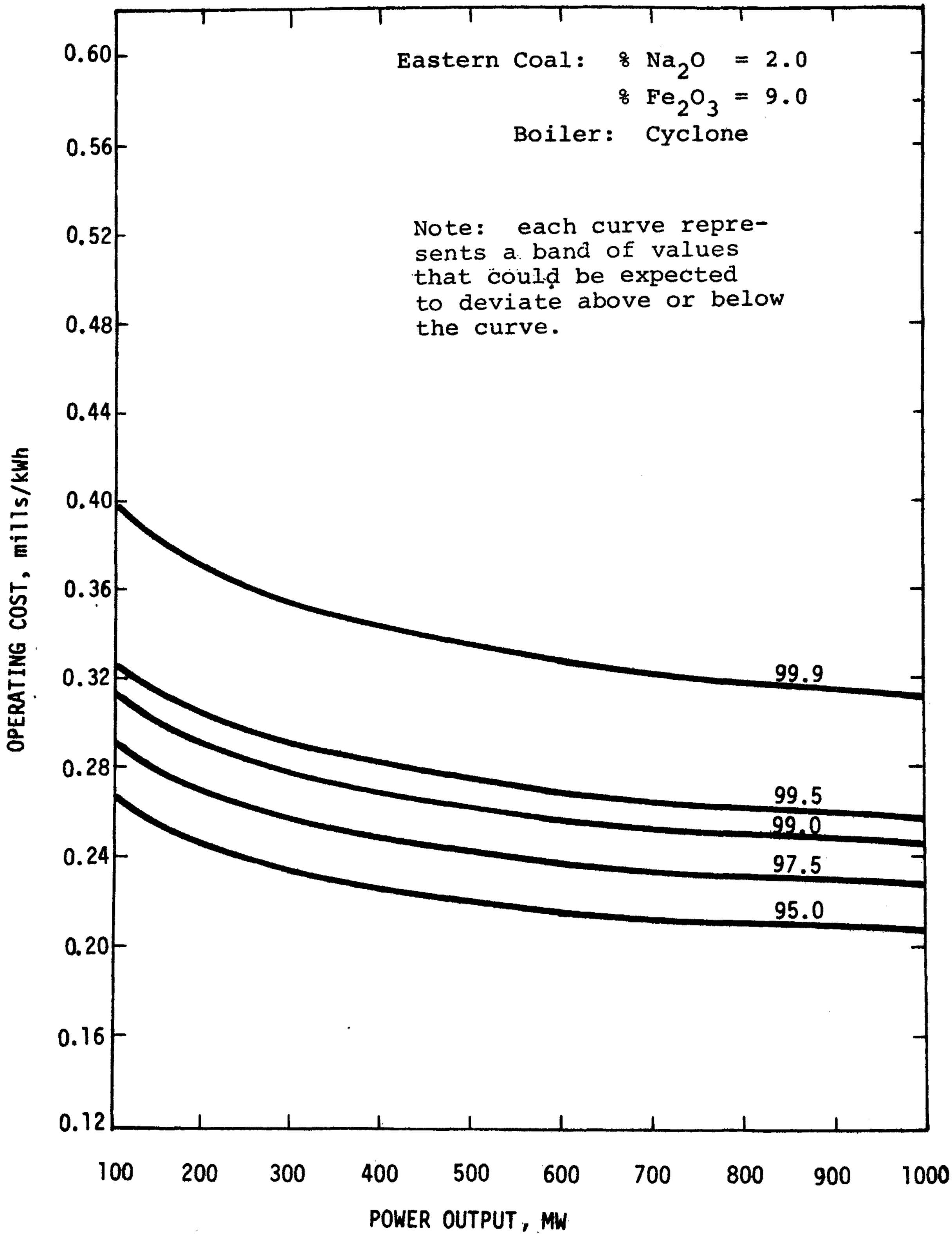

Figure B-23. Operating cost: hot-side ESP, cyclone-fired eastern coal.

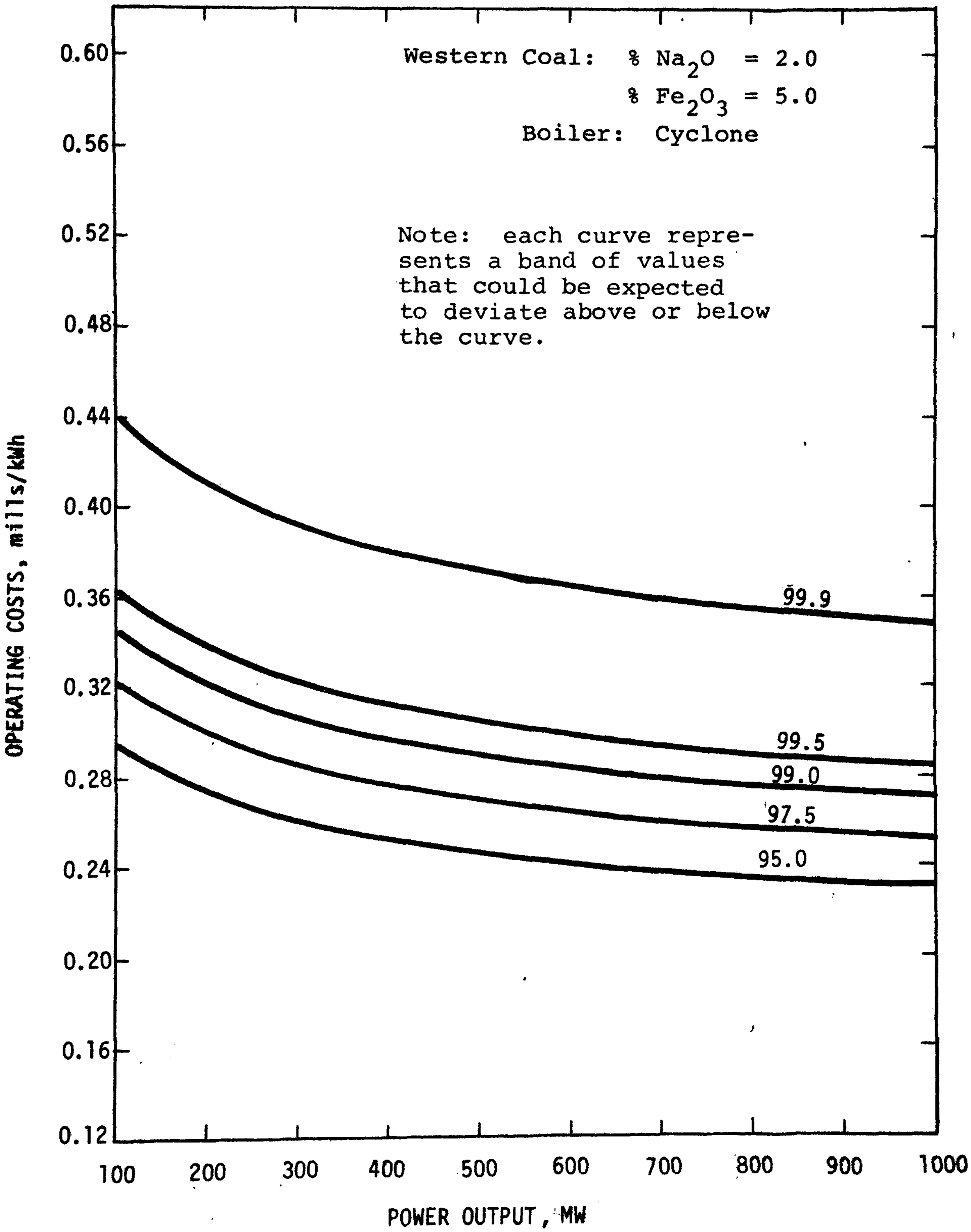

Figure B-24. Operating cost: hot-side ESP, cyclone-fired western coal.

APPENDIX C

PRE-OPERATING CHECKLIST FOR PRECIPITATORS

APPENDIX C. PRE-OPERATING CHECKLIST FOR PRECIPITATORS

1.) General

Before start-up of the precipitator(s) and auxiliary equipment, a complete check and visual inspection of the following items should be performed.

2.) Precipitator

	Check	Initial	Date	Recheck	Remarks
a) Duct spacing					
b) Collecting plates					
° Bowing					
° Bellying					
° Supports					
° Spacer bars					
° Corner guides					
c) Gas sneakage baffles					
d) Anti-swing devices					
e) Hoppers					
° Dust level indicators					
° Outlet connections					
° Access doors					
° Poke holes - anvils					
° Vibrators					
f) Insulator housing					
° Support bushings					
° Access doors					
° Ventilation system					
° Bushing connections					
° Bushing heaters					

	Check	Initial	Data	Recheck	Remarks
g) Flues					
° Nozzle connections					
° Expansion joints					
° Louver dampers					
° Guillotine dampers					
° Perf. distribution plates					
h) Line voltage					
° 460/480 volts-60 Hz					
° 575 volts - 60 Hz					
° 120 volts					
° Line matching transformer					
i) Discharge electrode wires					
° Upper steadying frame					
° Lower steadying frame					
° Hanger pipes					
° Lifting rods					
° C.I. weights - 15 25 35					
j) High-tension guard					
° Installation					
° Vent ports open					
° Ground connections					
k) Drag bottom conveyor					
l) Wet bottom agitators					
m) Heat jacket system					
° Recirculating fan					
° Electric heater - kW					
° Steam heater coils					
° Temperature transmitters					
° Pneumatic recorders					
° Steam control valve					
° Starters - pushbuttons					
° Thermostats					
n) Roof enclosure					
° Ventilation					
° Air conditioning					
° Monorail system					
° Roof exhausters					
° Louvers					
° Heaters					

	Check	Initial	Data	Recheck	Remarks
o) Gaskets for high temperature					
3.) <u>Auxiliary Equipment</u>					
a) Transformer-rectifier units					
° Surge arrestor gap					
° Transformer liquid level					
° Ground connections					
°° Precipitator					
°° Transformer					
°° Rectifier					
°° H.T. bus duct					
°° Conduits					
°° FW/HW switch box					
°° Alarm connections					
°° Contact making thermometer					
° Ground switch operation					
° High-voltage connections					
° Telephone jacks					
° Sound power jacks					
° Resistor board					
° Space heaters					
b) Rectifier control units					
° Controls grounded					
° Connections to equipment					
° Space heaters					
° Internal light and switch					
° Alarm connections					
° Space heaters					
c) Rapper control unit					
° Connections					
° Lights					
° Space heaters					
d) Vibrator control unit					
° Connections					
° Lights					
° Space heaters					

	Check	Initial	Data	Recheck	Remarks
e) F.D. Ventilation controls					
° Motor					
° Starters					
° Pushbutton stations					
° Alarm connections					
° Filters					
f) Electric heater controls					
° Hoppers					
° Insulator housing/ compartment					
° Roof enclosure					
° Control house					
g) Control house					
° Heaters					
° Ventilation					
° Motor control centers					
° Distribution panelboards					
° Lighting panelboards					
° Starters					
h) Screw conveyors					
i) Rotary feeder valves					
j) Zero speed detectors					
k) Speed reducers					
l) Trough type hoppers					
m) Inner doors - drag bottom level					
n) Air vibrators					
o) Air vibrator controls					
p) Water spray piping					
q) Pillow block assembly					

	Check	Initial	Date	Recheck	Remarks
r) Automatic back draft pampers					
s) Filter boxes - filters					
t) Butterfly dampers					

APPENDIX D

CHECKLIST FOR OBTAINING DESIGN AND OPERATING DATA ON PARTICULATE SCRUBBERS

APPENDIX D

CHECKLIST FOR OBTAINING DESIGN AND OPERATING DATA ON PARTICULATE SCRUBBERS

Design and Operating Parameters:

Start-up date ______________

Application ________________

Vendor _____________________

Design type ________________

Firing method ______________

No. of equipped boilers ______________

No. of scrubber modules ______________

Installed scrubber capacity, MW ______________

Reheat? ______________

Capital cost, \$/kW ______________

Coal type ______________

Sulfur in coal, pct. ______________

Ash in coal, pct. ______________

CaO in ash, pct. ______________

Gas flow, acfm ______________

Temperature, °F ______________

Gas flow/module ______________

Scrubber cross section ______________

Cross section (type) ______________

Length of scrubber ______________

Gas velocity, fpm ______________

Gas retention time ______________

Particle size distribution ______________

Inlet dust loading, gr/scfd ______________

Inlet SO_2, ppm ______________

L/G, gal/1000 acf ______________

Method of water injection (type) ________________

Nozzle type _______________

Flow rate per nozzle, gal/hr _______________

Pressure drop across nozzle, in. H_2O ____________

Number of nozzles ______________

Average droplet size __________________

Average droplet speed _________________

Open or closed loop ___________________

Total pressure drop, in. H_2O _______________

Type of scrubber ________________

Diameter of collector, in. ______________

Bed porosity ________________

Expanded bed height, ft _______________

Linear size of membrane ______________

Overall collection efficiency _________________

Fractional collection efficiency ________________

Water requirement, acre-ft/yr _________________

Acre-ft/MW yr _______________

Elec. power requirement ______________

Elec. power, pct. of generating capacity ____________

Manpower, total operators ________________

Availability, pct. ___________________

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Michael F. Szabo and Richard W. Gerstle		8. PERFORMING ORGANIZATION REPORT NO. PN 3216
9. PERFORMING ORGANIZATION NAME AND ADDRESS PEDCo Environmental, Inc. 11499 Chester Road Cincinnati, Ohio 45246		10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADL-037
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15. SUPPLEMENTARY NOTES IERL-RTP project officer for this report is Dennis C. Drehmel, Mail Drop 61, 919/541-2925.

16. ABSTRACT The report discusses the control of fine particulate from coal-fired utility boilers, using electrostatic precipitators (ESPs), wet scrubbers, and fabric filters. It provides guidelines to utility personnel, responsible for selecting fine particulate control equipment, on significant design and cost data correlations based on current design practice for ESPs and actual operating and cost data for wet scrubbers and fabric filters. It gives fractional efficiency prediction models for ESPs and wet scrubbers, allowing comparison of capital and operating costs under different coal/boiler application conditions and different levels of fractional efficiency.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Scrubbers	Air Pollution Control	13B	07A
Dust	Dust Filters	Stationary Sources	11G	13K
Coal	Fabrics	Particulate	21D	11E
Utilities	Mathematical Models	Fractional Efficiency		12A
Boilers			13A	
Electrostatic Precipitators				

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