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APPENDIX E

ENVIRONMENTAL CONTROL IMPLICATIONS OF GENERATING ELECTRIC POWER FROM COAL

1977 TECHNOLOGY STATUS REPORT

APPENDIX E
A REVIEW OF TECHNOLOGY FOR CONTROL OF FLY ASH EMISSIONS FROM COAL IN ELECTRIC POWER GENERATION

PREPARED BY SOUTHERN RESEARCH INSTITUTE

ENVIRONMENTAL CONTROL-
COAL UTILIZATION PROGRAM

ARGONNE NATIONAL LABORATORY

PREPARED FOR
UNITED STATES DEPARTMENT OF ENERGY

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ENVIRONMENTAL CONTROL IMPLICATIONS OF GENERATING ELECTRIC POWER FROM COAL

1977 TECHNOLOGY STATUS REPORT

Appendix E
A Review of Technology for Control of Fly Ash Emissions from Coal in Electric Power Generation

Prepared by
Southern Research Institute
Birmingham, Alabama
for
Argonne National Laboratory

December 1977

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FOREWORD

"Environmental Control Implications of Generating Electric Power from Coal" is a continuing Argonne National Laboratory program sponsored by the Division of Environmental Control Technology of the U.S. Department of Energy. This 1977 Technology Status Report is the third in a series of reports issued as part of the program, and represents efforts of Argonne and several subcontractors. The primary emphasis is on characterizing and evaluating recent developments in available and near-term control technologies through detailed engineering and cost analyses. The report also includes an assessment of the effect of recent regulatory developments, and comparative evaluations of several possible control technology combinations.

The main volume of the report is supplemented by seven appendices consisting of subcontractor reports that deal with particular control technologies. Each appendix is a separate volume, as indicated below, and is designed to be understandable

	Appendix, Title	Subcontractor
A*	Coal Preparation and Cleaning Assessment Study (Part 1), and Appendix (Part 2)	Bechtel Corp.
B	Assessment of Status of Technology for Solvent Refining of Coal	Air Products and Chemicals, Inc.
C	Assessment of Low-Btu Gas Combined Cycle Power Generation	Foster Wheeler Energy Corp.
D	Assessment of NO_x Control Technology for Coal Fired Utility Boilers	KVB, Inc.
E	A Review of Technology for Control of Fly Ash Emissions from Coal in Electric Power Generation	Southern Research Institute
F	Flue Gas Desulfurization in the United States - 1977	Tennessee Valley Authority
G	State-of-the-Art Review for Simultaneous Removal of Nitrogen Oxides and Sulfur Oxides from Flue Gas	Tennessee Valley Authority

*Appendix A is published as two separately bound volumes. Part 1 is the main text, and Part 2 consists primarily of data generated by merging coal washability and reserve data obtained from the U.S. Bureau of Mines.

without reference to other portions of the report. The principal volume of the report and the various appendices are issued independently as they are completed, in order to make the information available in a timely manner. Inquiries regarding the availability of specific volumes should be directed to Technical Information Services, Argonne National Laboratory, Argonne, Illinois 60439.

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1977 TECHNOLOGY STATUS REPORT

Appendix E: A Review of Technology for Control of Fly Ash Emissions from Coal in Electric Power Generation

Prepared by
Southern Research Institute

ABSTRACT

This report is an in-depth review and analysis of particulate control technologies applicable to coal-fired utility boilers. Sources and characteristics of fly ash, applicable emission regulations, and measurement techniques are also discussed.

Available control technologies (electrostatic precipitators, fabric filters, and wet scrubbers) are described in detail. In each case, the theory of operation, factors affecting performance, representative installations, costs, and secondary environmental impacts are analyzed.

Techniques under development for improving the performance or extending the capabilities of existing technologies are described. Advanced alternative technologies now in the research stage are also evaluated.

INTRODUCTION

This report presents the results of a study to assess the available technology for the control of particulate emissions from electric power generation plants and discusses the needs for additional information or research on particulate control devices to meet present or anticipated new emission regulations. The major emphasis in the report is on the control of fly ash emissions from pulverized coal power boilers, since this constitutes by far the largest source of particulate matter emitted to the atmosphere from electric power generation equipment.

Currently available equipment for removal of fly ash from flue gas includes electrostatic precipitators, fabric filters, and wet scrubbers. Historically, electrostatic precipitators have been used almost exclusively for the control of fly ash emissions from large power boilers, primarily due to their lower operating costs.

However, the operation of precipitators is influenced by high electrical resistivity of the fly ash and the size required to achieve a given collection efficiency increases as the fly ash resistivity increases. The resistivity of the fly ash produced by the combustion of some coals is extremely high so that alternative methods of fly ash removal have become economically competitive with precipitators.

The requirement for reduction of sulfur oxide emissions has also influenced the choice of particulate control devices. In some instances, wet scrubbers have been used for combined control of particulate matter and sulfur oxides.

This report discusses the general theory of operation of each of the major particulate control devices and the constraints on the operation of each type of device in terms of the operating efficiency, pressure drop, reliability, and other parameters as they are influenced by the properties of the fuel or fly ash. Special attention is given to the control of fine particles (less than 3 μm in diameter) since the small particles are of the greatest concern in terms of air pollution effects.

Research in the field of control devices is continuing under sponsorship of the Environmental Protection Agency and the Electric Power Research Institute in an effort to improve the performance of existing control devices, to improve the reliability of the control devices, and to investigate alternative methods of control of particulate emissions. This report covers the ongoing research and its potential impact on control of emissions from power generation equipment.

The cost data used for this report were obtained from government agencies, vendors, and public utilities. In order to obtain real costs, the nominal costs were adjusted to 1976 dollars with the Chemical Engineering Plant Cost Index. Considerable variation in the real costs of control devices is apparent from examination of the adjusted data, and projections for new installations cannot reliably be made from the historical cost data alone.

1. PARTICULATE EMISSIONS AND CONTROL

1.1 SOURCES OF FLY ASH

Fly ash is largely produced by the combustion of coal. The mineral matter of the coal is converted to ash, part of which is discharged from the bottom of the furnace as a solid or as molten slag, and part of the coal mineral content is discharged from the furnace as particles suspended in the flue gas. The particles are mostly spherical; some are transparent or translucent and hollow (cenospheres). However, irregularly shaped and opaque particles may be present to a small extent if the fusion temperature of the ash is high or if combustion of the coal is incomplete. The sizes of the particles vary over a wide range from sub-micron sizes up to the largest sizes that can be suspended in the flue gas. The average or mass median particle diameter is usually 10 to 20 μm. Particles with diameters of 1 μm or less will typically account for 1-10% of the weight of the fly ash.

The particle-size range and the average particle diameter depend on the type of furnace and how it is operated. The coal-fired boilers used in electric power plants are stoker-fired, cyclone-fired, or pulverized-coal fired. Stoker-fired boilers are often used in industrial or small utility systems. About half the mineral content of the coal is emitted as fly ash from these boilers. Pulverized-coal fired boilers are the most widely used type in electric utility power plants. They emit 70-100% of the coal ash in the form of fly ash. Cyclone boilers produce less fly ash (10-30% of the total coal ash) than the other types. However, the use of cyclone boilers in electric power plants is declining, since they produce more nitrogen oxides than the other types.

Stoker-fired boilers produce a coarser fly ash than pulverized-coal fired boilers, and cyclone-fired boilers tend to emit a finer fly ash than pulverized-coal fired boilers. However, there is considerable overlap in the particle-size ranges of fly ash, as can be seen in Figure 1.1. The solid lines show typical values, and dashed lines show the ranges of particle-size distribution reported for each type of boiler. The data in this figure were obtained by laboratory sizing techniques on collected fly ash samples.[1]

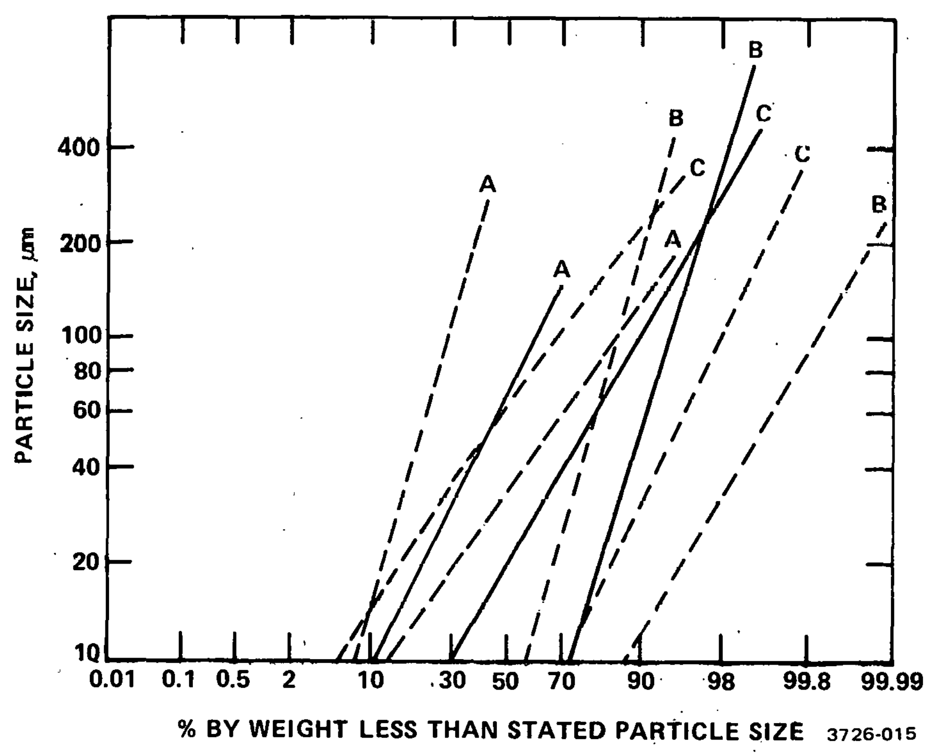

Figure 1.1 Estimated size distribution of fly ash particles emitted (before collection) from: A (spreader stoker-fired furnaces); B (cyclone-fired furnaces); C (pulverized fuel-fired furnaces).[1]

Figure 1.2 shows some recent particle-size distribution data for the size range below 20 μm.[2] These measurements were made with inertial impactors in the flue gas stream at the inlet of an operating electrostatic precipitator. Data were obtained from three installations. Plants 1 and 3 burn Wyoming bituminous coal and Plant 2 eastern bituminous coal. Properties of the coals are given in Table 1.1. These are typical values, as obtained by daily analysis.[2]

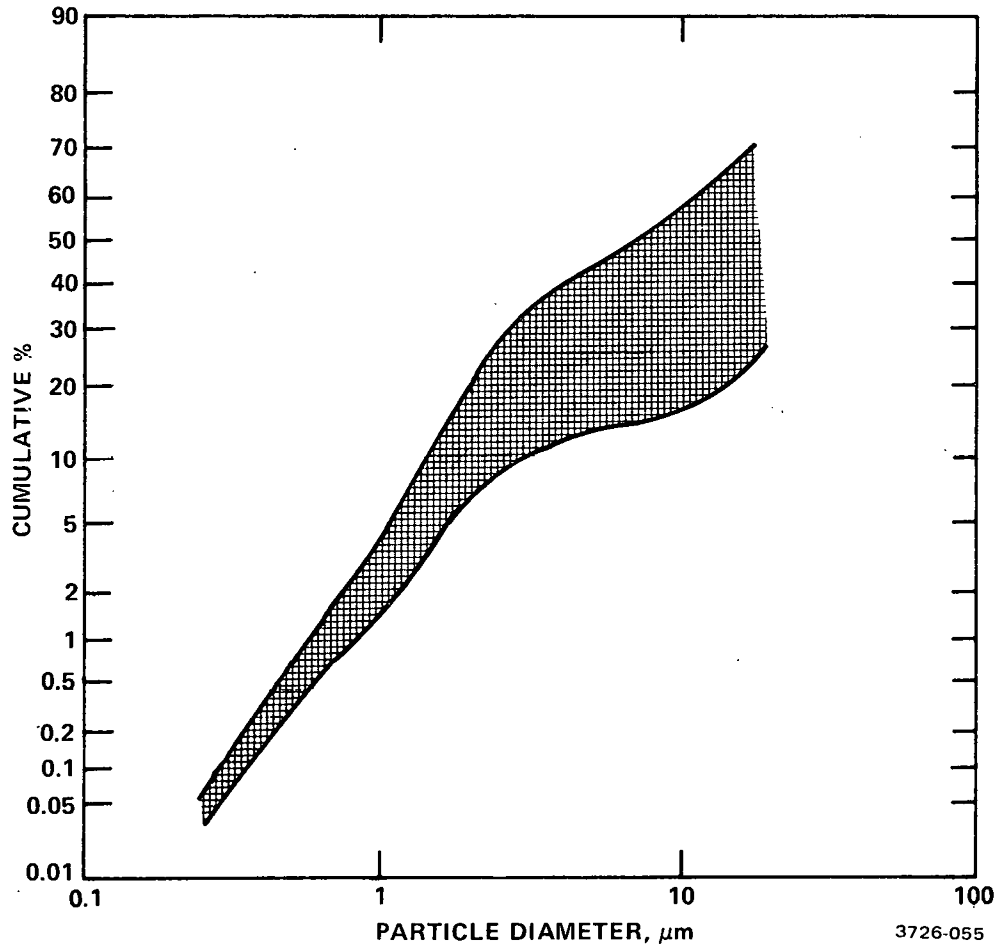

Figure 1.2 Particle size distribution range of fly ash particles <20 μm in diameter emitted from power plants (before collection).[2]

Table 1.1 Properties of Coals Producing the Fly Ash Characterized in Figure 1.2

	Plant		
	1	2	3
Heating Value, Btu/lb	12,000	12,000	10,000
Moisture, %	7	7	18
Volatile Matter, %	40	30	30
Fixed Carbon, %	44	50	42
Ash, %	8	14	10
Sulfur, %	0.5	1	0.5

The chemical composition of coal, specifically its contents of sulfur and inorganic elements, has an effect on the type and design of control equipment that is used. A prominent example of this effect has been the shift that is under way from eastern and midwestern coals with moderate sulfur contents to the low-sulfur western coals. As is discussed later in this report, the decrease in the sulfur content of the coal is usually reflected in decreased collection efficiency for fly ash in an electrostatic precipitator.

In comparison with eastern and midwestern coals, western coal deposits include more coals of lower rank--sub-bituminous coals and lignites.[3-5]

Coal rank is defined by ranges of values for properties such as fixed carbon, volatile matter, and heating value.[6] A typical bituminous coal would have a heating value of 14,000 Btu/lb, a sub-bituminous coal 9000 Btu/lb, and a lignite 8000 Btu/lb.

Although the western coals vary considerably in chemical composition and properties of the coal and coal ash, some general statements can be made.[5]

Generally, western coals are higher in volatile matter and moisture, and they are lower in fixed carbon and heat content. Western coals may have higher or lower ash contents than other U.S. coals.

The minor elements in coal, present in amounts of a few percent, are those generally present in rocks: silicon, iron, aluminum, phosphorus, sodium, calcium, magnesium, and sulfur.

Calcium and magnesium contents of western coals may be 2 to 4 times higher than in other coals, and potassium is often 2-8 times lower. Sodium ranges from high (3-4%) to low (<0.8%) in western coal (values reported for sodium as sodium oxide).

Sulfur is generally low in western coals and where it is, iron is generally also low. However, the sulfur content of the coal ash is generally higher in western coals than in other U.S. coals. The sulfur content of the ash (calculated as SO_3) ranges from 3.6 to 20.6% in western coals, compared with 1.1-3.1% in the interior province (roughly the midwest) and 1.6-2.1% in the east. This difference is attributed to the higher alkalinity of the ash from western coals.

A recent forecast of the production of bituminous and sub-bituminous coal in 1985 is given in Table 1.2.[7]

The shift from eastern coal to western low-sulfur coal will be supplemented by an expected shift from natural gas to coal for electric power generation, adding to the increase in the amount of high-resistivity fly ash that must be collected.

Trace elements (including those that may produce hazardous emissions on combustion of the coal) are present in western coals in about the same total amounts as in other U.S. coals. However, the amounts of individual elements can vary considerably. Barium, strontium, and zirconium are higher in western coals. Cadmium and selenium are present only in western coals.

Trace element concentrations as a whole can be correlated only moderately with geographic location, and not at all with coal rank. There are a few exceptions such as boron, which is present in relatively large amounts in lignites.

Table 1.2. Forecast 1985 Production (Million of Tons) of Coal[7]

	Sulfur Content, %			
Region	<0.7	0.7 - 1.5	>1.5	Total
East	39.2	135.9	487.8	662.9
West	209.8	94.6	9.5	313.9
Total	249.0	230.5	497.3	976.8

Trace elements are generally higher in U.S. coals than in the earth's crust.[8]

Changes in boiler operation made for the purpose of decreasing the amount of nitrogen oxides emitted (*e.g.*, by minimizing excess air) do not appear to affect the particle size distribution of fly ash. This subject was studied in full-scale boilers representing the range of present designs used in electric utility power plants with capacities of 125-800 MW and burning coal or mixtures of coal with oil or gas.[9] However, a substantial increase in particulate emissions has been observed in some coal-fired industrial boilers (<250,000 lb coal/hr).[10]

1.2 PARTICULATE CONTROL REGULATIONS

The policy under which the Environmental Protection Agency operates is based on the Clean Air Act of 1970, which defines a comprehensive Federal-state program for achieving environmental goals. The methods for reaching the desired levels of ambient air pollutants, including particulate matter, and the selection of emission sources to be controlled, were left to the states.

Each state has developed regulations limiting emissions from pollution sources, and hence there is some variation among them, although no state is allowed to adopt requirements for new sources that are less stringent than those set by the Federal government.

The Clean Air Act also authorized the Federal government to establish emission standards for both new and existing sources.

The Federal standards of performance for new stationary sources state that:[11]

"no owner or operator subject to the provisions of this subpart shall cause to be discharged into the atmosphere from any affected facility any gases which: (1) contain particulate matter in excess of 0.18 g per million cal heat input (0.10 lb per million Btu) derived from fossil fuel (2) exhibit greater than 20 percent opacity except that a maximum of 40 percent opacity shall be permissible for not more than 2 minutes in any hour. Where the presence of uncombined water is the only reason for failure to meet the requirements for this paragraph, such failure will not be a violation of this section."

In 1975 the Environmental Protection Agency issued regulations requiring continuous monitoring of emissions from new stationary sources and some existing ones. The items monitored in power plant emissions are sulfur dioxide, and other gases and, as a measure of particulate emissions, opacity. The information obtained in these tests may be used in the future for development of modified standards.[12]

Special problems are posed by fine airborne particles, those less than about 3 μm in diameter. These particles are the ones that are deeply inhaled into the lungs. Fly ash particles in this size range also carry disproportionately large concentrations of toxic chemical elements such as arsenic and other heavy metals. This effect appears to be due to the vaporization of some of the trace elements in coal during combustion and their subsequent deposition on the surfaces of fly ash particles in the ductwork, stack, or plume. Since the smaller particles of fly ash provide a larger surface area per unit mass, they can be expected to accumulate a disproportionate share of the deposit.

Regulations imposed by the states vary depending on their particular requirements and control philosophy. In general, the majority of the states adopt the same regulations for existing sources as the Federal standards for new sources. There are, however, some notable exceptions. The state of New Mexico has included in its regulations a specification that the emission of fine particulate matter, defined as particles less than 2 μm in diameter, shall not exceed 2% of the total. The Federal regulations for particulate emissions are at present under review and scheduled for revision in August, 1978. There has been speculation that these revisions will contain a provision limiting emission of fine particulate as well as an overall reduction from the present 0.10 lbs/million Btu to perhaps half that amount in new plants. On the other hand, there is some indication that no fine particulate limitation will be imposed as such, but that limits may be imposed on the emission of specific pollutant species if they are found to constitute a health hazard. Such regulations if issued may require the control of fine particulate in some instances even though the regulation may not specify it.

Since the study supporting any change in particulate emission regulations is not complete, the impact of such regulations cannot be predicted at this time.

1.3 AVAILABLE CONTROL EQUIPMENT

1.3.1 Collection Efficiency

Electrostatic precipitators, fabric filter baghouses, and wet scrubbers all can be designed and operated to be highly efficient in collecting fly ash, 99-99.9% on an overall mass basis.

When compared on the basis of fractional collection efficiency, specifically for the collection of fly ash particles below 1 μm in diameter, electrostatic precipitators and fabric filter baghouses have been shown to be capable of a high collection efficiency (>99%). Definitive data are not yet available from which the collection efficiency of wet scrubbers for submicron particles can be reliably estimated.

Non-uniform gas flow distribution, changes in dust loading of the gas, and the chemical and electrical properties of the fly ash have less effect on the collection efficiencies of a fabric filter or a wet scrubber than on the efficiency of an electrostatic precipitator.

1.3.2 *Energy Consumption*

The power requirements for electrostatic precipitators, which include the requirements for energization and for overcoming the pressure drop of 0.5 in. WG through the precipitator, are about 0.3% of the total plant output.

Power requirements of fabric filter baghouses are about 0.5% of the plant output, on the basis of a 4-in. WG pressure drop.

Wet scrubbers have a much higher pressure drop and a correspondingly high power requirement, estimated as 2% of the plant capacity for a 20-in. WG pressure drop.

To these values must be added power requirements for other auxiliary equipment and for fly ash disposal.

1.3.3 *Installation*

Scrubbers are more compact than precipitators, which in turn are more compact than fabric filter baghouses. Very roughly, for treating 10^6 acfm of flue gas, a wet scrubber would occupy less than 100,000 ft^3 of space, and electrostatic precipitator would require 200,000 ft^3 of space or more, for high-resistivity ash, and a fabric filter baghouse would need 800,000 ft^3.

This effect of equipment size is reflected in the ease of retrofitting the installation in an existing plant.

1.3.4 Maintenance

Overall experience of users of electrostatic precipitators appears to be satisfactory. The most common maintenance problems are mechanical failure of the discharge electrode, due mostly to arcing and corrosion, and rapper malfunction.

User experience with fabric filter baghouses has also been satisfactory, although experience in power plants is limited. However, fabric filters have been used successfully in a large number of metallurgical and other applications. Maintenance problems during operation are mostly due to the occasional development of a high pressure drop, usually due to failure of a fan or timer. Frequency of bag replacement is not considered to be a problem.

User experience with wet scrubbers has not been as satisfactory. Scale formation and solids buildup have reduced the availability of the equipment to levels that in some plants are marginally acceptable.

1.3.5 Costs

A comparison of the investment and annual costs of a fabric filter baghouse with the corresponding costs of 3 types of electrostatic precipitators is shown in Table 1.3. The comparison was made for collectors removing a high-resistivity fly ash with 99.5% collection efficiency from the flue gas of a 750-MW plant burning coal with 0.5% sulfur content. The volume of flue gas treated was 2.5×10^6 acfm at 300°F or 3.9×10^6 acfm at 750°F for the hot-side precipitator being compared. The gas volumes correspond to a 750-MW boiler operating at rated capacity. It is common practice to design for the increased gas volume associated with a 25% overload.

The values in Table 1.3 were calculated on an uninstalled base cost of $6,000,000 for a 750-MW electric power plant precipitator from information provided by equipment vendors, as de-

Table 1.3 Comparison of Costs for Electrostatic Precipitators and Fabric Filters Collecting High-Resistivity Fly Ash[a]

	Electrostatic Precipitators			
	Hot-side	Cold-side	Flue Gas Cond.	Baghouse
Design Factors				
Gas Volume, 10^3 acfm	3,640	2,500	2,500	2,500
Temperature, °F	750	300	300	300
Migration Velocity, cm/sec	8.5	4.75	8	-
Collecting Area, 10^3 ft^2	1,169	1,411	848	1,200 (468 bags)
Specific Collecting Area, $ft^2/10^3$ acfm	321	564	339	-
Filter Air/Cloth Ratio ft/min	-	-		2.08
Plant Area Required for Installation, 10^3 ft^2	28	35	19	32
Costs, 10^3 \$				
1. Uninstalled				
Base, Accessories, and Plenum	6,000	6,000	4,000	6,000
Flues	982	370	344	395
Support Structure	662	787	466	701
Subtotal	7,644	7,157	4,810	7,096
2. Erection	5,744	6,554	4,021	3,210
Subtotal (Uninstalled and Erection)	13,388	13,711	8,831	10,306
3. Installation				
Insulation	2,622	2,101	1,297	1,126
Gas Conditioning	-	-	1,750	-
Ash Handling @ \$5,000/hopper	240	270	180	140
Capacity Charge (\$800/kW)[b]	1,878	2,782	2,159	2,337
Land @ \$10,000/acre	6	8	4	7
Subtotal (Installation costs)	4,746	5,161	5,390	3,610
Total Investment	18,134	18,872	14,221	13,916
Annual Costs, 10^3 \$				
Fixed Charges @ 18% investment	3,286	3,763	2,641	2,462
Heat Loss @ \$1.75/10^6 Btu	286	-	-	-
Energy Loss @ \$0.02/kWh	284	264	343	511
Bag Replacement @ \$55/bag/2 yr	-	-	-	361
Sulfur Trioxide	-	-	500	-
Maintenance	77	84	97	24
Total Annual Cost	3,933	4,111	3,581	3,358

[a]Adapted from reference 13.

[b]The capacity charge is the additional plant cost to furnish power to the control system.

scribed in Section 2.2.10 of this report. The other costs were calculated from the base costs by using rations developed from a recent publication in which these costs were estimated.[13]

A further analysis of the costs is given in Table 1.4, which also includes cost data for a TCA wet scrubber.[14]

Information obtained from equipment vendors indicates that electrostatic precipitators, fabric filters, and wet scrubbers, in the sizes used in electric power plants, involve about the same length of time between placing the order and completing the installation: 18 months to two years. An even longer time can be involved if unusually complex ductwork is required in a retrofit installation; completing the installation may involve delays until other plant construction is scheduled. New installations have often been completed 2-3 years after the contract for the equipment was signed. Here also the delay is usually due to scheduling of other construction in the plant.

1.3.6 Secondary Environmental Impact

The disposal of collected fly ash presents an environmental impact problem regardless of the collection technique. Very little fly ash is used for any purpose other than land fill; attempts continue to be made to find uses for it in applications such as construction concrete or road surfacing.

Fly ash is collected dry in the hoppers of fabric filter baghouses or electrostatic precipitators and can be transported in the dry state by pneumatic (pressure or vacuum) or mechanical conveyors. Dry fly ash from baghouses is bulkier than that from precipitators.

However, fly ash is usually slurried with water for easier handling. The slurried fly ash can be pumped to a settling basin, if suitable land areas are available near the plant.

Table 1.4 Analysis of Cost Data[a]

	Capital Cost, 1000$	Capital Cost $/kW	Capital Cost $/acfm	Annual Cost, 1000$	Annual Cost mills/kWh[b]	Annual Cost $/acfm
Hot-Side Electrostatic Precipitator (750 MW)	18,134	24	4.98	3,933	0.75	1.08
Cold-Side Electrostatic Precipitator (750 MW)	18,872	25	7.55	4,111	0.78	1.64
Cold-Side Electrostatic Precipitator with Flue Gas Conditioning (750 MW)	14,221	19	5.69	3,581	0.68	1.43
Fabric Filter Baghouse (750 MW)	13,916	19	5.57	3,358	0.64	1.34
TCA Wet Scrubber (150 MW)	6,128	41	9.94	2,711[c]	2.6	4.44

[a]Data are for 99.5% collection efficiency of a high-resistivity dust.

[b]Based on 7008 hours operation (0.80 duty factor).

[c]Fixed charges 18% of $6,128,000 investment.

If this method is not practical, the dry fly ash can be conveyed to storage silos, from which it is discharged through wetting equipment to motor trucks for transport to disposal sites. The moisture content is adjusted to 15-20%. This reduces dusting and aids in compaction of the ash at the disposal site.

Fly ash from wet scrubbers is in a suspension in the scrubbing liquor and is deposited in the clarifier or settling basin from which the liquor in some installations is recycled to the scrubber and the sludge dried. The sludge also includes inorganic salts that have precipitated from the liquor. Partially soluble salts which can be leached into the groundwater can present more of an environmental impact problem than the fly ash itself.

A wet scrubber on a 100-MW boiler must be provided with 200 gallons per minute or more of water for make-up of the scrubbing liquor. This is a much larger amount of water than is needed for the occasional cleaning of equipment associated with precipitators or filters.

2. *AVAILABLE CONTROL TECHNOLOGY*

2.1 *EQUIPMENT*

Devices that are used at present for the control of particulate emissions (primarily fly ash) from electric power plants burning coal are electrostatic precipitators, of wire-plate design; fabric filters, in the form of baghouses; and wet scrubbers, which are of several designs (*e.g.*, venturis, turbulent contact absorbers, or spray impingement scrubbers) and which may also be used to remove sulfur oxides from flue gas. The gas-cleaning installation also may include a mechanical collector, such as a cyclone, upstream to remove the coarser particles of fly ash from the flue gas before it enters the final collector. Electrostatic precipitators are by far the most widely used control devices in the utility industry.

2.2 *ELECTROSTATIC PRECIPITATORS*

2.2.1 *Method of Collection*

The separation of particulate matter from a gas stream requires the application of a force to cause the particles to move relative to the gas stream. In electrostatic precipitators this force is that resulting from an electric charge on the particles in the presence of an electric field. The fundamental factors influencing precipitator operation are those governing the magnitudes of the particle charge and the electric field.

In all commercial electrostatic precipitators, charging of the dust takes place by the attachment of ions generated by an electrical corona. The process of corona generation involves the application of a high dc voltage to a small-radius electrode and a plate electrode. In the electric field between the wires and plates, the charged dust particles move to the plates, where they are deposited.

2.2.2 *Theory of Electrostatic Precipitation*

The theory underlying the process of electrostatic precipitation may conveniently be considered according to the concepts of ionization of the gas, the particle charging, the electric field, and the collection of the particles.

The electric field near the small-radius electrodes is high and when sufficient voltage is applied to initiate the corona process, electrons in the vicinity of the wires are accelerated to sufficient velocity to remove other electrons from the oxygen atoms in the gas. The process continues in what is termed an avalanche, producing large quantities of electrons and positive ions. The small-radius electrodes are usually negatively charged, and the positive ions move toward them. The electrons are rapidly swept away toward the grounded positive plates, and since the electric field diminishes, the velocity of the electrons is reduced below that necessary to ionize the neutral gas molecules. The electrons moving at reduced velocity are captured by the electronegative gases to form negative ions. These negative ions move toward the grounded plate and in the process collide with the suspended particles, where they are held by image-charge forces.

The particle charging mechanism depends upon the size of the particles being charged. Large particles distort the electric field lines by virtue of their different dielectric properties. The electric field lines intercept the particles, and ions which travel along these field lines are driven onto the particles until the charge on the particles creates an electric field in opposition to the applied field of such magnitude that the electric field lines are diverted. The particle charge at which this occurs is termed the saturation charge, and no further charging takes place by this process, which is called field dependent or field charging.

Ions are also subject to random thermal motion and can collide with particles even though they are not driven by electrical forces. Charging by this process is termed diffusion charging, and is the predominant charging mode for particles smaller than about 0.2 μm in diameter. Field charging predominates for particles larger than about 1 μm in diameter, and both mechanisms contribute to the charging of particles in the intermediate size range.

Detailed descriptions of the charging process and the equations relating particle charges and charging rate have been published.[15,16,17] The charging rate is primarily related to the number density of ions present in the interelectrode region, which in turn is related to the precipitator current. When current is not limited by other factors, charging of large particles takes place rapidly, reaching 90% of the saturation charge within a fraction of a second. Smaller particles generally charge at a slower rate, as do the large particles if current (free ion density) is lower. Recent studies of particle charging have provided expressions for combinations of field and diffusion charging.[16,18,19] In the most accurate model, charging is treated as a diffusion process in which the supply of gas ions, hence the charging rate, is limited by the rate at which the electric field can supply the ions to the vicinity of the particles.[16] This model predicted values of accumulated charge in particles within approximately 30% of experimentally measured values for particles between 0.15 and 1.4 μm.

The second important factor in precipitator operation is the magnitude of the electric field. The field is high near the small-diameter electrode and diminishes with distance toward the plate or cylindrical electrode. The electric field is determined by two components, one related to the geometry of the electrode system and applied voltage and the other related to the total charge contained within the interelectrode region. The electric field influences precipitation in two respects. The magnitude of the particle saturation charge is determined by the electric field in the immediate vicinity of the particle. The force acting on a charged particle is determined by the electric field near the collection electrode. The field near the collection electrode is influenced by the charge contained within the interelectrode region (space charge) as well as the applied voltage. The magnitude of the space charge is governed by the number of elemental charges within the space, which is governed by the current and relative number of ions attached to particles and the number of free or unattached ions. Practically, the space charge is related to the particle size of the inlet dust. Heavy concentrations of fine dust tend to result in high space charge, which suppresses the current in the inlet precipitator sections. A more complete description of the relation of the field to operating parameters and electrode geometry has been reported to the Environmental Protection Agency.[20]

Collection of dust in industrial precipitators is governed by the combination of forces acting on the particles. In practical precipitators, the gas is well within the turbulent flow regime, which tends to keep the particles distributed uniformly within the interelectrode region. The electrical forces, on the other hand, tend to cause the particles to move toward the collection electrode. In the boundary layer adjacent to the collection electrode, the gas flow is laminar and the electrical forces are large compared with the aerodynamic forces. Particles within the boundary of the laminar flow region are collected.

The collection of dust in a precipitator is therefore related to the probability that a particle would enter the boundary region. Equations relating collection efficiency to operating parameters have been derived by Deutsch.[21] The Deutsch equation relates the collection efficiency to the quantity of gas to be treated, the collection surface area, and a parameter called the migration velocity. The migration velocity as theoretically derived is

$$w = qE/6\pi a\mu$$

and is the terminal velocity reached when the electrical forces equal the aerodynamic drag forces on a particle. The parameters are the total particle charge (q), the electric field at the collection electrode (E), the particle diameter (a), and the gas viscosity (μ). The collection efficiency (η) is given by

$$\eta = 1 - \exp\left(- \frac{A}{V} w\right)$$

where:

A = collection plate area
V = gas flow rate
w = migration velocity. All are in consistent units.

The Deutsch equation applies strictly to a single particle size and has been shown to predict collection efficiency rather precisely when properly applied. It has become somewhat common practice to use the Deutsch equation empirically to predict the collection efficiency of a polydisperse dust when gas volume and plate area are varied, by using an empirical migration velocity derived from experimental data. Such an approach is not strictly correct and can lead to invalid conclusions.

The Deutsch equation assumes thorough mixing of the gas due to turbulent flow, a uniform concentration of dust particles, and a constant migration velocity for all particles. These assumptions or conditions hold true only for particles of nearly the same size and only for short lengths through the precipitator.

For the most precise use of the Deutsch equation (as, *e.g.*, the construction of a computerized mathematical model of the electrostatic precipitation process), it is applied to consecutive short segments of length through the precipitator, and the amount of fly ash collected from the gas stream as it moves through the precipitator is calculated for each incremental length.

In an analogous manner, the variation in collection efficiency for different particle sizes is taken into account by considering the suspended dust to be composed of a mixture of particles in a set of size ranges, a histogram, that fits the curve of particle size distribution. A value for migration velocity is calculated for each particle-size range in each increment of length through the precipitator.

Once collected, the dust must be removed from the collection surface. In some applications such as collecting liquid aerosol mists, removal is accomplished by coalescence of the particles and subsequent draining. In wet precipitators used to collect metallurgical dusts, the collection surface is irrigated by water flowing down the collection surface or sprayed into the interelectrode region. The most common system, however, is the dry collection of dust and the subsequent removal by rapping the collection electrodes. The dust falls in sheets or agglomerates into hoppers below the collection surfaces. The impact or rapping intensity required varies depending on the properties of the dust and the dust layer thickness. The rapping process and the subsequent falling of the dust into the hoppers result in some reentrainment of the dust and the system must be properly designed to prevent this reentrainment from becoming excessive.

Dust deposited in the hoppers is removed by either a pneumatic or a hydraulic system through valves or other means to prevent air inflow or gas discharge to the removal system.

2.2.3 Factors Affecting Performance

From a practical as well as a theoretical standpoint the factors governing precipitator performance are (1) particle size and concentration of the entering dust, (2) electrical conditions within the precipitator (current and voltage), (3) re-entrainment of the dust, and (4) uniformity of the gas flow.

The particle size of the fly ash produced from electric power boilers varies with the type of boiler and the fuel being burned. The mechanism of formation of fly ash within a boiler is not completely understood. Evidence indicates that individual coal particles are probably fractured during the combustion process and the residual mineral matter agglomerates into spheres comprised of silicates of principally aluminum, iron, and calcium if the temperature in the combustion zone is sufficiently high (>2000°F). Some fly ash is not formed into spheres but has the appearance of irregularly shaped particles with no evidence of having been fused. This type of fly ash is produced from lignites with high percentages of water at low combustion temperatures (<1900°F). This type of ash is, however, unusual in the United States.

Precipitators used for fly ash removal are generally installed following the air preheater, at which point the flue gas temperature is typically 300°F. Some precipitators (hot-side) are installed ahead of the air preheater, where the flue gas temperature is 600-800°F. Hot-side precipitators are discussed in Section 2.2.9. If a mechanical collector such as a cyclone is installed ahead of the precipitator, the particle size of the fly ash is altered, since the mechanical collector removes the large size fraction of the fly ash.

The effect of particle size on collection efficiency can be seen from Figure 2.1, which shows the fractional collection efficiency for fly ash of different particle sizes.[22] The data are taken from field tests on a full-size precipitator. It is apparent that a larger fraction of smaller fly ash particles would result in a lower overall migration velocity and would give a lower overall efficiency unless a larger collection area is used.

Another effect of particle size on precipitator performance is that, as higher efficiencies are required, a larger percentage of the finer size fraction must be collected. This has the effect of requiring a proportionately larger precipitator size to go from, say, 99 to 99.9% than to go from 90 to 99%.

A second factor influencing precipitator performance is its electrical characteristics. They are, in turn, related to the electrode geometry and the physical and electrical characteristics of the fly ash being collected.

The physical arrangement of the electrodes requires that the corona current pass through the collected dust layer. The voltage drop across this dust layer is determined by the resistivity of the dust, the current density, and the thickness of

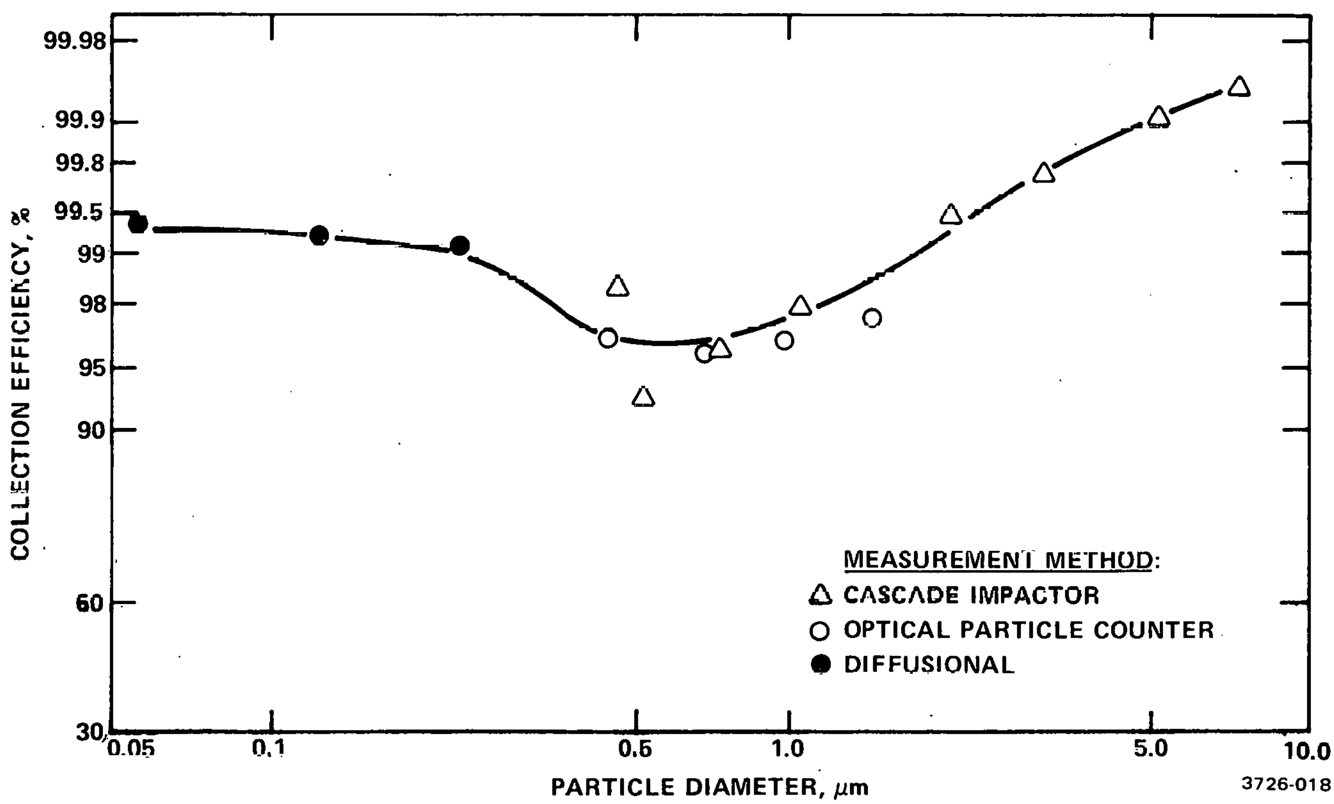

Figure 2.1 Fractional collection efficiency for a hot-side electrostatic precipitator installed on a pulverized-coal boiler. The measured overall efficiency was 99.5%.[22]

the dust layer. If the dust resistivity is high (> 5×10^{10} ohm-cm) the current will be limited by electrical breakdown within the dust layer. For moderate resistivity dust, the breakdown will result in a spark being propagated across the electrodes.

When precipitating dust with low electrical resistivity, the current is limited only by electrical breakdown of the gases within the interelectrode region. Current densities of 50 - 60×10^{-6} A/ft^2 or perhaps higher are possible if the electrical resistivity of the dust is low.

If the resistivity of the dust is moderately high (around 5×10^{10} ohm-cm) the electric field within the dust layer can exceed the electrical breakdown conditions for currents in the range of 20 - 30×10^{-6} A/ft^2. When breakdown occurs in the dust layer, a spark is propagated to the corona electrode. Precipitator operation is usually limited to spark rates of around 50-100/min in each electrical section. The maximum current is so related to the dust resistivity that current densities as low as 5×10^{-6} A/ft^2 are found in precipitators collecting dust with resistivities above about 1×10^{12} ohm-cm.

Voltages in a precipitator are governed principally by electrode geometry, the particle size and concentration of the dust, the dust resistivity, and the composition and properties of the gas. Large voltage drops across the dust layer can alter the applied voltage but have little influence on total performance. Fine dust at the inlet can also influence the voltage by a space charge effect.

Fly ash resistivity is determined principally by the composition of the coal. Combustion of coal containing sulfur results in sulfur oxides, principally sulfur dioxide (SO_2), in the flue gases. Except perhaps for that in the form of metal sulfates, all of the sulfur in the coal appears in the flue gases.

About 1% of the SO_2 is oxidized to SO_3, which combines with the moisture present in the flue gas to form sulfuric acid vapor. At the temperatures at which most precipitators operate (around 300°F or lower), some of the sulfuric acid vapor present is condensed or is adsorbed on the fly ash surface. The presence of this sulfuric acid on the fly ash reduces the electrical resistivity of the ash in relation to the quantity of sulfuric acid present and the temperature of the flue gases. In general, coals containing sulfur in quantities greater than about 1.5% produce fly ash with reasonably low resistivities at temperatures below 300°F. Coals with sulfur in quantities less than 1% generally produce ash with moderate to high resistivities. The absolute value of the resistivity of the fly ash can vary, depending on other factors, mainly moisture content of the flue gases and mineral composition of the ash.

The important mineral constituents of fly ash as they influence resistivity are the alkali metals (sodium, lithium, and potassium), iron, and calcium. The alkali metals appear to be the primary charge carriers and these metal ions affect the electrical resistivity in relation to their concentration.

For low-sulfur coals, resistivity is predictable from the composition of the ash. The presence of iron appears to modify the availability or in some instances the species of ion participating in the conduction process. Details of methods for predicting resistivity of ash from low sulfur coals have been published.[23]

Calcium appears to affect the resistivity of fly ash as a result of its reaction with the available sulfuric acid, thus requiring a larger quantity of H_2SO_4 to achieve a given reduction in resistivity than for an ash low in calcium.

The mechanism by which sulfuric acid acts to reduce resistivity is not clearly understood. It might chemically attack the fly ash surface to release additional alkali ions to participate in the conduction process. It might also directly participate in the conduction process. Whatever the mechanism, it is obvious that sulfur in the coal plays an important role in determining fly ash resistivity and precipitator current density. Shifts from high to low sulfur coals to meet sulfur oxide emission standards have often created high resistivity problems that reduce the effectiveness of electrostatic precipitation.

Laboratory studies on fly ash resistivity are being carried out by the Environmental Protection Agency and by the Electric Power Research Institute.[24] Measurements are made in environments of water and sulfur dioxide in concentrations in the ranges normally encountered in the emissions from electric power boilers. Efforts are being made to obtain correlations of fly ash resistivity with coal composition which can then be used to develop quantitative relationships between coal composition and maximum useful precipitator current density. The relationships are used to estimate the theoretical migration velocities for the range of fly ash particle sizes encountered in power boilers.

The parameters measured also include the amounts of additives adsorbed onto the surface of the ash particle and their effect on resistivity as a function of temperature, moisture content, and changes in the total gas corona characteristics.

A third factor influencing precipitator performance is reentrainment of collected dust, or bypassing of the dust-laden gases around the electrified regions. Reentrainment can take place in a variety of ways. Dust being precipitated can strike the dust layer with sufficient velocity to dislodge additional particles. Rapping of the plates can cause dust to be propelled into the gas stream and falling of dust into the hoppers can result in reentrainment of dust already removed. Gas sneakage resulting from the necessity for maintaining electrical clearance above and below the electrodes as well as gas sweepage through the hoppers constitute other factors influencing performance.

The influence of gas sneakage and reentrainment are reduced considerably by proper baffling and by proper design of rapping gear. Reentrained dust is generally not dispersed as individual particles, so the redispersed dust is more readily collected than would be indicated by the sizes of the discrete particles. Dust reentrained from the first field is readily collected in the subsequent fields. The reentrained dust appearing at a precipitator outlet is principally that resulting from reentrainment of dust collected in the last field.

Recent studies of reentrainment indicate that between 25 and 40% of the total emissions from a precipitator is reentrained dust. More complete descriptions of these studies have been published.[25,26]

A fundamental analysis of the structural mechanics of collector plate impaction and vibration in precipitators is the subject of research at Princeton University.[27]

Basic studies on agglomeration of fine particles and on the use of advanced electrical and boundary layer gas-flow techniques in the collection of high-resistivity fly ash are being made at Stanford University.[27]

Nonuniform gas flow is another factor in precipitator performance. The size of the flue gas ducts and space limitations make it difficult to achieve good uniformity of gas flow. As a standard, the Industrial Gas Cleaning Institute has recommended that the gas entering a precipitator should be such that 85% of the local velocities should be within 25% of the mean and no single point should differ more than ±40%.[28]

Sizing

Precipitator sizing is based on the quantity of gas flow, the properties of the gas, the collection efficiency, the electrical properties of the dust, and the particle size of the fly ash. Present practice is to base the size on that of an existing precipitator collecting ash from similar coal, on pilot plant tests, and on empirical relationships. Figure 2.2 shows the relationship between the size of precipitator required and collection efficiency for three values of current density. The currents selected cover the range of values for high, medium, and low resistivity ashes. The data are typical for well designed and maintained precipitators, operating at temperatures below about 300°F.

One of the unknown factors in design is the allowable current density. Selection of the design current density involves a prediction of the resistivity based on coal or ash composition or the measurement of the resistivity in plants burning the same or comparable coal. The art of precipitator design is based to a great extent on being able to recognize the relevant factors influencing the resistivity and the allowable current density.

Many types of empirical relationships have been developed to permit the selection of design parameters from coal composition. Most of these were developed on the basis of precipitators operating at relatively low collection efficiencies and the same parameters are not appropriate for some of the high efficiency precipitators currently being installed.

Studies of fundamental relationships in the electrostatic precipitation process and the development of a computer model of the process have resulted in a method for basing a design on engineering methods. This approach has been presented in detail.[29]

Research is being carried out at Washington State University on the determination of particle migration velocities in electrostatic precipitators, to obtain information usable in the design of precipitators.[27]

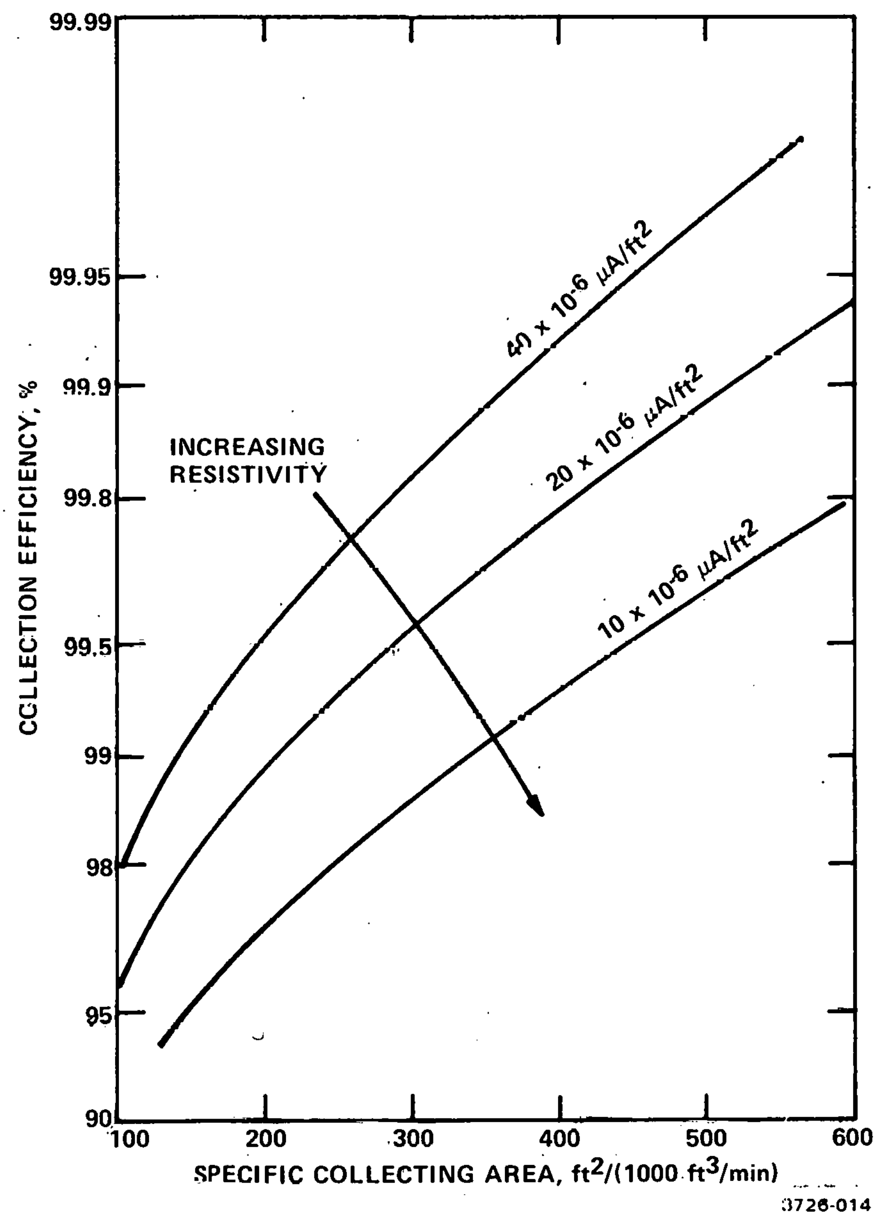

Figure 2.2 Computed performance for an electrostatic precipitator at 10, 20, and 40 x 10^{-6} μA/ft^2.

2.2.4 *Energy Requirements*

Precipitator power requirements are associated with the efficiency level and dust properties. The current densities vary among precipitators collecting dusts of varying resistivity; however, a larger collecting surface area is required when collecting a high resistivity dust.

The bases for computing power costs for energization of precipitators are the current density, secondary voltage, and the plate area. Power densities range from around 0.3 to 1.5 watts/ft^2, depending upon the dust resistivity. Energy required for a precipitator is determined from the power density, plate area, and operating time.

In addition to that required for electrical energization, fan power is also required due to the pressure drop through the precipitator. Fan power can be computed from the equation

$$P = \frac{746\ rp}{6356\ n}$$

where:

P = power, watts

r = gas flow, acfm

p = pressure drop, in. water gauge (assumed to be 0.5)

n = combined fan and motor efficiency (assumed to be 0.40)

The sum of the power requirements for energization and for overcoming the pressure drop is about 0.3% of the power plant output.

The costs of energy for precipitator operation are discussed in Section 2.2.10.

2.2.5 *Representative Installations*

Table 2.1 lists a number of installations that represent the variety used in electric utility power plants that burn coal.

Table 2.1 Examples of Electrostatic Precipitator Installations in Electric Utility Power Plants

No. of Units	Boiler Capacity, MW	Design Collection Efficiency, %	Type of Precipitator	Coal Sulfur, %	Collecting Plate Area, ft^2 [a]	Flue Gas Volume, 1000 acfm[a]	Specific Collecting Area, ft^2/1000 ft^3/min	Precipitation Rate Parameter, cm/sec	Temperature, °F	Uninstalled Cost, 1000 $[a,c]	Erected Cost, 1000 $[a,b]	Purchase or on Line Date	Uninstalled Cost, $/ft^2 Collecting Area[b]	Uninstalled Cost, $/kW Boiler Capacity[b]
2	100 ea	98.0	Cold Retrofit	0.9	73,728	385	191	10.4	285	345	-	2/75	4.68	3.45
1	250	99.0	Hot Retrofit	0.7-5	331,724	1,274	260	8.98	721	2,446[c]	12,640	2/76	3.55	4.89
2	125 ea	99.0	Hot Retrofit	0.7-5	173,750	714	250	8.91	655					
1	660	99.5	Cold New	1.1-5.1	663,552	2,120	313	8.63	300	1,637	-	7/77	2.47	2.48
1	550	99.5	Cold Retrofit	1.5-5	654,438	2,000	327	8.23	300	2,552	15,080	6/76	3.90	4.64
1	450	99.8	Cold New	2.4-4	442,368	1,520	291	10.82	275	2,388	-	7/76	5.40	5.31
1	30	99.3	Hot Retrofit	1.2-1.37	48,153	163	295	8.58	705	254	-	10/75	5.28	8.47
1	100	99.3	Hot Retrofit	1.2-1.37	126,720	440	288	8.78	775	945	-	12/75	7.46	9.45
1	550	99.5	Hot New	0.6	806,096	2,474	325	8.26	650	3,877	-	7/74	4.81	7.05
1	350	99.1	Hot Retrofit	0.4	512,256	1,700	301	7.94	700	2,138	-	2/77	4.17	6.11
4	800 ea	99.5	Hot New	0.2-0.8	1,902,182	5,142	369	8.94	815	8,667	-	8/77	4.56	10.83
1	550	99.6	Hot New	0.25	832,204	2,314	359	7.8	820	4,995	-	9/78	6.00	9.08
3	- ea	97	Cold Retrofit	2.2-9	42,166	202	208	8.54	306	556	-	6/76	12.94	-
6	150 ea	99.6	Cold Retrofit	0.7	322,560	575	560	5.0	320	1,642	-	1978	5.09	10.95
1	750	99.56	Cold New	0.36-1.8	1,376,256	3,400	404	8.2	335	5,270	-	7/77	3.83	7.03
2	750 ea	98.6	Cold New	0.2-0.5	1,179,648	2,800	420	5.7	283	4,379	-	1/77	3.71	5.84
1	200	99.8	Cold New	1.5	255,897	684	374	8.45	311	2,045	-	1/77	7.99	10.23
1	85	99.0	Cold Retrofit	0.6	89,923	286	314	6.6	300	753	-	1/77	8.38	8.86
1	125	99.0	Cold Retrofit	0.6	147,455	415	355	6.6	300	1,003	-	1/77	6.80	8.02
1	180	99.0	Cold Retrofit	0.6	211,968	597	355	6.6	300	1,125	-	1/77	5.31	6.25
1	90	96.3	Cold Retrofit	1.9	47,692	300	158	10.5	400	569	-	2/77	11.94	6.32
4	818 ea	99.32	Hot New	-	1,804,032	5,104	353	7.06	820	7,521	13,180	4/76	4.17	9.19
2	500 ea	99.5	Hot New	-	967,680	3,000	322	8.21	720	4,440	8,804	1975	4.59	8.88
3	660 ea	99.33	Hot New	-	1,036,800	3,888	266	9.39	700	4,612	9,110	1973	4.45	6.99
1	900	99.67	Cold Retrofit	0.6	1,472,652	3,000	490	-	275	8,434	-	1975	5.73	9.37
1	600	99.6	Cold New	0.4-0.6	1,636,962	2,000	818	-	300	8,157	-	1975	4.98	13.60
1	500	99.33	-	-	1,136,255	2,331	488	-	-	-	-	-	-	-

[a]The figures listed are for single units.

[b]1976 dollars.

[c]For the total of 3 units.

2.2.6 Maintenance

A satisfactory precipitator installation is one that not only meets the initial start-up guaranteed performance but that continues to operate satisfactorily for extended periods between plant outages for routine servicing. Many such installations are in operation and provide a minimum of operational difficulty.

Some installations, on the other hand, have an exceptionally high incidence of problems. Most of these problems are mechanical in nature and can be traced to inadequate design of the structural members, poor installation practice, or poor maintenance.

Several surveys have been conducted in an effort to identify the major sources of problems. A survey conducted by the Industrial Gas Cleaning Institute in 1969 identified problems in the order listed in Table 2.2. The numbers identified with each problem are percentages of the respondents identifying the particular component as a maintenance problem.[30]

Table 2.2 Most Common Maintenance Problems

Component	% of Respondents
Discharge Electrode Failure	68
Rapper Malfunction	40
Insulator Failure	28
General Dust Build-up Causing Short	28
Hopper Plugging	24
Transformer Rectifier Failure	20

The results of a similar survey conducted by the Air Pollution Control Association in 1974 are shown in Table 2.3.[31,32]

Table 2.3 Power Plant Electrostatic Precipitator Maintenance Problems

	Major Maintenance Problem, %	Component Failure Frequency, %		
		Frequent	Infrequent	Very Seldom
Discharge Electrodes	35.2	29.5	38.6	28.4
Dust Removal Systems	31.8	36.4	42.0	20.5
Rappers or Vibrators	5.7	9.1	38.6	47.7
Collecting Plates	13.6	4.5	7.9	68.2
Insulators	1.1	8.0	34.1	48.9

This survey was based on replies to a questionnaire from the TC-1 Committee of the Air Pollution Control Association and involved the utility, cement, paper, and metallurgical industries. Only data pertaining to the utility industry is included in Table 2.3. Table 2.3 shows the most commonly encountered component problems, along with the frequencies of component failure.

Discharge electrode failures are typically caused by electrical arcing, corrosion, and fatigue, in descending frequency. The collecting electrode problems are most commonly caused by fatigue at the point of suspension, followed by corrosion as the next most common cause. Those rapping systems using vibrators, either pneumatic or electric, appear to require more maintenance than impulse-type systems. Failures of support insulators are caused primarily by arc-overs from accumulations of dust or moisture on the surface of the insulator. Problems with the dust removal systems are caused primarily by hopper plugging, followed by screw conveyor and dust valve deficiencies.

Other problems which cause difficulty, but to a lesser extent, are

- Dust buildup on the upper outside corners of hoppers.
- Corrosion in the less accessible parts of the precipitator, *e.g.*, around the access doors and frames, box girders, and housing.
- Rapping system drives, wear of rappers and bushings, and movement of the point of impact.
- Plugging of gas distribution plates.

Another point of inquiry in the Air Pollution Control Association survey had to do with overall experience with the equipment from an operation and maintenance viewpoint. The utilities' responses were:

Utilities - Operation of Precipitators

Excellent	Good	Fair	Poor
14.8%	45.5%	29.5%	10.2%

Utilities - Precipitator Maintenance

Excellent	Good	Fair	Poor
13.6%	52.3%	13.6%	20.5%

Some of the data reported represent precipitator installations that have been in service for many years and often these installations have not received proper maintenance attention. Problems of excessive corrosion due to improper insulation, plate buckling due to inadequate design, and other mechanical problems can be overcome by proper attention to engineering details during design and erection of the system.

2.2.7 *Installation*

Retrofitting an installation with an electrostatic precipitator can present problems because of the physical size of the precipitator. The problem is most severe if the precipitator is installed ahead of the air heater, where there is generally less space available. Very few such installations have been made.

Even in a cold-side installation, it is sometimes necessary to design the precipitator with taller plates than usual, or to use a chevron configuration or a stacked precipitator arrangement.

2.2.8 *Flue Gas Additives*

One approach to improving the performance of electrostatic precipitators on existing plants is through the use of flue gas additives, which can serve several purposes. One of the most common difficulties with electrostatic precipitators is high resistivity ash resulting from a change in fuel (from high sulfur to low sulfur coal, for example) or from failure to properly assess the resistivity characteristics of the ash in the design phase. Such problems can be overcome through the use of flue gas additives to reduce the ash resistivity, or to reduce reentrainment.[33,34]

A consequence of burning a low-sulfur coal to avoid excessive emissions of sulfur dioxide is that the concentration of sulfur trioxide as well as that of sulfur dioxide in the flue gas is lowered, and the problem of excessive ash resistivity is incurred. One way to overcome this problem is to add sulfur trioxide from an external source (vapor from anhydrous sulfur trioxide or sulfuric acid). Alternative sources more frequently used at the present are sulfur dioxide (which is vaporized and passed over a catalytic oxidizer in the presence of air) or elemental sulfur (which is burned to sulfur dioxide and then finally converted to sulfur trioxide in a catalytic oxidizer).

Although ammonia is not a naturally occurring component of flue gas, it is sometimes added in place of sulfur trioxide to treat ash from low-sulfur coal. The role of ammonia in this connection is not clearly understood. There are theoretical reasons for discounting the value of ammonia for adjusting resistivity, and there is no consistent experimental evidence that the compound has this effect. These statements not withstanding, there is clear proof that ammonia injection can improve the efficiency of precipitation, but it probably does so through other mechanisms.[34,35]

One useful effect from ammonia addition is an improvement in the electrical properties of the gas stream within a precipitator. After addition, ammonia reacts with normally occurring sulfur trioxide and water vapor to form a fume of ammonium sulfate. The fume particles are then electrically charged, and the added quantity of charged particulate increases the electrical field through a space-charge effect.

Another useful effect of ammonia addition is to lower reentrainment losses of collected ash. This effect is probably the consequence of increased cohesive forces between the ash particles, which lead to larger aggregates that are less likely to be reentrained.[36]

Although flue-gas conditioning with chemical additives remains primarily a technique for modifying electrical resistivity (as typified by the use of sulfur trioxide), it is gradually becoming more important for the other purposes described in connection with ammonia.

There is another mechanism that is claimed for triethylamine as an additive: increased agglomeration of ash particles <u>before</u> they are collected. However, there is no definitive experimental data to support the claim. There is still another mechanism by which other additives are intended to be effective: catalytic oxidation of naturally occurring sulfur dioxide to sulfur trioxide.

Additives that are on the market are being continually diversified. Much needs to be learned about both the chemical compositions of the proprietary formulations and the mechanisms of this operation, not only to predict when the different additives can be used effectively, but to obtain a broader understanding of precipitator problems that can be solved with chemical additives.

The amount that flue gas additives contribute to operating costs is discussed in Section 2.2.10.

2.2.9 Hot Precipitators

The increasing use of low-sulfur coal and the accompanying high ash resistivity at normal precipitator operating temperatures has led to the use of so-called hot precipitators located upstream of the air heater. The flue gases ahead of the air heater are generally in the range of 600 to 900°F and the resistivity of most fly ash is sufficiently low at these temperatures so current is not limited by fly ash resistivity.

There are several disadvantages to the use of hot precipitators and the choice of hot-side or cold-side precipitators will generally favor cold-side operation unless the ash resistivity is exceptionally high.

The properties of the flue gas become important in hot-side precipitators because of the reduced gas density. The corona onset voltage and the sparkover voltage are both reduced and the difference between the two is also reduced. The effect is a greater problem of control of the voltage due to the steepness of the voltage-current curve. The problem may be further aggravated in the case of precipitators installed at high altitudes.

The increase in gas volume at elevated temperatures is a further disadvantage. The increased gas volume reduces the specific collection area (plate area to gas volume), which for a given size boiler results in lower efficiency or a requirement for a larger plate area. This is off set by the increase in the migration velocity. The gas viscosity is also increased at elevated temperatures and this further reduces the precipitator performance. Mechanical problems are also more severe with hot-side precipitators since expansion is greater. Provision for the increased expansion must be made to prevent buckling, warping, or failure of the shell and internal members. It is sometimes necessary to change the materials of units operating at high temperatures; the most common materials change is the use of stainless steel rather than mild steel wire.

In spite of these shortcomings, the use of hot precipitators does have advantages, especially when the fly ash and flue gas composition result in a resistivity at cold-side temperatures of around 1×10^{12} ohm-cm or higher. At such resistivities, the current density would be severely reduced and the size of the precipitator required would be so large that a hot-side precipitator would be indicated.

Figure 2.3 illustrates the relationship between the sizes of a hot side precipitator and a cold side precipitator for the same efficiency, as the dust resistivity varies.

There have been many hot side precipitators installed in various geographical areas as indicated in Table 2.4. The table lists the various design parameters for the hot side units.

Practically, hot side precipitators are often difficult to retrofit to existing installations because of the more complex ductwork. The flue gases go from the boiler to the precipitator, back to the air heater, and then to the stack. The additional ductwork adds to the cost of a hot system as a result of the added ducting as well as the insulation requirements.

Some difficulties have been experienced with mechanical details of hot side precipitators due to structural failure

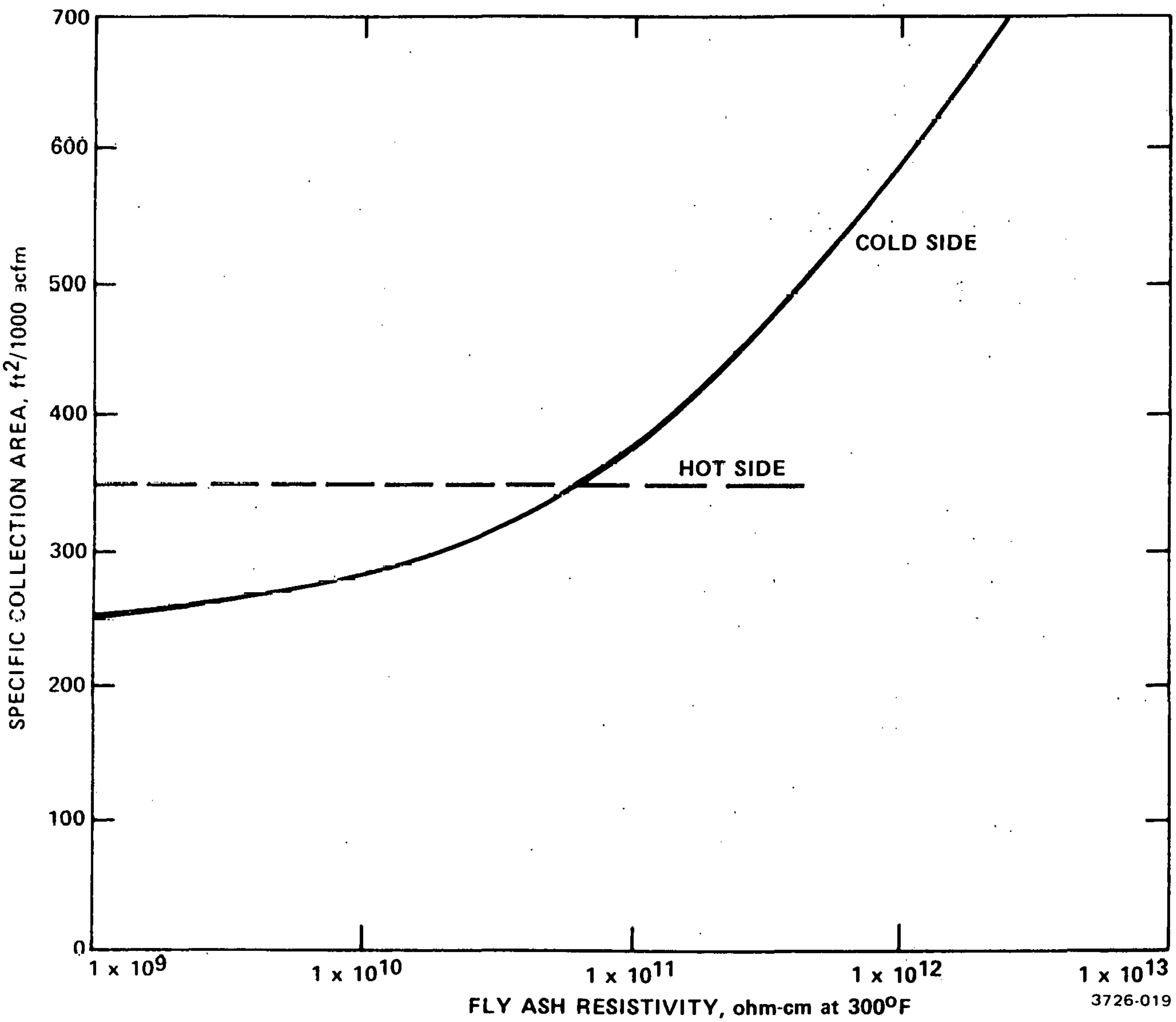

Figure 2.3 Illustration of the effects of fly ash resistivity on precipitator size for 99.5% collection efficiency. Curves are plotted on the basis of actual cubic feet per minute of gas flow. For 700°F hot-side and 300°F cold-side temperature, the ratio of gas flow for the same size boiler would be about 1.5. Hot-side resistivity is assumed to be not limiting.

Table 2.4 Some Hot-Side Electrostatic Precipitator Installations

Company	Station	Collection Efficiency, %	Effective Migration Velocity, cm/sec	Specific Collecting Area, ft^2/ 1000 ft^3/min	Temperature, °F	Volume Flow Rate, 1000 acfm	Outlet Loading, gr/acf	Date Operational	Generating Rate, MW
Duke Power	Allen	99.2	9.03	270	650	1,250		1972-73	870
Duke Power	Buck	99.0	9.75	240	800	337			
Duke Power	Buck	99.08	10.0	238	690	640			
Duke Power	Cliffside	99.0	9.75	240	800	340			
Duke Power	Cliffside	99.0	10.65	220	690	400		72	132
Wisconsin Power and Light	Columbia	99.5	-	-	810	2,770		74	486
Public Service of Colorado	Comanche	99.5	8.7	310	828	1,322		73	350
Duke Power	Dan River	99.0	10.8	215	690	402		71	150
Sego	Gaston	99.73	11.5	250	650	1,160	0.0163	72	250
Iowa Power	George Neal	99.0	10.65	220	650	690		72	147
Alabama Power	Gorgas	99.0	8.5	270	650	1,000			750
Dayton Power and Light	Hutchings	99.83	10.0	324	640	313	0.005	72	412
Duke Power	Lee	99.15	11.3	215	672	1,118	0.018	70	210
Duke Power	Lee	99.0			690	825			
Wisconsin Power and Light	Nelson Dewey	99.5			550	487		73	200
Consolidated Edison	Ravenswood	99.57	11.1	245	520	4,079	0.005	67	1000
Duke Power	Riverbend	99.0	10.1	235	690	600			
Cedar Falls	Streeter	99.0			809	250		73	52
Commonwealth Edison	Will County	98.5	9.15	235	675	1,425		73	300
Carolina Power and Light		-	-	-	625	670		72	114
Salt River	Navajo	99.5			800	4,000			750
Public Service of New Mexico	San Juan	99.5		310	700	470		73	350
Alabama Power	Barry	99.0	8.91	250	655	1,428		76	250
Alabama Power	Barry	99.0	8.98	260	721	1,274		76	125
Alabama Electric Cooperative	McWilliams	99.3	8.58	295	705	163		75	30
Alabama Electric Cooperative	Tombigbee	99.3	8.78	288	775	440		75	100
Northern Indiana Public Service	Schafer	99.5	8.26	325	660	2,474		76	550
Commonwealth Edison	Waukegan	99.1	7.94	301	700	1,700		77[a]	350
Arkansas Power and Light	Whitebluff	99.5	8.94	369	815	5,142		77[a]	800 ea.
Dairyland Power Cooperative	Alma	99.6	7.8	359	820	2,314		78[a]	550
South Carolina Public Service	Scherer	99.32	7.06	353	820	5,104		76	818 ea.
Gulf Power	Ellis	99.5	8.21	322	720	3,000		75	500 ea.
Alabama Power	Miller	99.33	9.39	366	700	3,888		73	660 ea.

[a]Expected date.

of the shells or insulators. These difficulties can be overcome by proper attention to the requirements for thermal expansion and conventional structural design methods.

2.2.10 Costs

For purposes of comparison or generalization, costs that are usually considered are capital equipment costs, maintenance costs, and operating costs.

Comparison of capital equipment costs may be made on an uninstalled, erected, or installed basis. It is useful to define the erected cost as the cost of the erected precipitator only, with the term installed cost reserved for the cost of the total installation, including the additional ductwork and ash-handling equipment.

Precipitator capital costs vary widely, depending upon the collection efficiency, the electrical and physical properties of the dust, the design details of the precipitator, and the nature of the installation itself. Installed costs of precipitators vary so widely that it is difficult to derive exact relationships between cost and precipitator capacity. The installation cost often includes the dismantling of an existing precipitator, the addition of supporting steel, varying amounts of ductwork, the location of the precipitator (piggy back on an existing unit, or on the roof of the plant, for example). The costs of precipitators depend primarily upon the size of the precipitator, whether the installation is to be made in an area of high wind or snow loads, or in an earthquake area, and the location of the installation relative to the supply of structural steel. These and other variables cause erected costs to vary by a considerable amount. A representative list of installations is given in Table 2.1, above.

The methodology used in developing rational cost data for electrostatic precipitators was to obtain from vendors or users typical uninstalled costs of precipitators, both hot-side and cold-side units. These costs were adjusted to 1976 costs by the following procedure. It was assumed that the year in which the equipment was contracted for was two years prior to the year in which the installation came on line. The cost of the uninstalled equipment was then calculated in 1976 dollars by adjusting the cost by an inflation factor, which was the Chemical Engineering Plant Cost Index[37] for the interval between the contract year and 1976. The factors used were: 1975-1976, 1.06; 1974-1976, 1.16; 1973-1976, 1.33. Table 2.1 summarizes the data for a group of both hot- and cold-side installations.

The collection plate area required to achieve a given collection efficiency was then determined for both hot-side and cold-side units from mathematical model projections. The uninstalled precipitator cost was then calculated for a given gas volume from the projected plate area and the unit plate area cost.

The erected cost was estimated to be approximately twice the uninstalled cost, on the basis of experience of vendors, for new installations.

Costs of ductwork and ancillary equipment were determined from relationships developed by the Tennessee Valley Authority.[38]

Details of the methodology and the assumptions made in arriving at the cost data are discussed in the following sections.

Hot-Side Precipitator Costs

Hot-side precipitators are relatively insensitive to the sulfur content of the fuel and generally so to the composition of the ash, since at the usual temperature preceding the air heater the resistivity of fly ash is sufficiently low that current is not limited by dust resistivity. Consequently, in contrast to cold-side precipitators, the size is governed primarily by the collection efficiency required and the gas volume.

Figure 2.4 shows the relationship between collection efficiency and specific collecting area (the ratio of plate area to gas volume) for hot-side precipitators collecting fly ash. There will be some variation in the relationship, depending upon the particle size of the ash, the uniformity of the gas flow, and the gas temperature. However, the scatter of the data is not large and the plate area required to achieve a given efficiency for a specified gas flow can be determined from data of this type.

The cost per unit of collection plate area was determined from Figure 2.5. Figure 2.6 shows the uninstalled precipitator cost as related to the gas volume as projected for hot-side precipitators with collection efficiency of 99.5%. The figures also include uninstalled precipitator costs for eight installations for which data are available. The collection efficiencies for the installations are noted on the figure. The scatter of the data indicates the degree of uncertainty associated with the different manufacturers and the circumstances peculiar to each installation.

Figure 2.7 shows the estimated variation in uninstalled hot-side precipitator costs for various gas flows based on collection efficiencies ranging from 99 to 99.6%. The curves in Figure 2.7, like that in Figure 2.6, are based on data from Figures 2.4 and 2.5.

Figure 2.8 shows the erected precipitator costs for hot-side units, based on the assumption that erected costs are twice the uninstalled precipitator costs.

Figures 2.6 through 2.8 show costs based on the gas flow rate. In order to relate precipitator size to boiler capacity, Figure 2.9 shows a plot of gas flow in actual cubic foot per minute (acfm) at the temperature of the flue gas (600 to 800°F) relative to the boiler capacity in megawatts (MW). The curve is based on design gas flows for hot-side precipitators for which data are available.

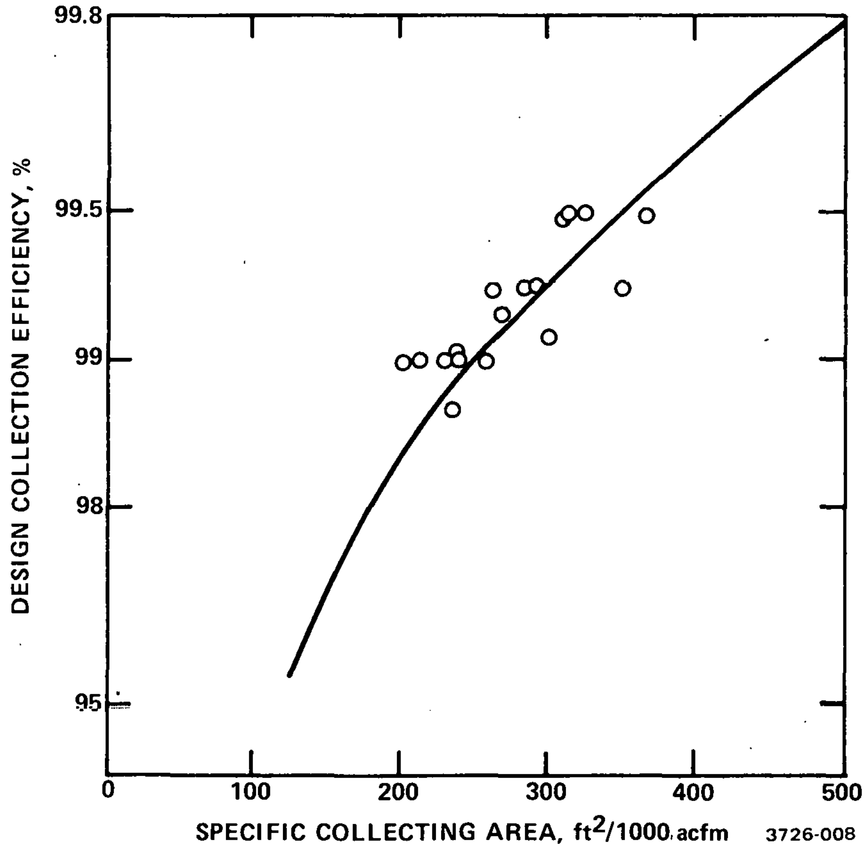

Figure 2.4 Design collection efficiency *vs.* specific collecting area for hot-side electrostatic precipitators.

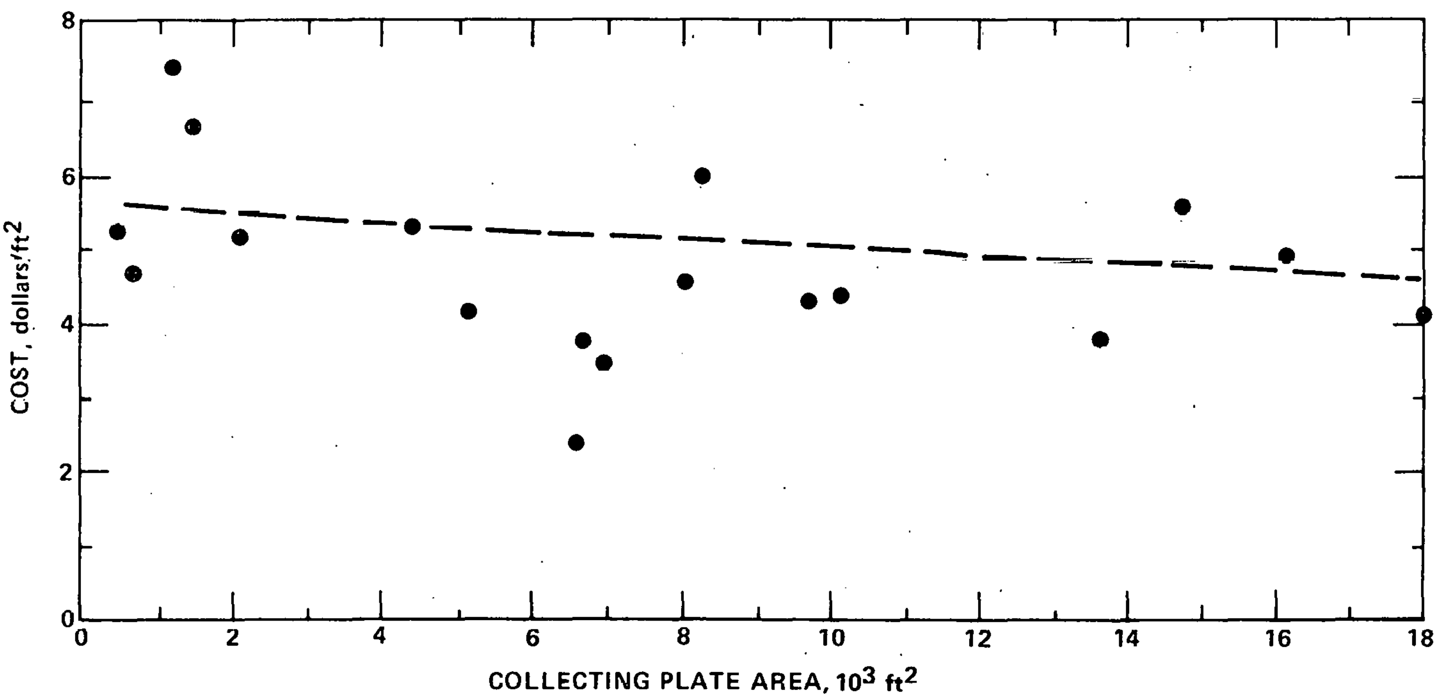

Figure 2.5 Cost (uninstalled) per unit of collecting plate area *vs*. collecting plate area for hot-side electrostatic precipitators.

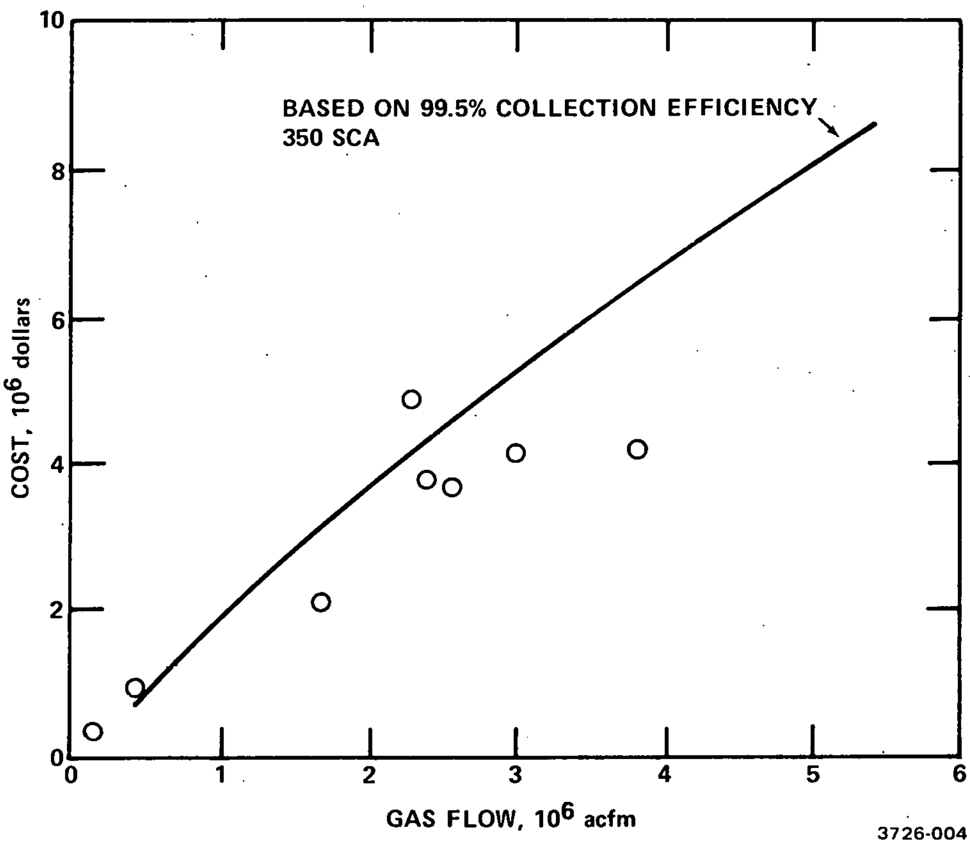

Figure 2.6 Cost (uninstalled) for hot-side electrostatic precipitators, collection efficiency 99.5%, *vs.* gas volume flow rate.

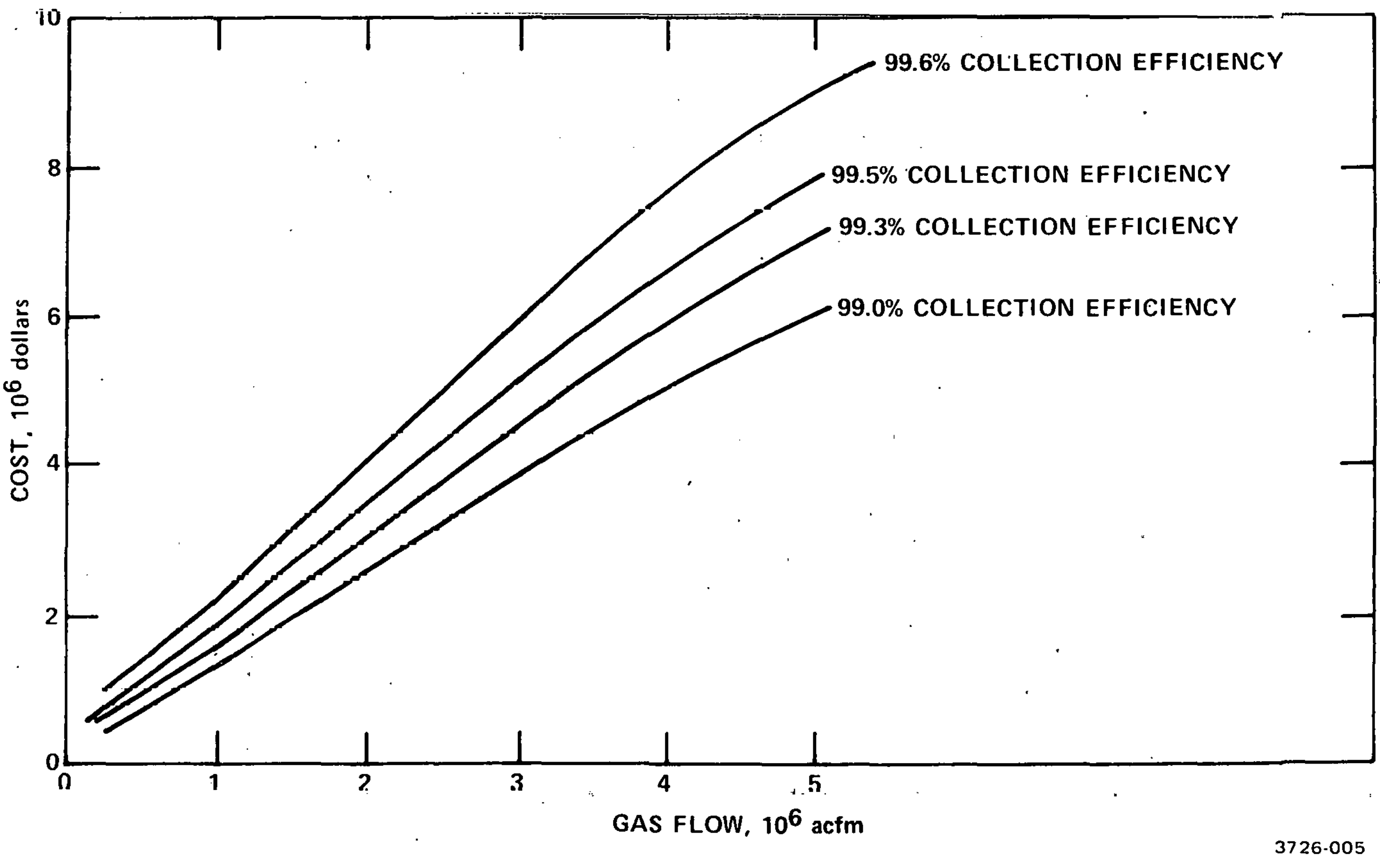

Figure 2.7 Costs (uninstalled) of hot-side electrostatic precipitators *vs.* gas volume flow rate at several values of collection efficiency.

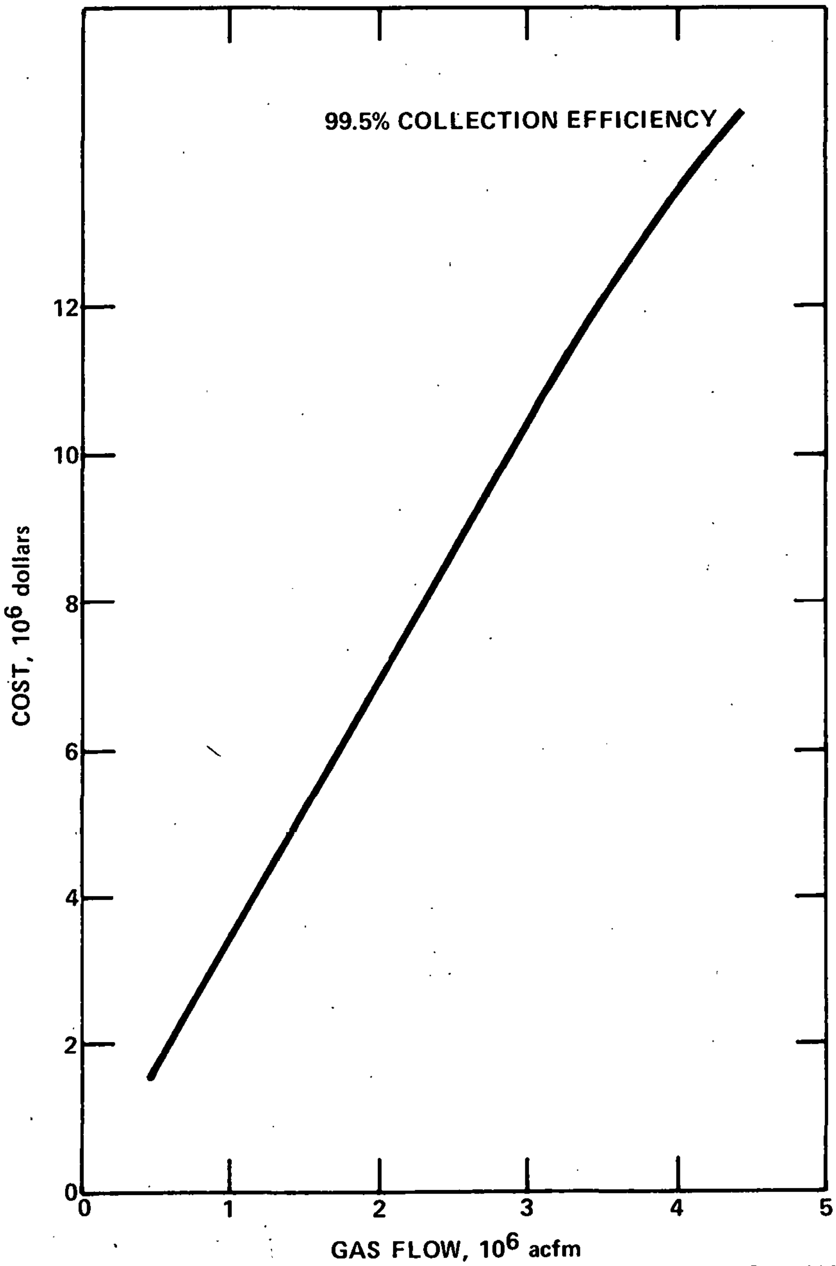

Figure 2.8 Cost (erected) for new hot-side precipitators *vs.* gas volume flow rate.

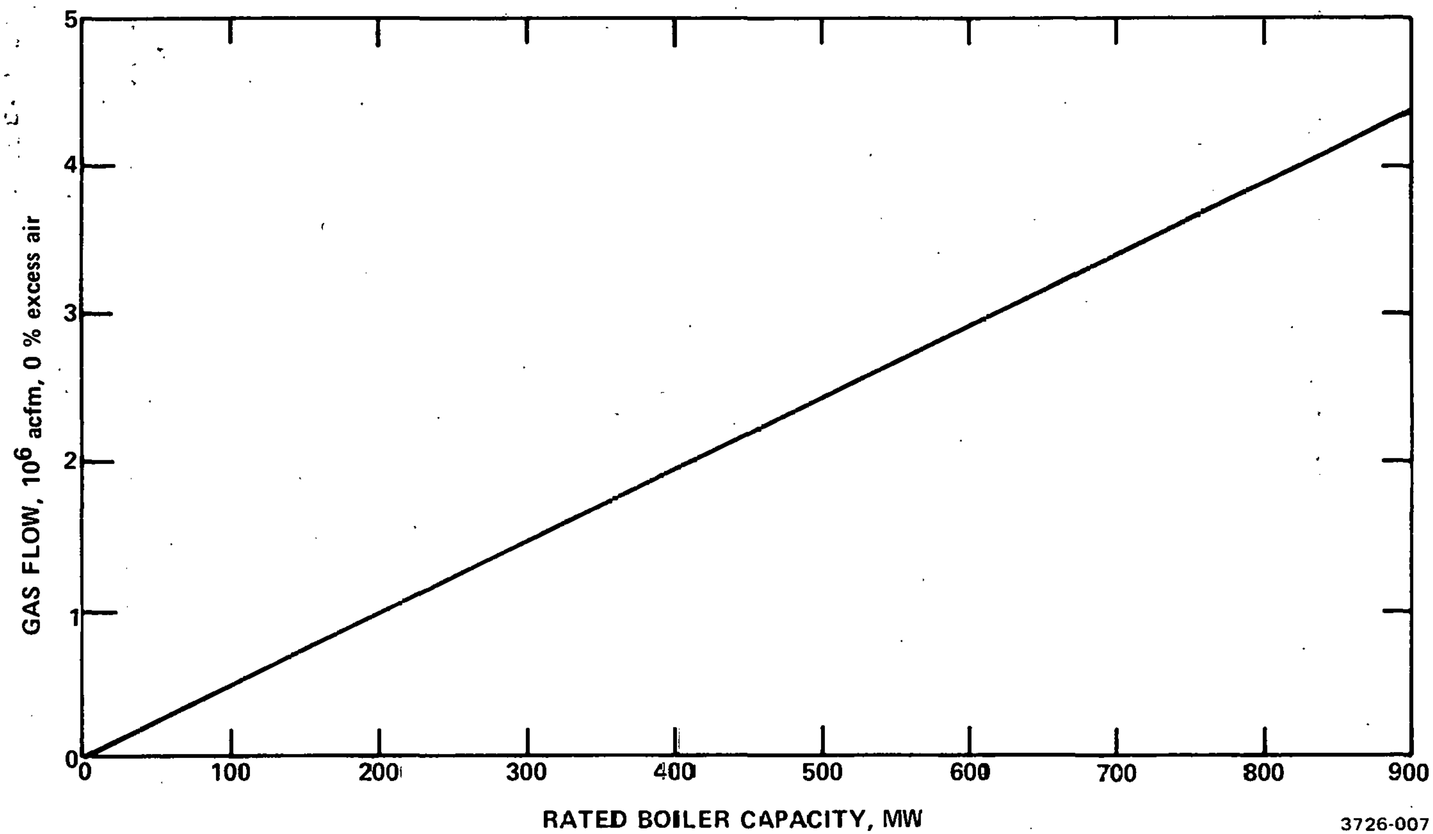

Figure 2.9 Gas volume flow rates for hot-side precipitators *vs.* boiler capacity.

Cold-Side Precipitator Costs

The cost of a precipitator installed downstream of the air heater is influenced by the electrical resistivity of the dust, in addition to those factors that determine the cost of hot-side units. Dust resistivity can vary widely, depending upon the sulfur content of the fuel and the chemical composition of the ash. In general, coal with a sulfur content of around 1.5% or greater produces ash with sufficiently low resistivity that the operating current for the precipitator is not limited. Coal with a sulfur content of less than 1.5% generally produces ash with a resistivity that limits the precipitator current. The degree to which current is limited depends upon the quantity of sodium in the ash as well as the sulfur in the coal. Thus, there are all degrees of resistivity, which determines the magnitude of the current and hence the size and cost of a precipitator to achieve a given collection efficiency.

Figure 2.10 shows the relationship between the specific collecting area and efficiency for the range of fly ash resistivity that has been encountered. The curve for low resistivity would correspond to average current densities of around 30-40 x 10^{-6} A/ft^2. The curve for a very high resistivity ash corresponds to current densities of 5-10 x 10^{-6} A/ft^2. The ash that would limit current density to these low values would typically result from coal of less than 0.5% sulfur and the ash would contain less than around 0.2% sodium as Na_2O.

On the basis of data such as those in Figure 2.10, the uninstalled precipitator costs for low, moderately high, and very high-resistivity fly ash (99.5% collection efficiency) were calculated and are shown in Figure 2.11.

Figure 2.12 shows the erected costs for precipitators collecting ash of three different resistivities. The erected costs were computed as twice the uninstalled costs.

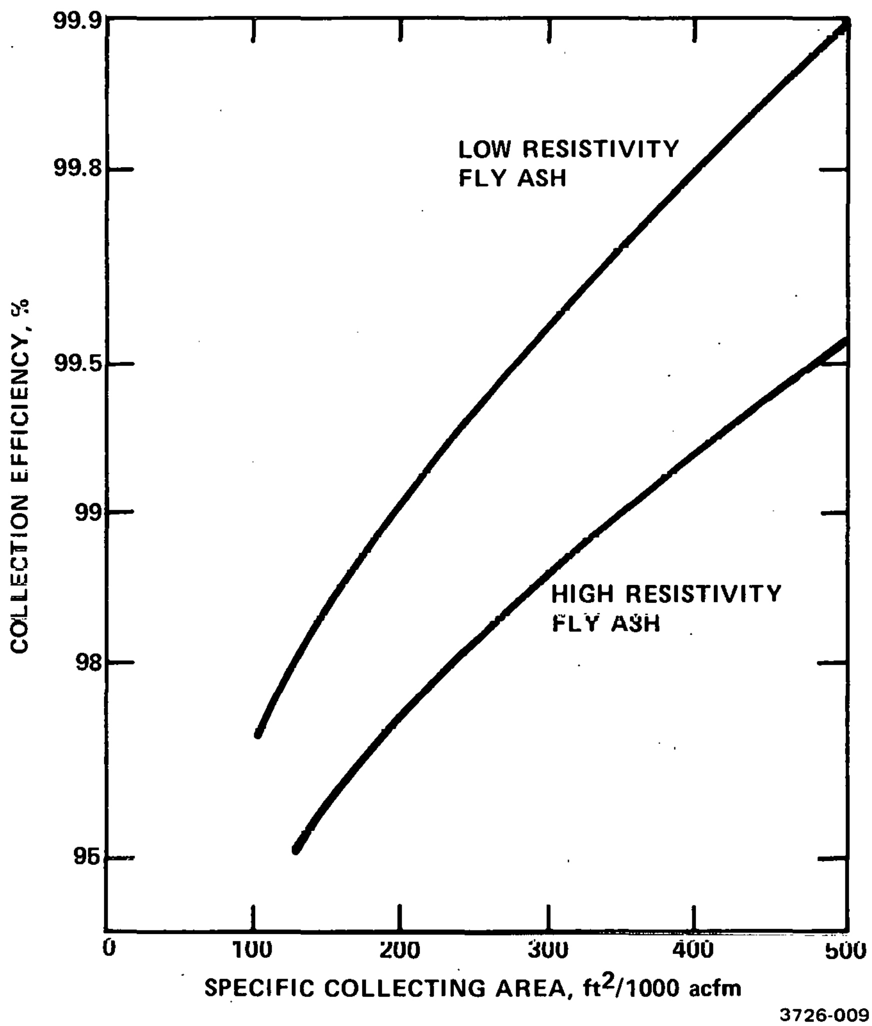

Figure 2.10 Collection efficiency *vs.* specific collecting area for cold-side precipitators collecting fly ash of low and high electrical resistivity.

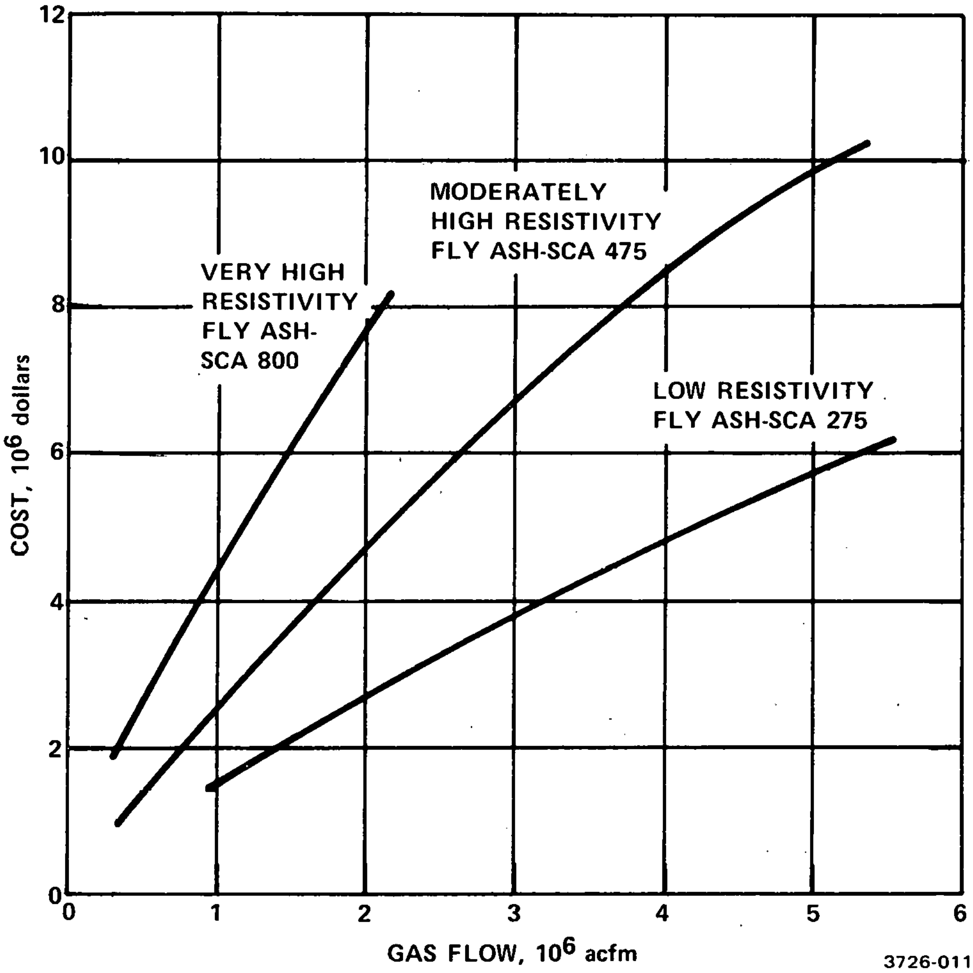

Figure 2.11 Cost (uninstalled) for cold-side electrostatic precipitators collecting low, moderately high, and very high resistivity fly ash (99.5% collection efficiency) *vs*. gas volume flow rate.

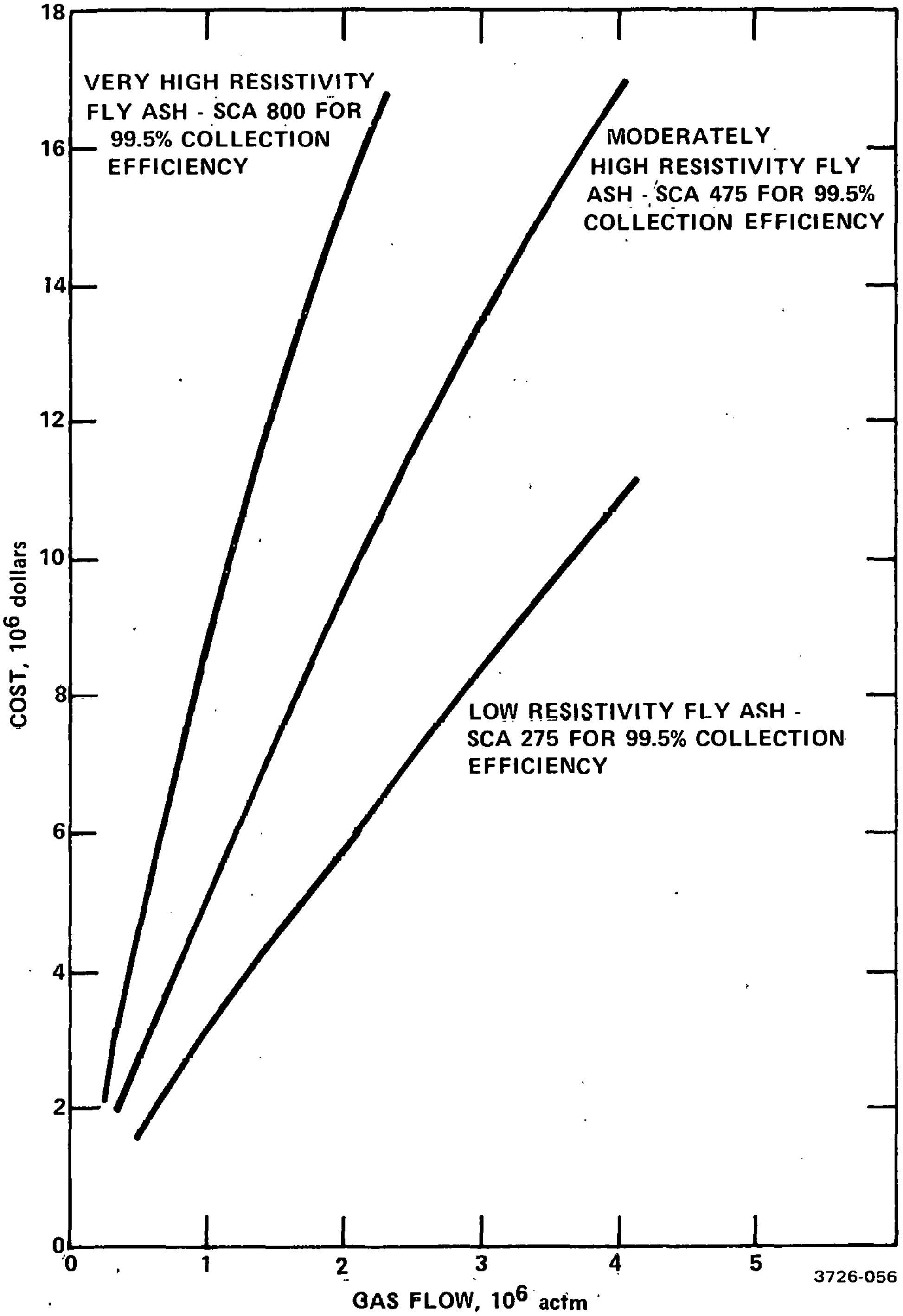

Figure 2.12 Cost (erected) for cold-side electrostatic precipitators collecting fly ash with low, moderately high, and ver high resistivity.

The relationship between gas flow and boiler capacity for cold-side precipitators is shown in Figure 2.13. The data points correspond to design gas flow for cold-side precipitators for which data are available.

A comparison of the erected costs of hot- and cold-side precipitators on boilers of different capacities is shown in Figure 2.14 for three different ash resistivities. For a low resistivity ash, the cost clearly favors a cold-side unit. For a moderate resistivity ash, the erected costs of hot- and cold-side precipitators are comparable. For a very high resistivity ash, the erected cost of a hot-side unit would be considerably less.

Ancillary Equipment and Construction Costs

Costs for control of particulate emissions also include ash handling equipment, ductwork, and pipes, pumps, and other ancillary equipment. Many of these items are common to all types of dust control equipment, so that cost comparisons could be made equally well on the basis of either the installed or erected cost of the control device. However, some installations, notably hot precipitators, require more ductwork than others. Installed ductwork is estimated at about $30/ft^2, and depending on the particular plant layout, the incremental cost for the additional ductwork could be included in the estimate.

For cold-side precipitators, the total cost of the ductwork, ash handling system, and I.D. fans is about 43% of the erected precipitator cost. A breakdown of the cost of these items is given in Table 2.5.[38]

Maintenance Costs

Maintenance costs can vary among precipitator installations for a variety of reasons. The quality and age of the

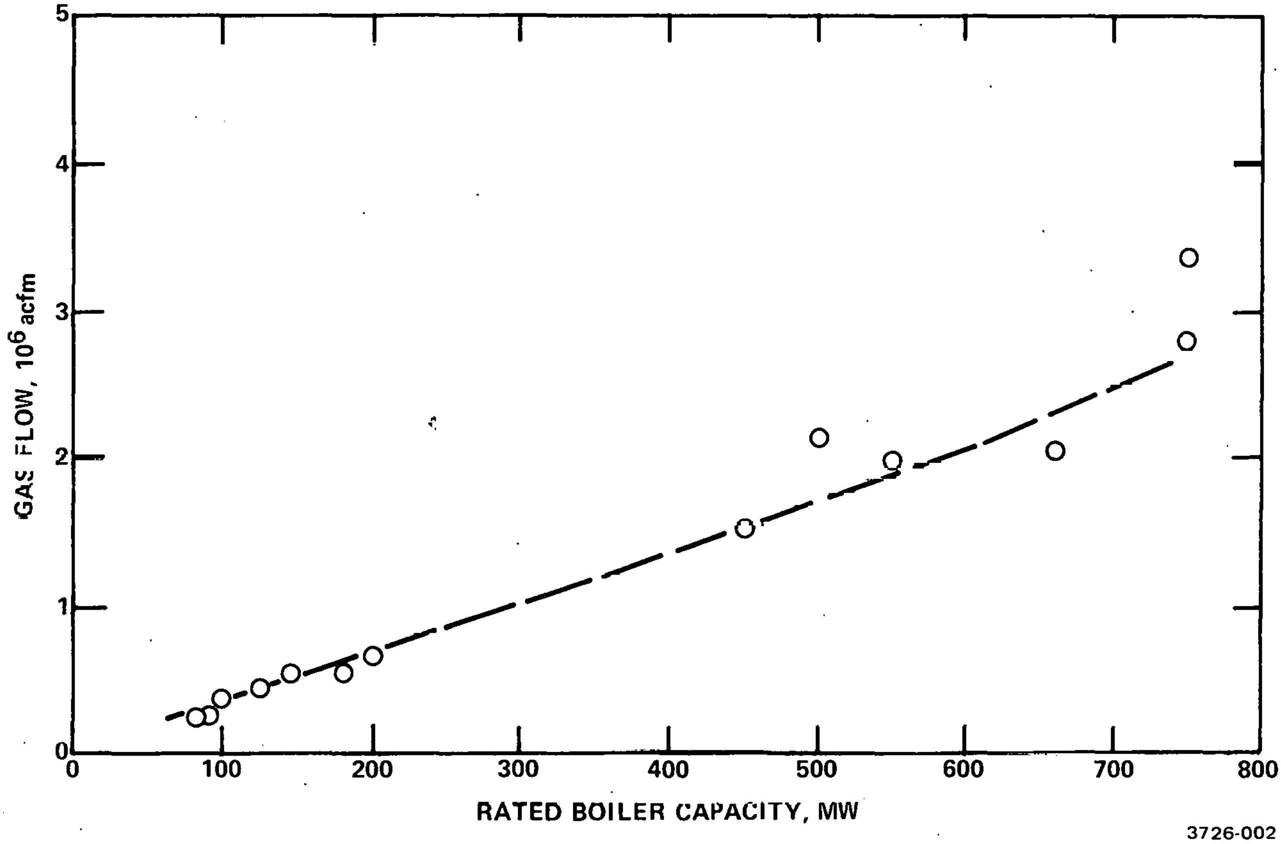

Figure 2.13 Gas volume flow rate for cold-side electrostatic precipitators *vs.* boiler capacity.

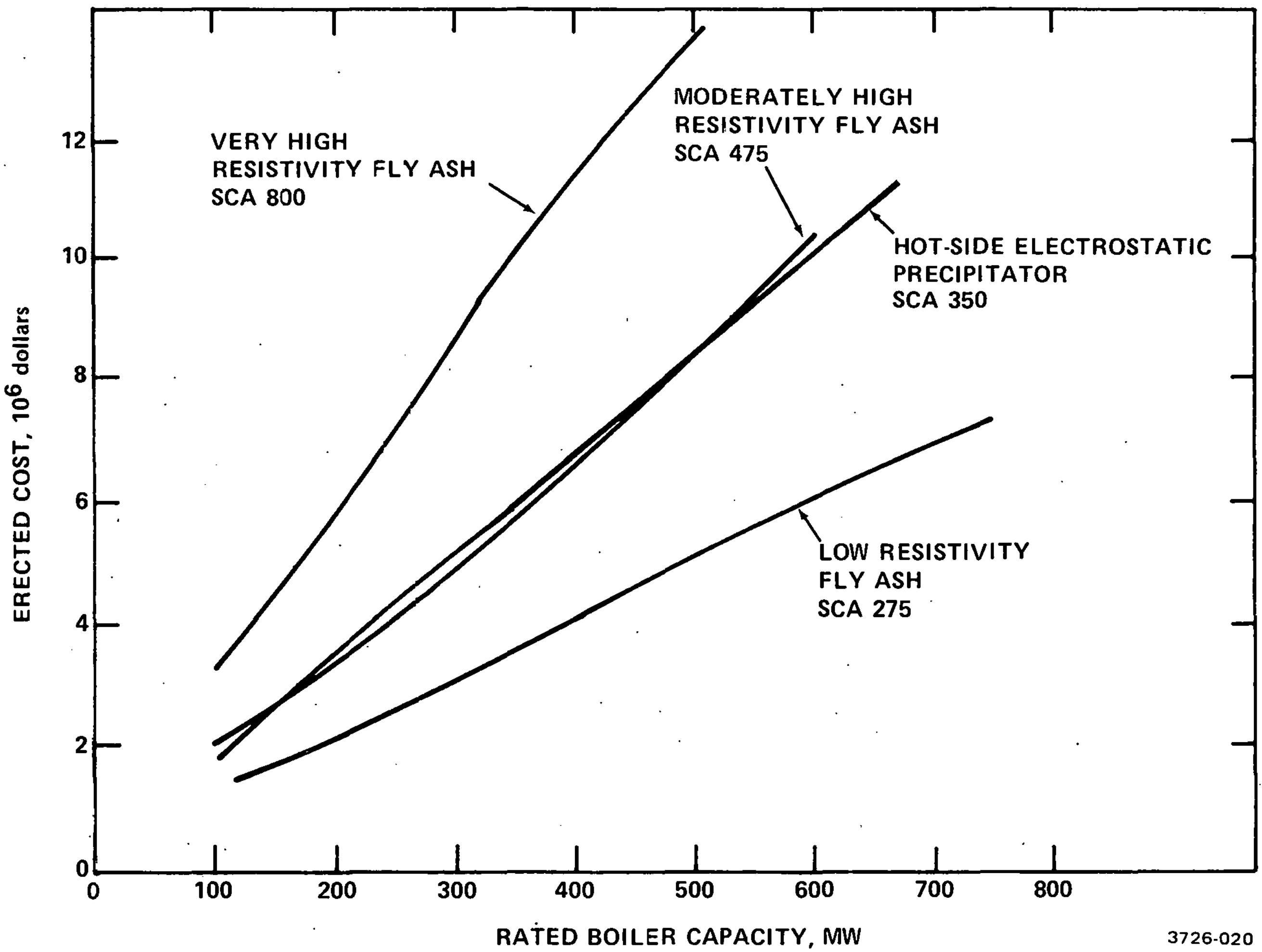

Figure 2.14 Cost (erected) for hot- and cold-side electrostatic precipitators collecting low, moderately high, and very high resistivity fly ash (99.5% collection efficiency).

Table 2.5. Material Costs for Large Modern Electrostatic Precipitators[38]

Items	% of Total Cost
TR Sets	8.26
Control Panels	6.88
External High Voltage System	2.03
Electrical Devices	0.03
Casing	15.83
Hoppers	10.20
Collecting Plates	13.80
High Voltage System	5.78
Rapper System	8.47
Inlet Plenum	2.79
Outlet Plenum	2.61
Internal Access	0.55
External Access	1.20
Superstructure	3.51
Ventilation Equipment Support	0.23
Operating Floor Insulation	0.75
Hopper Dust Control	0.74
Safety Interlocks	0.80
Support Structure	10.61
Access Facilities	4.93
Total	100.00

installation, the type of fuel, and the operating conditions, for example, can cause precipitator components to fail for the causes discussed elsewhere in this report.

Figure 2.15 is a histogram showing the average costs per year per 1000 ft^2 of collecting surface for a group of 24 precipitators. The average maintenance cost for the group of precipitators for which records are available from one utility is $55.60/1000 ft^2 per year. For 18 of the precipitators, the maintenance cost was below the average. For 3 of the precipitators, the cost was very high, in one case over 3 times the average cost.

Maintenance costs for a given installation can be influenced by the period covered by a study. Costs can be very high if a major overhaul, such as wire or plate replacement, is involved.

The average annual cost of $55.60/1000 ft^2 agrees reasonably well with data reported in 1969,[39] taking into account the increase in labor and material costs since then.

Operating Costs

Accurate data on operating costs is not available from most utilities, since operating labor costs for precipitators are not kept as a separate item. Generally, no operating personnel are required, except for periodic recording of electrical data and log keeping, which can be done on a part-time basis.

Precipitator power requirements are discussed in Section 2.2.4.

Energy costs for a precipitator are computed from the power density, collecting plate area, operating time, and unit energy cost. In addition, the power required due to the pressure drop through the precipitator must be calculated.

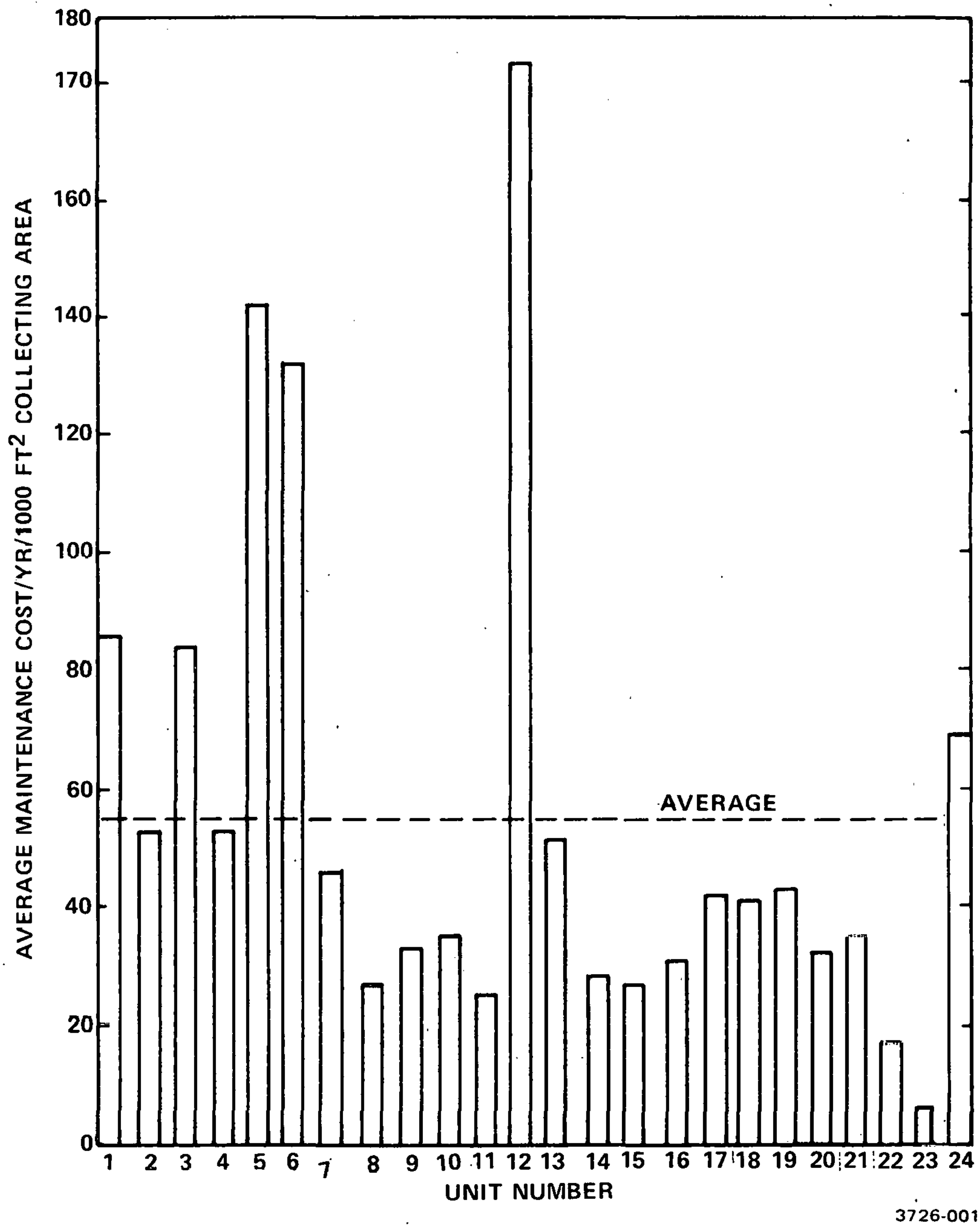

Figure 2.15 Maintenance costs for electrostatic precipitators.

Table 2.6 lists the operating labor costs and energy costs for hot- and cold-side precipitators collecting fly ash with different resistivities.

The costs of flue gas additives that are used in some installations to improve the collection efficiency for fly ash are listed in Table 2.7. A TVA study showed that the cost of sulfuric acid injection at the Widows Creek Steam Plant in 1968 was $80,000 per boiler, or about 0.18 mills/kWh based on a 90% load factor.[40] Some cost data on the use of one proprietary additive were obtained from a 1977 survey of utility companies.[24] Table 2.7 shows the range of the data. The actual cost for the conditioning agent is dependent on the number of tons of coal burned as well as plant output related to capacity.

2.2.11 Secondary Environmental Impact

Even though fly ash is collected in a dry state in the hoppers of an electrostatic precipitator, it is usually disposed of as a slurry for convenience in handling. The slurry is pumped to the disposal site. If this method is not practical, dry fly ash can be conveyed to a storage silo, from which it is discharged through wetting equipment to motor trucks for transport to disposal sites. The moisture content can be adjusted to 15-20% to reduce dusting and aid in compaction of the ash at the disposal site.

There is some concern that the amount of sulfur trioxide or sulfuric acid that is added to the flue gas as a conditioning agent may be enough to contribute to the air pollution burden under some conditions; however, there is not enough information on this question to indicate whether the concern is justified.

Sulfur trioxide is used in concentrations up to 20 ppm of stack gas. If as much as 5 ppm escapes being absorbed by the fly ash and is emitted as sulfuric acid, it would add 0.01 grains/ft^3 to the emissions.

Table 2.6 Electrostatic Precipitator Costs

Item	Boiler Size, MW 300	400	500	600	700	800	Temperature	Fly ash Resistivity	Specific Collecting Area, ft²/1000 acfm
Precipitator energy cost, $/yr[a]	94,600	119,800	151,400	182,900	214,400	246,000	Hot-side		350
	88,000	123,200	158,400	193,600	220,000	264,000	Cold-side	Low	275
	66,500	93,100	119,700	146,300	166,200	199,500	Cold-side	High	475
	28,500	39,900	51,300	62,700	71,300	85,500	Cold-side	Very High	800
Fan power cost, $/yr	29,600	39,500	49,400	59,200	69,100	79,000	Hot-side		
	19,700	27,600	35,500	39,500	49,400	59,200	Cold-side		
Operating labor cost, $/yr[b]	9,800	11,000	12,300	13,200	13,800	14,700	Hot-side		
	6,500	7,400	8,200	18,800	9,200	9,800	Cold-side		
Maintenance cost, $/yr	29,200	55,500	70,100	84,600	99,200	113,800	Hot-side		350
	15,300	21,400	26,000	32,100	38,200	44,300	Cold-side	Low	275
	26,400	37,000	44,900	55,400	66,000	76,600	Cold-side	High	475
	33,400	46,500	56,500	69,800	83,200	96,400	Cold-side	Very High	800
Capital cost, erected, 10^3 $	5,300	7,000	8,500	10,100	11,800	13,400	Hot-side		350
	3,100	4,200	5,200	6,100	7,100	8,300	Cold-side	Low	275
	5,000	6,700	8,400	10,000	11,700	13,600	Cold-side	High	475
	8,900	11,600	14,000	16,000	17,700	19,400	Cold-side	Very High	800

[a] Basis: 8760 hr/yr, 0.8 duty factor, power at $0.02/kWh, power supply efficiency 70%, collection efficiency 99.5%

[b] Reference 38.

Table 2.7 Use of a Flue Gas Additive by Coal-Fired Electric Power Plants

	Plant Capacity, MW	Cost	
		Equipment Installed, 10^3 $	Chemical, $/ton coal
Proprietary Additive[a]	200	73	0.84
	600	60	0.62
Sulfur Burner	200	710[b]	0.10
	600	1,560[b]	0.10
Sulfuric Acid Injection[40]	115	-	0.80[c]

[a]Data obtained in a 1977 survey of utility power plants.[24]

[b]Values in 1976 dollars, calculated from a base cost obtained from a vendor, by the power rule:

$$\text{cost} = \text{base cost} \times \left(\frac{\text{size, MW}}{\text{base plant size, MW}}\right)^{0.7}$$

[c]Value estimated as twice the value quoted in Reference 40.

2.3 FABRIC FILTERS

2.3.1 Method of Collection

Fabric filters have been used for many years to remove dusts from industrial process gases, notably from cement kilns and metallurgical operations. They have also been installed on a number of small power boilers; but it is only within the past few years that they have been considered for removing fly ash from large electric utility boilers burning coal.

In most of the baghouse designs used at present for filtration of stack gases, as in many other fabric filter applications, the fabric is formed into a vertically hung tube or sleeve closed at the top. The stack gas is drawn through the bag from inside it, and the collected dust forms a loosely deposited cake inside the tube. In most baghouses, the flue gas flow is periodically turned off and the dust removed from the fabric by agitation, partial bag collapse, air back flow, a combination of these methods, or by reverse air pulse. The filter is thus regenerated and prepared to resume filtering. The collected dust falls into a hopper, from which it is carried away for disposal.

2.3.2 Theory of Filtration

Fabric filters collect particles by the mechanisms of impaction, interception, and diffusion. In addition, electrostatic forces can be important in fabric filtration. However, after a new fabric collector has been in operation for several minutes, collection mechanisms are different from those of classical filter theory. The reason for this change is that, after an initial phase of collection, the cake of filtered material that builds up on the fabric surface and the interstices of the fabric provides most of the filtration until it is removed in the part of the filtering cycle in which the filter is cleaned and regenerated.

As the cake grows thicker with time, the pressure drop across the filter increases. When a preset pressure drop across a compartment containing filter bags is reached, or when a preset time has expired, the compartment is isolated from the gas flow for bag cleaning. The method of cleaning depends on the fabric structure. Woven bags are cleaned by shaking or reverse air flow or both. Felted bags are sturdier and can be cleaned with a pulsed jet of air, which creates a disturbance which is propagated along the bag, removing the dust cake as it travels from the top to bottom. After the dust is removed, the isolated compartment is reexposed to the gas flow. A collection process now occurs which is similar to that of initial cleaning by an unused bag. But now the interstices of the filter material are still loaded with particulate matter which is not dislodged by cleaning. After a number of cleanings, bags build up an interstitial accumulation to a constant level, in which condition the bag is considered to be broken in. Because of this residual dust loading, the filter cake is more quickly reestablished when filtration commences. The pressure drop-versus-time relationship for a freshly cleaned bag is nonlinear until the filter cake is reestablished; this often takes several minutes and has important consequences for modeling studies of fly ash collection by woven bags.

The collection mechanism of woven fabric filters differs in some details from that of nonwoven filters when fly ash is being collected.[41] These differences can be traced to the basic fabric structure and the method of cleaning. Woven materials do not have as many interstitial voids as do felted materials and after cleaning require a longer time to reestablish the filter cake. In laboratory studies with redispersed fly ash the time-average outlet dust concentration was nearly independent of the inlet dust concentration. By contrast, for felt bags, cleaned with pulsed jets of air, the emissions depended on the inlet dust concentration. Thus, woven fabrics offer better filtration characteristics when inlet dust loadings can change and outlet emissions must be held at or below some specified value. A 1976 summary of fabric filter installations for flue gas control of coal-fired boilers noted that of 8 existing or planned utility boilers with fabric control devices, all use woven fabrics, and of 28 industrial intermediate-size boilers with fabric filters, 24 use woven bags.[42] Hence, the preponderance of fabric filter control devices used on coal-fired boilers are made from woven fabrics. This, coupled with the relative insensitivity of woven filters to inlet dust loading, indicates that in future fabric filter installations on coal-fired boilers, woven filter bags will probably be used. Therefore, in the following discussion of fabric filtration, attention will be focused on woven filters.

Fabric Structure

A fabric is a porous, flexible textile material made by weaving or felting. For a woven fabric the yarn is formed by twisting fine fiber strands of individual filaments. Depending on the particular material from which the yarn is made, individual fibrous filaments may or may not occur within the interyarn (interstitial) spaces.

Filter fabrics made from spun staple yarns of twisted, relatively short fibers will show many more interstitial filaments than fabrics of fiberglass and synthetic continuous filament yarns. These filaments should be beneficial in high efficiency filtration, since they help in maintaining a moderate residual dust load and in supporting the filter cake. On the other hand, the more rounded fibers of fiberglass and other synthetic continuous filament materials also have good filtration characteristics. In a study of fabric structure and the related filtration performance, it was concluded that there were several factors which influenced the efficiency of a fabric filter. The ultimate performance of a fabric filter was linked to the interyarn spacing or pore-size distribution of a fabric in that the presence of a significant number of pores with a characteristic dimension roughly ten times the mass median particle diameter of the dust being filtered leads to bleeding or leaking of dust, *i.e.*, increased penetration due to the inability of the dust to bridge these pores.[43]

Collection of Dust

Three types of dust filtration with fabric filters can be identified.[44] Type I, the initial phase, begins with the unused fabric and ends with the first cleaning of the fabric. Type II, the middle phase, begins when a bag is cleaned the first time and ends when the residual fabric dust load remains constant after each cleaning cycle. Type III, the last phase, is characterized by the fabric being fully filled with dust and having a stabilized value of pressure drop and residual dust load immediately after cleaning. Figure 2.16 illustrates the three types of dust filtration. During the initial phase of cleaning, the mechanisms of impaction, interception, and diffusion operate, and filtration can be described with classic filtration theory.[45,46] Fabrics constructed from staple yarns begin this initial phase with the capture of individual particles by single projecting fibers within the flow field, presumably in interyarn space. Smooth-surface yarns (fiberglass and synthetic fibers) form deep channel-like pores with few, if any, projecting fibers. Deposition occurs in these pores under velocity conditions which are at least an order of magnitude greater than the average face velocity of the fabric.[41]

Particulate matter collected by the fabric filter builds up first in the vicinity of the pores. As it builds, a cake is formed through which most of the flow must pass. Particles entrained in the flow stream are captured by the cake. The cake-capture filtration continues until the pressure drop across the bag face reaches the point where filter cleaning is initiated and the initial phase of filtration ends.

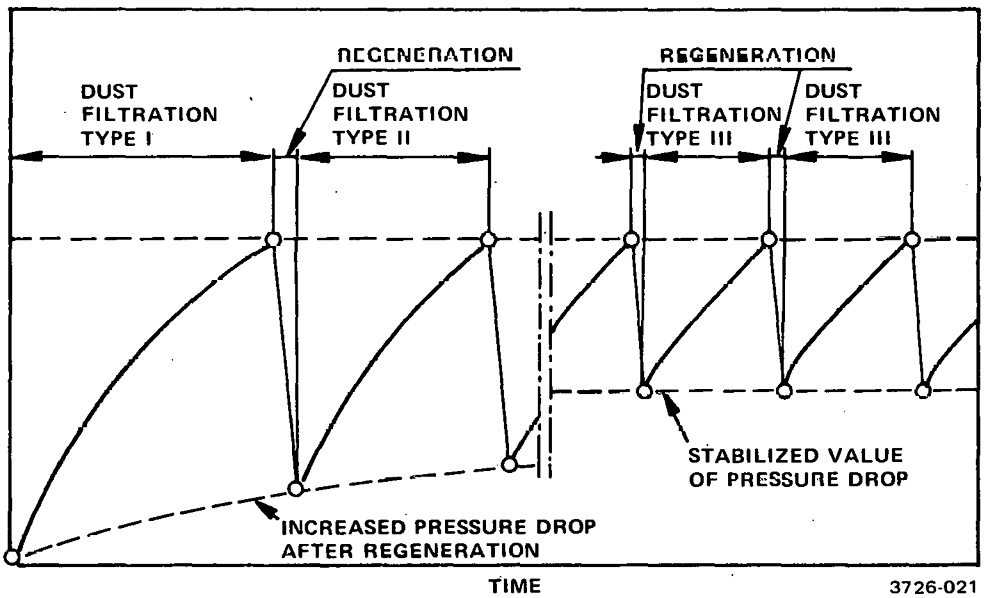

Figure 2.16 Types of dust filtration.[44]

In the second phase of filtration, the residual dust load on the fabric filter accumulates. After cleaning, the filter is never returned to the unused state since particulate matter will coat the filter in at least a mono-layer. Mechanical shaking followed by or in conjunction with reverse air flow can never overcome the Van der Waals forces of adhesion between the fly ash and, for example, fiberglass filter bag fabric. After each cleaning more particulate matter is left "embedded" in the filter than in the last cleaning until some constant residual dust loading is left. The time required for this dust load to build up is a function of many variables. These variables include weave, pore size, air-to-cloth ratio (air flow divided by filter area), frequency of cleaning, method of cleaning, and mass median diameter of the dust.

When the filter bag is seasoned, Type III filtration commences. At the beginning of a filtering cycle, the pores or interstices are loaded with dust and this residual dust layer plays an important part in the formation of the filter cake. Filtration begins with the capture of individual particles by other particles of the residual dust layer. These deposited particles then act as additional obstacles for future capture of other particles. A series of loose chain-like aggregates form which project into the flow. Further accumulation occurs until the fabric pores are bridged and the filter cake is formed. During the formation of the filter cake, the pressure drop increases non-linearly with increasing dust deposit, or time if inlet dust concentration and filtration velocity are constant. When the cake is formed, pressure drop across the filter increases linearly with increasing dust deposit or time until cleaning. Figure 2.17 shows this type of behavior for four different fabrics.[46]

Experiments on the deposition of fly ash (spherical particles) and talc (flat particles) in woven bags and the regeneration of the bags show differences in behavior of the particles in the filter fabric. The shape of the talc particles apparently facilitated the closure of pores and retarded the seepage of the particles through the fabric.

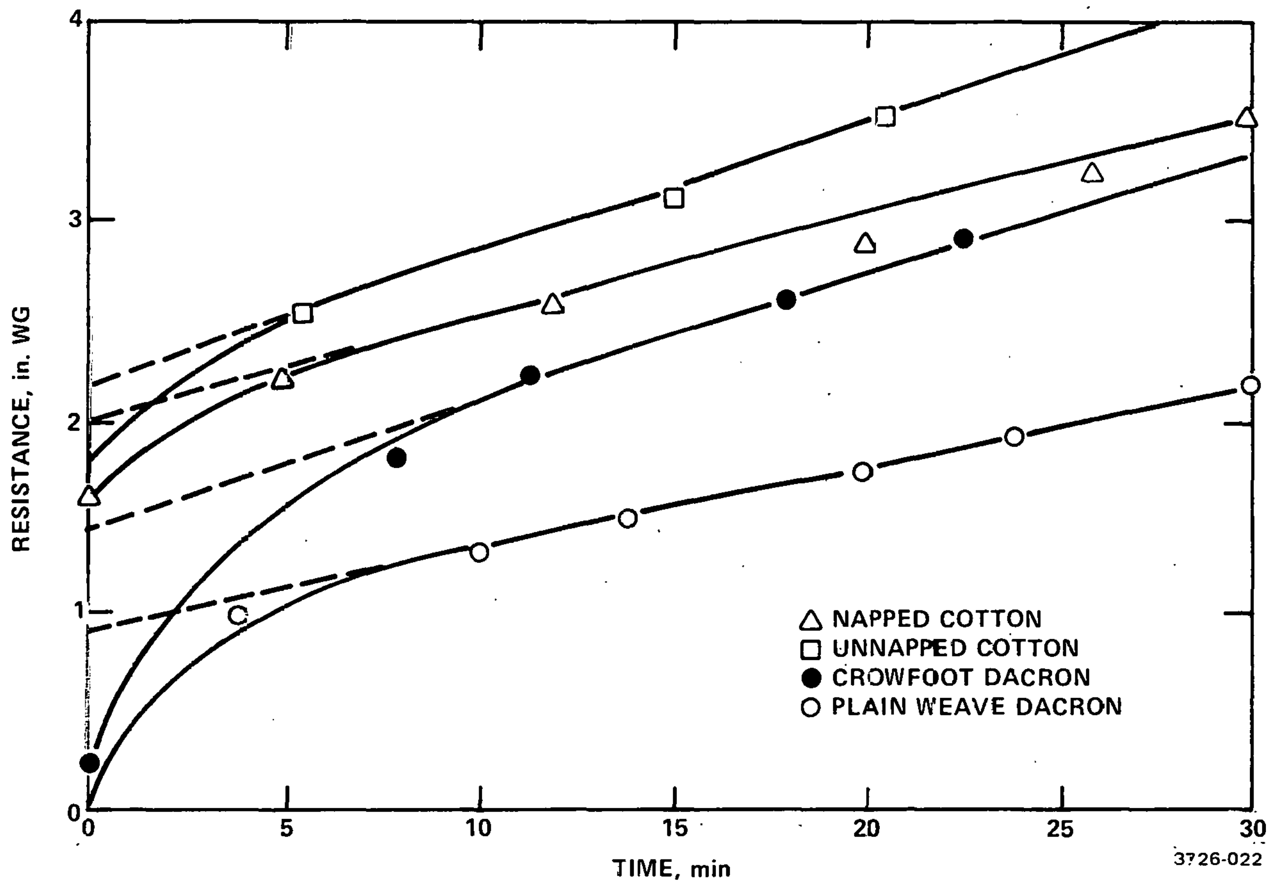

Figure 2.17 Resistance changes during fly ash filtration for well-used fabrics. Inlet loading: 3.5 gr/ft^3; filter velocity: 3 ft/min, 30 min filter cycle.[46]

The overall mechanism of particle collection involves some combination of impaction, interception, and diffusion on and within the filter cake. There is conjecture as to the exact collection mechanisms that act in the filter cake, but Cooper and Hampl[47] in their model studies of fabric filter collection assume that the flow and collection by the filter cake are similar to those in nuclepore and membrane filters with low porosity. The model also assumes that some of the interyarn spaces or pores stay open during the filtration cycle. A study of the penetration mechanisms of fly ash through needled felt fabric filter material indicated three mechanisms of penetration: direct penetration, gradual seepage of the dust, and the breakage and penetration of plugs of material in the vicinity of pinholes. Although this work was done on felted materials, some of the penetration mechanisms may be similar for woven filters, especially when they are viewed as arrays of evenly sized and spaced pores with a filter cake layer that almost covers them.

2.3.3 Factors Affecting Performance

Factors which can influence fabric filter performance with fly ash include the fabric structure, air-to-cloth ratio, maximum pressure drop before cleaning, method of cleaning, cleaning frequency, intensity of cleaning, and flue gas temperature and humidity. These factors can be broken down broadly into two categories: factors which are basic to the design of a fabric filter system for optimum performance and factors which relate to the behavior of the system as installed. During the design of a baghouse, questions of fabric, method of cleaning, air-to-cloth ratio, operating temperature, and humidity need to be considered. Once the baghouse is operating, cleaning rate, duration and intensity of cleaning, and other variables related to the operation of the collector are adjusted to keep pressure drop before the cleaning below the maximum allowable.

Other occurrences can influence the collection efficiency of the baghouse. Bags can be blinded, or clogged, during boiler start-up. Temperature excursions through acid dew points may corrode the baghouse structure and adversely affect the life and performance of the bags. Another potential problem is air preheater failure, which can drive temperatures above safe operating limits for the bags.

Fabric filter performance is not influenced by some of the factors which are considered critical in electrostatic precipitator and scrubber operation. Woven fabric filters are relatively insensitive to inlet dust loading. Also, fly ash resistivity is of little consequence for fabric collectors since collection does not depend on electrostatic attraction. In contrast to the operation of a scrubber, fabric filter collection efficiency is not a function of particle wettability or pressure drop.

The insensitivity of fabric filters to inlet dust loading is well known.[46] A laboratory study by Dennis and Wilder[41] showed for a specified dust/fabric combination and a fixed operating mode for the collector that the average mass emission and its related size properties may be nearly independent of the concentration and size of the inlet dust. These results led the authors to conclude that no simple relationship exists between typical outlet and inlet concentrations for most fabric filters. The insensitivity of outlet emission rate to inlet dust concentration is understandable if considerable penetration arises from leakage. If so, emissions consist primarily of previously collected dust deposited within the fabric.

Electrostatic effects in fabric filters may not be entirely negligible, since it has been observed that collection of dust by a fabric filter is enhanced if it has a static charge, especially in the presence of an electric field.[48] On the other hand, fabric filters are obviously quite efficient in fly ash collection when no attempt at static electrification is made.

Studies on electrostatic effects in fabric filters are conducted under a grant from the EPA to Carnegie Mellon University. This program involves research on the determination of the electrostatic characteristics of different fabrics and their effects on filtration performance. The possibility of controlling filter cake porosity through the use of electrostatics is being studied.[49]

The pressure drop across a baghouse is a factor in performance. An operating pressure drop of 3-4 inches (water gauge) is typical for fly ash collection, but some industrial baghouses operate substantially above 10 inches water gauge. Pressure figures such as these are values averaged over the filtering cycle. When filtration begins, the pressure drop increases nonlinearly until a filter cake is built and then increases linearly thereafter. Figure 2.17 shows this behavior as well as the fact that fabric filters can operate for substantial lengths of time at pressure drops less than four inches of water.

Figure 2.18 shows[41] that directly after cleaning the penetration drops quickly to levels characteristic of precipitator operation (0.01-0.001). The results shown in Figure 2.18 are for unnapped cotton sateen bags. Penetration may either increase or decrease with time after cleaning, depending on the filter material, construction, and material being collected. Figure 2.18 shows that for unnapped cotton sateen bags collecting fly ash the penetration decreases with time. On the other hand, Figures 2.19 and 2.20 show how penetration can level off and remain constant with loading of seasoned fiberglass bags.[50]

Penetration increases rapidly with increasing face velocity (air-to-cloth ratio). Figures 2.21 through 2.23 illustrate this effect for a utility boiler baghouse.[51] Figure 2.21 shows penetration as a function of particle diameter and boiler load (air-to-cloth ratio). Here the penetration of particles larger than

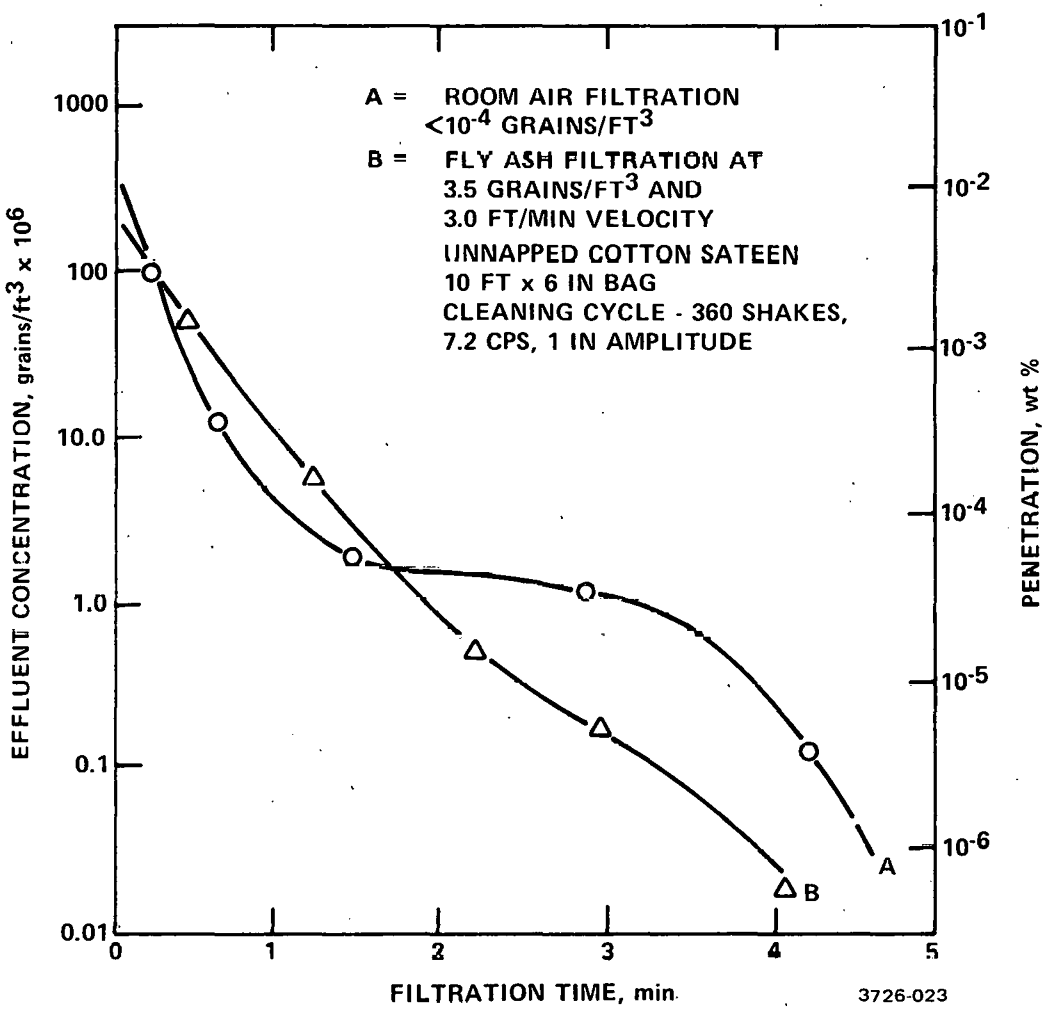

Figure 2.18 Calculated effluent concentration *vs.* time for fly ash and ambient air dust based on measurements with an optical particle counter.[41]

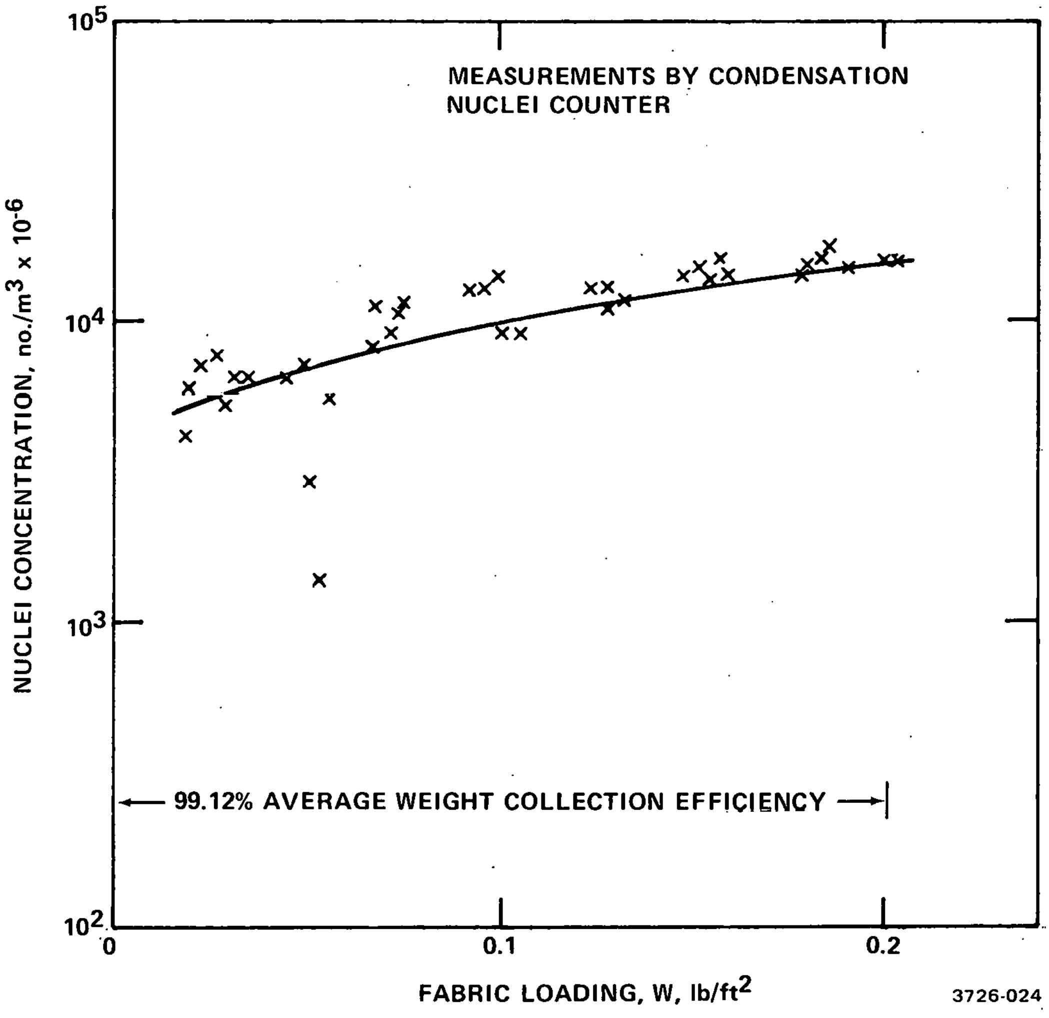

Figure 2.19 Effluent concentration of fly ash *vs.* fabric loading for used Sunbury fabric with GCA fly ash.[50]

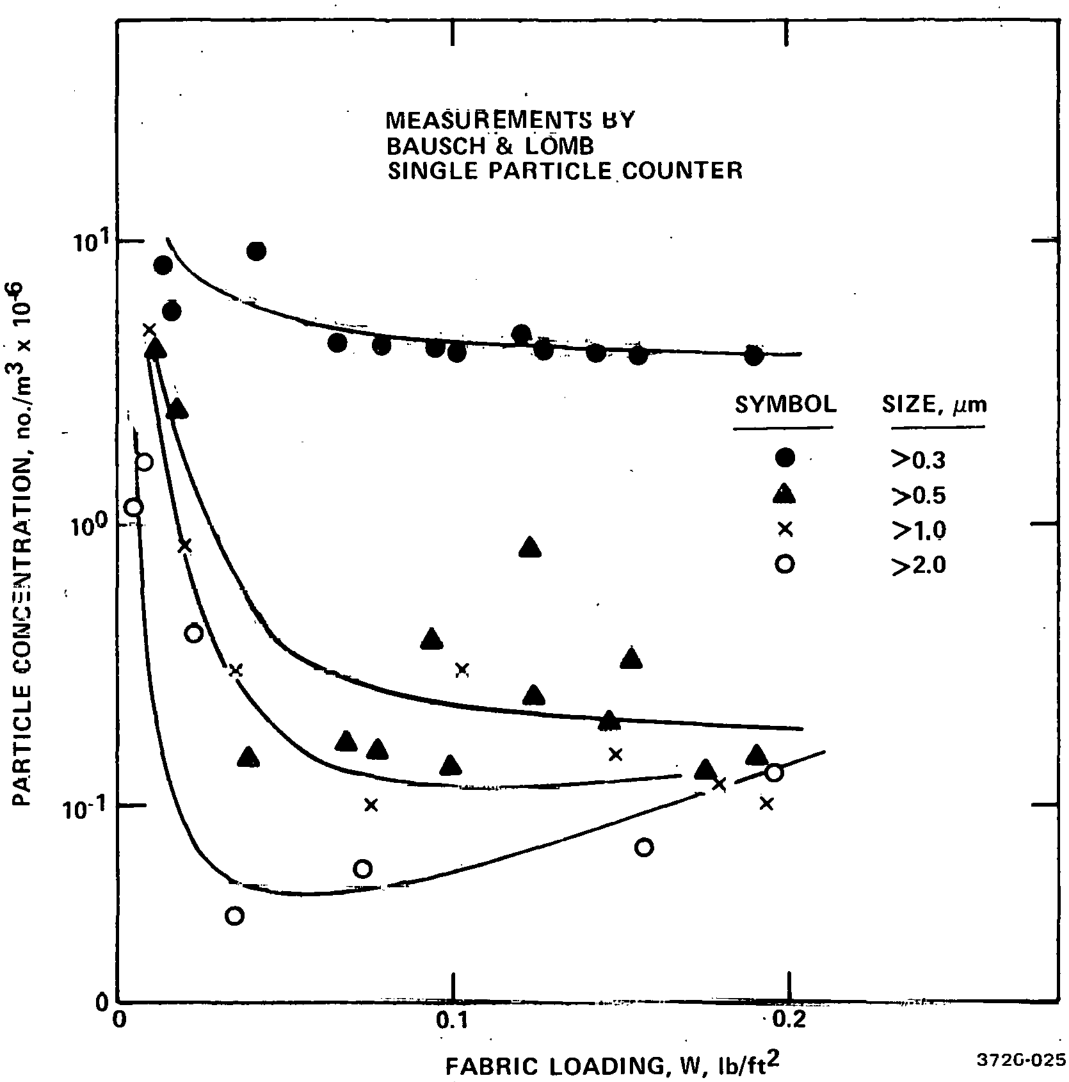

Figure 2.20 Effluent concentration of fly ash *vs.* fabric loading and particle size for used Nucla fabric with GCA fly ash.[50]

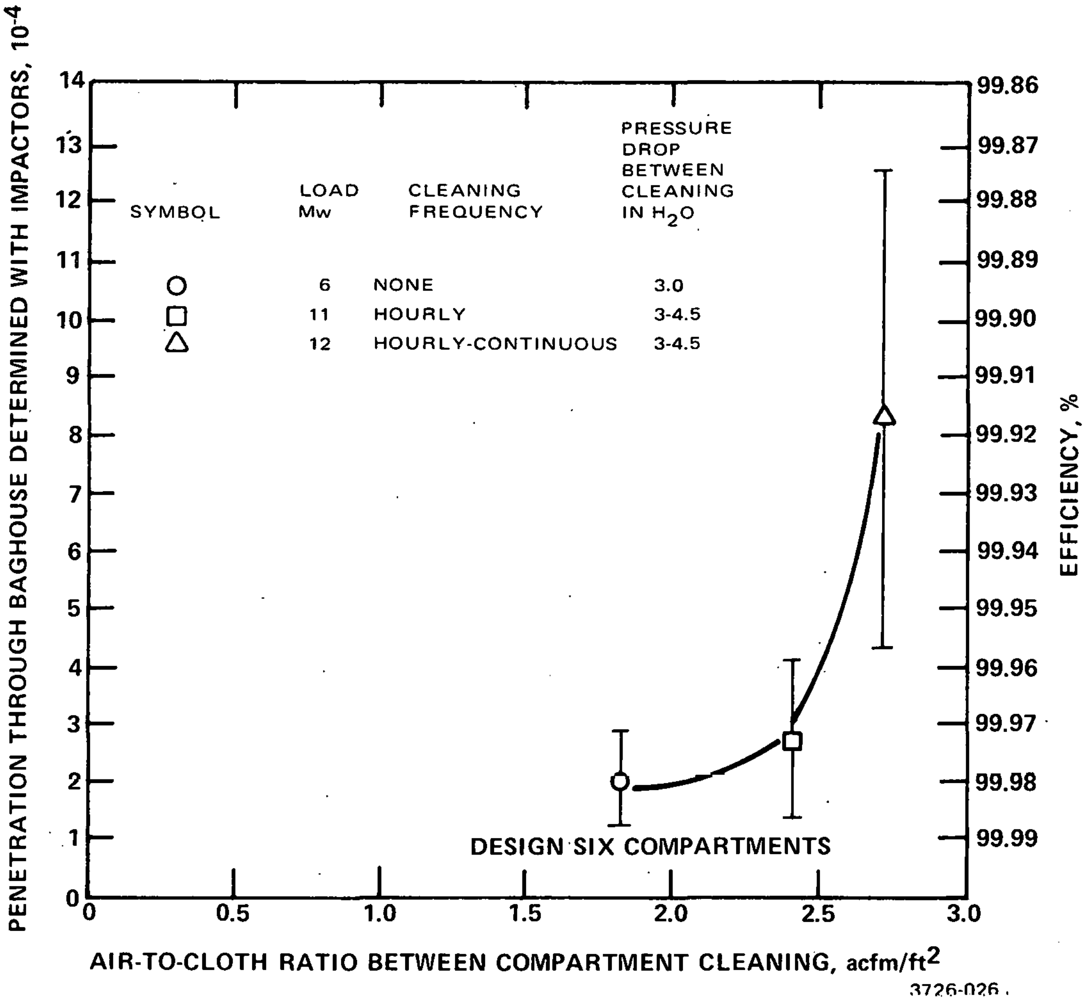

Figure 2.21 Penetration (with one standard deviation limits) as a function of air-to-cloth ratio.[51]

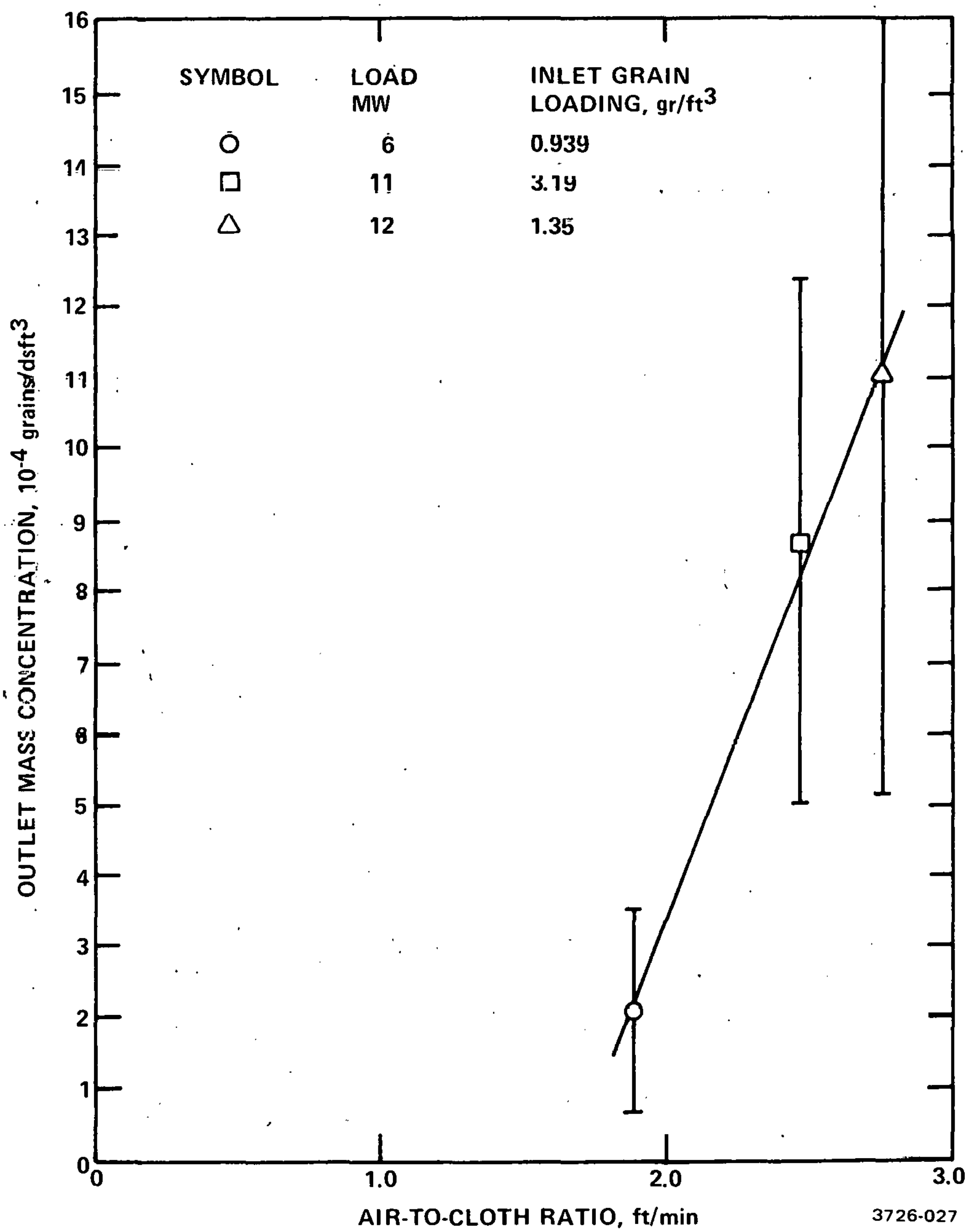

Figure 2.22 Average outlet mass concentration (with one standard deviation limits) as a function of air-to-cloth ratio.[5]

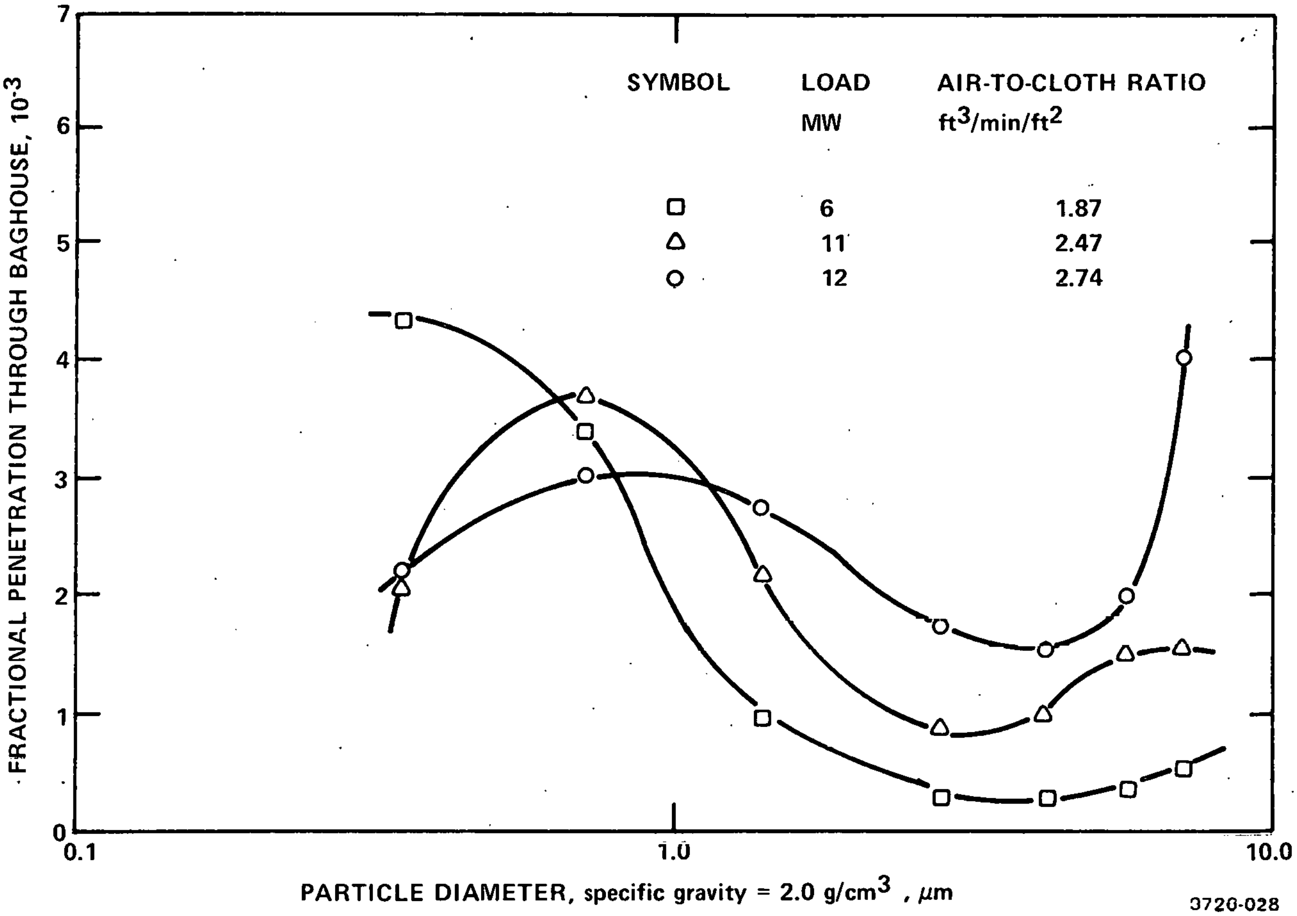

Figure 2.23 Penetration as a function of particle diameter and load.[51]

1.0 μm diameter increases with increasing air-to-cloth ratio. This indicates that the increase in penetration may be tied to an increased seepage of larger agglomerated particles. Such an increase in penetration by large particles was found in measurements made at the Sunbury station of Pennsylvania Power and Light.[52] Figure 2.22 shows typical outlet mass concentrations as a function of boiler load (air-to-cloth ratio). At lower air-to-cloth ratios, particles with larger diameters show reduced penetration.

Fabric filter performance is degraded by the presence of pinhole inclusions in the filter cake. These pinholes can be seen on the surface of a fabric upon which dust is collected, and occur with both woven and felted fabrics.[50,53] In one test the number density of such holes on a woven fabric was 250/m^2.[50] Calculations which consider the size and number density of these pinholes indicate that 8% of the total gas flow through the fabric is through these pinholes.[50] It has been conjectured that the increase in penetration in the 2 to 5 μm range of particle sizes is mainly the result of pinhole leaks which allow relatively more coarse particles to pass through.[50] The number of pinholes increases as the air-to-cloth ratio increases.[54]

There is some agreement, then, that emissions from fabric filters are the result of indirect fault processes such as seepage or pinhole leaks or both, rather than the result of a failure to collect these particles in the first place. If so, the following penetration characteristics can be explained:

(1) Increased penetration due to increased face velocity can be understood to result from the increased prevalence of pinholes at high velocity, and from increased pressure drop which may lead to increased seepage.

(2) Constant penetration as the dust cake thickens can be understood because of the inability of an established pinhole to seal once formed. The high gas velocity through the pinhole may preclude effective hole blocking, except by very large particles.

(3) Continuously decreasing penetration as the dust cake thickens can be understood if the fabric and dust do not interact to form pinholes.

(4) Constant penetration for particles of all sizes is explained if particles get through pinholes. A hole has no size fractionating capability.

(5) The insensitivity of outlet emission rate to inlet concentration is explained if considerable penetration arises from seepage. In this case, emissions are primarily of previously collected dust deposited within the fabric, and dust which is currently collecting may not have a major influence.

Fabric Filter Modeling Studies

The goal of any fabric filter modeling study is to develop techniques for predicting and analyzing fabric filter drag (pressure drop per unit face area) and fabric filter collection efficiency as a function of particle size.[47] Although much information is available on dust filtration,[55] little effort has been devoted to the characterization of fabric filters for model studies.[56-59]

Most attempts at modeling have made two significant restricting assumptions:[46,55-57] (1) fabric drag is a linear function of time or dust loading and (2) collection efficiency models are based on the collection properties of arrays of cylinders. Figure 2.17 shows that the linear drag assumption is a poor approximation immediately after cleaning. This is especially important in that the highest emission rate occurs during this period of non-linear drag.

As a result of the second assumption, the model uses an equation for the collection efficiency of clean, very small diameter fibers collecting dust by impaction, diffusion, and interception mechanisms.[60] It is doubtful that the equation can be applied to the conditions typical of filtration by fabric filters.[47] If these conditions are assumed to be an air-to-cloth ratio of 2 cm/sec (4 ft/min), fly ash particles 10 μm in diameter, fibers 800 μm in diameter (a typical yarn diameter), and a filter packing density of 0.3, the Stokes number is 0.02, lower than the critical Stokes number, below which the impaction mechanism does not contribute to collection. Diffusional collection is also negligible. Even allowing for the effect of nearby fibers, particle penetration is 0.99 or 99%.

Models for Fabric Drag

Two convenient parameters for characterizing fabric filter systems are the fabric drag and filter cake resistivity. Fabric drag, S, is defined by the following relationship between the volume flow rate Q, the fabric face area A, and the pressure drop across the filter, ΔP:

$$S = \frac{\Delta P}{(Q/A)}$$

The quantity Q/A is the air-to-cloth ratio. The filter cake resistivity can be predicted with the Kozeny-Carman equation (or its variants).[61] One version of this equation is:[61,62]

$$K_2 = \frac{25}{6} \frac{\mu(1-\varepsilon)S_p^2}{\rho_p \varepsilon^3}$$

where:

K_2 = filter cake resistivity, sec^{-1}

μ = gas viscosity, poise

ε = filter cake porosity (fractional void volume)

S_p = surface to volume ratio of particulate material, cm^{-1}

ρ_p = particle density, g/cm^3.

K_2 is quite dependent upon particle size (increasing for smaller particles) and the porosity of the cake deposit.

Since drag is proportional to pressure drop, models of fabric drag must take into account the nonlinear behavior of pressure drop (drag) with time after cleaning. Approaches which take into account the nonlinear behavior of the drag, S, vs the weight of particulate collected, W, have been made,[47,63] *e.g.*, by fitting equations of the form[63]

$$S = aW^b$$

to data obtained for the nonlinear part of the drag vs weight curve. In this approach correlation coefficients >0.90 were found for 104 of 106 data sets. Both a and b could be correlated with filter cake resistance to flow. Unfortunately, this model relies on empirical correlations and is not designed to allow calculation of specific filter parameters.

Although the more recent approach of Cooper and Hampl[47] attempts to start from a fundamental consideration of the flow through filter fabric and dust cake, it also relies on empirical correlations to fit parameters described by their theory.

The filter is viewed as a collection of pores which are either unclogged (open) or caked with particulate matter. Resistance to flow by open and caked pores is different because the air velocity through the open pores is much higher than through the cake. Values of these resistances are dependent on velocity gradients for open pores and dust packing effects for clogged pores. If the pores are either caked or open and if the decrease in population of open pores is proportional to the number of pores still open as well as an increase in fabric dust loading, dW, then

$$dN = - \frac{N}{W^*} dW$$

where:

N = number of open pores per face area of filter,

W^* = fabric loading characteristic of pore-caking.

Integration yields the fraction of pores open at a given dust loading W:

$$\frac{N}{N_0} = e^{-W/W^*}$$

where:

N_0 is the number of pores per unit area of fabric when $W = 0$.

If the caked and open pores contribute to the fabric drag in proportion to their resistances to flow and numbers, then

$$\frac{ds}{dW} = K_0 f(W) + K_2 g(W)$$

where:

S = fabric drag

W = fabric dust load

K_0 = open pore resistance to flow

K_2 = clogged pore resistance to flow (filter cake resistivity)

and $f(W) = e^{-W/W^*}$ (fraction of open pores)

$g(W) = 1-f(W)$ (fraction of caked pores).

Integration of this equation yields an expression for the drag S as a function of fabric dust loading:

$$S = S_R + K_2W' + (K_R - K_2)W^*g(W')$$

where:

$$W' = W - W_R$$

is the difference between the fabric dust loading, W, and the residual dust loading of a seasoned fabric, W_R. Residual loading is not normally known, although it can be determined in the laboratory. S_R is the drag of this seasoned fabric, which must be determined empirically, and K_R is resistance to flow by the seasoned fabric after cleaning. Figures 2.24 and 2.25 show the results obtained by fitting the four unknown parameters in the above nonlinear equation to data obtained from actual fabrics filtering mica dust. W_I is the dust loading above which the fabric drag *vs.* dust loading curve is linear.

Figures 2.24 and 2.25 show that constants can be evaluated so as to fit experimental data with the nonlinear expression. The parameters in the model may be theoretically predictable, but until they are, such correlations must be used. Such a model promises to be an improvement on the linear drag model because it can describe that part of the filter performance for which flow and emissions are greatest, the low-loading, nonlinear part.

Models for Fabric Filter Efficiency

As mentioned previously, theories of particle collection by clean cylindrical fibers for the evaluation of collection efficiency have shortcomings, and some investigators have concluded that there is no adequate theory for predicting the penetration of fabric filters by fly ash.[64] While it is true that there are no proven models for collection efficiency calculation in fabric filtration, Cooper and Hampl[47] have presented the first

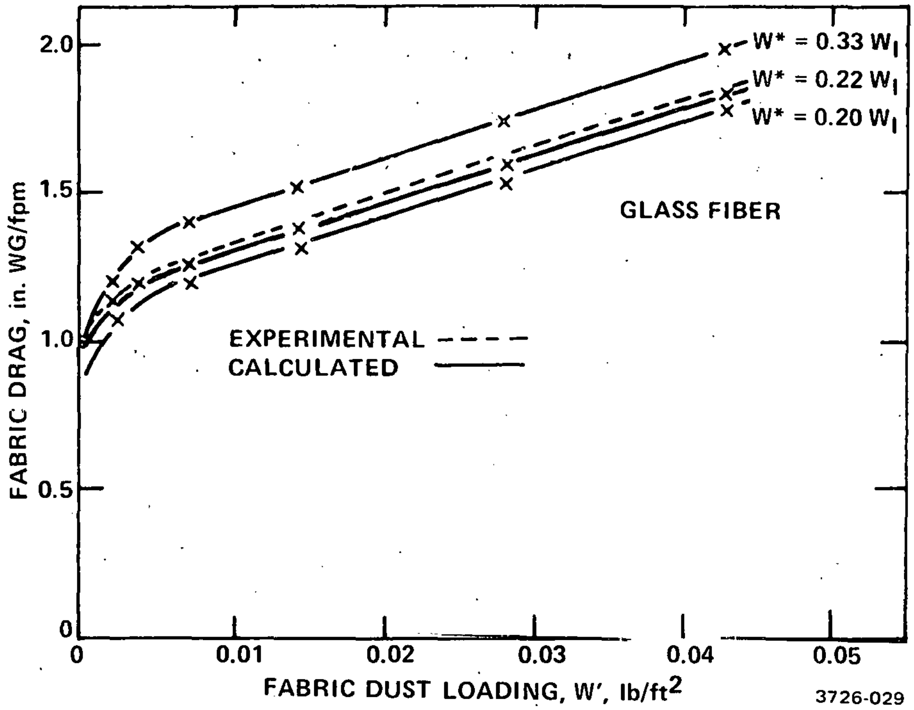

Figure 2.24 Fabric drag *vs.* fabric dust loading. Calculated and experimental curves for glass fiber filter.[47]

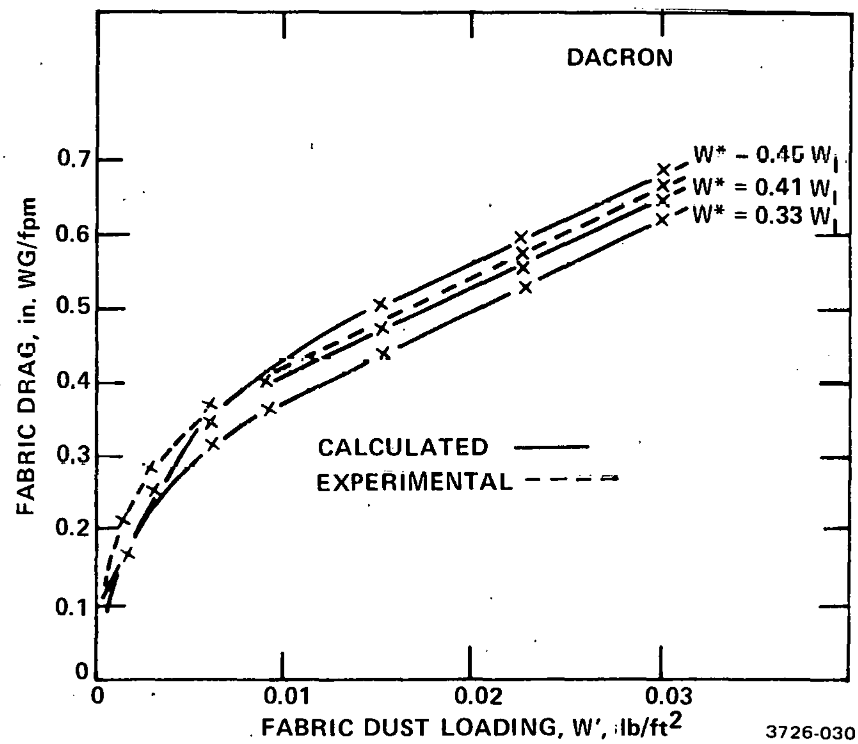

Figure 2.25 Fabric drag *vs.* fabric dust loading. Calculated and experimental curves for Dacron fabric filter.[47]

comprehensive attempt at modeling the collection efficiency of woven fabric filters. Since the fabric produces a flow which is directed through the interstices of the weave at and near the intersections of the yarns, flow through the filter was modeled as that through an array of apertures. This model is designed to calculate the fraction of incoming particles captured in the filter cake, in the fabric, and in pinholes which go through both cake and fabric. The collection mechanisms modeled are impaction, interception, and diffusion.

Cake collection is modeled only approximately since the cake structure is uncertain when polydisperse aerosols are collected. The same basic scheme is employed for analyzing cake capture by impaction, interception, and diffusion.

Figures 2.26 through 2.28 show some of the results of single and multiple bag penetration calculations assuming the nonlinear drag model. The inlet size distribution was log normal with a mass median aerodynamic (*i.e.*, particle density 1 g/cm^3) diameter of 6.0 μm and a geometric standard deviation of 3.0. This size distribution approximates that of fly ash from a coal-fired boiler equipped with a baghouse (Sunbury Station of Pennsylvania Power and Light Co.). An initial fabric drag was used that was roughly that of the Sunbury fabric and correlations were used to obtain the flow resistances K_R and K_2. Figure 2.26 shows penetration *vs.* time curves for a single bag with nonlinear drag and pinhole penetration effects included. The major features include the maximum penetration by 0.3 μm diameter particles and the initial exponential decrease for those particles being filtered out primarily by the cake. Figure 2.27 shows the same situation with no pinholes, so that all flow is through the fabric pores or filter cake. The most marked difference is that collection efficiency for all particle sizes continues to increase as the cake thickens, a result which conflicts with data collected in the field. This again indicates that emissions through pinholes play an important role in limiting the efficiency of the filtering process.

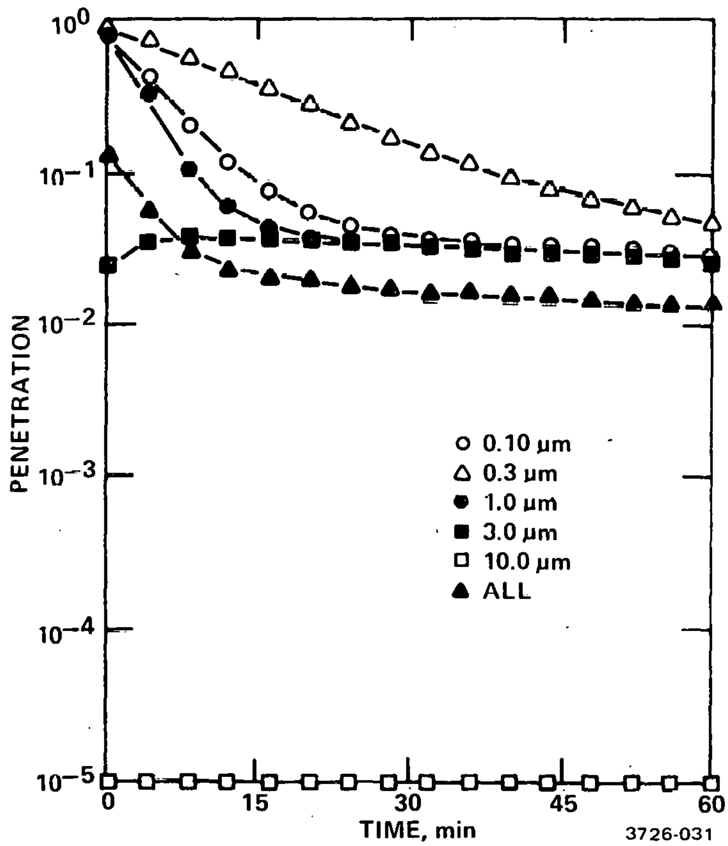

Figure 2.26 Baghouse simulated penetration vs. time; single bag, nonlinear drag, with pinholes.[47]

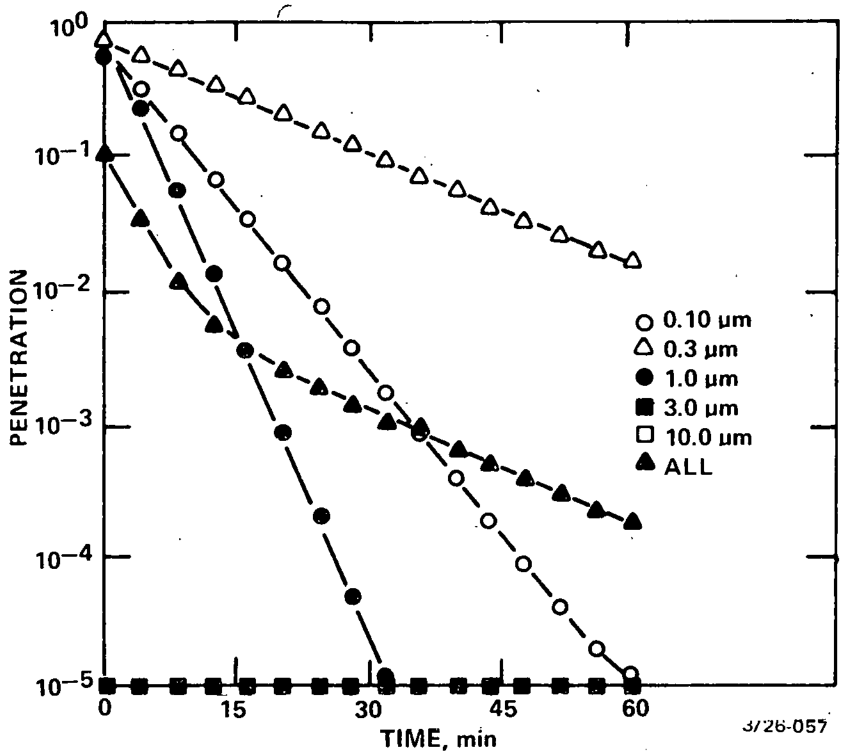

Figure 2.27 Baghouse simulated penetration vs. time; single bag; nonlinear drag, without pinholes.[47]

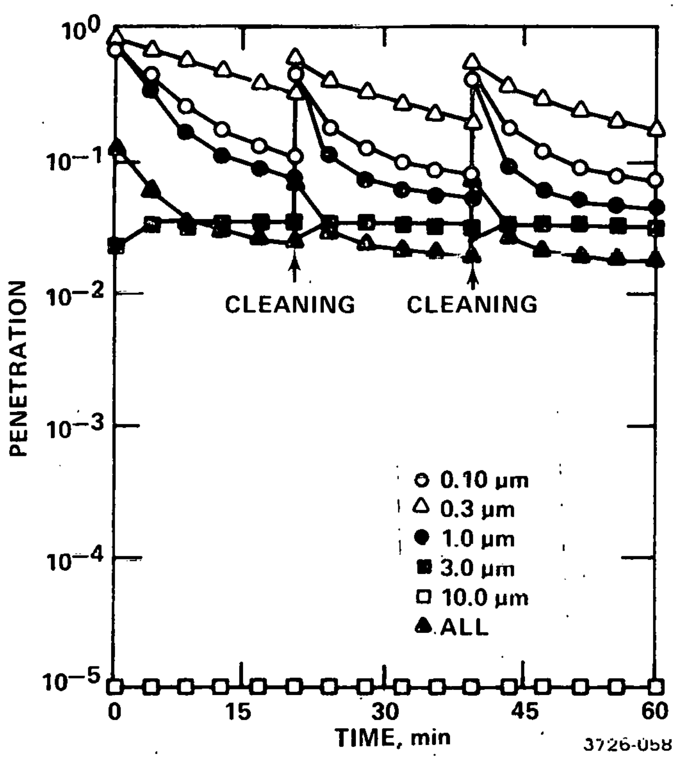

Figure 2.28 Baghouse simulated penetration vs. time; three bags, nonlinear drag, with pinholes.[47]

Figure 2.28 shows the calculated penetration versus time behavior of a three bag system with nonlinear drag and pinhole emissions considered. Initially, all the bags have the same flowrate. After one bag is cleaned, only two have the same flowrate and the third is much higher in flow. Finally, all three have been cleaned once and a repetitive pattern develops. This figure shows the changing pattern for particle penetration versus time with particle size as a parameter. The relative order of penetration with respect to particle size is the same as is shown in Figure 2.26 and the asymptotic behavior caused by the pinhole emissions is evident.

The pressure drop aspect of the model correlates well with field data after appropriate curve fitting procedures have been used. The collection efficiency aspect of the model is at an earlier stage of development. It is entirely theoretical and has not been compared with experimental data. Hence the model must be used with caution. However, the model is a useful first step for describing filter performance.

Fabrics

Fabrics of different construction (*e.g.*, woven, felted, or knitted) from a variety of yarn sizes and twists and with various fabric finishes are available for filter applications. The natural fibers cotton and wool have long been used in baghouses for collecting industrial and metallurgical dusts. Synthetic fibers, such as the acrylics, polyesters, polyamides, and the flurocarbon polymers (*e.g.*, Teflon) are also used in these applications.

At present, only woven glass fiber bags have demonstrated the capability of withstanding the combined action of sulfur oxides and heat (450°F) in full-scale baghouses on electric utility power boilers burning coal. Glass fiber with the E chemical composition, the type most widely used for glass fiber fabrics, is used.

Because glass fibers are relatively brittle, they are unusually subject to breakage initiated by yarn-to-yarn abrasion. To reduce the abrasion, glass fiber filter fabrics are coated with finishes that provide lubrication. Various combinations of silicones, graphite, and fluorocarbons are used.

Most baghouses on electric utility boilers use fabrics woven from combinations of filament and texturized yarns, in an attempt to combine bag strength with bulk and porosity of the fabric.

Methods of Regeneration

The operation of a baghouse involves periodic cleaning of the bag fabric to remove the deposited dust and to regenerate the filtering surface. In the process, the deposit must be removed quickly and uniformly without removing too much of it, since the collection efficiency of the next cycle is improved if a certain minimum of dust is retained on the filter after regeneration. With some fabrics, notably those made of glass fibers, the fabric may be damaged if the cleaning action is too vigorous.

The methods that are used for cleaning are mechanical shaking (woven fabrics), a reverse air pulse or jet (felted fabrics), and reverse air flow causing bag collapse (woven and felted fabrics).

The bags in baghouses used for collection of fly ash from electric utility power boilers are cleaned by reverse air, pulse jet, mechanical shaking, or a combination of these. The low pressure and gentle action of reverse air flow regeneration of the filter fabric is used in some installations. Bags used with reverse flow regeneration are often equipped with anti-deflation rings to prevent complete collapse of the bags, which may lead to reduced bag life. Other systems combine gentle mechanical shaking and reverse flow to achieve a higher degree of cleaning than reverse flow alone. The principal effect of reverse air flow appears to be that it inhibits the propulsion of dust particles into the cleaned gas during the shaking.

In cleaning by mechanical action, a baghouse compartment must usually be taken out of service and the filtering process interrupted. As a result, the capacity of the baghouse must be somewhat higher than would otherwise be required. A general problem in the use of mechanical shaking is that the fabric may be flexed excessively at the bottom, which is fastened, and fiber abrasion may result.

In pulse-jet cleaning, a sharp pulse of compressed air is released, typically at the end of the filter bag, producing a combined effect of gas flow reversal in the bag and fabric deformation. The dust deposit can be dislodged with only a brief interruption of the filtering process in the bag. The time involved is only about 0.1 sec. The fabric receives a minimum of flexing.

An extension of the concept of pulse-jet cleaning is reverse jet cleaning, in which a ring of jets of moderately compressed air is continuously moved up and down the bag, usually at a rate of a few feet per minute. Abrasion, fabric wear, and deposition of dust on the cleaning mechanism have presented problems in the use of this method.

Pulse-jet cleaning is better applied to felted than to woven fabrics, which tend to be overly cleaned by the process and then to leak dust excessively in the next filtering cycle while the filter cake is being repaired.

For the same volume of gas cleaned, felted baghouse filters regenerated with pulsed jets of air can be operated at filtration velocities 3-4 times those used in baghouses equipped with woven filters cleaned by reverse air flow and mechanical shaking. On the other hand, a felted filter baghouse can have a pressure drop somewhat greater than that of a baghouse with woven bags. The power for compressing the pulsed air can also be significant, *e.g.*, as much as that for the primary fan. Although some filters for collecting fly ash from power boilers have felted bags, an overall comparison has not yet been made.

2.3.4 Representative Installations

The two most important baghouse installations for assessing the present status of fabric filter technology are the Sunbury Station of Pennsylvania Power and Light Company and the Nucla Station of Colorado Ute Association. They are the only installations for which any appreciable amount of data on fractional collection efficiency has been obtained. Both plants burn low sulfur fuels, and both are relatively small plants (4 baghouses on 4 boilers totaling 170 MW at Sunbury and 3 units of 13 MW each at Nucla).

At the Sunbury Station,[65] the fuel burned is a mixture of anthracite silt, bituminous coal, and petroleum coke; the mixture has a high ash content and a low sulfur content. The normal mix is 75% anthracite silt (typical analysis: heating value on wet basis, 8,680 Btu/lb, 28.0% ash, 16.4% moisture, 8.4% volatile matter, 0.8% sulfur), 5% bituminous coal (typical analysis: heating value, wet basis, 12,159 Btu/lb, 15.3% ash, 5.3% moisture, 27.1% volatile matter, 2.6% sulfur), and 20% petroleum coke (typical analysis: heating value, wet basis, 14,054 Btu/lb, 1.7% ash, 6.4% moisture, 13.3% volatile matter, 5.3% sulfur).

Electrostatic precipitators which were installed originally were inefficient in cleaning the gas, probably because of the high electrical resistivity of the fly ash.

Four identical pulverized coal boilers provide steam for two turbines, with each turbine rated at 87.5 MW. Each boiler produces about 225,000 cfm of flue gas at 325°F and has a separate baghouse. Thus there are 4 baghouses, each with 1,260 bags 11.5 inches in diameter and 30 feet, 4 inches in length. The bags are made of woven glass fiber with a Teflon-base finish. The active air-to-cloth filter ratio is 2.067:1 cfm/ft^2, and the filtering velocity is 2 ft/min. Bags are taken off stream for cleaning which is accomplished by reverse gas flow with no mechanical shaking. The pressure drop through the baghouse is about 2.5 in. water gauge.

At the Nucla Station,[51,66] there are three 13-MW generators, each with a stoker-fired travelling-grate boiler with fly ash reinjection. The fuel is a western coal containing, on average, 14% ash and 0.7% sulfur.

A separate baghouse is used for each boiler. The design gas flow is 86,240 acfm. Each baghouse contains 672 graphite-silicone-coated glass fiber bags 8 inches in diameter and 22 feet in length, with a total cloth area of 30,964 ft^2/baghouse. The design air-to-cloth ratio is 2.79:1. Bags are taken off stream for cleaning and are cleaned by a combination of gentle mechanical shaking and reverse air flow. The pressure drop through the baghouse is about 4.5 in. water gauge.

Some characteristics of these installations are listed in Table 2.8. The table also provides some information on other installations at electric power plants.[65,67,68] In addition to the Sunbury and Nucla plants, baghouses are in operation at the Holtwood Station of Pennsylvania Power and Light Company and at the Crisp County plant at Cordele, Georgia.

Baghouses are being installed at the Kramer Station of Nebraska Public Power, and they are on order for 6 plants: Jim Bullock Station of Colorado Ute; Monticello Station of Texas Utilities; Harrington Station Unit 2 of Southwestern Public Service; Cameo Station of Public Service of Colorado; North Daomy Station of Sierra Pacific Power; and the Ray D. Nixon Station of the City of Colorado Springs.

Table 2.8 Electric Utility Baghouse Installations

Utility	Station	Location	Boiler Capacity, MW	Installation Date	Boiler	Fuel	S, %	Ash, %
Pennsylvania Power and Light	Sunbury	Shamokin Dam, Pa.	2x87.5	1971-3	Pulverized coal fired	Anthracite silt Bituminous coal Petroleum coke	1.8	22.1
Pennsylvania Power and Light	Holtwood	Holtwood, Pa.	73	1975	Pulverized coal fired	Anthracite silt Bituminous coal Petroleum coke		
Colorado-Ute Electric Association	Nucla	Nucla, Co.	3x13	1973	Stoker fired		0.7	12
Crisp County Power Comm.		Cordele, Ga.		1975		Bituminous coal	1	10
Nebraska Public Power System	Kramer	Bellvue, Ne.	113 (4 units)	1976	Pulverized coal fired	Bituminous coal	1	11
Southwestern Public Service	Harrington No. 2	Amarillo, Tx.	318	1978	Pulverized coal fired	Subbituminous coal		
Texas Power & Light Co.	Monticello	Mt. Pleasant, Tx.	1150 (2x575)	1977	Pulverized coal fired	Lignite		
Colorado REA		Montrose, Co.	12 (2x6)		Stoker			
Public Service Co. of Colorado	Cameo	Grand Junction, Co.	22	1977				
Department of Public Utilities	Ray D. Nixon	Colorado Springs, Co.	175	1977				
Colorado-Ute Electric Association	Bullock		2x6	a				
Sierra Pacific Power	North Valmy		250	a				

-Continued-

[a]Planned, not yet installed

Table 2.8 Electric Utility Baghouse Installations (Continued)

Utility	Station	Flue Gas Temperature, °F	Flue Gas Vol, acfm	Air/Cloth, acfm/ft²	Pressure Drop, in. WG	Fabric	Regeneration
Pennsylvania Power and Light	Sunbury	325	900,000 (4x270,000)	2	2.5	Woven glass fiber, 10 oz	Reverse flow
Pennsylvania Power and Light	Holtwood	360	200,000	2.4	4.5	Woven glass fiber, 10 oz	Reverse flow and shake
Colorado-Ute Electric Association	Nucla	360	258,000 (3x86,000)	2.8	4.5	Woven glass fiber, 10 oz	Reverse flow and shake
Crisp County Power Comm.		325	60,000	4	2.8	Woven glass fiber	Reverse flow
Nebraska Public Power System	Kramer		550,000	2	-	Woven glass fiber	Reverse flow
Southwestern Public Service	Harrington No. 2		1,500,000	3	-	Woven glass fiber	Reverse flow and shake
Texas Power & Light Co.	Monticello		3,800,000	2.4	-	Woven glass fiber	Reverse flow
Colorado REA							
Public Service Co. of Colorado	Cameo						
Department of Public Utilities	Ray D Nixon						
Colorado-Ute Electric Association	Bullock						
Sierra Pacific Power	North Valmy						

Performance

Tests conducted on the fabric filter installations at the Sunbury Plant of Pennsylavania Power and Light Company[52,67] and the Nucla Station of Colorado Ute[51,66] include both the total mass collection efficiency and the fractional collection efficiency. Typical data on total mass collection efficiency are summarized in Table 2.9.

Fractional collection efficiencies were measured at the Nucla Station with impactors and with an Electrical Aerosol Size Analyzer (EASA). The impactor data covered a range of particle sizes from about 0.5 to 10 μm and the EASA data covered sizes from about 0.04 to 1 μm. Because of instrumentation limitations, the EASA data were taken during the interval between bag cleanings and there is a discontinuity between the impactor data and the EASA data.

Figure 2.29 is a plot of the fractional collection efficiency data from two series of tests at the Nucla Station and one series of tests at the Sunbury Station. Collection efficiencies were higher than 99% for all particle sizes between 1 and 10 μm. The data indicates that the collection efficiency may increase for ultrafine submicron particles, but the data is inconclusive, since it does not include the losses during bag cleaning.

Table 2.9. Collection Efficiency Measurements on Baghouses on Electric Utility Boilers

Plant	Inlet Loading, gr/ft^3	Outlet Loading, gr/ft^3	Collection Efficiency, %	Air:Cloth, ft/min
Sunbury[52]	2.54	0.00195	99.9	2.07
Nucla[66]	1.35	0.0011	99.9	2.7
Nucla[51]	2.005	0.0035	99.8	2.79

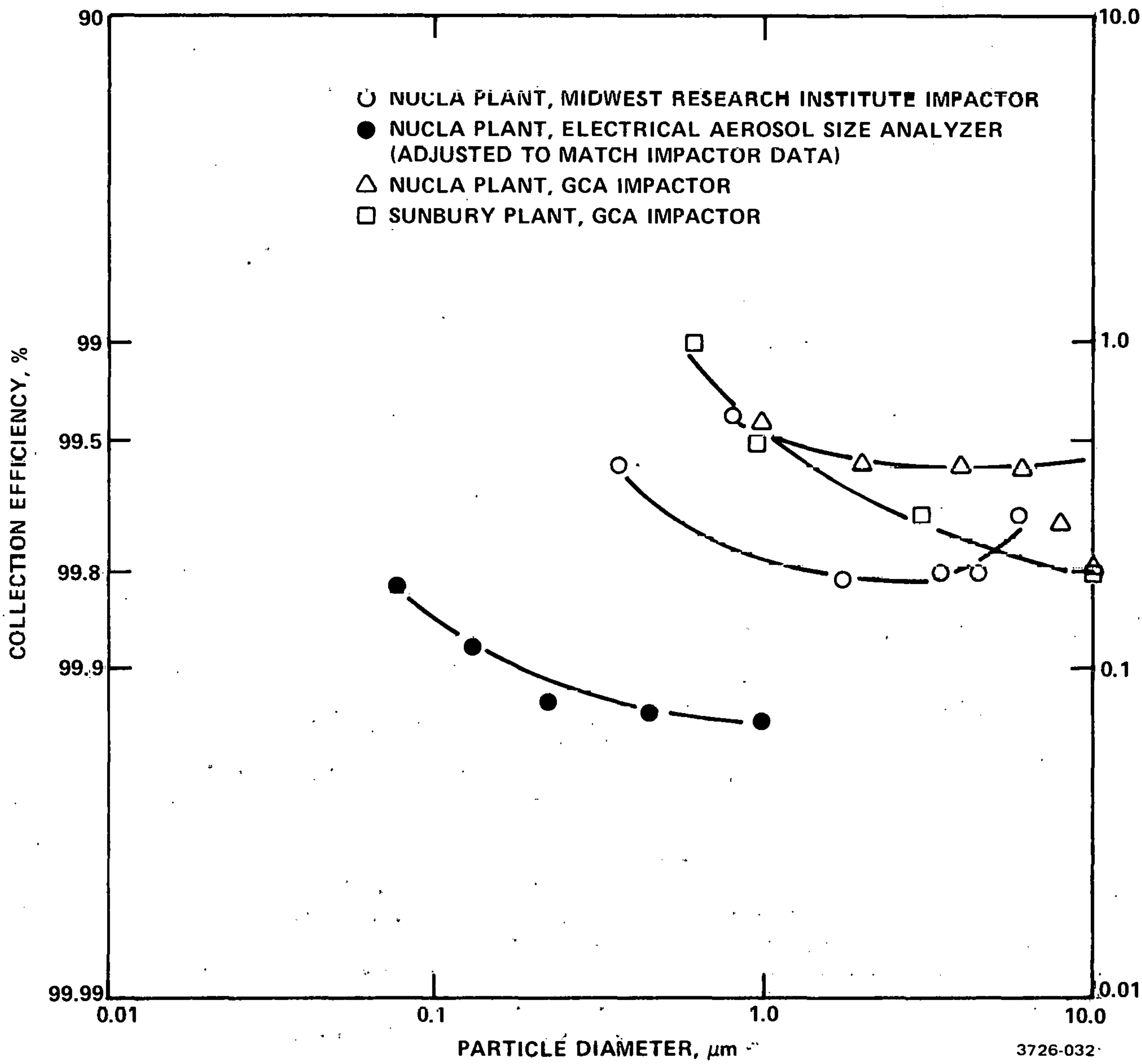

Figure 2.29 Fractional collection efficiencies of baghouses on electric utility boilers.[51,52,56]

The Environmental Protection Agency and the Electric Power Research Institute have plans for evaluating the collection efficiency and costs of fabric filters at some of the new installations. The Tennessee Valley Authority is considering the installation of a prototype baghouse collecting fly ash from 10,000 to 20,000 acfm of flue gas at one of the TVA plants, in order to compare performance with electrostatic precipitators in plants burning low-sulfur coal.

2.3.5 Energy Requirements

The power required for operation of a baghouse is principally that needed for operating the I.D. fans against a pressure drop of about 5 in. water gauge and for reverse air fans and compressed air for regenerating the filter.

Table 2.10 shows the power requirements for the Nucla baghouses.[51] The total of 212 kW is 0.5% of the power plant output.

Table 2.10. Power Requirements for Nucla Baghouses[a]

	Operating Power, kW	Time and Capacity Factor	Average Power, kW
I.D. Fans	52	0.55	29
Compressor	76	1.00	76
Air Dryer	6.5	0.43	3
Reverse Air Fans	56	1.00	56
Hopper Heaters	72	0.16	12
Baghouse Preheat Systems	162	0.15	24
Ash Conveyor (net increase)	22	0.50	11
Total			212

[a]The data in the table is from Reference 51, except that the power required for the I.D. fans is taken to be 52 kW, corresponding to the normal pressure drop of 4.5 in. WG in the baghouse.

The power consumption of the Sunbury baghouse may be estimated from the costs given in Section 2.3.8. The power consumed by the I.D. fans can be estimated by the equation in Section 2.2.4 as 660 kW on the basis of a 2.5 in. WG pressure drop. To this may be added an estimated 165 kW for the power requirements of the collapse fan and compressor for a total of 825 kW or 0.5% of the plant output.

2.3.8 Maintenance

Maintenance records for the Nucla baghouse for the first two years of its operation were surveyed in 1976 and are summarized in Table 2.11. The maintenance times, in manhours, and number of occurrences are given for four time periods of approximately six months each. During the first three periods, bag replacement was the highest maintenance item. This problem may have been solved by the installation of thimble gas flow straighteners to reduce severe erosion at the inlet of the gas bag that began soon after start-up. Of the total 2,016 bags, 18% were replaced during the first two years of operation, mostly before the installation of the gas flow straighteners.

After this experience, the maintenance requirements appear to be leveling off at about 8 man-hours/1000 baghouse hours of operation. Other items of equipment requiring maintenance are listed in Table 2.11.

The major problem at the Sunbury Station is reported to be the occasional development of high differential pressures, usually caused by failure of the collapse fan or a gas inlet or collapse air damper, or a cleaning cycle timer. The problem is usually corrected within 30 minutes without effect on boiler operation.[65,67]

Table 2.11 Nucla Baghouse Maintenance Summary[51]

Maintenance Category	Period[a] Dec '73-July 74	Aug '75-Jan 75	Feb '75-July 75	Aug '75-Dec 75	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: manhours/occurrences. The four periods have the same amount of baghouse operating time.

Bag failures have been few (37 as of May 1, 1976). The bags in three of the baghouses were replaced after two years of service, but those in the fourth baghouse are the original ones. Abrasion of the collapse fans by fly ash particles has been a troublesome problem.

Information on the more general operating problems encountered in a variety of industrial applications for fabric filters was obtained in a survey made in 1970.[46] The problems listed by the respondents are shown in Table 2.12. They are grouped into five casuality categories. The largest category of problems reported was the first: 60 fabric-dust related problems. Of these the most frequent type was blinding: 14 problems of blinding of the fabric by the dust. Over 25% of all problems reported were from blinding, flexure wear, and interstitial abrasion.

Blinding can be caused by water leaks in the boiler, and it is also caused by oily particles from fuel oil used in start-up.

In some installations the bags are precoated with powdered limestone to prevent damage to the fabric from sulfuric acid in the gases from the fuel oil used in start-up combustion.

A recent study of bag failures on industrial power boilers showed that they increased from about 0.1%/yr at an air:cloth ratio of 2 ft/min to about 10%/yr at an air-to-cloth ratio of 6 ft/min.[68]

2.3.7 Installation

Retrofitting baghouses in utility installations can be expected to present some problems because of the volume or space required. At the Sunbury Station, the baghouses were installed on top of electrostatic precipitators that had been used previously. The precipitators were gutted and used as structural supports for the baghouses.

Table 2.12. Causes of Operating Problems with Fabric Filters[46]

Fabric-dust interactions	9 types of problems	60 problems reported
Filter element difficulties	2 types of problems	6 problems reported
Filter element-hardware interactions	5 types of problems	12 problems reported
Collector design problems	5 types of problems	27 problems reported
System design problems	2 types of problems	7 problems reported
	23 types of problems	112 problems reported

2.3.8 Costs

Capital costs and operating and maintenance costs for the Sunbury plant are shown in Table 2.13. Similar data for the Nucla plant are given in Tables 2.14 and 2.15. In order to facilitate comparison, the costs have been converted to 1976 dollars by the use of the Chemical Engineering Plant Cost Index.[37]

The operating costs shown in Table 2.13 should be increased by an allowance for the power consumed by the I.D. fans.

The pressure drop across the Sunbury baghouse and the baghouse duct work was designed to be less than 6 in. WG, which was dictated by the capacity of the existing I.D. fans.[65,67] Therefore, a more exact comparative value for the operating cost should allow the cost of, *e.g.*, 1180 kW for a 4.5-in. WG pressure drop (Section 2.3.5). At $0.02/kWh, this would add $95,000/yr to the operating cost, increasing the annualized cost to 1.5 mills/kWh at 73% capacity. Also, the capital cost should reflect an allowance for fan cost, of perhaps several thousand dollars, for the increased fan power.

The higher costs for the Nucla plant, compared to those for the Sunbury plant, are explained as being due to the small size of the plant and its remote location, with, for instance, a limited supply of local skilled labor.

It was not necessary to install additional I.D. fans at the Nucla plant, either, since the four already installed provided sufficient draft. The power requirements for this plant are listed in Table 2.10, with the assumption that the pressure drop is 4.5 in. WG. Again, the capital cost should strictly be increased by several thousand dollars to correct for the fan cost.

Table 2.13 Installed Capital Cost and Operating and Maintenance Costs, Sunbury Station[65,67]

Bag Filter Installation Costs		Total Cost, 1000$
Western Precipitator Contract (1000$)		
4 Baghouses		
Materials	$1,685	
Labor	1,357	$3,042
Vacuum cleaning system		
Materials	$ 40	
Labor	58	98
Associated structures		
Materials	$ 126	
Labor	28	154
Baghouse, design and engineering		656
Hopper enclosures, design and engineering		93
Supplements and contingencies		214
		$4257
Structures and improvements		495
Land and land rights		2
Boiler plant equipment		1,583
Ash removal equipment		
Precipitator modifications		
Accessory electrical equipment		96
Overhead		882
Total construction cost		$7,315

Estimated Operating & Maintenance Cost

(@ $12/manhour)

Cost Description	Cost, $ 1975	1974	1975
Collapse fan power consumption	$24,700	$ 21,600	$ 19,700
Air compressor power consumption	4,000	3,500	3,200
Instrument department labor	1,300	1,100	1,900
Mechanical maintenance labor	2,800	6,800	16,600
Electrical maintenance labor	9,900	4,400	6,400
Construction department labor	5,300	2,700	2,100
Complete bag replacement			
Material		55,700	101,800
Labor		12,800	23,300
Total	$48,000	$108,600	$175,000

Table 2.14 Components of Capital Cost, Nucla Baghouse[51]

Item	Cost, 1000$	% of Total
Equipment and installation		
Baghouse and general	2,088	66
Ash conveyor system	300	10
Retrofit items	252	8
Total field cost	2,640	84
Indirect costs to Colorado-Ute	144	5
Engineering and fee	360	11
Installed cost	3,144	100
Unit factors: $87/kW, $13/acfm, $36/ft² filter area,		

Table 2.15 Nucla Baghouse Estimated Operating Costs[51]

	$/yr	%	mills/kWh[b]
Direct costs			
Operation labor[a]	$(9,500)	(3.3)	(0.05)
Maintenance 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 costs	$53,000	18.5	0.28
Indirect 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 costs	$234,000	81.5	1.25
Total	$287,000		1.53

[a]Not added since no new costs were incurred.

[b]Based on 188 x 10^6 kWh/yr, 55% capacity

The indirect costs to Colorado-Ute in Table 2.14 included administrative and supervisory costs, risk insurance, interest during construction, and travel and office costs. The engineering costs in Table 2.14 included 20% for retrofit items and 7% for the ash conveyor system, the remainder being attributable to ductwork, foundations, and other items related to the installation.

Figure 2.30 shows the range of installed costs, per kilowatt of boiler capacity (in 1976 dollars), for baghouses collecting fly ash. This range was estimated from information obtained from manufacturers. Also plotted in Figure 2.32 are the installed costs of the Nucla, Cameo, and Sunbury baghouses, showing the higher unit costs associated with smaller installations.

2.3.9 *Secondary Environmental Impact*

Fabric filters present no special problems of secondary environmental impact other than the disposal of the collected fly ash, which is bulkier (20-30 lb/ft^3) than the fly ash collected in an electrostatic precipitator (40 lb/ft^3). The disposal methods described in Section 2.2.11 apply also to fly ash from baghouses.

2.4 *WET SCRUBBERS*

2.4.1 *Method of Collection*

A wet scrubber removes a material (a gas or suspended liquid or solid particles) from a gas stream by exposing the stream to droplets, films, or foams of water or aqueous solutions. Scrubbers have been used for many years in the chemical industry for absorbing gaseous components, products, or impurities from process streams. They have also been used since about 1900 for removing dusts from process off-gases in metallurgical plants.

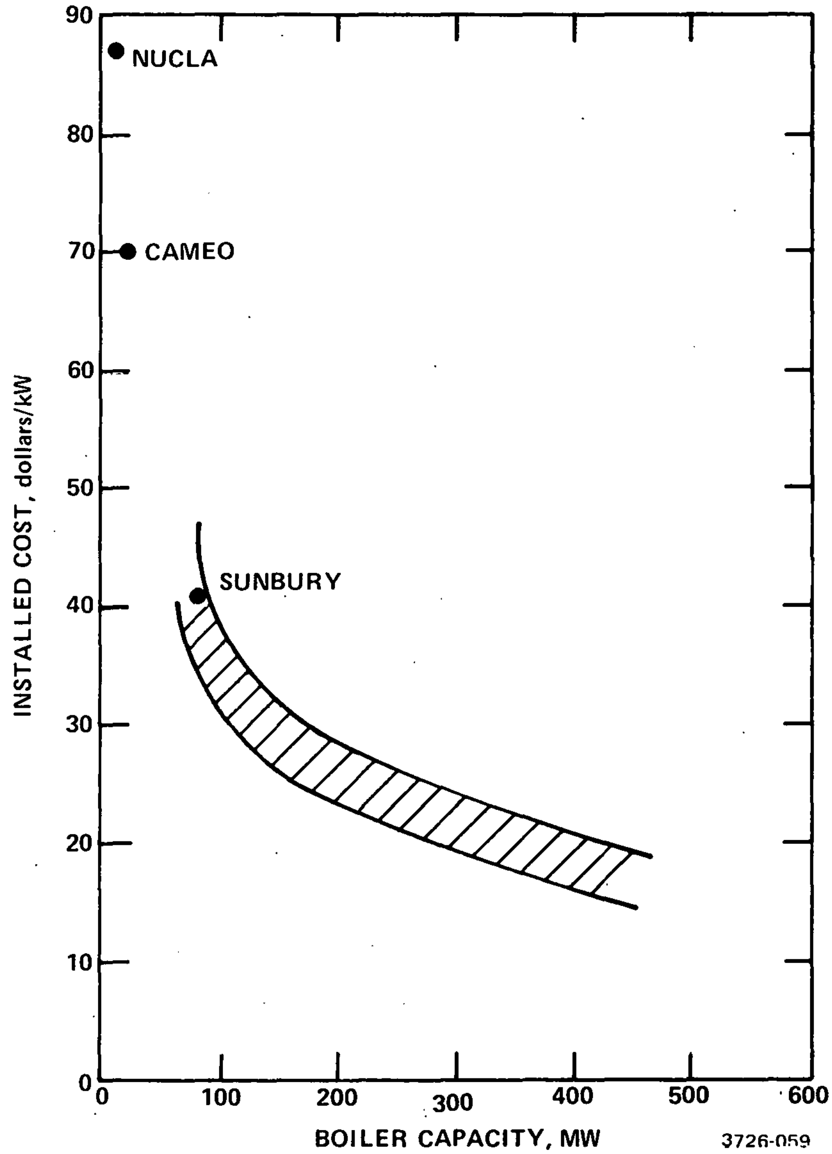

Figure 2.30 Baghouse costs (installed).

Over the past several years, wet scrubbers have been introduced into the electrical utility industry for removing sulfur oxides from flue gas from the combustion of coal. Within the past 10 years, several scrubber installations have been designed primarily for the removal of fly ash.

Types of Scrubbers

A wide variety of scrubber designs are used in chemical and metallurgical installations.[69]

The simplest scrubbers are hollow spray towers, which are used for gas absorption. These scrubbers will remove solid particles to some extent, but they are not effective in removing particles less than a few microns in diameter unless high pressure sprays are used, as in an injector venturi design, in which the pressurized liquid is sprayed axially into a venturi and a high relative velocity is maintained between the droplets and the co-current gas flow. Particles larger than 1-2 μm can be collected effectively in such a scrubber.

This concept of high relative velocity of liquid droplets is used more effectively in the more usual venturi design, in which the gas flowing through the venturi atomizes the liquid introduced at the venturi throat. Efficient collection of submicron particles can be obtained at relatively high pressure drops (10-100 in. WG) in this type of scrubber.

Impingement scrubbers, in which the gas flow with entrained liquid droplets is directed through orifices to impinge on plates, also can achieve good collection of small particles.

Other scrubber designs are generally based on the use of a flowing liquid film spread out over a large surface area made by packing the scrubber with shaped elements or fibers.

The types of scrubbers used for removing fly ash from flue gas in electric utility power plants are the moving-bed scrubber and the venturi scrubber. The specific design of moving bed scrubber that is used is the Turbulent Contact Absorber, in which a low-density packing (hollow plastic spheres) is kept in motion by the gas and flooded by the scrubber liquid. Some of the venturi scrubbers that are used are designed with variable throats. One installation is based on a spray impingement scrubber. All scrubbers used for this application are equipped with entrainment separators, to collect liquid droplets in the gas emerging from the scrubber. The entrainment separator (or mist eliminator) contains wetted packing or sprayed baffles.

2.4.2 *Theory of Scrubbing*

As with other fly ash collectors, the operating mechanisms in wet scrubbers depend on the particle size of the fly ash. There are also some differences in mechanism between a scrubber in which the fly ash is collected by a liquid film, as on a wetted wall, and a scrubber in which the ash is collected by dispersed droplets.

Taking the process of collection by droplets as the example, the mechanism involves inertial impaction of fly ash particles on the liquid droplets for particles above about 0.5 μm in diameter; diffusion of particles to the droplets, for particles smaller than about 0.1 μm; and interception (a modification of impaction to allow for particle diameter) for particles with diameters that are of the same order of magnitude as those of the droplets.

For constructing a mechanism for inertial impaction, the collecting droplet can be assumed to be a rigid sphere. A particle will impact on the droplet if the inertial force of the particle is sufficient to carry it through the boundary layer of the air flowing around the drop.

The factors that determine the collection efficiency by impaction are (1) the velocity distribution of the gas flowing by the droplet, the nature of the gas flow being described in terms of the Reynolds number; (2) the trajectory of the particle, which depends on the mass of the particle, its air resistance, the flow rate of the gas, and the size of the droplet; and (3) the adhesion of the particle to the droplet, which is assumed to be 100%.

The equation of motion of the particles can be derived[69] in terms of a dimensionless factor K_p

$$K_p = \frac{C' \rho_p d^2_p u_o}{9 \mu_G d_c}$$

in which

- C' is the Cunningham correction factor
- ρ_p is the particle density
- d_p is the particle diameter
- u_o is the undisturbed gas velocity, relative to the collector
- μ_G is the gas viscosity
- d_c is the droplet diameter

Various empirical or semi-empirical relationships can be used to correlate K_p with collection efficiency. For example, in a venturi scrubber, the penetration

$$Pt = 1 - \frac{\%\ \text{collection efficiency}}{100}$$

is given by the following semi-empirical relation (for the collection of particles by impaction).[69]

$$Pt = \exp \left[- \frac{2Q_L\, u_G\, \rho_L\, d_d\, F(K_{pt}, f)}{55 Q_G\, \mu_G} \right]$$

in which

K_{pt} is the parameter K_p evaluated at the velocity of the gas in the throat, u_G.

$$F(K_{pt},f) = \left[0.7 + K_{pt},f - 1.4 \ln\left(\frac{K_{pt},f + 0.7}{0.7}\right) - \frac{0.49}{0.7 + K_{pt}\,g}\right]\frac{1}{K_{pt}}$$

Q_L/Q_G is the volumetric ratio of liquid to gas

ρ_L is the liquid density

μ_G is the gas viscosity

d_d is the diameter of the droplet

f is a parameter that basically represents the ratio of droplet velocity to gas velocity, but is determined empirically and includes some other design parameters.

In the Turbulent Contact Absorber, impaction of particles on the liquid film is considered to be the predominant mechanism of collection.

As with the venturi scrubber, the collection of particles in the Turbulent Contact Absorber can be expressed[69] in terms of the dimensionless factor K_p.

In this instance,

$$K_p = \frac{v_{Gb}\, d^2_{pa}}{9\, \mu_G\, d_c}$$

in which

v_{Gb} is the interstitial gas velocity $= v_G \left(\frac{1}{\varepsilon - Hd}\right)$

v_G is the superficial gas velocity

ε is the void fraction of the bed

Hd is the fraction of the total bed volume taken up by liquid

d_{pa} is the aerodynamic particle diameter $= d_p (\rho_p C')^{\frac{1}{2}}$

d_p is the particle diameter

ρ_p is the particle density

C' is the Cunningham correction factor

μ_G is the gas viscosity

d_c is the diameter of the packing

Although these equations are useful in showing the relationships among fundamental factors, a simpler approach can be used for the design of scrubbers in practice. This approach involves specifying the cut diameter, the particle diameter in the size distribution (which typically follows a log-normal distribution curve) which must be collected with 50% efficiency if the scrubber is to met the required overall collection efficiency. The cut diameter is then used to select a scrubber design on the basis of design equations that have been developed empirically for different scrubber types.

Because of the emphasis now being placed on the capability of air pollution control equipment for removing the fine fractions of fly ash (≲2 μm), the Environmental Protection Agency has conducted comparative evaluations of several scrubber types over the past few years. Some of the results of these evaluations are shown in Table 2.16.[70]

Table 2.16. Fine Particle Control by Scrubbers[70]

Name	Pressure Drop, in.WG	Smallest Diameter Collected at Stated Efficiency, μm	
		80%	50%
Vale tray (Koch Flexitray)	12	1.6	1.0
Vaned centrifugal (Ducon)	3	1.6	1.3
Mobile bed (UOP TCA)	12	0.7	0.35
Venturi (Chemico)	10	0.9	0.7
Wetted fiber (Encort Corp.)	7	1.1	0.6
Impingement plate (Sly Impinjet)	12	1.7	1.3
Venturi rod (Environeering Hydro-Filter)	107	0.5	0.3

2.4.3 Factors Affecting Performance

The principal factors that affect the performance of scrubbers in the collection of fly ash are (1) the power input to the scrubber, and (2) the particle size distribution of the fly ash.

The power input is reflected in the ratio of the droplet velocity to the gas velocity (parameter f or v_G in the above equations). It has also been shown that collection efficiency, expressed in terms of transfer units N

$$N = \ln\left(\frac{1}{1-\eta}\right)$$

in which

η is the collection efficiency, which is correlated with the total power consumption of the scrubber by

$$N = \alpha P^{\beta}$$

in which

P is the total power used

and α and β are correlation parameters that are characteristic of the particulate matter being collected.[71] The correlation is independent of the type of scrubber used.

The effect of pressure drop on collection efficiency is seen from the data in Table 2.16. The effect is also shown by the data in Figure 2.31. This shows fractional collection efficiency curves for two venturi scrubbers as measured with impactors. One scrubber is being operated at a pressure drop of 10 in. water gauge in collecting fly ash from a coal-burning power plant. The collection efficiency is 90% for 1 μm particles and drops to <50% for 0.5 μm particles. The other is being operated at 100 in. water gauge in collecting fume from an iron melting cupola. It has a collection efficiency of 99.9% for 1 μm and 95% for 0.5 μm particles.

Figure 2.32 shows values of penetration, and the corresponding collection efficiency, calculated from a mathematical

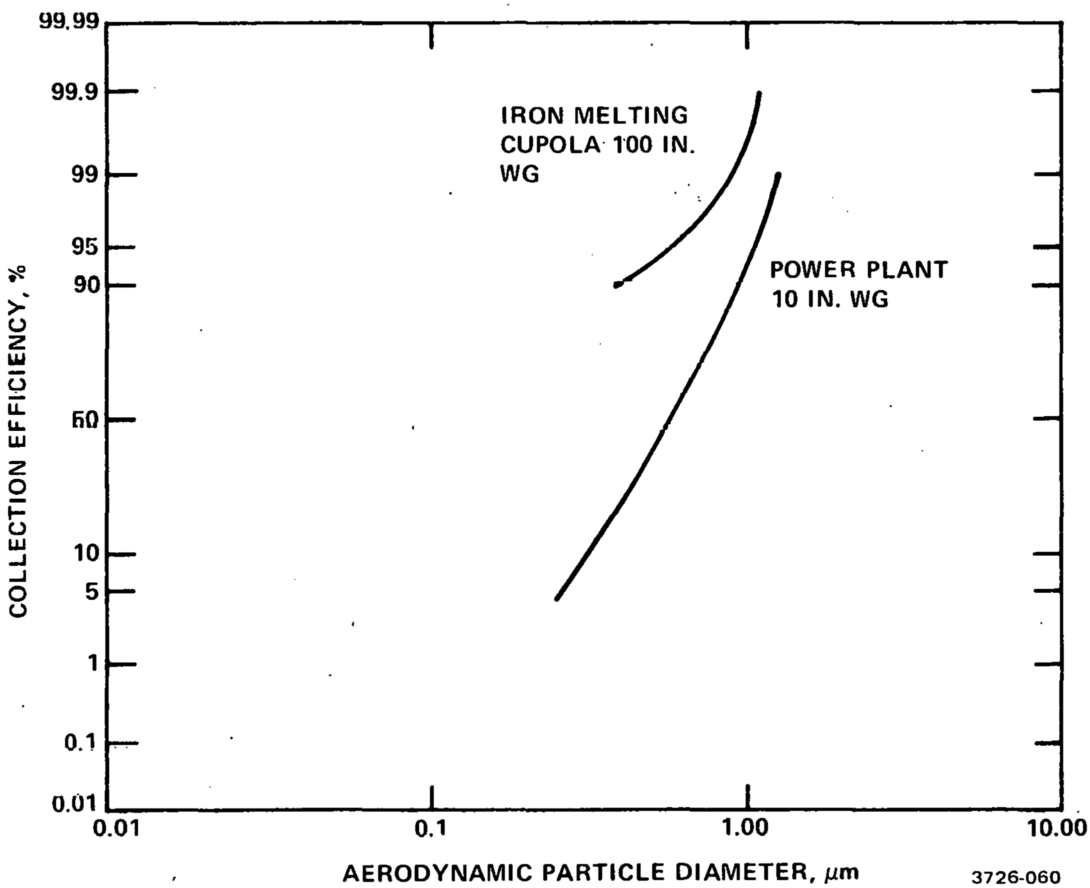

Figure 2.31 Efficiency *vs.* particle diameter for venturi scrubbers.[70]

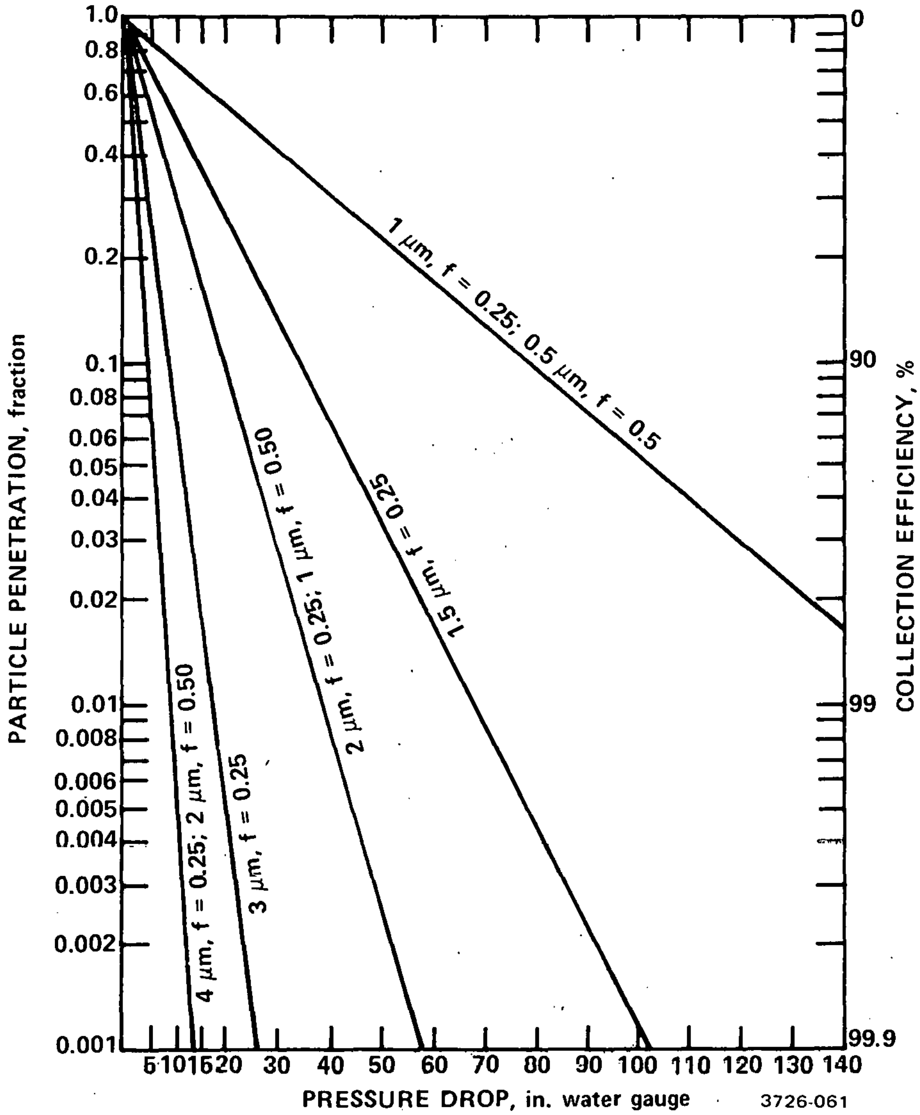

Figure 2.32 Penetration calculated from a venturi scrubber model as a function of pressure drop and particle aerodynamic diameter.[69]

model of a venturi scrubber[69] to show the dependence of collection efficiency on pressure drop, for several values of particle size and f, the empirical ratio of droplet velocity to gas velocity. It is apparent from Figure 2.32 that with a venturi scrubber the pressure drop necessary for high collection efficiency can become large enough to be an obstacle to the use of a scrubber for collecting the fine particles of fly ash.

Data such as these, and the relatively few measurements that have been made on the fractional collection efficiencies of scrubbers collecting sub-micron-size particles, have led to the conclusion that not much further improvement can be obtained in the collection efficiency of scrubbers operating by the mechanism of impaction only. Thus, attention is being paid to other collection mechanisms that can take place in scrubbers. These mechanisms are discussed in Section 3.

With regard to the effect of particle size distribution of fly ash on performances, the collection mechanism for the larger particles ($\gtrsim$0.5 μm in diameter) is predominantly impaction, as previously mentioned. Theory and experiment agree that collection efficiency will decrease as the particle size decreases. This effect is shown in Figure 2.33, in which the collection efficiency (down to the limit of measurement for impactors, about 0.3 μm) is plotted against particle size.[70]

As was also mentioned, for the collection of very small particles, those less than about 0.1 μm in diameter, the predominant mechanism becomes diffusion of the particle to the droplet, due to random bombardment of the particle by gas molecules (Brownian motion). Calculation of particle deposition rates and the resulting collection efficiency for the diffusion mechanism shows that the collection efficiency should increase with decreasing particle size $\lesssim$0.5 μm.

A plot of collection efficiency *vs.* diameter of fly ash particles for a scrubber would therefore be expected to show a minimum value for collection efficiency at ~0.1 - 1 μm. This

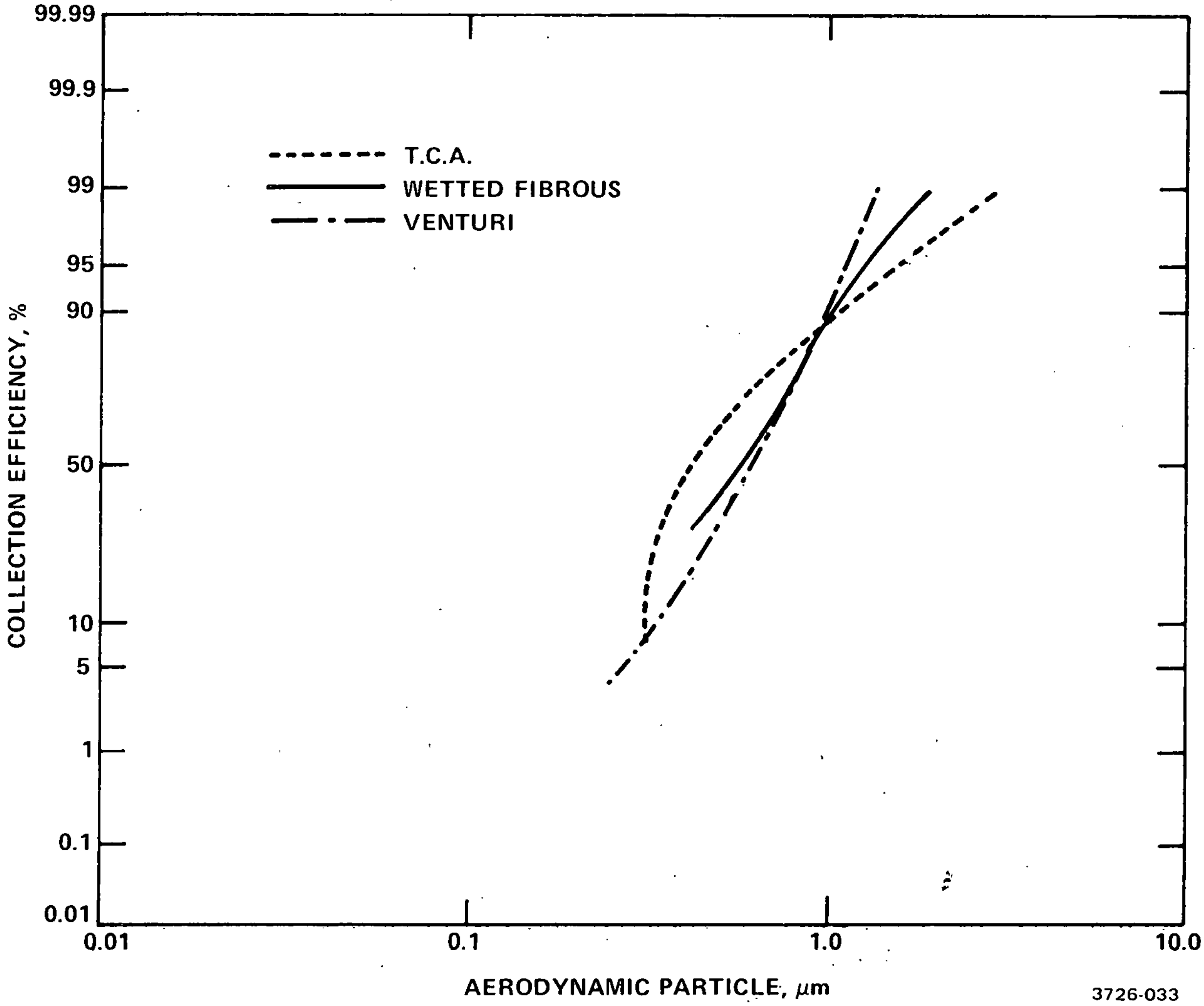

Figure 2.33 Fractional collection efficiency of scrubbers *vs.* particle size of fly ash being collected.[70]

prediction appears to have been confirmed, at least in general form, by the few measurements that have been made on full-scale installations. An example is Figure 2.34, which shows the fractional collection efficiencies measured on a full-scale TCA scrubber collecting fly ash.[14,72]

2.4.4 *Energy Requirements*

Power requirements for a wet scrubber include the power needed to overcome the relatively high pressure drop of 10-30 in. water gauge through the scrubber as well as the power for pumping and in some installations stack gas reheat. For Cherokee No. 3 scrubber for which detailed data is given in Section 2.4.5, the pressure drop is 10-18 in. water gauge.

The power required to overcome this pressure drop may be estimated by the following calculation.

The power used for scrubbing (not including liquid pumping costs) is estimated to be 6 watts/acfm gas flow for a high efficiency unit. For the gas flow in a scrubber of 520,000 acfm, the power consumption is 3 MW, or about half the total power consumption of the scrubber (6.39 MW).[14,72] The example used is the Cherokee No. 3 scrubber of the Public Service Company of Colorado, further discussed in Section 2.4.5.

2.4.5 *Representative Installations*

There are about 20 electric utility power boilers in the United States on which wet scrubbers have been installed for collection of fly ash. Most of the installations are retrofitted, the scrubbers having been installed in series with mechanical collectors or electrostatic precipitators. Typically, the power boilers are at present burning low-sulfur (*e.g.*, 1%) coal, and the electrostatic precipitators that had originally been installed were not collecting the high resistivity fly ash with the expected efficiency.

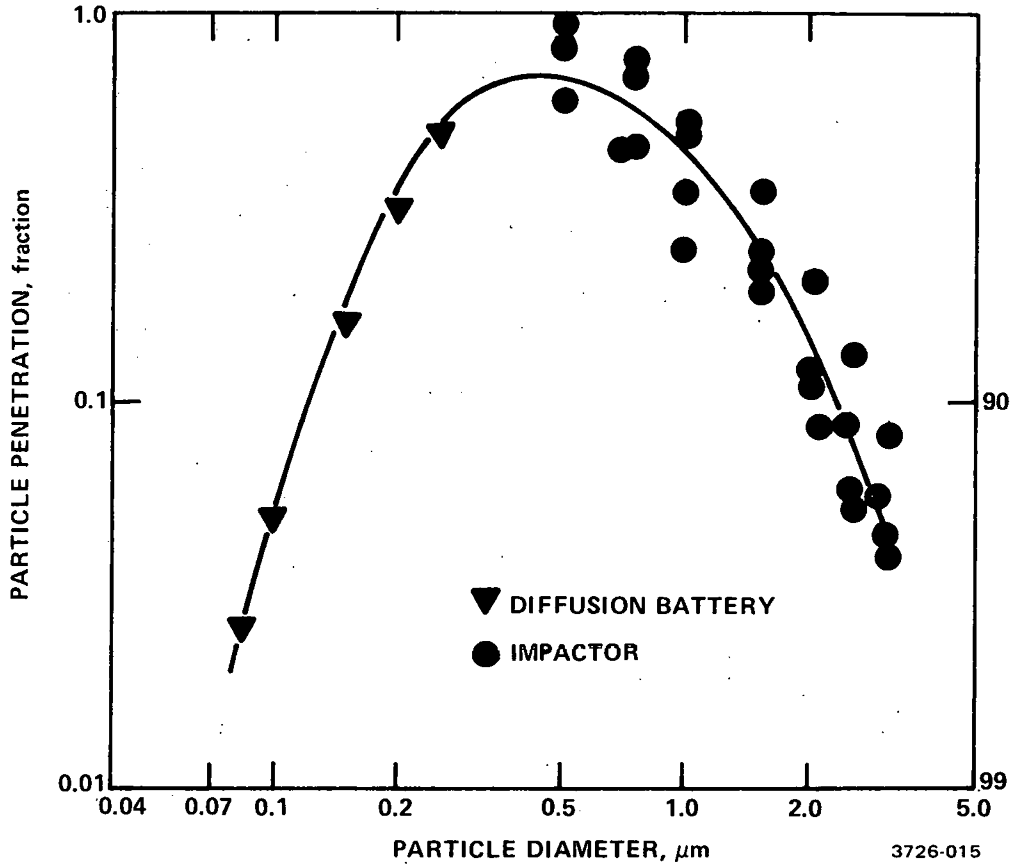

Figure 2.34 Fractional collection efficiency of TCA scrubber *vs*. particle size of fly ash in the fine particle range. Overall collection efficiency 95%.[14,72]

Pertinent data on most of these installations are listed in Table 2.17.[73-78] There are as many or more scrubbers installed for control of sulfur dioxide emissions (*e.g.*, limestone and alkali scrubbing systems), in which some fly ash is also removed.[78]

The following are some additional features of some of the installations listed in Table 2.17.

Public Service Company of Colorado

The Public Service Company of Colorado has equipped 5 boilers (Arapahoe Unit 4, Cherokee Units 1, 3, and 4, and Valmont Unit 5) with Universal Oil Products TCA (Turbulent Contract Absorber) scrubbers for the removal of fly ash. At the Valmont Station, the scrubber is installed in parallel with an electrostatic precipitator and preceded by a mechanical collector. At the Arapahoe and Cherokee Stations, the scrubbers are in series with previously existing mechanical collectors and electrostatic precipitators, with a scrubber bypass. The Arapahoe, the Cherokee Unit 1, and the Valmont scrubbers each have 2 modules, the Cherokee Unit 3 has 3 modules, and the Cherokee Unit 4 has 4 modules. All were retrofitted to previously existing units. Some details of these installations are given in Table 2.18.[75]

The coal burned at the Valmont station is a Wyoming low-sulfur (0.6% S) sub-bituminous coal with an ash content of a 5.2%. The ash is alkaline, with a CaO content of 20%. Because of the alkalinity of the fly ash-liquor slurry, the scrubber removes 45% of the sulfur dioxide in the flue gas. The other plants burn a Colorado bituminous coal.

The major cause of down time on the Valmont scrubber has been scale formation. It accumulates at the wet-dry interface immediately downstream of the presaturating quench nozzles and on the underside of the first layer of grid bars that support the packing.

In an attempt to alleviate the scaling problem, one of the Valmont scrubbers has been converted into a combined fly

Table 2.17 Wet Scrubber Installations in Electric Utility Power Plants

Plant	Boiler Capacity, MW	Scrubber, Type	No. of Scrubbers	Availability, %	Efficiency: Particulate matter, %	Efficiency: SO_2, %	L/G, Gal/1000 acf	Pressure, in. WG	Gas Flow (Total)	Starting Date	Installed Cost, 1000 $[a]	Annual Operating and Maintenance Cost, 1000 $[a]
Pennsylvania Power & Light Holtwood Station	80	Venturi	1	90-95	99	20	12.5	5-6	209,000 scfm	1970		
Kansas Power & Light Lawrence Station												
Unit 4	125	Marble bed	-							1968		
Unit 5	430	Marble bed	-							1971		
Arizona Public Service Four Corners Station	575	Venturi	6	75	99.2	30	9	28	1,658,000 acfm/340°F	1971	43,800	600
Commonwealth Edison Will County No. 1	175	Venturi/ TCA	2	40	98	90	-	-	770,000	1972	20,800	1,700
Pacific Power & Light Dave Johnston Station Unit 4	330	Venturi	3		99	40	13	15	1,500,000 acfm/270°F	1972	11,000	
Detroit Edison Co. St. Clair No. 6	180	Venturi								1974		
Montana Power Co. Colstrip Units 1 & 2	660	Venturi								1975	19,000 (Unit 1; 360 MW)	
Northern States Power Co. Sherburne County No. 1 & 2	1360	Marble bed								1976		
Public Service Co. Colorado												
Cherokee Station No. 1	110	TCA	2	55					302,000 scfm	1973	5100	
3	150	TCA	3	95	97	20	55.9	10-18	360,000 scfm	1972	6200	660
4	350	TCA	4	82					897,000 scfm	1974	14,700	
Valmont Station	180	TCA	2	76	96	45	58.3	10-18	299,000 scfm	1971	5300	910
Arapahoe Station	100	TCA	2	86	96	45	54.2	10-18	299,000 scfm	1973	6100	950
Kansas City Power & Light La Cygne Station	820	Venturi	7	84	98	80	-	-	2,760,000 acfm/285°F	1973	43,000	3,000
Duquesne Light Co.												
Phillips Station	400	Venturi								1973	41,000	
Elrama Station	500	Venturi								1974	46,500	
Nevada Power Co. Reid Gardner Station												
Units No. 1 & 2	250	Venturi								1974	5500 (for each 125 MW unit)	
Unit No. 3	125	Venturi								1976		
Philadelphia Electric Co. Eddystone Station	100	Venturi								1973		
Minnesota Power & Light												
Clay Boswell Station	350	High Pressure Spray	1		99	20	8	4	1,300,000 acfm/340°F	1973		
Aurora Station	116	High Pressure Spray	2		98	20	8	4	291,160 acfm/340°F	1971		

[a]Values are in 1976 dollars.

Table 2.18 Public Service Company of Colorato Scrubber Operating Data[3,75]

	Araphahoe Unit No. 4	Cherokee Unit No. 1	Cherokee Unit No. 3	Cherokee Unit No 4	Valmont Unit No. 5
Boiler Size	100 MW	100 MW	150 MW	350 MW	180 MW
Air Quality Control Equipment	Mechanical collector electrostatic precipitator, wet scrubber, in series with scrubber bypass	Mechanical collector, electrostatic precipitator, wet scrubber, in series with scrubber bypass	Mechanical collector, electrostatic precipitator, wet scrubber, in series with scrubber bypass	Mechanical collector, electrostatic precipitator, wet scrubber, in series with scrubber bypass	Wet scrubber in parallel with mechanical collector and electrostatic precipitator
Scrubber Type	Particulate TCA manufacturer UOP	Particulate TCA manufacturer UOP	Particulate TCA manufacturer UOP	Particulate TCA manufactuere UOP	TCA 1/2 particulate, 1/2 lime/limestone scrubbing; manufacturer UOP
Flue Gas Treated	299,000 scfm 520,000 acfm @ 300°F and 24.7 in. mercury	302,000 scfm 520,000 acfm @ 295°F and 24.8 in. mercury	360,000 scfm 610,000 acfm @ 280°F and 24.7 in. mercury	897,000 scfm 1,520,000 acfm @ 275°F and 24.7 in. mercury	299,000 scfm 463,000 acfm @ 260°F and 26.3 in. mercury
Total Recirculated Liquor Flow	28,200 gal/min	30,000 gal/min	33,400 gal/min	84,000 gal/min	27,000 gal/min
L/G, gal/1000 acf	54.2	57.7	54.7	55.3	58.3
Pressure Drop Across Scrubber	10-18 in. WG (depends upon operating conditions)	10-18 in. WG (depends upon operating conditions)	10-18 in. WG (depends upon operating conditions)	10-18 in. WG (depends upon operating conditions)	10-18 in. WG (depends upon operating conditions)
Total Make-up Water Required, gal/min	203 gal/min (with occasional mist eliminator wash)	203 gal/min (with occasional mist eliminator wash)	380 gal/min (with occasional mist eliminator wash)	744 gal/min (with occasional mist eliminator wash)	Particulate 210 gal/min SO_2 removal 70 gal/min
Number of Scrubber Modules	2 1-67% flow 1-33% flow	2 1-67% flow 1-33% flow	3 1-60% flow 2-20% flow	4 4-25% flow	2 2-50% flow
Scrubbing Medium	981,000 plastic spheres, 3 stages	977,500 plastic spheres, 3 stages	1,177,500 plastic spheres, 3 stages	3,071,680 plastic spheres, 3 stages	870,000 plastic spheres, 3 stages
Mist Eliminator	316 stainless steel Chevron-2 stages, 7 passes	Fiberglass Chevron-2 stages, 7 passes	Fiberglass Chevron-2 stages, 7 passes	316 stainless steel Chevron-2 stages, 7 passes	316 stainless steel Chevron-2 stages, 7 passes
Reheater Design	Direct; steam coil reheat 60,000 lbs/hr auxiliary steam	Direct; steam coil reheat 50,000 lbs/hr auxiliary steam	Direct; Steam coil reheat 41,200 lbs/hr auxiliary steam	Indirect; sidestream air reheater 135,000 lbs/hr auxiliary steam	Direct; steam coil reheat 50,000 lbs/hr auxiliary steam
Electric Power Requirements	5.20 MW	5.14 MW	6.39 MW	14.40 MW	5.30 MW
Slurry Disposal	Pumped to ash disposal ponds open loop	Pumped to clarifier open loop	Pumped to clarifier open loop	Pumped to clarifier open loop	Pumped to ash disposal pond 1/2 closed loop 1/2 open loop
Type n	Dry booster fan	Dry booster fan	Dry booster fan	Dry booster fan	Dry booster fan

ash-sulfur dioxide scrubber by retrofitting a lime scrubber to it. This combination is now being tested.

All the scrubbers are operated in a basic open loop configuration; the scrubber blowdown is discharged to an ash settling pond. Makeup water is added to the scrubber as needed.

Pacific Power and Light Company Dave Johnston Plant

This scrubber system includes three Chemico venturi scrubbers connected to a single stack. The boiler burns a western low-sulfur sub-bituminous coal containing 0.5% sulfur and 12% ash, with a heating value of 7400 Btu/lb. The ash is alkaline, with a high calcium content (20% CaO).

The scrubber liquor is recycled via settling ponds. The liquor is made alkaline by the suspended fly ash and hence removes some (about 50%) of the sulfur dioxide present in the flue gas. Problems of scale formation and deposition of solids in the scrubber are made worse by the formation of calcium sulfate in the liquor. These problems have been alleviated by the addition of lime and other chemicals to the liquor, but the added lime causes the absorption of further amounts of sulfur dioxide. The problem of solids deposition is most severe at the wet-dry interfaces in the scrubber.

Arizona Public Service Company Four Corners Plant

This plant has 3 boilers (175, 175, and 225 MW), each equipped with two Chemico venturi scrubbers. The boilers burn a sub-bituminous coal with a low sulfur content (0.68%) and an unusually high ash content (22%) with a low CaO content (4%) in the fly ash. Each scrubber is preceded by a mechanical collector. About 30% of the sulfur dioxide in the flue gas is removed in the scrubbers.

The blowdown liquor from the scrubbers is sent to thickeners and settling ponds, with overflow returned to the scrubbers, and with makeup water added.

Problems are encountered with solids buildup and scaling. The addition of lime has helped by creating a softer scale.

Pennsylvania Power and Light Company Holtwood Station

The Holtwood scrubber is a retrofit installation consisting of a Chemico single stage fixed venturi, in which water is added through a plumb bob shape in the center at the throat and tangentially around the upper section. The scrubber is in parallel with an existing electrostatic precipitator that treats a part of the flue gas which is remixed in order to provide heat for the gas leaving the scrubber.

The coal burned is anthracite mine tailings from the Susquehanna River. The coal contains 16-17% ash, 0.5-0.75% sulfur, and 18-20% moisture. About 20% of the sulfur dioxide in the flue gas is removed in the scrubber. The scrubber liquor (pH 2.5) is sent to a thickener from which the overflow is recirculated. Lime is added to the thickener underflow fly ash slurry to neutralize it.

The principal operating problem has been plugging of the mist eliminator.

Minnesota Power and Light Company Clay Boswell and Aurora Stations

Krebs-Elbair spray impingement scrubbers have been retrofitted on two units at the Aurora Station and installed on a new unit at the Clay Boswell Station.

This scrubber is a box in which high pressure sprays are directed against an impingement plate that incorporates louvered openings to produce rapidly moving liquid drops. There are also sprays in the inlet duct. This design uses less water than other scrubbers, but requires more power. The gas from the scrubber passes through a Chevron mist eliminator followed by additional sprays for further quenching.

The coal burned is a Montana sub-bituminous coal containing low sulfur (0.8%) and 9% ash. The fly ash contains 9-13% CaO.

The impingement plates are designed so that they can be partly pulled out of the scrubber and washed with a high pressure water jet to remove scale, without having to shut down the scrubber. Nevertheless, it is necessary to manually clean the scale from the wet-dry interface in the inlet duct.

The Aurora units are operated as open loop or once through, with clear scrubbing liquor returned to the scrubber from the ash ponds. The Boswell units are also open-loop, but the liquor goes through clarifiers, the overflow from which is mixed with clear makeup water and recycled to the scrubber. The liquor has a pH of about 4; no additives are used. From 15 to 30% of the sulfur dioxide in the flue gas is removed in the scrubber.

Performance

The information available on these scrubbers indicates that in general they remove fly ash efficiently on an overall mass basis. There is not much experimental data on the fractional collection efficiency of these or other wet scrubbers. Some of the most definitive data was obtained on the TCA scrubber at the Cherokee Power Plant of the Public Service Company of Colorado.[14,72]

Figure 2.34 is representative of the data obtained. It indicates that the collection efficiency reaches a minimum at a particle diameter of about 0.5 μm, *i.e.*, in the same particle size range in which fabric filters and electrostatic precipitators also show the lowest collection efficiency. On an overall mass basis, the scrubber was operating at the design particulate removal efficiency of 95%.

In making the particle-size measurements on this installation, interference was encountered from the entrainment of liquid droplets in the gas emerging from the scrubber, even though the scrubber was equipped with an entrainment separator. This has been a common problem in sampling fly ash scrubber effluents. As a consequence, it is difficult to compare the data obtained with similar data on other installations.

2.4.6 *Maintenance*

TCA mobile-bed scrubbers for removing fly ash have been plagued by a variety of maintenance problems, including breakage of the plastic spheres used as contactors. The most serious problems have been with scale and solids formation.

Heavy formation of calcium sulfate scale has been noted as the chief cause of down time on one TCA installation. The scale accumulates and hardens in regions of low flow rates. Scale formation is also a problem with venturi scrubbers, in which it builds up in the venturi throat, is broken off, and plugs lines.

There has been some success in controlling solids deposition (as distinct from scale formation) by water treatment, *e.g.*, by the addition of lime, as noted above. The chemical composition of the water used also plays a part in the scale formation, which should therefore be less of a problem if softer water is used. However, some scaling has been observed in one plant using an acid water.

Operating problems such as those caused by scaling and plugging have reduced the availability of the equipment (the proportion of time that the equipment is operating) to levels that in some instances are marginally acceptable (70-80%). Studies by EPA and utilities that have been evaluating scrubbers for fly ash collection indicate that the utilities are switching to fabric filters or electrostatic precipitators for fly ash collection in new installations. If sulfur dioxide must also be removed from the flue gas, the trend is to install an efficient dry collector for particulate matter ahead of a sulfur dioxide scrubber.

2.4.7 Installation

Retrofitting scrubbers in utility installations has presented few problems; scrubbers are more compact than electrostatic precipitators or baghouses.

2.4.8 Costs

Capital costs and operating and maintenance costs are given in Table 2.17 for some of the scrubbers listed. The values for installed cost are plotted against boiler capacity in Figure 2.35. The curve is drawn to represent the plot of costs for scrubbers installed for fly ash collection. Other values from Table 2.17 that are plotted in Figure 2.35 are for scrubbers designed for collection of both fly ash and sulfur oxides.[78]

The installed cost of the No. 3 scrubber at the Cherokee Station of the Public Service Company of Colorado includes the items listed in Table 2.19.[14] In 1976 dollars, the cost is $6,128,300, which is $41/kW at 99% collection efficiency and $9.94/1000 acfm.

Table 2.20 summarizes the operating and maintenance costs for the scrubber. The table does not include indirect costs such as general plant overhead or capital charges. The total direct operating costs are approximately $1,608,200/yr in 1976 dollars. The costs in Table 2.20 were calculated from published data on the installation, which were modified as noted in order to make the costs comparable with the other data in this report. The power consumption of the scrubber is taken at 6.39 MW, which is the amount used for operation at its full rated electrical load. Table 2.21 lists the items included in the maintenance costs.

The value of $41/kW for the Cherokee scrubber may be compared with an average value of $85/kW and a range of $50 to $137/kW for scrubbers installed for removal of sulfur oxides, or sulfur oxides and fly ash, as found in a 1975 survey of electrical utility power plants.[78]

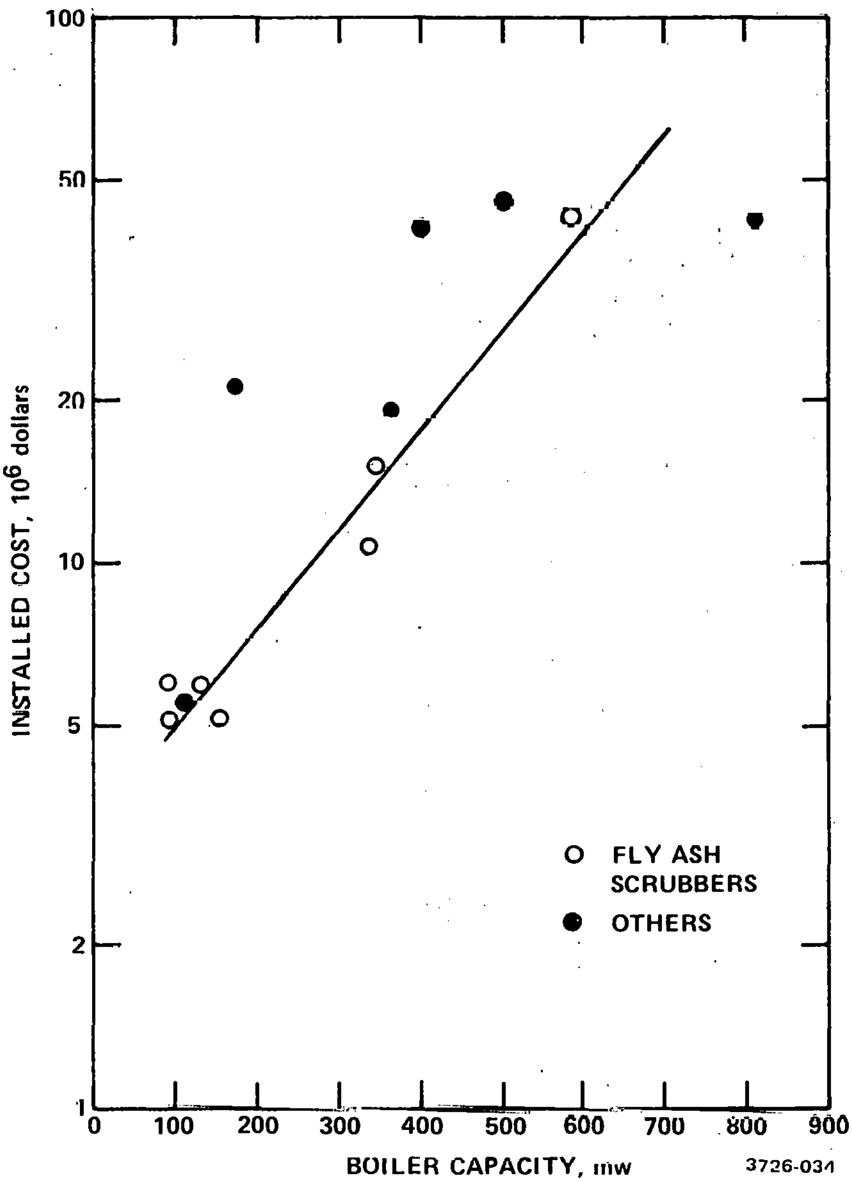

Figure 2.35 Fly ash scrubber costs (installed)

Table 2.19 Cherokee No. 3 Scrubber Capital Cost Breakdown

Account		Installed Cost[a]	%
Excavation and Earthwork		$ 26,700	0.4
Concrete		141,100	2.3
Structural Steel and Buildings		454,000	7.4
Process Equipment			
Scrubber Vessel	$649,500		
Ductwork	314,400		
Presaturator	91,800		
Scrubber Fans and Motors	272,900		
Sootblowers	71,000		
Sootblowing Air Compressors	78,500		
Reheater	59,100		
Dampers and Isolation Gates	74,800		
Recirculation Pumps and Motors	68,500		
Miscellaneous Pumps and Motors	9,100		
Stack Lining	121,700		
Instrument Air Compressors	15,000		
Monitoring Equipment	23,000		
Miscellaneous Equipment	23,100	1,872,400	30.6
Piping		329,000	5.4
Electrical		622,000	10.2
Painting		39,200	0.6
Instrumentation		369,500	6.0
Insulation		155,000	2.5
Indirect Field Costs (includes: Field Supervision and Payroll Expenses; Construction Supplies; Temporary Facilities; Demolition; Construction Equipment)		539,000	8.8
PSCC Overhead Costs		104,400	1.7
Engineering		566,200	9.2
Pre Start-up and Revisions		94,900	1.6
Post Start-up and Maintenance		201,300	3.3
Contractor Fee		516,600	8.4
Interest During Construction		97,000	1.6
Total		$6,128,300	100.0

[a]Data are from References 14 and 72. Costs are updated to 1976.

Table 2.20 Cherokee No. 3 Scrubber Operating and Maintenance Costs

	Total Annual Cost, $[a]	% of Total Annual Operating Cost
Operating Labor		
Control Operator	6,700	0.42
Auxiliary Tender	12,900	0.80
Operating Supervision	3,200	0.20
Utilities[b]		
Electricity @ $0.02/kWh	894,600	55.63
Steam @ $1.75/10^6 Btu	426,400	26.51
Water	5,200	0.32
Air	21,700	1.35
Maintenance		
Labor	49,600	3.08
Instrument Repair Labor	6,200	0.39
Material	17,200	1.07
Operating Supplies		
Lime	75,600	4.70
Polyethylene Balls	60,900	3.79
Miscellaneous		
Increase in Ash Handling	28,000	1.74
Total	1,608,200	100.0

[a] Data are from References 14 and 72. Costs are updated to 1976 by the use of the Chemical Engineering Plant Cost Inde except for the costs of electricity and steam, which were calculated as shown. An 0.80 duty factor was used.

Table 2.21. Items in Maintenance Cost, 4th Quarter, 1973, through 3rd Quarter, 1974, Cherokee No. 3 Scrubber[a]

	Labor	Expense
Scrubber Tower and Reheater	$ 5,872	$ 8,419
Fans	2,848	718
Duct and Breeching	7,269	738
Pumps	10,134	2,363
Piping, Valves	13,501	1,387
Soot Blowers	654	328
Instruments and Controls	311	274
High Pressure Steam	448	70
Total	$41,037	$14,297

[a]Costs updated to 1976 by the Chemical Engineering Plant Cost Index. Data are from References 14 and 72.

2.4.9 Secondary Environmental Impact

Fly ash is removed from the scrubbing liquor in a clarifier or settling basin. Problems of secondary environmental impact may result from the presence of soluble and partly soluble inorganic salts in the liquor, especially leaching and contamination of groundwater. There is not enough information with which to judge the importance of this problem.

3. *ADVANCED COLLECTION DEVICES*

3.1 *NEED FOR DEVELOPMENT*

Improvement in existing control device technology and the development of potentially advanced techniques are needed (1) to improve the capabilities for the control of fine particle emissions, (2) to overcome limitations due to the properties of the effluent gases and particulate matter, (3) to extend the capabilities to higher temperatures and pressures, and (4) to reduce the cost of the control devices. Research in the area of advanced control devices includes modifications or additions to existing systems as well as the development of new approaches.

Each of the existing control devices has certain limitations. Precipitators, for example, are limited by the magnitude of the charge on the dust particle, the electric field, and the reentrainment of the dust. Improvements that are possible in precipitator technology are those that improve one or more of these functions. Since resistivity of fly ash adversely affects both particle charge and electric field, advances are needed to overcome these detrimental effects in addition to extending the performance of precipitators not limited by resistivity.

Fabric filters achieve substantial collection efficiencies but the physical size is a problem in application to large power boilers. Also, pressure drop and bag life are areas that need attention. Some sacrifices in efficiency might be tolerated if higher air/cloth ratios could be achieved without reducing bag life. Improvements in fabric filtration may also be possible by enhancing the electrostatic effects that contribute to the rapid formation of a filter cake after cleaning.

Scrubber technology needs considerable study to control scaling and fouling and improve overall reliability. The collection of fine particles through the use of supplementary forces acting on particles to cause them to grow or otherwise be more easily collected is an area that has received considerable study.

Use of alternative systems to the three conventional control devices has also been investigated in an effort to achieve better efficiencies at lower costs. The difficulty has been that the removal of particulate matter from a gas stream requires that a force be applied to the particles and methods for application of this force are limited. So far, alternative forces, such as sonic agglomeration, have not proven very successful.

Finally, the development of alternative combustion systems for improved fuel efficiency and for control of gaseous pollutants requires extension of the operating range of particulate control devices to higher temperatures and pressures than are now used. This requires either the use of alternative materials or the development of alternative systems.

This section describes some of the studies of alternative particulate control systems and advances in existing systems.

3.2 PARTICLE PRECHARGING FOR ELECTROSTATIC PRECIPITATORS

The concept of precharging the particles prior to their entering a pollution control device is, at present, of most interest in its use for improving the collection efficiency of electrostatic precipitators, especially those that may be marginally below the performance required to meet present air pollution standards. Although some improvement in the collection efficiency of fabric filters and scrubbers is possible by precharging the particles to be collected, the extent of improvement does not yet appear to justify the additional complexity of a precharging system.

A precharger at the inlet of an electrostatic precipitator offers the possibility of obtaining conditions nearer to the optimum for charging the particles and a more uniform distribution of electric field strength and ion number density.

At present, the only practical method for charging the particles is by means of an electrical corona. Since particle charging takes place rapidly in a high density ion field, precharging devices must provide a copious supply of ions. A second requirement for a high charge is a high electric field. If both these conditions are met, a significant charge can be achieved on the particles entering a control device, and collection efficiency can be improved.

In a well-designed precharger, the electric field strength and ion density can be much higher than in a conventional electrostatic precipitator. Since a precharger is smaller in physical size than a precipitator, special materials and engineering techniques which would be prohibitively expensive for a full-scale precipitator can be used in a precharger.

A precharger can improve the performance of an electrostatic precipitator in collecting a high resistivity dust because the dust can be charged faster and to a higher value. In a conventional precipitator, a particle of a high resistivity dust can travel a considerable distance through the precipitator before becoming charged. With a precharger ahead of the precipitator, the dust particle entering the precipitator will have reached its charge when it enters. In addition, the larger dust particles can reach a higher saturation charge if a high average field can be maintained in the precharger.

The physical mechanisms by which particles are charged in a precharger are the same as in a conventional electrostatic precipitator (Section 2.2.2).

The dominant charging mechanism depends on the particle size. In the field-charging process, by which most of the relatively large particles (those above 1 μm or so in diameter) are charged, the particle intercepts a gas ion which is moving along electric field lines of force until it is attracted by its image charge on the particle. The charging rate and saturation value of the charge are thus affected by the magnitude of the applied electric field.

Particles smaller than about 0.2 μm are mostly charged by a diffusion process, in which a gas ion will collide with a particle if the thermal kinetic energy of the gas ion is large enough to overcome the repulsive force of the partially charged particle.

The thermal energy of the ions is relatively independent of the applied electric field, but depends strongly on the temperature of the gas.

The factors that affect particle charging rate include the ion density, the ion mobility, the strength of the electric field in the charging region, the temperature of the gas, and the molecular velocity. The particle size and its dielectric constant also affect the charging rate.

Unfortunately, the problem of back corona which arises in the collection of a high resistivity dust is even more severe in the precharger itself when it is operated at a higher current density than a conventional precipitator, to the extent that dust particles will be deposited on the passive electrode in the precharger.

If these electrodes could be maintained free of accumulated particles, the back corona problem would not arise. However, there are formidable engineering problems associated with the design of clean electrodes. Mechanical wiping systems usually can not withstand the harsh environmental conditions normally encountered in industrial electrostatic precipitators.

The techniques of chemical conditioning and increasing the temperature of operation, which are applied to electrostatic precipitators to alleviate the problem of collecting high resistivity dust, can also be considered for alleviating the problem in chargers.

Another problem with the use of chargers is the accumulation of charged particles in the region through which the corona current is conducted. The effects of this space charge on electrical performance are observed most frequently when a large number density of fine particles is provided. The ratio of charge to mass, under a given set of charging conditions, increases as the particle diameter decreases. Thus, for a given total mass concentration in a gas stream, the number of ions attached to particles, under steady-state operating conditions, is greatest for the particle size distribution having the smallest mean diameter.

Since the space charge depends only upon the relative number densities of ions and particles, it can be alleviated only by designing the corona discharge system to provide a sufficiently high ion density or by diluting the number density of the particles before the gas stream enters the charging region.

Another problem is that the dust that is collected and subsequently reentrained in the conventional electrostatic precipitator will not be affected by the presence of the precharger. Hence, even though the entering dust can be charged to a higher value than in a conventional precipitator electrode system, the collection efficiency would not be proportionally increased unless a precharger were located ahead of each field.

Research on prechargers at present is limited to a project sponsored by the Electric Power Research Institute on a high intensity ionizer[27] and fundamental studies of the charging process sponsored by the Environmental Protection Agency.[79]

The high intensity ionizer is being developed by Air Pollution Systems, Seattle, Washington. Some of the details of the system are proprietary and have not been released. However, information that has been released indicates that the ionizer is comprised of a venturi section as the grounded electrode and a disc as the corona electrode with a configuration such as that shown in Figure 3.1. The gas velocity in the venturi section is about 50 ft/sec and is maintained sufficiently high to prevent excessive dust accumulation on the venturi wall. In addition, purge air is periodically puffed through the venturi to remove accumulated dust.

The ion density in the APS ionizer is reported to be 10^{10} ions/cm^3 and the average applied electric field 10-20 kV/cm. The system is reported to function with these conditions even when the dust has a high electrical resistivity. Tests on a 3-field pilot-scale (2000 cfm) precipitator are reported to show substantial increases in efficiency with the ionizer operating. Figure 3.2 is a schematic drawing of the installation.[80] Further tests are planned with larger precipitators, by the Tennessee Valley Authority and by the Electric Power Research Institute at the Arapahoe Station of the Public Service Company of Colorado.

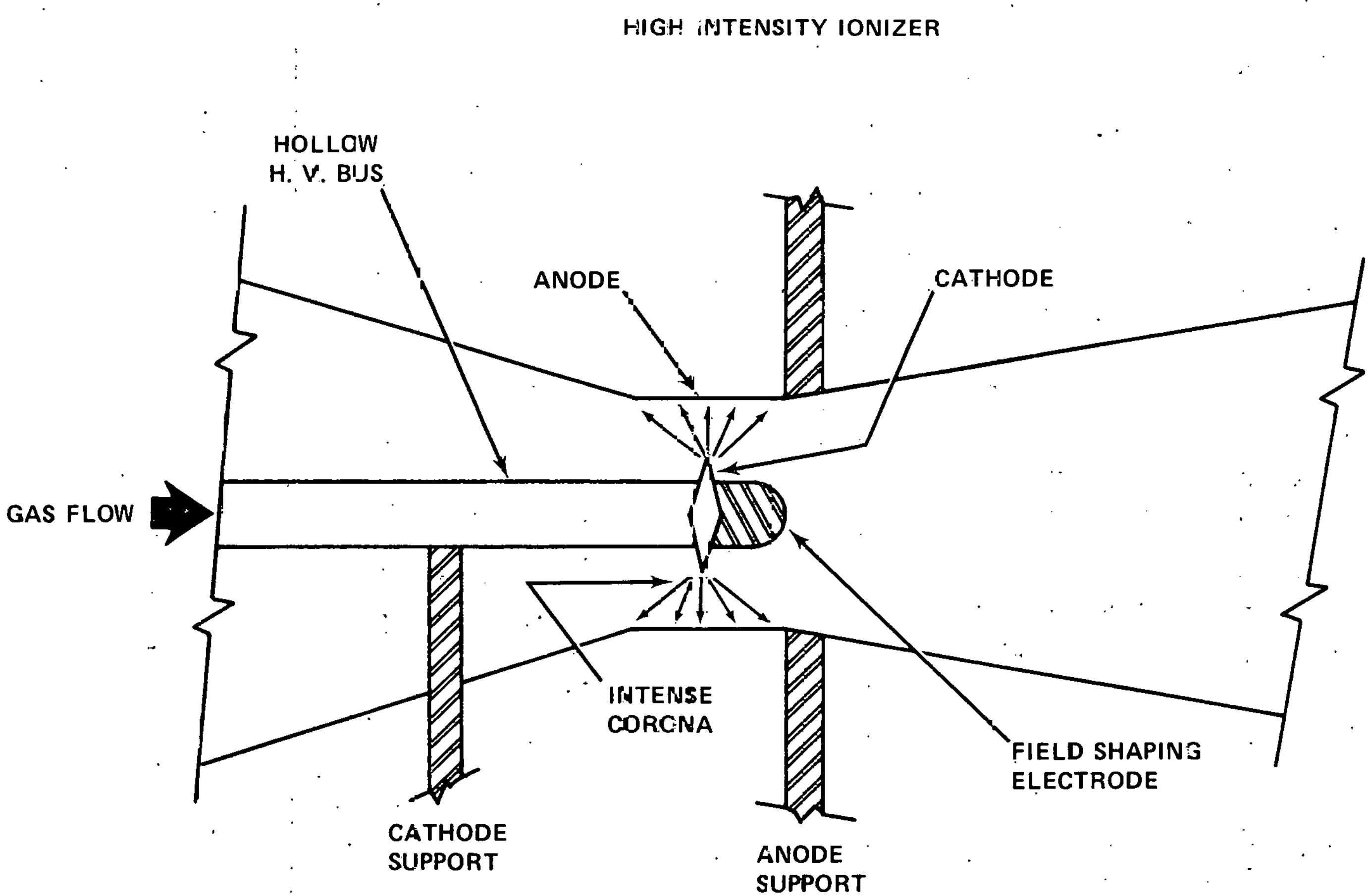

Figure 3.1 High intensity ionizer.[80]

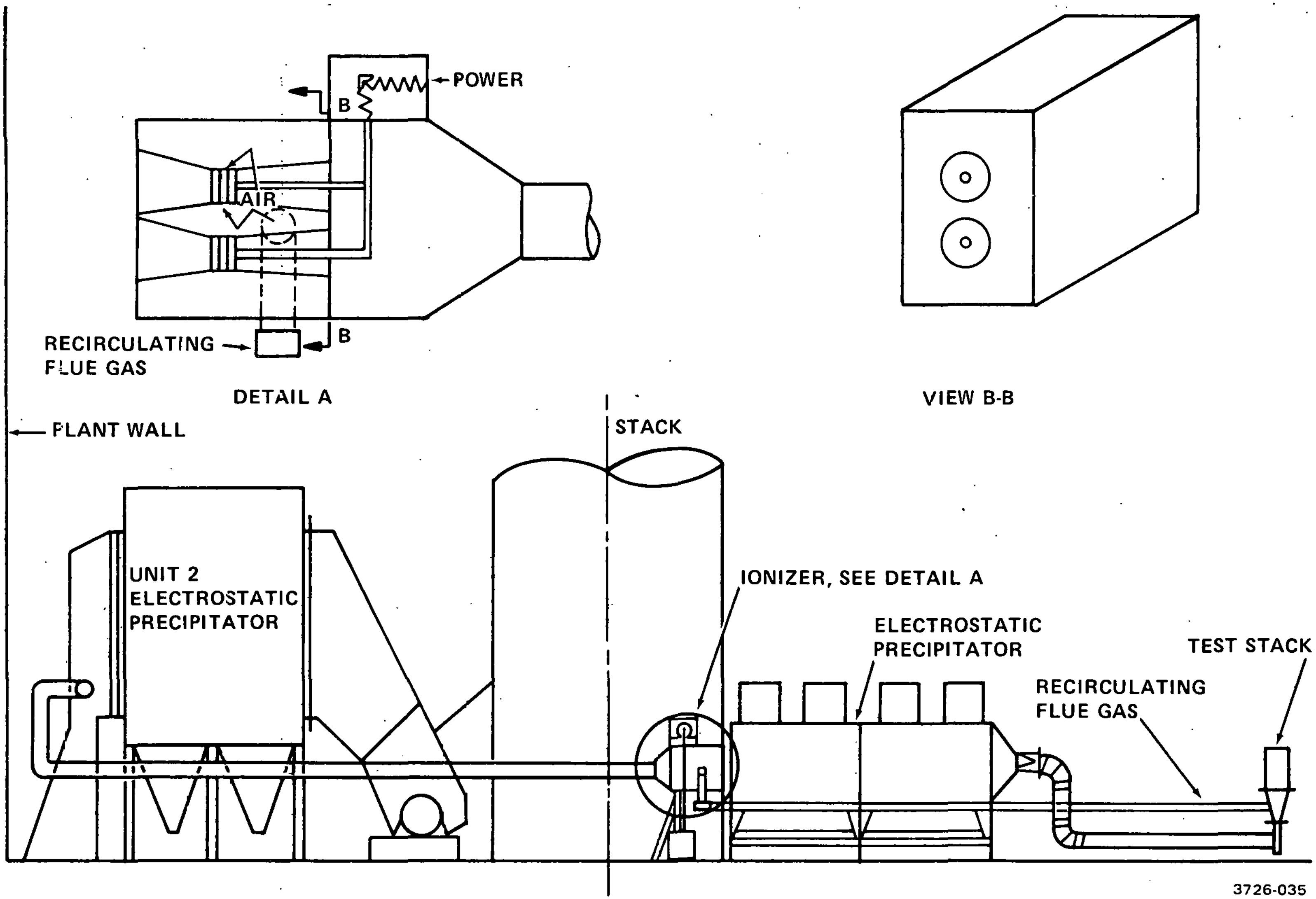

Figure 3.2 Ionizer-precipitator configuration for the John Sevier pilot test.[80]

EPA studies of the precharging concept have been of a more fundamental nature, but still directed toward an optimized precharger. Studies have been made of the parameters influencing both diffusion and field dependent charging. Studies are also being carried out to indicate the limitations on precharger current due to electrical resistivity of the dust and means for overcoming the resistivity in the precharging section.

The advantages to the precharging of dust in a precipitator will probably be resolved during the current research programs when further data are available.

3.3 FILTERS

Attempts are being made by manufacturers, with assistance from the EPA, to develop fabric filters that have longer life and greater resistance to degradation at high temperatures (500-1000°F).

Several organic fibers that are almost as stable to heat as glass fibers are potential competitors in filter fabrics in utility boiler baghouses. These fibers would be expected to be less brittle than glass fiber. One example is Teflon, the fluorocarbon polymer usable to 500°F.

Teflon also has excellent resistance to chemical attack. It is several times as expensive as glass and presents problems due to yarn slippage and creep. However, Teflon fibers in a laminated fabric such as Gortex[81] should be more mechanically stable. The heat-resistant polyamide fiber Nomex has been tried in full-scale baghouses, where it has been found to be stable for varying lengths of time, which so far have been generally judged insufficient.

Acrylic fibers (usable to 260°F) and polyester fibers (usable to 270°F) have been used in pilot plant on flue gas in Australia, where the flue gas temperature is only 240°F.[82]

Bench-scale studies on spun-bonded non-woven polyester fabric filters have been made by the EPA.[83]

Non-woven fabrics made of fine fibers (diameters in the micron range) deposited on a porous backing are being developed by the Donaldson Company and the EPA.[84] The backing, made of fibers with conventional diameters (20-50 μm) provides strength for the fine fiber layer.

This application of fine fibers makes use of the expectation from filtration theory that collection efficiency increases as the fiber diameter decreases. Test results indicate that in some configurations such as a cartridge of pleated fabric, the collection efficiency is improved (or the size reduced or the air-to-cloth ratio increased) to the extent that performance is as good as or better than that of conventional filter bags. The pressure drop across the double mat filter is about the same as that across a polyester felt. The dust cake appears to build up on the fabric surface so that it is removed satisfactorily by conventional means of regeneration.

Research on the influence of fiber characteristics on filtration is being studied under a grant from the EPA to the Textile Research Institute. An attempt is being made to obtain quantitative relationships between air filtration efficiency and five fiber properties: surface roughness, cross-sectional shape, linear density, crimp, and staple length. Filter fabrics are being made from non-woven random web polyester fibers for which these characteristics are known.[49]

A study is being made under a grant to Harvard University on mechanisms of dust penetration through filters, including direct penetration, slippage of particles through the filter after capture, and penetration by plugs breaking from the filter cake. The objective is to increase air-to-cloth ratio while minimizing penetration and pressure drop.[49] In addition, studies on needle-punched fabrics are being conducted under a grant to North Carolina State University.[83]

Several ceramic, inorganic, or metal fibers are possibilities for filters, especially for hot-side operation at temperatures around 700°F. Some inorganics that have been considered are asbestos, alumina-boria-silica, zirconia-silica, carbon, and boron nitride.

Felts of metal fibers are being developed by the Brunswick Corporation. The present efforts are directed toward operation at 200-700°F in competition with glass fiber baghouses. Laboratory tests at room temperature suggest that such filters can operate at flow rates of 100 ft/min with collection efficiencies greater than 99.5% for particles 0.3-1.5 μm in diameter. Plans are being made for a test installation at the Arapahoe Station of Colorado Public Service.[85]

Granular bed filters also represent an advanced filtration device. They are discussed in Section 3.5.3.

3.4 SCRUBBERS

The use of various techniques to increase the collection of small particles is being investigated by the Environmental Protection Agency. This approach has resulted from realization of the effect illustrated in Figure 2.34, namely the limitation on collection efficiency imposed by a high pressure drop. Various auxiliary techniques are being considered for improving collection. If, for example, the particle size could be doubled by some sort of treatment, the penetration could be decreased by two orders of magnitude (*e.g.*, from 0.3 to 0.003).

Coagulation and agglomeration are possible mechanisms for increasing the particle size. These effects might be produced by heat, sonic or ultrasonic vibration,[86] or chemical reaction. Condensation of water vapor on the particles is another possibility for increasing their size. Other techniques that might also be used take advantage of gradients between the particle and the collection surface, *e.g.*, diffusiophoresis, the movement of the particle due to the vapor gradient toward a liquid surface during vapor condensation, or thermophoresis, particle movement in the temperature gradient due to the greater transfer of momentum from the gas on the warmer side of a particle than on the cooler side. Thermophoresis is such a weak effect, under conditions of practical use, that it is not of great interest; but diffusiophoresis can have a significant effect in scrubbers under some operating conditions. The effect is also enhanced when it is accompanied by condensation produced by the injection of steam into conventional scrubbers.

The diffusiophoretic force, and hence the collection efficiency of a scrubber operating in a regime in which this force is effective, are relatively independent of the size of the particles being collected. This force might be used for improving the collection efficiency of a wet scrubber for submicron particles.[87-93]

The injection of steam into a scrubber and its condensation on the particles also improves the collection efficiency by increasing the size of the particles and thus increasing the likelihood of their being captured by impact. The Environmental Protection Agency has evaluated several scrubbers modified by steam injection designed to improve collection efficiency. The most effective of these modified scrubbers are the Aronetics ADTEC Scrubber and the Steam-Hydro Scrubber (Lone Star Steel).

The ADTEC scrubber is designed to use heat from waste gas to heat a pressurized flow of hot water, which then is sprayed in a jet scrubber. The spray droplets and the particulate matter collected by them are recovered in a cyclone. The draft induced by the operation greatly reduces fan power requirements, and can in some applications provide sufficient draft for the entire system.

In tests conducted on ferro-alloy furnace emissions, the total mass collection efficiency averaged 95.1% on a dust having a mass mean diameter of about 3 μm and a mass mean aerodynamic diameter of about 6 μm. The geometric standard deviation was about 10, indicating that about 30% of the particulate mass was in particles less than 0.5 μm, an unusually fine dust.[89]

The fractional efficiency of the scrubber for collecting this dust is shown in Figure 3.3. For particles above 0.5 μm, the collection efficiency is 99% or greater.

The Steam-Hydro scrubber also operates on heat from the waste gas. High pressure steam generated by the heat is injected by a nozzle into a mixing tube in which the steam and particulate matter are mixed. A shock wave is created which enhances the scrubbing action. The particulate matter is then separated in a cyclone. The system creates enough draft so that fans are not needed.[89]

Tests of collection efficiency were made on an installation operating on an open hearth furnace. The average collection efficiency was 99.86%. The fractional efficiency is shown in Figure 3.4.

Table 3.1 shows a comparison of these modified scrubbers with conventional highly efficient venturi scrubbers. The ADTEC and Steam-Hydro scrubbers are more efficient than a venturi with an extremely high pressure drop. However, the calculated amounts of energy required by the devices are in line with those of the venturis.[70]

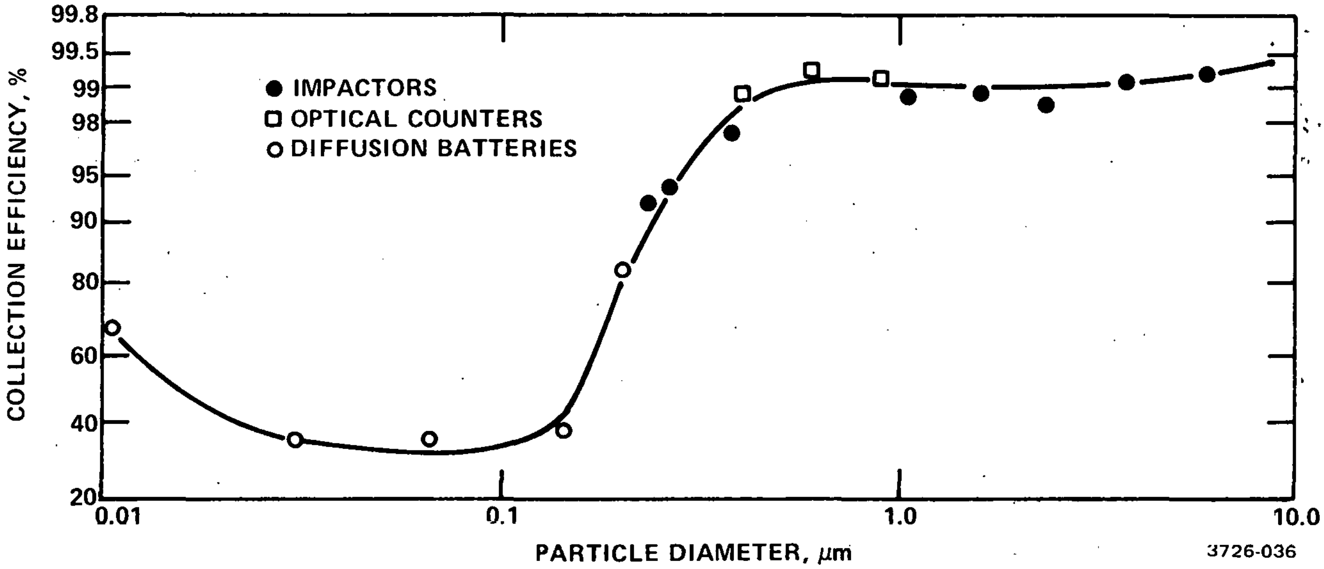

Figure 3.3 Fractional collection efficiency of the Aronetics scrubber (using equivalent diameters). Overall collection efficiency 95.9%.[89]

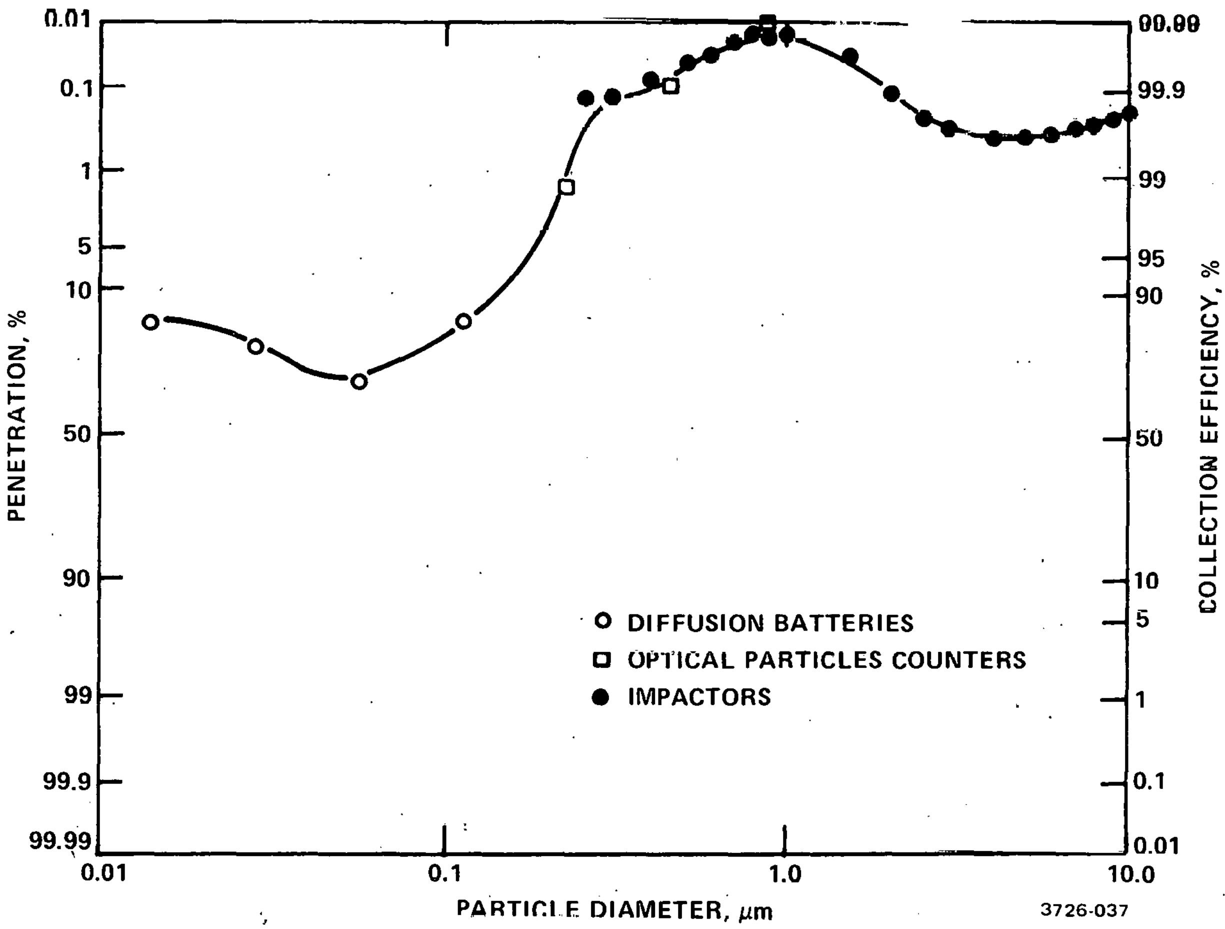

Figure 3.4 Fractional collection efficiency of the Lone Star Steel Steam-Hydro Scrubber. Overall collection efficiency 99.9%.[89]

Table 3.1. Fine Particle Control by Wet Scrubbers[70]

Scrubber	Power Consumption, hp/1000 acfm	Smallest Diameter Collected at 50% Efficiency, μm
Venturi (10 in. WG)	1.6	0.7
Venturi (108 in. WG)	17	0.3
ADTEC	2.4[a] 400 [b]	0.13
Steam-Hydro	200-300[b]	<0.1

[a]Water pumps plus motors, assumed 60% overall power efficiency.
[b]Waste heat.

Thus, the modified wet scrubbers that have been evaluated so far do not appear to offer any advantage over conventional high energy venturi scrubbers except under certain conditions, *e.g.*, when waste heat is available.

3.5 HYBRID COLLECTION DEVICES

These are control devices that use combinations of techniques for collecting particulate matter.

The hybrid devices that are the furthest developed are: (1) charged-droplet scrubbers; (2) wet electrostatic precipitators; and (3) granular-bed filters. These devices are discussed in detail in this section. Some other devices are noted at the end of this section.

3.5.1 Charged Droplet Scrubbers

The concept of charged droplet scrubbing is based on improving the probability of capture of particulate matter by using the electrostatic forces developed between oppositely charged particles on liquid droplets (Figure 3.5).[94] As discussed above in Section 2.4, the particle capture mechanisms active in particulate removal by scrubbing are impaction and diffusion, both involving the relative motion of the particles to be removed and the liquid droplets. Large particles (above 1-2 μm) are relatively massive and the inertial forces brought about by

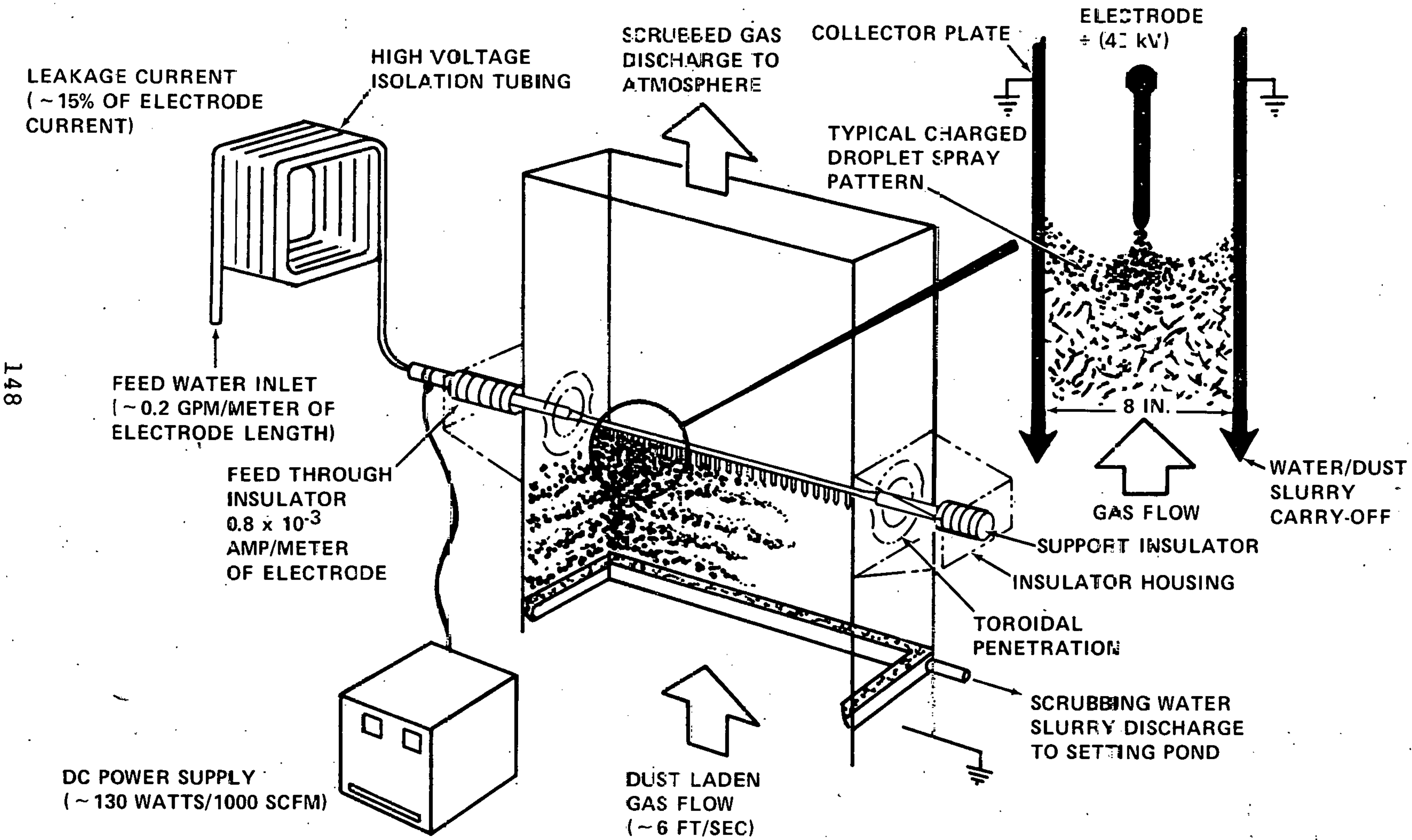

Figure 3.5 TRW charged droplet scrubber.[94]

aerodynamic turbulence are sufficient for high collection efficiency. The efficiency is dependent on the degree of turbulence and can be related to the total energy supplied to the system, either through the gas or the liquid droplets. At the smaller end of the particle size spectrum, particles have unfavorable inertial characteristics, and so they tend to follow the streamlines of the gas flow around a liquid droplet and do not impinge on it by inertial forces. Particles below about 0.1 μm are subject to random Brownian motion and diffuse readily to the water droplets. In the size range between 1.0 and 0.1 μm, both inertial and diffusion forces are relatively small and collection efficiencies for scrubbers are lowest for particles in this size range. Charged droplet scrubbers are intended to augment collection within this size range by increasing the probability of contact between the droplet and particle.

The electrostatic force between particles charged with opposite polarities is well defined by theory. The force $F \sim \frac{q_1 q_2}{r^2}$ where q_1 and q_2 are the charges on the dust and spray droplet particles, respectively, and r is the distance between them.

Liquid droplets can be electrically charged by several means; the methods that have received most attention are mechanical spraying followed by corona charging and electrohydrodynamic spraying. The latter technique provides the highest charge density on the particle surface. As is shown in Figure 3.5, water is raised from ground potential to about 40 kV by passage through a long electrical resistance path in the form of insulating tubing. It is then introduced into a hollow electrode which contains a series of hollow, elongated spray tubes, from which it issues into a grounded scrubber vessel. Droplets are formed by the action of electrical force and surface tension. The charge density is limited only by corona breakdown or by the Rayleigh limit, which for liquid droplets is the limit determined by surface tension and electrostatic forces. For water the charge limit E_b is given by

$$E_b = 2 \left(\frac{\sigma}{E_0 S} \right)^{\frac{1}{2}}$$

where E_0 = permittivity of free space = 8.854×10^{-12} coul/Vm

σ = surface tension of liquid, N/m.

S = electrode radius, m

Figure 3.6 shows the relationships between maximum charge for water droplets and the droplet size in micrometers.[95]

Dust charging is accomplished by an electrical corona in the same manner as in conventional electrostatic precipitation. The charging of very small particles is by diffusion and is related to the free ion density and time. Since the system is wet, there would be no limitation due to back corona.

The charge on very fine particles depends upon many factors. However, in a practical situation the charge would be limited to values in the range given in Figure 3.7.

The forces acting between a 100 μm particle and dusts of different particle sizes are shown in Figure 3.8. It is apparent that the force decreases rapidly as the distance between particles increases. When the electrostatic forces become small compared with the aerodynamic forces, they can be neglected.

The overall effect therefore on the charged droplets is that when the particles come into close proximity, the electrostatic forces will cause the particles to be captured by the droplets. This has the effect of improving the collection efficiency of particles in the range between the larger ones that would be captured by inertial forces and the very small ones that would be captured as a result of diffusional forces.

Studies of charged droplet scrubbing, both theoretical and experimental, have been conducted by Hanson, Eyraud, Sparks, Kraemer, Pilat,[95-99] Penney,[100,101] Lear,[94,102,103] Melcher,[104]

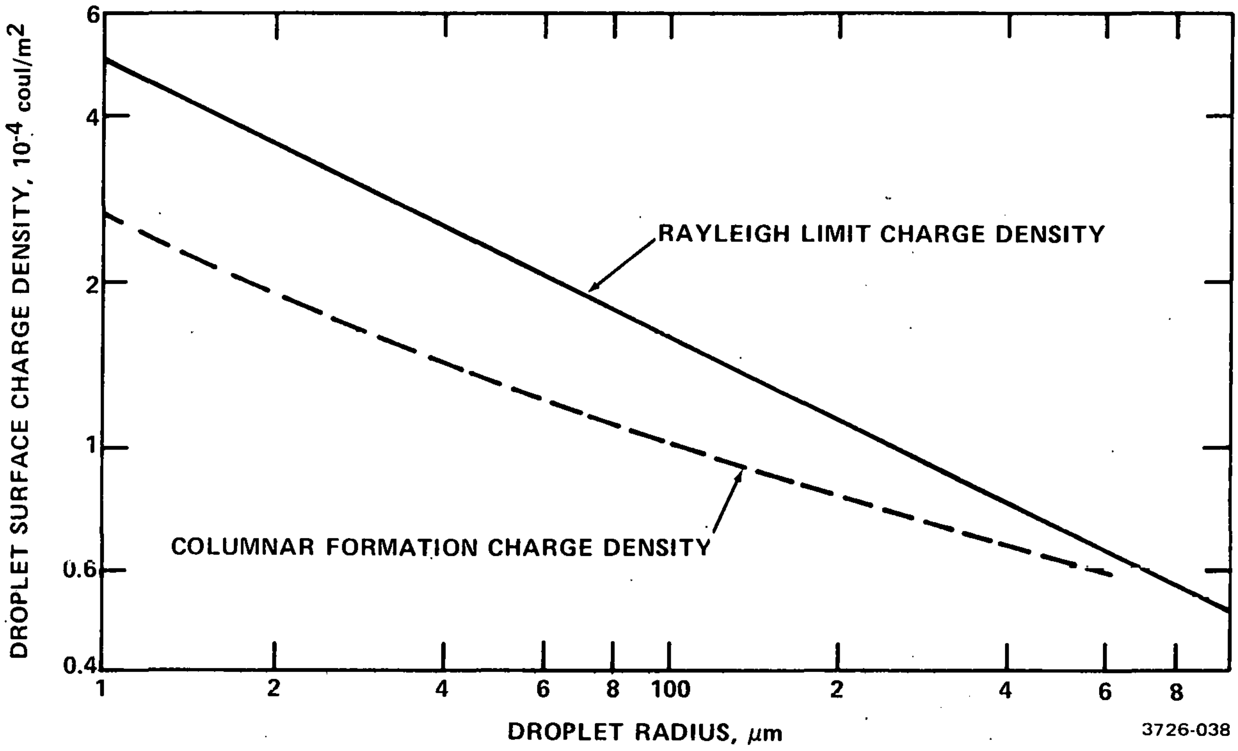

Figure 3.6 Limits of surface charge densities on water droplets (Rayleigh limit) and columnar segments of water.[94]

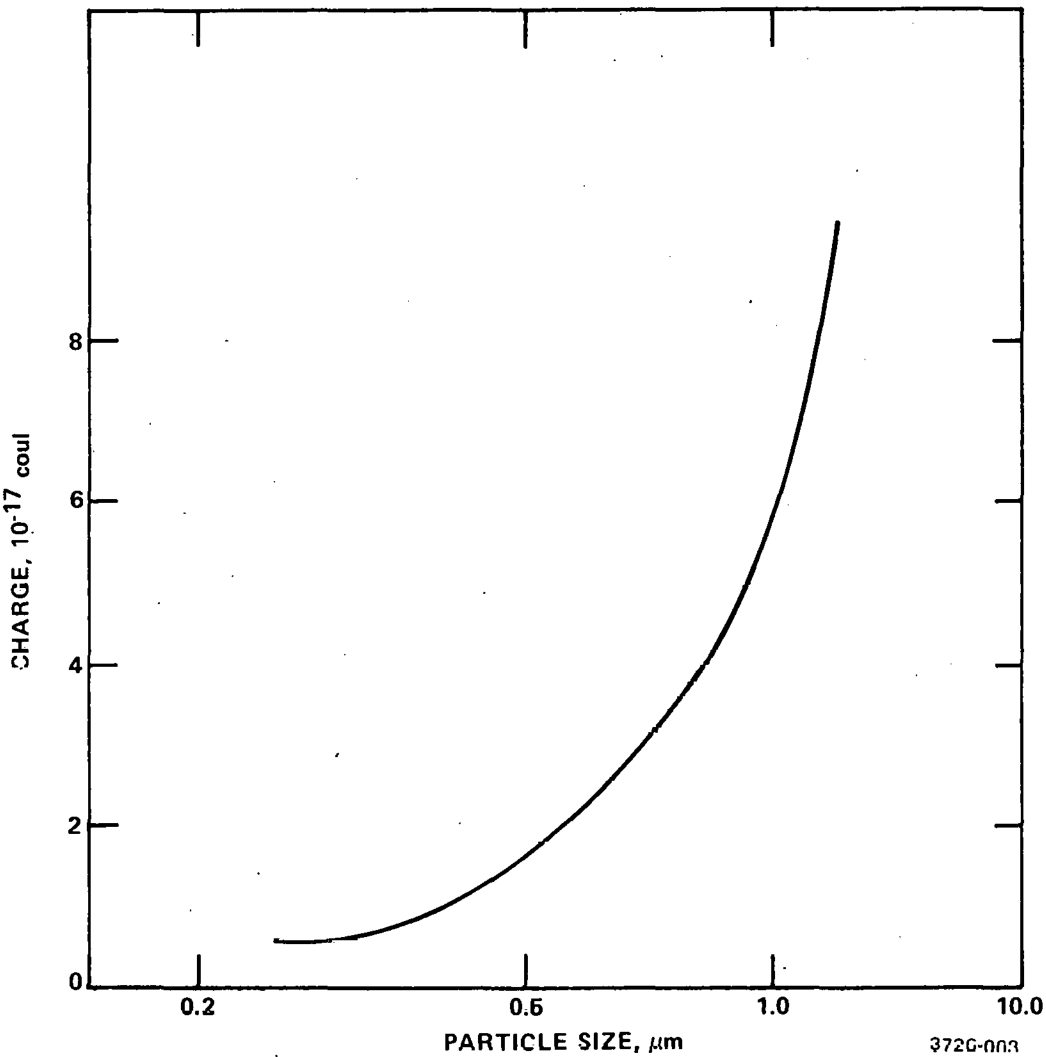

Figure 3.7 Theoretical particle charge as a function of particle size.

and others. Pilot-scale studies sponsored by the EPA have shown that collection efficiencies of wet scrubbers can be substantially improved by electrostatic augmentation, as indicated in Figure 3.9. The data shows the expected decrease in efficiency with decreasing particle size for the scrubber with no electrostatic augmentation and the increased collection efficiency when particle and droplet are oppositely charged.

The future of charged droplet scrubbing for fly ash collection does not appear promising. The collection efficiency for particles in the 0.1 to 1 μm range is not so high that it would be economically attractive in view of the alternative conventional electrostatic precipitator or fabric filter control devices.

3.5.2 Wet Electrostatic Precipitators

Wet electrostatic precipitators, which have been used for many years for the collection of the fine particles from metallurgical furnaces, are now being considered for control of fly ash and sulfur dioxide emissions from coal-fired power plants.[105-108]

In a wet precipitator, the wire-plate or wire-cylinder design of a conventional dry electrostatic precipitator is modified by the addition of spray nozzles or weirs that provides a means for irrigating the collection electrodes (either plate or cylinder). Solid particles deposited on the collection electrodes are washed into hoppers. If liquid particles are to be collected, irrigation of the collection electrodes may not be needed, or the amount of irrigation may be reduced.

In the iron and steel industry, wet electrostatic precipitators have been used since about 1930 to remove dust, containing iron oxide, silica, carbon, and other matter, from the blast furnace exhaust gas so that the gas can be burned to recover its fuel value. Wet electrostatic precipitators are preferred to dry precipitators because the exhaust gas is already saturated with water when it enters the collector.

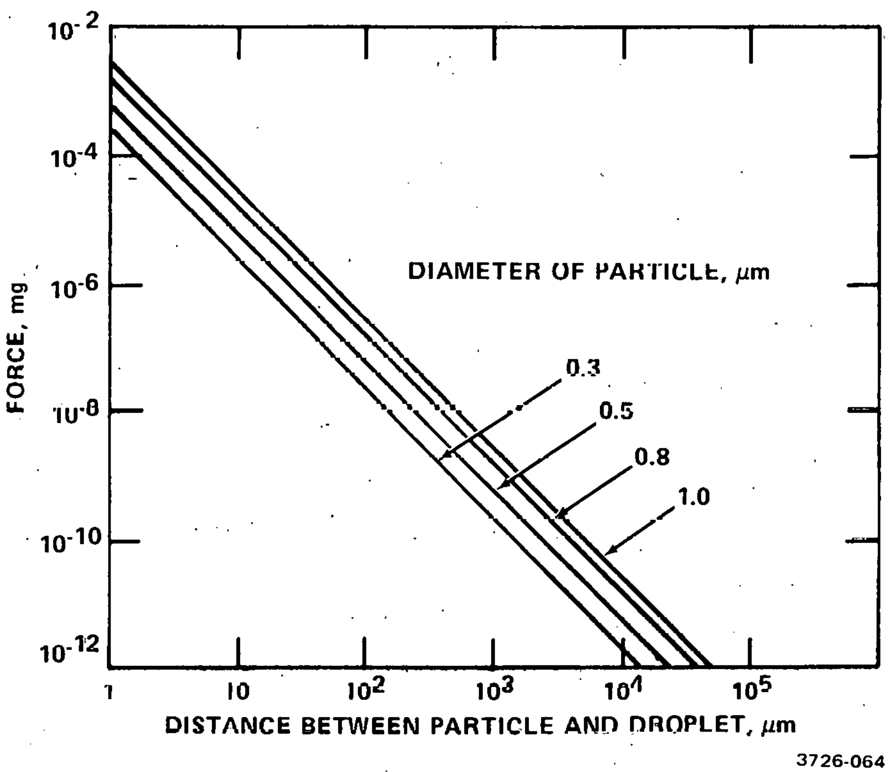

Figure 3.8 Force acting between particle and 100 μm droplet.

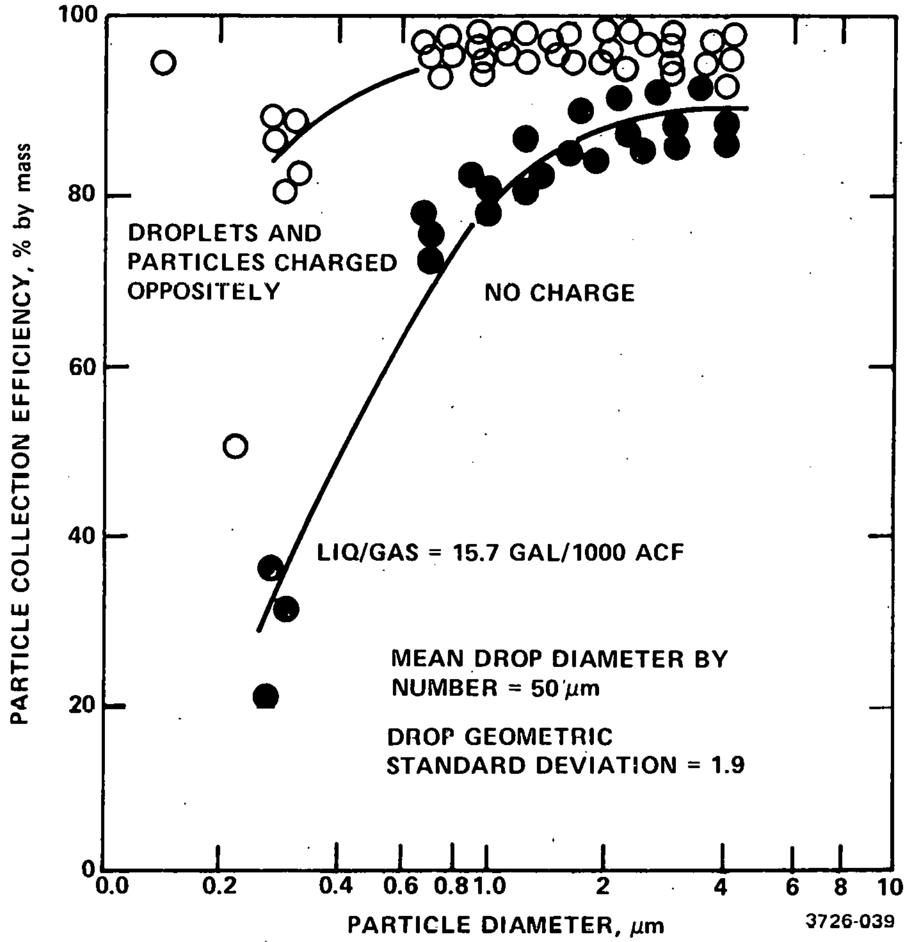

Figure 3.9 Particle collection efficiency of electrostatic spray droplet scrubber as a function of particle size.[94]

However, the use of wet precipitators on blast furnaces is decreasing. In the blast furnaces that are being built, the gas is under pressure (15-20 psi), which allows the use of a high-energy venturi scrubber for cleaning the gas. With the energy available from expansion of the gas in the venturi throat, a scrubber can clean the gas with less added cost for operation and maintenance and with less capital cost than an electrostatic precipitator.

Wet electrostatic precipitators are used on other metallurgical furnaces, such as basic oxygen furnaces, electric arc furnaces, and cupolas. They are especially useful when the dust contains water-soluble components. However, these components are frequently materials that introduce corrosion problems, and wet scrubbers, having a simpler construction, may be preferred for these applications also.

Wet electrostatic precipitators are used in collecting the grit produced in the scarfing of steel slabs to remove surface bloom. A wet collection system is appropriate in this application because a high-pressure water jet is needed for dislodging and granulating the bloom.

Wet electrostatic precipitators are also used to collect tar and oil in coke oven and petrochemical emissions. Since the materials collected are liquids, irrigation of the collection electrodes is often not required. Similarly, acid mists from the production of sulfuric and phosphoric acids are collected in wet electrostatic precipitators.

The application that has created the most interest recently is the collection of fumes from aluminum pot lines. Aluminum is produced by electrolysis of alumina dissolved in a bath of molten cryolite with carbon electrodes. A wet collector is preferred because of fouling by condensed tars from the hot electrodes. Sulfur oxides and hydrogen fluoride are also present in the effluent, and they are removed along with the particulate matter in the wet electrostatic precipitator.

Although wet electrostatic precipitators have not yet been installed in electric power plants, pilot scale tests are being made by equipment manufacturers on their use for the simultaneous removal of fly ash and sulfur oxides.[106] Wash liquors containing lime or other alkalies are used, and scale formation or solids deposition, similar to that encountered in wet scrubbers, is encountered.[106]

Experiments and calculations were carried out at Southern Research Institute on a laboratory-size wet electrostatic precipitator to develop methods for calculating performance and to investigate its suitability for simultaneous removal of fly ash and sulfur oxides from flue gas in coal-burning electric power plants.[105]

Measurements of collection efficiency for various sizes of liquid aerosol particles (dioctyl phthalate) from 0.5 to 2 μm in diameter agreed with values calculated for a dry electrostatic precipitator in a computerized mathematical model with the same values of operating parameters. Electrification of the system did not enhance the removal of sulfur dioxide with either a water or alkaline (sodium hydroxide) solution irrigating the precipitator.

Calculations of the removal of sulfur dioxide indicate that the gas-liquid interfacial area on the wetted walls of a wet electrostatic precipitator is not large enough for effective removal of sulfur dioxide. The contact area can be increased by the introduction of sprays, which would best be located in an inexpensive low pressure spray tower preceding the precipitator itself, in order to reduce interference with the electrical operating conditions of the precipitator.

Cost calculations show that a wet electrostatic precipitator, despite the lower energy costs due to its low pressure drop, costs about twice as much as a Turbulent Contact Absorber scrubber, for both capital and operating costs.[105] Solids deposition observed in a wet scrubber would also be encountered in a wet precipitator and because of the more complex structure of the precipitator would be more troublesome than in a wet scrubber. In comparison with a dry electrostatic precipitator collecting fly ash from low sulfur coal, a wet electrostatic precipitator would allow the collection plate area to be decreased by a factor of two or more, but the increased materials cost required by wet operation would partially or completely offset the cost savings.

3.5.3 Granular Bed Filters

Granular bed filters have been used in industrial installations for the removal of particulate matter from the effluents from waste heat boilers in the forest products industry, in the cleaning of gases from clinker coolers in the cement industry, and in the cleaning of lime kiln effluents. Experimental studies have also been conducted for a wide variety of potential applications, including the removal of radioactive particles from the air in ventilation systems, the cleaning of waste gases from open hearth furnaces, and the simultaneous desulfurization and particulate removal from the gas from coal-fired boilers.

Granular bed filters consist of closely packed granules of river stone, alumina, or other materials that are capable of withstanding the environment of the flue gases to be cleaned. The sizes of the granules vary with the application, the usual sizes ranging from around 1/16-in. diameter to 1/4-in. diameter.

The physical arrangements of granular bed filters include a wide range of designs that permit the gas to flow through the filter medium and provide a means for removing the collected dust. Two basic methods of cleaning the filter medium are used. Fixed bed filters generally employ back flushing or mechanical agitation to dislodge the collected particulate matter and permit it to fall into a hopper for removal. Examples of the fixed bed concept are the Squires Panel-Bed Filter,[109-112] and the Ducon Granular Bed Filter.[113] Figure 3.10 shows one design of the Squires filter.[114] The Electric Power Research Institute is supporting research on the Squires Panel-Bed Filter at the City University of New York (RP 257).

In one design of the Ducon filter, dust-laden gas passes downward through horizontal filter beds. When the accumulated dust causes the pressure drop to reach a specified value, the individual filter element is isolated from the clean gas outlet by means of a shut-off valve and is cleaned by a reverse upward flow of air or gas.

A third type of granular bed filter is the modular unit marketed by Rexnord (Figure 3.11). Filtering is accomplished by a granular bed through which the gas flows. Periodically, one of the modules is taken off line and back flushed with heated ambient air accompanied by mechanical raking of the dirty granules.[115]

In moving bed filters, the filter medium and the collected dust are removed from the filter and the dust separated from the medium externally. An example of a moving bed filter is the dry scrubber, marketed by Combustion Power, Inc.[116] Figure 3.12 is a schematic of the filter system. The filter medium

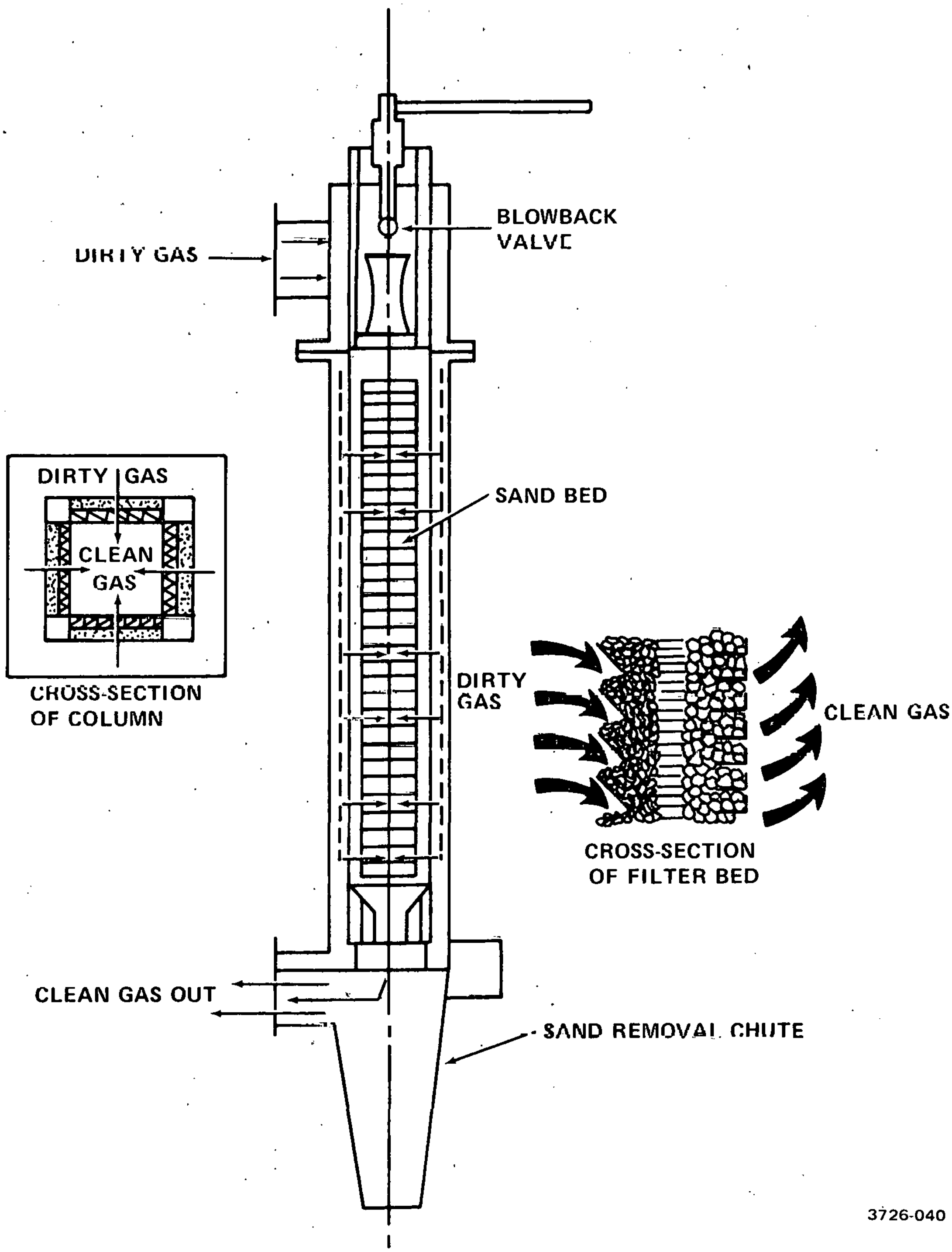

Figure 3.10 Schematic drawing of Squires panel-bed filter unit.[1]

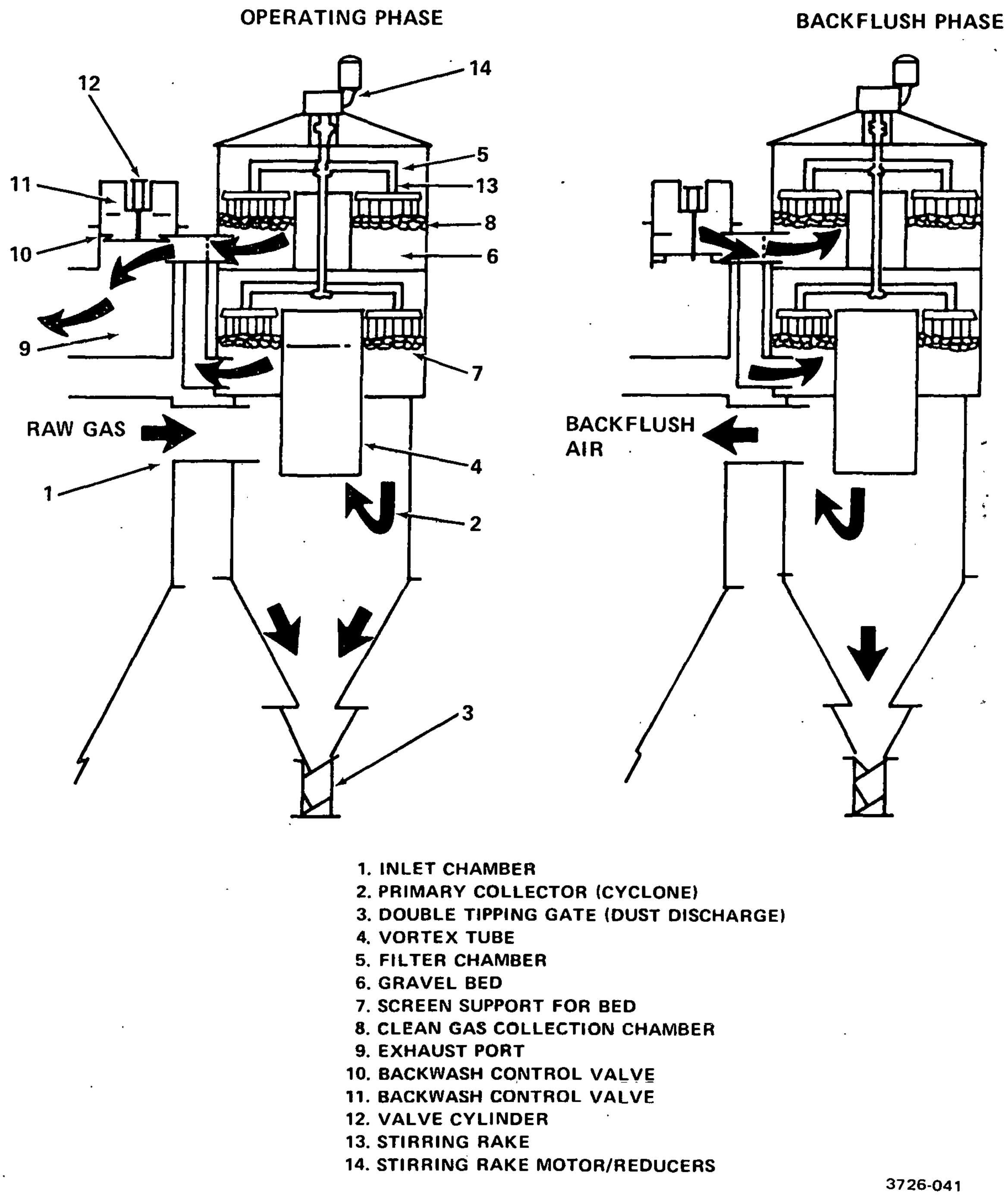

Figure 3.11 Operation of a gravel-bed filter.[115]

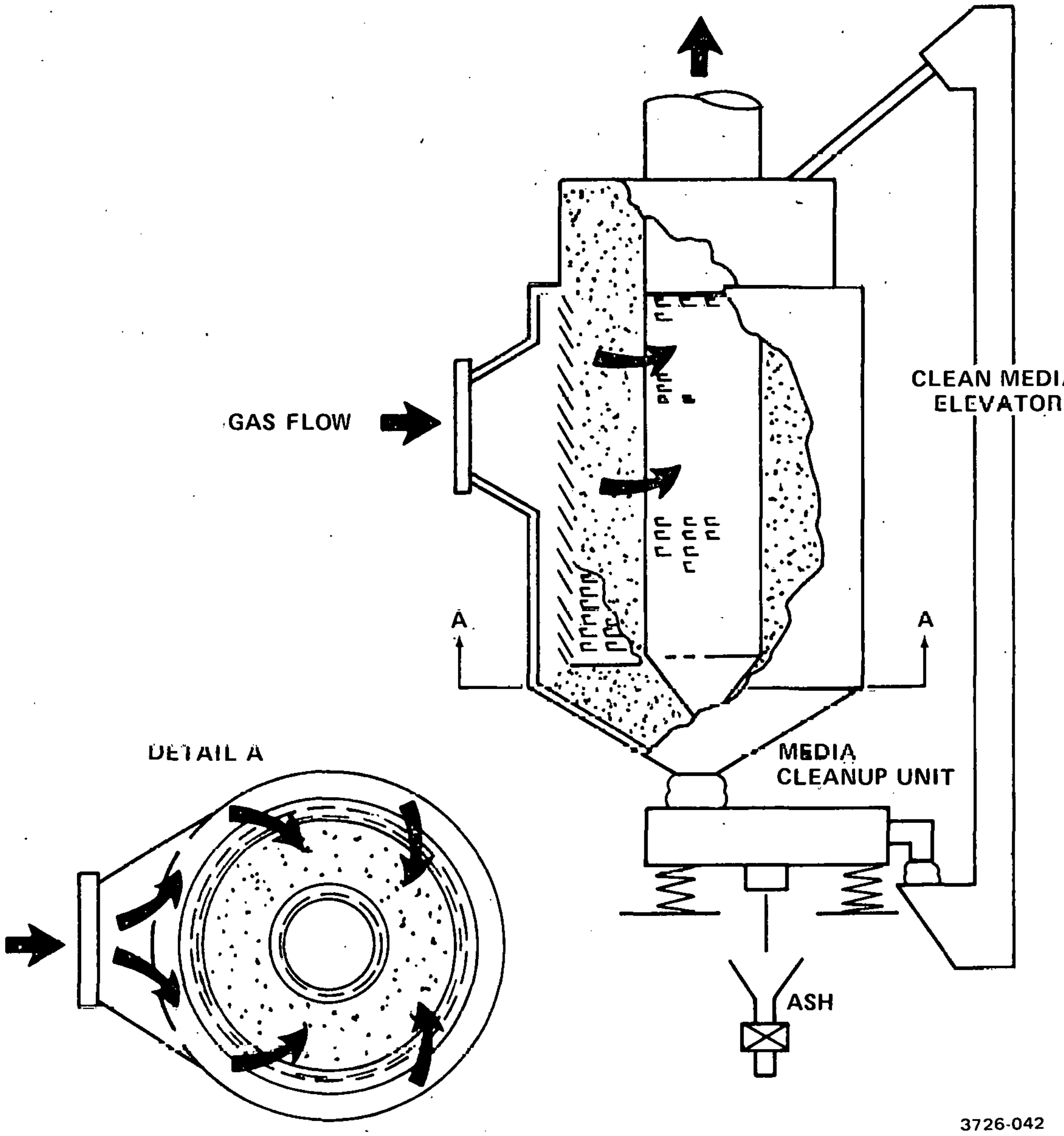

Figure 3.12 Combustion Power Company dry scrubber.[116]

is cleaned by vibration of the granules to separate the dust, which falls into an ash hopper. The medium in the Combustion Power Dry Scrubber is contained in the annular space between two cylinders, which are louvered to permit entrance and exit of gases. The medium continuously moves downward past the louver openings to keep them from plugging and to prevent formation of a filter cake. The particulate-laden medium is removed from the bottom of the filter, cleaned, and recycled by means of an elevator to the top of the filter.

Mechanisms of Filtration

The mechanisms by which granular bed filters remove particulates from gas streams depend on the operating parameters. The filtering action can approach that of fabric filters under some conditions, in that a filter cake can form on the outer layers of the granules. However, the accompanying pressure drop across the filter bed can be large and the energy required for a reasonable gas flow will be high.[117-119]

Figure 3.13 shows the pressure drop across a laboratory-scale granular-bed filter plotted against particulate loading for two sizes of granules, 3 mm and 1.5 mm. Also plotted on the same figure are the pressure drops for two glass-fiber filters. Figure 3.14 shows the corresponding collection efficiencies. It is apparent from these data that fabric filters give lower pressure drop when operated under conditions where a filter cake is allowed to form. At 4.5 in. WG, typical for fabric filters, this is true for the 1.5 mm granular bed but not for the 30 mm granular bed. For most industrial installations, granule size, inlet dust burdens, and cleaning cycles

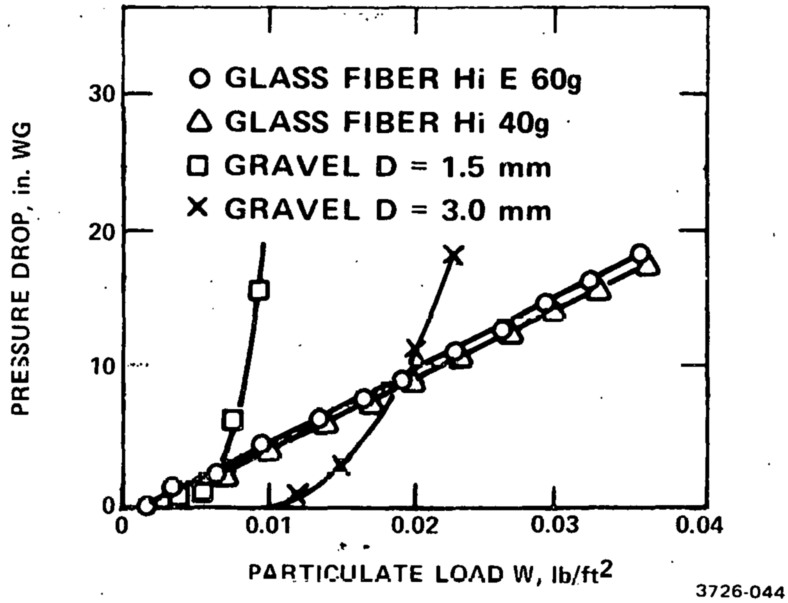

Figure 3.13 Pressure drop as a function of particulate loading for granular-bed filters with two different granule sizes as compared with pressure drop for glass fibers.[118]

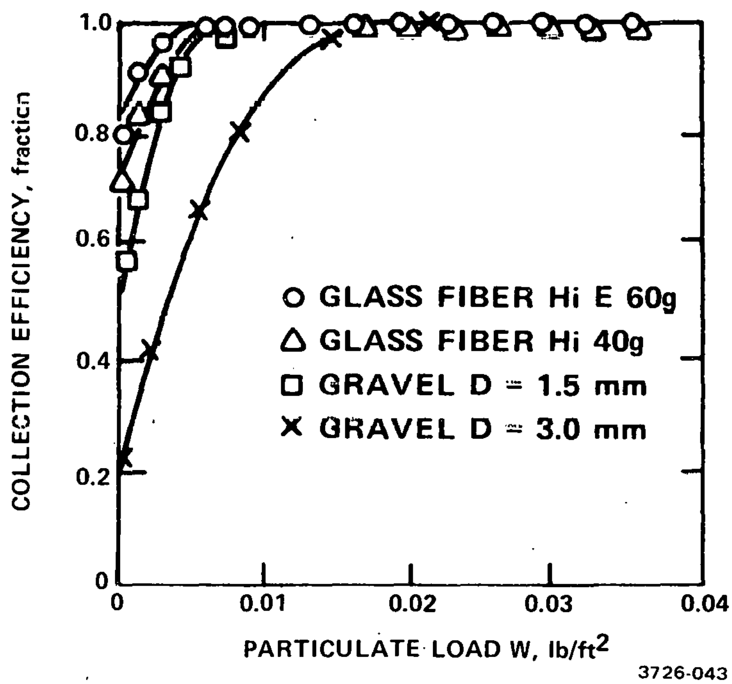

Figure 3.14 Efficiency as a function of particulate loading for granular-bed filters with two different granule sizes as compared with glass fibers.[118]

are selected to minimize the pressure drop so that a filter cake in the sense of conventional fabric filter performance does not form.

The collection mechanisms active in granular bed filtration are primarily diffusion, interception, and impaction. The contribution to the overall efficiency by each of these mechanisms depends upon the particle size of the dust being collected and the operating parameters of the filter.

Diffusion

Diffusion to the granules is governed by the Brownian motion of the particles, the dimensions of the intergranule space, and the residence time. The difficulty in theoretically predicting diffusional collection lies primarily in determining the dimensions of the intergranular spaces and the flow rates in these regions. Several attempts have been made to model the collection efficiency by diffusion for monodisperse aerosols. One of the most successful models for collection in a granular bed that includes diffusion, sedimentation, and impaction was developed by Bohn and Jordan.[119] Experimental studies were conducted of the collection of sodium oxide aerosols in a filter bed with varying granule sizes. Figure 3.15 shows experimental data and predicted values of penetration of 1.4 μm diameter particles as a function of flow velocity. The data show that diffusional collection decreases with increased flow velocity and becomes insignificant for velocities above 1 in./sec. Since most commercial filters operate in the vicinity of 20 in./sec gas flow, collection of particles of 1.4 μm by diffusion could be neglected. However, for much smaller particles diffusion could still be significant.

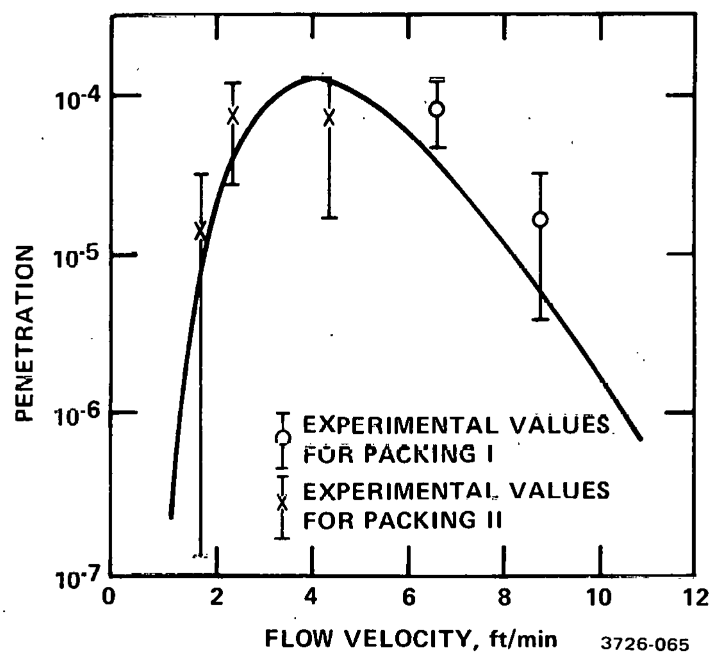

Figure 3.15 Penetration of sodium oxide aerosols as a function of flow velocity; packing I is a relatively more permeable packing of sand layers for flow velocities of 1-2 in./sec (32-80 ft^3/min); packing II is a less permeable packing obtained by adding a thin layer of very fine graded sand for flow velocities of 0-1 in./sec (32 ft^3/min).[119]

Impaction

Inertial impaction is one of the primary mechanisms for collection of particles in granular bed filters. The spaces between granules present a tortuous path for the dust-laden gas which the larger particles cannot follow. They are therefore separated from the gas stream and impinge on the filter medium. Within the filter bed, the gas flow through the intergranular spaces reaches much higher velocities than the average. Also particles downstream divert the gas stream, so that the larger particles impinge upon the granules and are held by molecular or mechanical forces. As particles are deposited, the spacing is reduced so that the gas velocities are higher. Consequently, smaller particles are collected by impaction. The process continues until the dust is removed from the filter medium.

The separation of particles from a gas stream by impingement is dependent upon the size and density of the particles, the velocity of the gas stream, and the properties and flow pattern of the gas. These parameters determine the probability of collection within each layer of the filter. With a multiplicity of layers, the overall collection efficiency is increased by the number of opportunities for impact and hence the collection efficiency increases with increasing thickness of the filter bed.

Interception

The collection of dust by interception is also related to gas flow. Figure 3.16 illustrates particle capture by interception. In this mode, particles follow the streamlines around a granule. However, if the particle passes within a distance equal to its radius, it will impinge on the granule and be collected. The major difference between the two modes

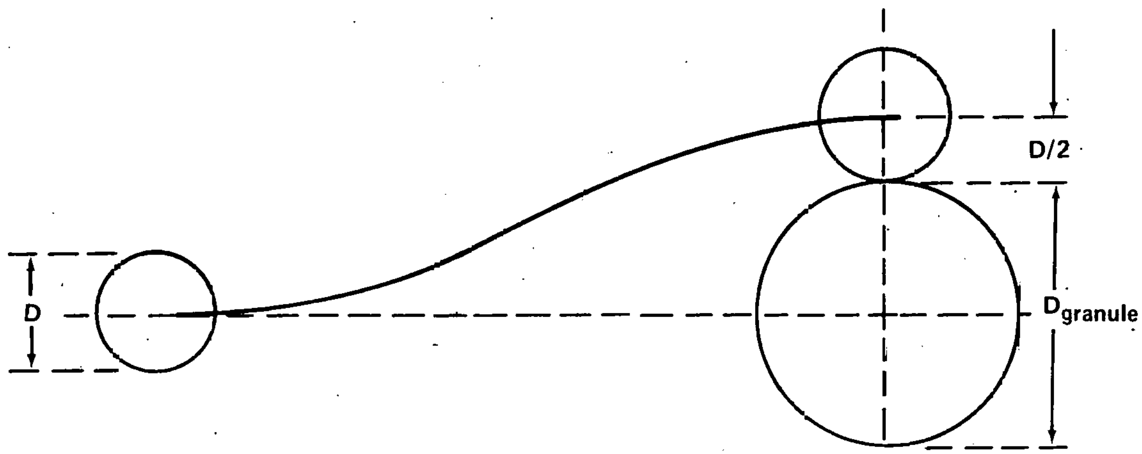

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Figure 3.16 Direct interception; path of particle center coincident with path of airstream.

of collection is in the behavior of the particles, whether they follow the streamlines of the gas flow or as the result of their inertia do not follow it.

Many studies have been conducted on the fundamental relationships of particle capture by the mechanisms of inertial impaction, interception, diffusion and combinations of these mechanisms. However, verification of the various theories has not included work with full-scale granular bed filters. The theoretical studies do indicate the important parameters and are useful in showing trends, even though they cannot predict absolute efficiencies in full scale systems. In practical granular-bed systems, design is a compromise between the various parameters. To achieve a reasonable compromise between size and capacity, velocities in the vicinity of 100 ft/min are used in full-sized filters.

Test Results

Test data for granular-bed filters is limited because of the small number of installations relative to the number of the more conventional particulate control devices. However, data are available for several installations collecting dust from bark boilers in the forest products industry, lime kilns, and clinker coolers. Table 3.2 is a compilation of the data available from the literature.

Quantitative relationships derived from the field test data available on full-scale units do not confirm the effects of gas velocity, pressure drop or other parameters on collection efficiency suggested by theory. This is probably due to variations in other factors, such as particle size of

Table 3.2 Summary of Granular Bed Filter Test Data

	Granule size	Pressure drop, in. WG[a]	Inlet dust loading, gr/dscf	Outlet dust loading, gr/dscf	Collection efficiency, %	Notes
Combustion Power Dry Scrubber[c]						
Bark Boiler	1/4 x 1/8 in.	7.6	0.74	0.08	89	Av of 2 tests
Bark Boiler	6-8 mesh	10.7	0.71	0.05	93	Av of 2 tests
Lime Kiln	6-8 mesh	7.4	3.89	0.17	96	
Bark Boiler	6-8 mesh	11.4	0.15	0.02	86	Av of 2 tests
Bark Boiler	1/4 x 1/8 in.	3.6	0.201	0.038	81	Av of 4 tests
Bark Boiler	-[b]	5.2	0.14	0.008	94	Av of 8 tests
Bark Boiler	-[b]	9.6	0.41	0.06	85	Av of 3 tests
Bark Boiler	-[b]	13	0.33	0.05	87	Av of 4 tests
Rexnord Filter[d]						
Clinker Cooler	6 mesh	10	1.13	0.029	97	Av of 5 tests

a. design value

b. not reported

c. reference 116

d. reference 115, gas flow 8342 acfm per module; bed depth 4.5 in.

the dust, concentration, or other parameters in the various tests. Laboratory tests, on the other hand, do indicate the change in efficiency with changes in the factors that influence diffusion in very low velocity systems or impaction in high velocity systems.

Field test data do show an extreme dependence of efficiency on particle size of the inlet dust. Systems that include mechanical collectors preceding a granular-bed filter operate in an efficiency range of 80-90%. The particle size of the inlet dust in such systems is probably around 5 μm mass mean diameter. Systems such as clinker coolers that produce dust in the range of 50 to 100 μm mass mean diameter have collection efficiencies of around 99%.

Fractional collection efficiency measurements on a fixed-bed filter have included some anomalous results, indicating that the filter generates dust in the small particle-size range by mechanical abrasion of the filter medium.

Granular bed filters appear to offer few advantages over fabric filters for collection of small particles such as fly ash from coal or oil-fired boilers. For larger particles, where inertial forces are significant, granular bed filters can be effectively utilized. The principle advantage of granular bed filters is their potential for withstanding a high-temperature, high pressure environment. The filter would be capable of operation at flue-gas temperatures above the present capabilities of fabric filters and would not be damaged by brief high-temperature excursions.

Some applications of granular filters to removal of very small particles have been studied where the length of the filter would offer advantages in diffusional collection of hazardous materials.

A systems study of granular bed filters, sponsored by the EPA, is being performed at present, as is the evaluation of a venturi design for a dry scrubber with a moving granular bed.[120]

3.5.4 Other Devices

The ELECTRO-TUBE, developed by Air Pollution Systems, is an electrostatic particle collector which combines a wetted wall electrostatic precipitator with precharging of the particles.

Evaluation of a pilot-scale ELECTRO-TUBE in the collection of titanium dioxide as a test aerosol indicates that the device may have the same collection efficiency as a conventional wet electrostatic precipitator, but with somewhat less power consumption.[121]

The APITRON (American Precision Industries, Inc.) combines electrostatic charging and fabric filtration. One form that is being tested is a vertical concentric cylindrical design, with the dust-laden gas entering the center of the cylinder, in which there is an axial wire corona electrode, negatively charged. The gas flows through a concentric coarse screen that is positively charged and then through a filter bag, on which the dust is deposited and from which it is recovered by mechanical means.[114]

A recent exploratory investigation of high-gradient magnetic separation on a laboratory scale indicates that it is worth further study for cleaning metallurgical exhaust gases. The experiments were conducted with a laboratory apparatus containing a filter bed of steel wool 8 in. in length and 3.5 in. in diameter. Dust that had been collected by an electrostatic precipitator from the exhaust gas of a basic oxygen furnace was redispersed in air for use as the test dust. The dust-laden air was passed through the steel wool filter to which a magnetic field (3 kilogauss) was applied.

The gas velocity was 1000-2000 ft/min and the pressure drop across the filter was 2-12 in. WG; these values are within the limits considered competitive with other collectors.[122]

The Environmental Protection Agency supports research at Battelle Northwest on the collection of electrically charged sub-micron water droplets (also charged solid particles) on uncharged (polypropylene or stainless steel) fibers.[123,124]

More information is needed on the effect of electric fields on fabric filters under industrial conditions of high dust loadings before any conclusion can be drawn about the feasibility of using electric fields for gas cleaning.

3.6 PARTICULATE CONTROL DEVICES FOR HIGH TEMPERATURE AND HIGH PRESSURE OPERATION

The need for removal of particulates from gas streams at high temperatures and pressures stems from the interest in combined cycle systems which utilize both gas and steam turbines. Such combined cycle systems have the potential of considerable improvement in the efficiency of fuel utilization.

Combined cycle systems are currently under investigation in two areas: (1) a fluidized bed combustion system in which the fuel is completely burned and the hot gases used to drive a gas turbine and to generate steam to drive a steam turbine; (2) a high temperature-high pressure gasifier that produces a clean fuel to power a gas turbine followed by a heat recovery steam generator and steam turbine.

Both the fluidized bed combustors and fluidized bed gasifiers have the potential of sulfur oxide removal as a part of the process to eliminate problems of flue gas desulfurization that are inherent in present power generating practice.

The potential efficiency obtainable coupled with the possibility of sulfur oxide removal are the major reasons for the interest in combined cycle systems.

The major problems with combined cycle systems are associated with corrosion or erosion of the gas turbine. Limits must be placed on the concentrations of sodium, potassium, vanadium, and lead in the flue gases to prevent excessive rates of hot corrosion or fouling of the turbine components. The limits of alkali metal compounds to insure reasonable turbine life are reported to be extremely stringent (40 parts per billion).[125] These maximum concentrations impose limits of temperature and fuel processing to insure that the alkali metals are retained in the particulate matter.

Particulate matter must be removed to prevent erosion of the turbine components. Erosion is primarily due to the impact of particles in the high velocity region of the turbine. The kinetic energy due to the impact of large particles can cause mechanical failure of the turbine components or rupture of the surface of coatings.

3.6.1 *Turbine Requirements*

In order to establish the requirements of the hot gas clean-up system, limits should be established for the maximum allowable dust concentration entering the turbine. This concentration should also be related to the particle size of the inlet dust, since it is well established that the turbine tolerance to particulate matter is greater for fine particles than for large ones.

A review of the literature shows that there is a lack of definitive data on the maximum permissible dust loading. The maximum concentration in the various particle size bands varies with flow conditions and velocities within the turbine, which can vary with turbine design. Based on a theoretical analysis, a maximum concentration of 0.001 to 0.002 gr/scf has been projected for particles within the 2-5 μm diameter size range.[125] Essentially no particles larger than 5 μm should be allowable, but relatively low collection efficiencies would be permitted for removal of particles below around 2 μm.

The inlet dust loadings and size distributions in the effluents from various fluid-bed combustion and gasification systems have likewise not been firmly established. Therefore, only approximate requirements can be made in terms of dust control equipment collection efficiencies. One estimate of the particulate emissions from a multiple fluid-bed gasifier indicates that 8% of the total emissions of 20 gr/scf is projected to be within the 2-5 μm size range. Assuming an outlet concentration of 0.001 gr/scf, the efficiency of removal of particles in this size band would be 99.94%.

3.6.2 *High-Temperature Particulate Collection Systems*

Processes for removal of particulates from hot gas streams have been reviewed in a study sponsored by the Environmental Protection Agency.[126] Particulate removal systems investigated included cyclones, granular bed filters, electrostatic precipitators, molten salt scrubbers, and metal fabric filters. Studies of the effects of temperature on the mechanisms of particle collection have been made by a number of investigators.[127-133] The following sections describe the influence of temperature and pressure on the collection mechanisms as they relate to the various control devices.

Cyclones

Cyclones, which are widely used for removing dusts from industrial gases, operate by imparting a centrifugal force to a dust-laden gas stream. Typically, a cyclone is constructed of a vertical cylinder with a conical lower section. The gas stream enters the upper part of the cylinder tangentially and forms a vortex. The gas stream flows in a spiral down the wall of the cone; near the bottom it reverses direction and flows up a central exit duct, with the dust falling to the bottom of the cone.

Cyclones are relatively simple devices with no moving parts, their performance is well established, and they are relatively trouble-free in operation.

The efficiency of cyclone collectors is dependent upon the cyclone dimensions and the gas and particle characteristics. The critical parameter as far as temperature and pressure effects are concerned is gas viscosity. Equations developed by Leith and Mehta[134] show that the inertial parameter Ψ in the efficiency equation $\eta = 1 - \exp\left[-2C\Psi\left(\frac{1}{2n+2}\right)\right]$ is inversely proportional to the gas viscosity. Since increasing temperature and pressure increase gas viscosity, the effect would be a decrease in collection efficiency.

Figure 3.17 shows the collection efficiency as a function of particle size for a cyclone operating at 20°C and at 1100°C at 1 atmosphere and at 15 atmospheres pressure and the same inlet velocity. The data were computed on the basis of the efficiency equations developed by Leith and Licht[135] with gas viscosities corresponding to the temperature and pressure shown.[127]

Power requirements for a cyclone also increase with increasing temperature and pressure, as shown in Figure 3.18. The curve shows the specific power ratio required for a given collection efficiency as a function of temperature for various particle sizes at pressures of 1 and 10 atmospheres.[127]

Referring to Figure 3.17, it is apparent that the collection efficiency of a cyclone decreases rapidly for particles below around 10 μm in diameter and is much lower than would be required in a primary gas clean-up system. However, in combination with other devices, cyclones are proposed to reduce the inlet dust loading to the primary clean-up system, if it is sensitive to inlet dust concentration.

Electrostatic Precipitators

The effect of temperature and pressure on electrostatic precipitator performance is twofold. First, the voltage-current

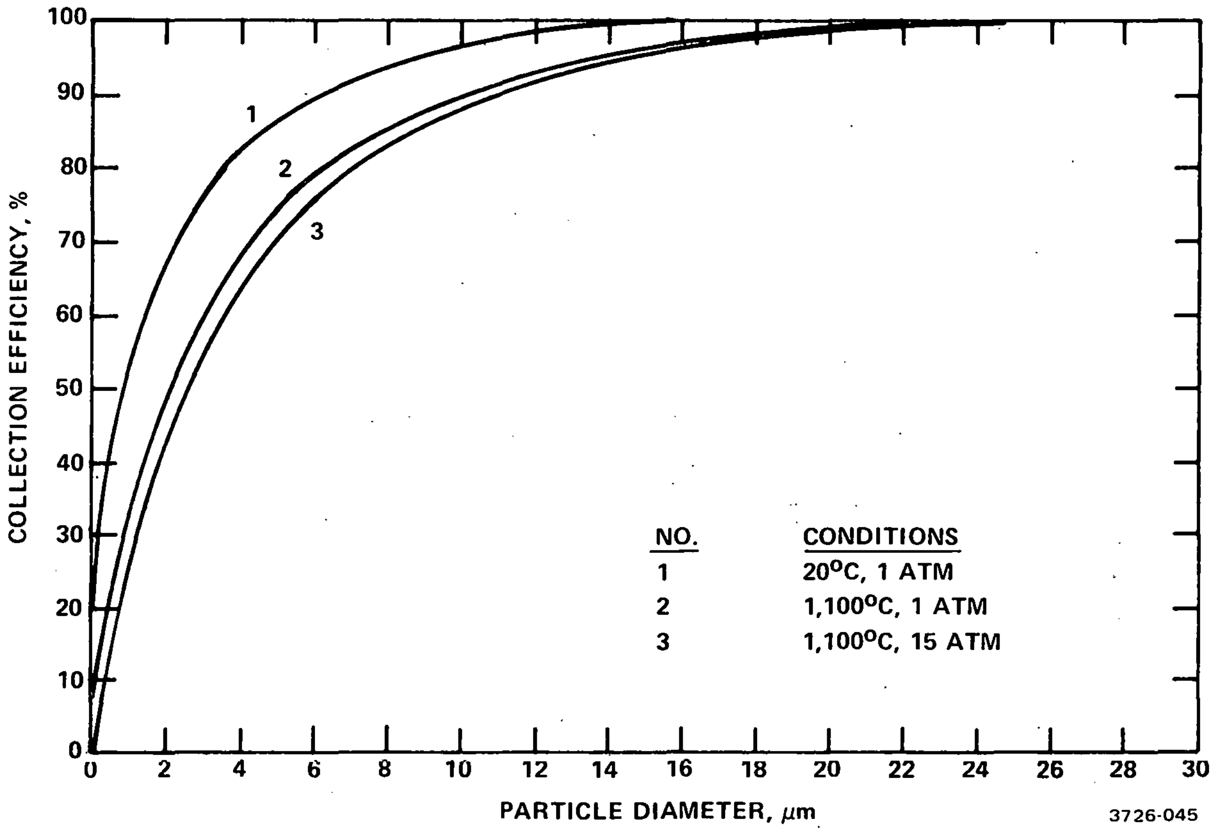

Figure 3.17 Effects of high temperature and pressure on the collection efficiency of a high-efficiency cyclone.[127]

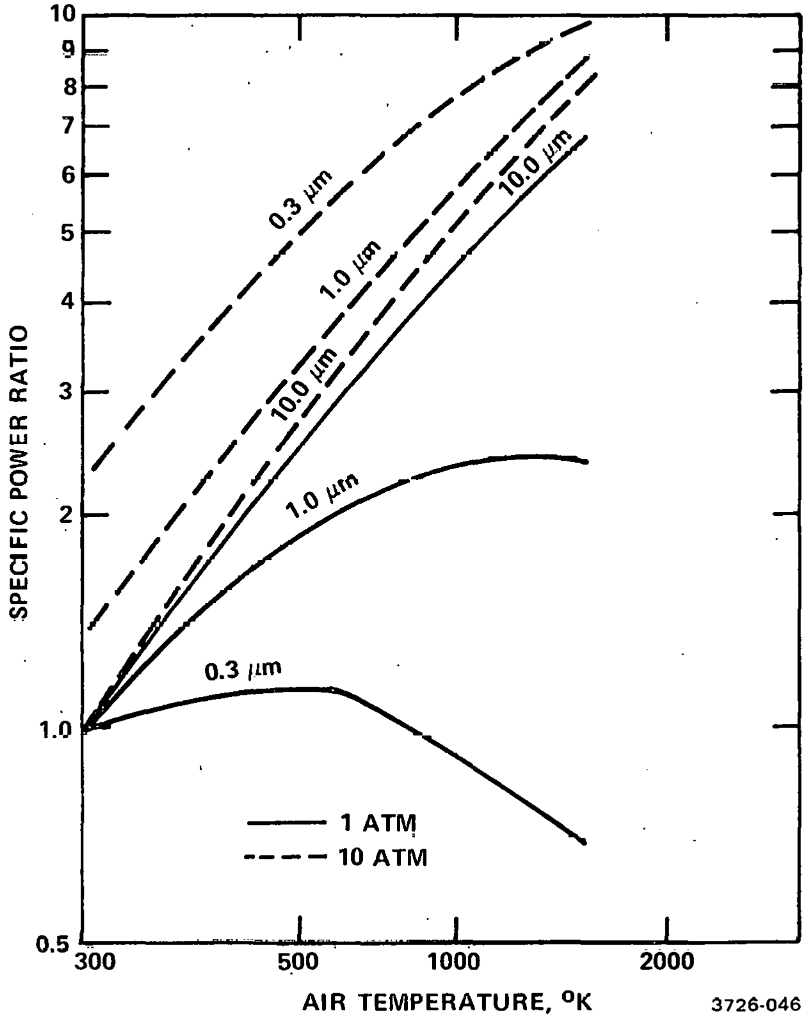

Figure 3.18 Specific power requirements for a cyclone as a function of temperature and pressure.[127]

characteristics are altered by virtue of a change in gas density. Increasing temperatures reduce gas densities, whereas increasing pressures increase gas densities, so that the effects of increasing both temperature and pressure tend to be off-setting. A reduced gas density reduces the corona threshold voltage, because the increased mean free path permits electrons to achieve a higher velocity between collisions for a given electric field strength. A second effect of reduced gas density is an increase in the apparent mobility of the charge carriers. Because of the decreased density, electrons from the corona penetrate further into the interelectrode region before attachment to form ions and ions penetrate further prior to attachment to dust particles. Since the mobilities of electrons and ions are orders of magnitude higher than the mobilities of charged particles, the average mobilities will be effectively increased. This mobility change will cause an increased slope of the voltage-current curve. The result is a narrower range between the corona onset and sparkover voltages so that control is more difficult. A third effect of reduced gas density is a reduction of the sparkover voltage, so a precipitator would operate at a lower electric field for charging and collection.

The effects of reduced gas density can be partially overcome by reversing the polarity and utilizing a positive rather than a negative corona.

Increases in gas temperature and pressure influence precipitator performance also by reducing the migration or drift velocity. The increase in gas viscosity associated with increases in both temperature and pressure cause the aerodynamic drag forces to increase. The migration velocity is inversely proportional to the gas viscosity so that an increase of from 500°K to 800°K in gas temperature would cause about a 40% decrease in migration velocity.

Studies of precipitators for the cleaning of high temperature and pressure gases were conducted by Shale[132,133] and

Brown and Walker.[129] Shale reported an efficiency of 99.9% at 650°F and 65 psig with an inlet dust concentration of 1.5 gr/ft^3, in a pilot scale wire-tube type precipitator. Brown and Walker showed efficiencies of around 90% for a pilot wire-pipe type precipitator with a plate area/gas volume ratio of 134 ft^2/1000 cfm at 1650°F and 115 psia.

The status of electrostatic precipitators for clean-up of hot gases is still unknown, since all of the work to date has been on small pilot-scale units. Scale-up to sizes required for large-size power generation equipment would result in poorer performance than in pilot-size units. The major problems in full-size units would perhaps be mechanical. The physical size of a precipitator to operate at temperatures of 1500°F or over and efficiencies of 99.5% or above would be quite large. The design of the shell to withstand the pressure at that temperature and to maintain electrode alignment is a problem that has not yet been solved.

Research in the area of hot gas clean-up with electrostatic precipitators is continuing under sponsorship of the Environmental Protection Agency.

Granular Bed Filters

The efficiency of collection of particles by granular bed filters is influenced by the temperature and pressure of the gases as they alter the collection mechanisms. Inertial impaction depends upon the particle separation from a gas stream which is diverted around a collecting body. The efficiency of collection by impaction is a function of the particle mass, velocity, the resistance of the gas to particle motion, and the frontal diameter of the collecting body. The resistance of the gas to particle motion increases with increasing temperature for relatively large particles due to the increase in gas viscosity. Increases in pressure would have a similar influence on viscosity and hence a reduction in collection efficiency of large particles would be expected with increase in pressure.

Collection of small particles, on the other hand, would be enhanced by increasing temperature, as a result of the increased Brownian motion.

Data on the performance of granular bed filters for operation at temperatures usable for clean-up of gases to turbines in combined cycles is very limited. Combustion Power Company has operated a granular bed filter on a pilot-scale combined-cycle system for a short period.[116] The program involves fluidized bed combustion of refuse supplemented with coal. Initial trials resulted in a build up of material on the turbine blades. Catastrophic failure of the internal support members was experienced during the only trial at 1800°F. This resulted in delays and reevaluations of the program and no efficiency data are available at the elevated temperatures. The fluidized bed system has been modified and the program resumed.

The Combustion Power granular bed system for high-temperature operation is similar in overall concept to that used for low-temperature particulate collection except for the design of the louvers, the granules, and the materials of construction. The granules used in the Combustion Power System are aluminum spheres about 1/16 in. in diameter, which are available at a cost of around $1.00/lb. The louvers are arranged so that the granules clear them of dust as the granules migrate toward the bottom of the system.

Results of the evaluation of the Combustion Power granular bed filter will not be available until completion of the present program.

The Squires Panel Bed Filter has had limited trials at 900°F. The filter unit was a 3 in. x 1 ft section installed on a pilot fluidized bed combustor. Test data were highly variable and the results of the test program were inconclusive.

The concept of the Squires filter is that a filter cake is allowed to form much the same as in a fabric filter. The filtering action is therefore dependent on the filter cake, which is supported by the granules, and not on the granules themselves. The concept should permit high collection efficiencies, but at the expense of relatively high pressure drops. At the 300°F test temperature, pressure drops of around 8 in. water gauge were measured.[136]

The future of panel bed filters for high temperature (above 1500°F) application remains uncertain. For combined cycle operation, the evidence is that efficiencies must be very high in order to prevent damage to turbine blades. On the other hand, the pressure drop must be kept sufficiently low to prevent energy losses in the gas clean-up system from canceling the efficiency advantage of the combined cycle approach.

A fourth concept for hot gas clean-up is the use of high-temperature filtration by either a metal fabric or a ceramic medium. Limited test data have been reported on a Brunsmet metal fabric developed by Brunswick Corporation. Plans have been made for further tests of the Brunsmet filter in the EPRI facility at the Arapahoe Station of Public Service Company of Colorado in Denver, but the temperature available in the test facility will be no higher than about 900°F.[85]

4. SAMPLING AND MEASUREMENT TECHNIQUES

The data required for determining the efficiency of control devices in collecting fly ash is obtained by sampling flue gas and measuring the physical and chemical properties of the ash. Only within the past few years have adequate sampling and analytical techniques become available, and even these techniques are continually being evaluated and improved. There is still no complete agreement among those who use the techniques with regard to the interpretation of some of the results.

The relevant techniques are those used to measure the mass and particle-size distribution of fly ash collected by sampling the flue gas upstream and downstream of the pollution control device. In the methods used at present, mass is measured by weighing. The particle-sizing techniques employ inertial impaction, light scattering, diffusion, and electrical mobility of the particles for their characterization.[137] The applicability of these techniques and some of the problems involved in their use on the effluent gas streams from industrial processes are discussed below, as are some improved techniques under development by the Environmental Protection Agency and others.

4.1 PARTICULATE MASS CONCENTRATION

Mass concentrations of particulate matter in flue gas are measured by drawing a sample of gas through a probe and filter and weighing the collected material. This is the basis of EPA

Method 5, the manual test method that is used in determining compliance with Federal regulations.[138] There is some difference of opinion as to how the results should be interpreted, especially with regard to condensation of vapors in the probe and filter box. Some investigators making performance tests of control devices on emission sources prefer to use a sampling train that differs from that used in Method 5 in that the filter for trapping particulate matter is located in the stack instead of outside the stack at the end of the sampling probe (proposed Method 17).[139] Thus, condensation of vapors in the probe and filter box is avoided. Another advantage of the alternative system is that the particles are trapped before they enter the probe, from which they may not be adequately recovered despite the probe washing procedure specified in Method 5.

There is a need for improved techniques for sampling particulate matter in flue gas downstream from wet scrubbers. Problems are encountered due to the presence of acid mist and the water-saturated condition of the flue gas.[140]

The only instrumental method that is regularly used for continuous measurement or monitoring of mass emissions is the opacity monitor or light transmissometer, which is commercially available, and which has been demonstrated to be usable in power plant stacks. Opacity is only an indirect measure of mass and must be related to it empirically for any specific installation.[141,142]

Other methods that are being considered for monitoring mass emissions include the following, which are mostly still in the development stage:[143,144]

Light scattering by suspended particles. Designs for measuring forward scattering that have been investigated so far require rather complicated optics. Instrumentation that measures back-scattered light in-stack is already commercially available. The light source is a light-emitting diode incorporated into a probe inserted into the stack.

Deposition of electric charge on an electrometer sensor by impinging particles (the triboelectric effect). This technique has been used both in-stack and on extracted samples. Better results are obtained on sources that emit particles relatively uniform in size and charge. Probe losses have been a problem. Some instruments using this approach are already on the market.

Attenuation of beta radiation by deposited particulate matter. This technique requires an extractive system in which some kind of filter is used to collect the sample. The equipment that has been used so far for interfacing with the flue gas is mechanically complicated and requires excessive maintenance. Probe losses have also been a problem.

Change in vibrational frequency of a quartz crystal on deposition of particles (piezoelectric microbalance). This method is subject to probe losses and loss of sample by particles not adhering to the surface after deposition. It is subject to interference from gas and moisture. Commercial devices based on this method have been used for monitoring low concentrations of particles in ambient air, but the applicability of the method for monitoring stack gases remains to be demonstrated.

4.2 PARTICLE SIZE AND SIZE DISTRIBUTION

These techniques may be classed according to the physical mechanism that is used to obtain the data: inertial, optical, diffusional, and electrical. In their present state of development, instruments employing these techniques are used to complement each other in covering the particle-size range below 10 μm. Inertial devices are used for the larger particle sizes (>0.5 μm). They include cascade impactors and cyclones.

Diffusional and electrical instruments are best suited for the smaller sizes (<0.3 μm), and optical counting equipment is applicable for intermediate sizes.[145-147]

Cascade Impactors

The particle-size distribution of a suspended dust can be determined by utilizing its inertial properties in a cascade impactor, with which particles can be classified by size over the range from about 0.5 to 10 μm in diameter. In a cascade impactor, the gas stream passes through a series of impactor jet-impingement plate combinations. Material passing the last impaction stage is caught on an after-filter. After sampling for an appropriate length of time, the catch of material on each stage is weighed.

In order to use a cascade impactor for measuring particulate size distributions, the cut point (the aerodynamic particle diameter for which half the particles passing the stage will be collected and half will pass on to the next stage) is determined by calibration for each stage in the impactor.

A wide variety of cascade impactors has been developed for use in industrial source sampling. To accommodate high and low mass loading situations, these units range in flow rate from 1 ft^3/min to 0.03 ft^3/min. The high flow rate impactors have up to 264 holes per stage, which permit reasonably low jet velocities. Other units, such as the 0.03 ft^3/min impactor, have only a single hole per stage. Some impactors use slot jets. Commercially available impactors have from ten to two stages. Some are designed so that stages can be removed or interchanged to allow for better resolution of a specific particle size distribution.

Some cascade impactors have been designed for use with precollector cyclones attached after the nozzle and prior to the first impactor stage. These cyclones remove the particles greater than about 10 μm in diameter and permit longer sampling times to be used by removing particles which would normally be caught on the upper impaction stages.

In most sampling situations the cascade impactor can be inserted directly into the duct or stack. This practice eliminates the probe losses that occur with mass sampling trains (*e.g.*, EPA Method 5). However, nozzle losses and internal losses of particulate mass can still lead to inaccurate mass loading calculations.

Probably the most serious problem associated with cascade impactors is the uncertainty of the weight of collected dust because of unstable collection substrates. The bare metal plate cannot be used as a collection surface because of poor particle retention due to particle bounce and reentrainment. The reentrainment of large particles will bias the size distribution toward the fine particle sizes. Two collection substrates are used to reduce this effect: a glass fiber mat or a thin film of grease. Neither is completely satisfactory, but the errors in weight can be reduced to tolerable levels by conditioning the substrate for several hours in the flue gas before use.[148]

Efforts are under way to develop inertial sizing devices with extended size ranges and automatic, real time, readouts of the particle size information; but to date, no such device has been used successfully in an industrial flue gas atmosphere.

It is possible to extend the sizing capability of a cascade impactor to sub-micron particles by operating the device at pressures of about 0.01 to 0.1 atm. Such an impactor has been designed for source sampling.[149,150]

Table 4.1 gives specifications for some instruments being considered for monitoring the particle-size distribution of emissions.[151]

The Environmental Protection Agency is supporting the development of a low pressure cascade virtual impactor (impaction into a dead air space) with a beta gauge readout. Another automatic readout mechanism which has been used with cascade impactors for real-time data analysis is the piezoelectric microbalance. However, beta gauges seem to be the most practical for readout because they do not have problems with overloading or electrical contact, and they need not be exposed directly to the hot gas stream. A prototype impactor with beta gauge readout has been completed and a miniaturized version is being developed for in-stack use.[151]

Cyclones

Small cyclone collectors are practical alternatives to cascade impactors for measuring particle-size distribution in gas streams. They have the advantage of being able to collect relatively large samples segregated by particle size. They are reliable devices which may be operated for long periods of time and over a wide range of flow rates without particle reentrainment. Unlike impactors, they do not use collection substrates that can interfere in the measurements. However, they are somewhat bulky and for in-stack measurements may require larger sampling ports than impactors.

The Environmental Protection Agency has developed a "Source Assessment Sampling System" for semiquantitative "level one" analyses of particulate effluents from stationary sources.[152] A schematic drawing of the train is shown in Figure 4.1. Because of the large sizes of cyclones required to achieve the desired

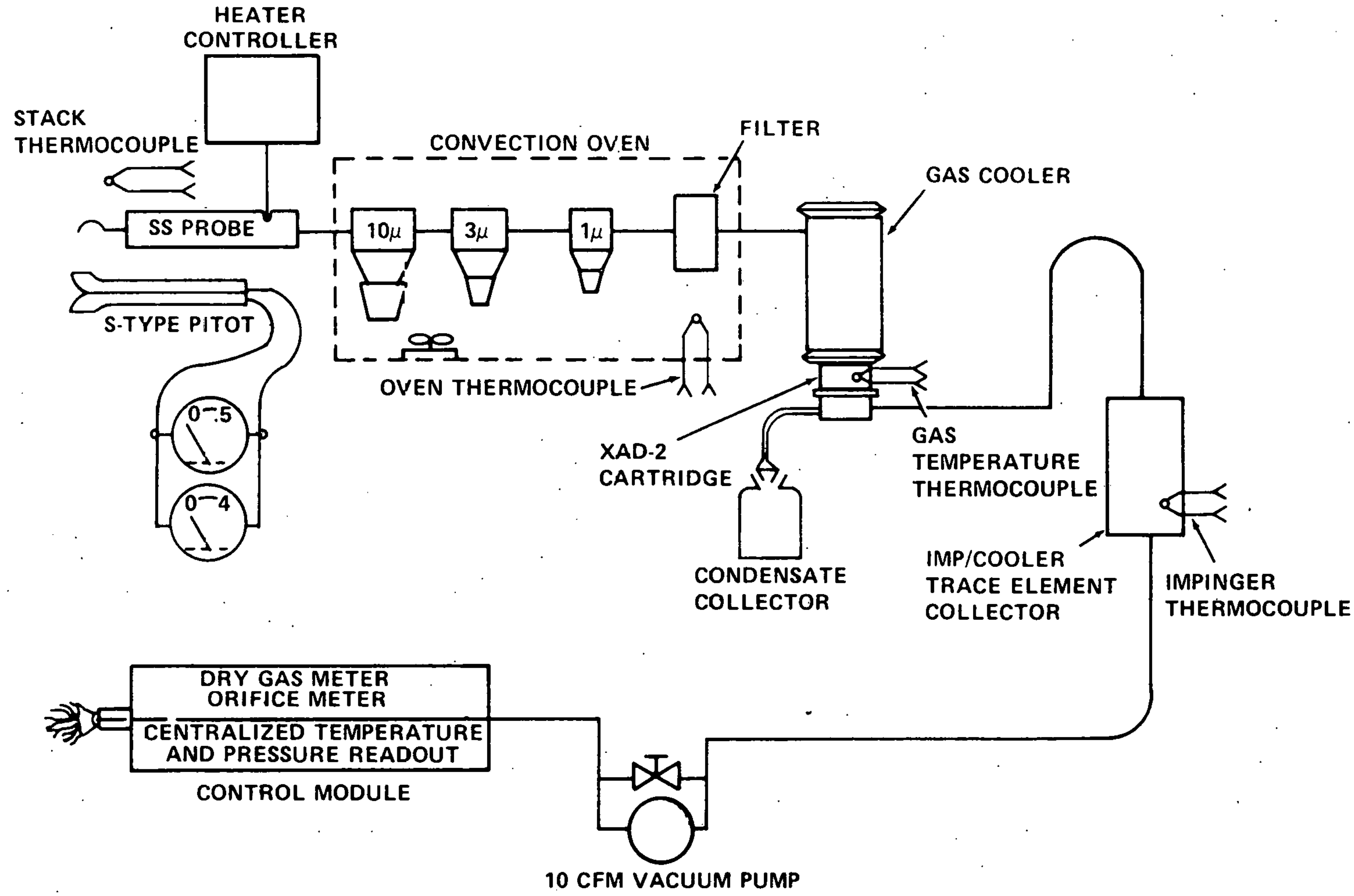

Figure 4.1 Schematic diagram of the source assessment sampling system.[152]

Table 4.1. Instruments for Monitoring Particle-Size Distribution of Emissions[151]

Instrument	Operating Principle	Size Range, μm (unit density)	Number of Size Intervals	Mass Concentration Range (g/m^3)	Instrument Flowrate (liters/min)	Data Rate
Brink Impactor	Manual impactor with cyclone	<0.4 to >14	9	0.1 to 6	1.4	manual
Andersen Impactor	Manual impactor with cyclone	<0.4 to >8.3	10	0.02 to 3	20	manual
Southern Research Institute Series Cyclone	Manual cyclone	<0.3 to >7.0	4	0.1 to 25	20	manual
Environmental Systems Corp. PILLS IV	Single particle dual angle light scattering	0.3 to 3.0	10	10^3 to 10^6[a]	NA	batch 5-15 min
GCA Beta Impactor	Impactor with beta detection of mass	0.3 to >6.5	7	0.3 to 20	9	real time
Celesco Piezo-electric Impactor	Impactor with piezoelectric detection of mass	0.09 to >35	10	50×10^{-6} to 0.08	0.2	batch 10-15 min
Environmental Research Corp. Impactor	Impactor with beta detection of mass	0.07 to 10	5	ambient to 0.15	283	real time

[a]particles/cm^3

cut points of 1, 3, and 10 μm at 400°F and at a flow rate of 4 ft^3/min, the cyclones are operated out of stack in an oven.[152]

A recent example of a cyclone system is the cluster of 5 cyclones operated in series, shown in Figure 4.2. The measured cut points under laboratory conditions are 0.32, 0.6, 1.3, 2.6, and 7.5 μm. The set is made of titanium for in-stack measurements.[147] Although design equations are available for cyclones in the sizes used for air pollution control, the design of the much smaller cyclones that are used for sampling gas streams is not a straightforward procedure. An adequate theory is not yet developed for predicting the cut points over the wide ranges of temperature, pressure, and gas flow rate that are encountered in sampling flue gas and other industrial effluents.

The design of the system shown in Figure 4.2 involved the combined use of theoretical equations,[135] comparison with previously calibrated prototypes, and extrapolation of dimensions from cyclones that had similar cut points. Figure 4.3 shows the calibration curves for the system.[153]

Optical Counters

Optical counters have not been used extensively in stack sampling. They cannot be applied directly to the effluent gas stream. The sample must be extracted, cooled, and diluted. The main advantage of optical counters is that with them emission fluctuations can be observed in real time. After extraction, the useful particle size range is approximately 0.3 to 1.5 μm. This size range overlaps the usable range of impaction, which presents fewer problems. In an optical counter, light is scattered by individual particles as they pass through a small viewing volume, the intensity of the scattered light being measured by a photodetector. The sizes of the particles determine the amplitude of the scattered light pulses, and the rate at which the pulses occur is related to the particle

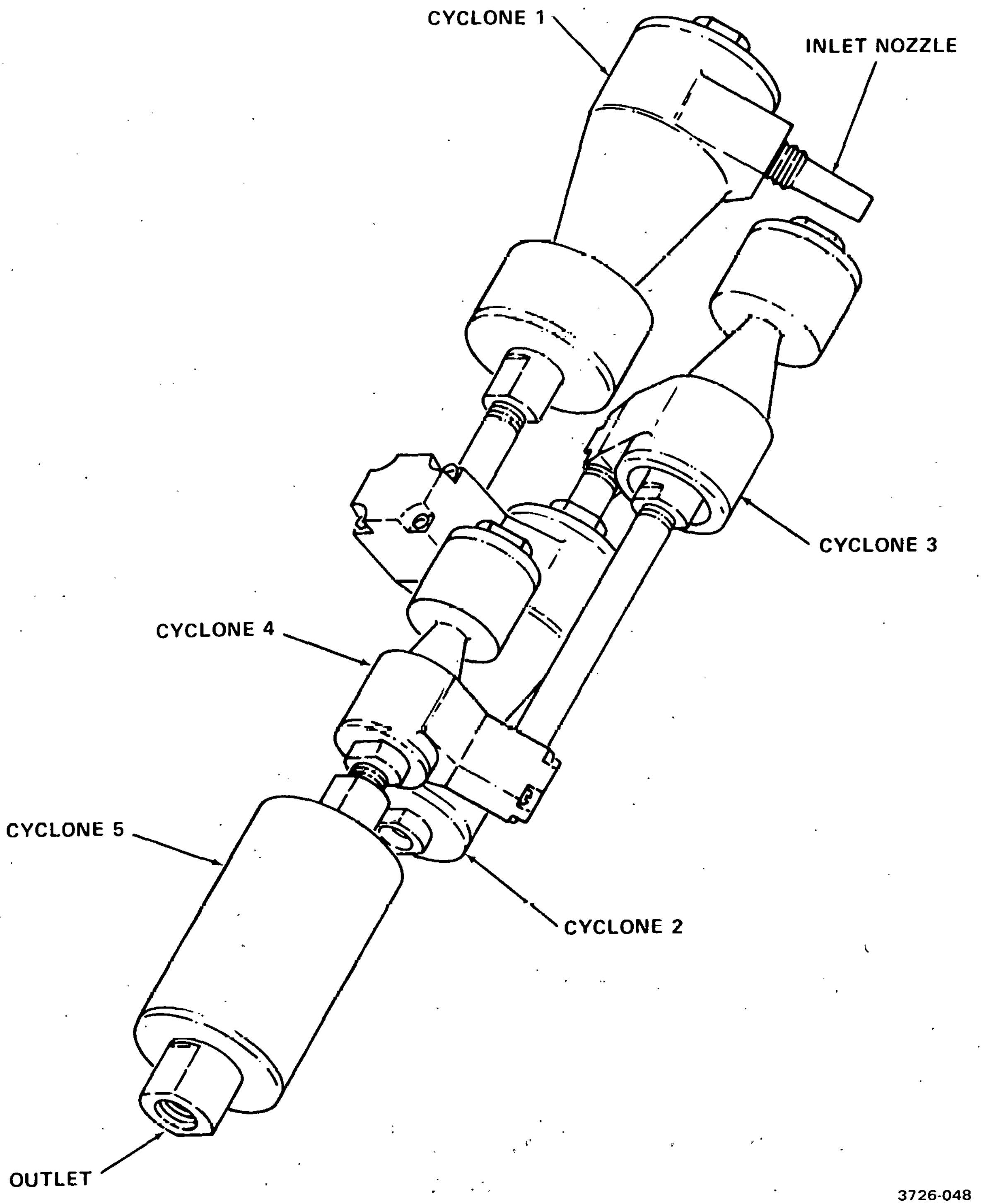

Figure 4.2 Southern Research Institute five series cyclone system.[17]

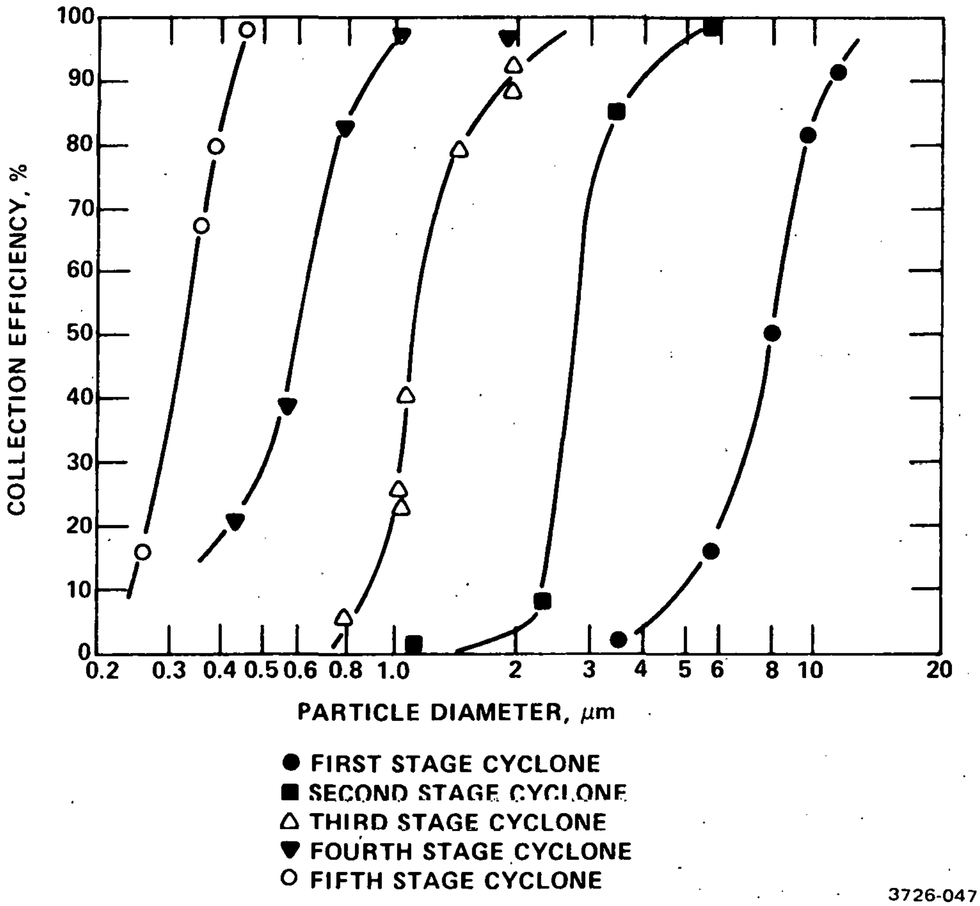

Figure 4.3 Laboratory calibration curves for the Southern Research Institute five series cyclone system. (Flow rate 1.0 ft^3/min; particle density 1.0 g/cm^3)[153]

concentration. Thus, a counter of this type gives both size and concentration information. The simultaneous presence of more than one particle in the viewing volume is interpreted by the counter as a larger single particle. To avoid errors arising from this effect, dilution to about 300 particles/cm^3 is generally necessary. Errors in counting rate also occur as a result of electronics deadtime and from statistical effects resulting from the presence of high concentrations of sub-countable (diameter < 0.3 μm) particles in the sample gas stream.[154] The intensity of the scattered light depends upon the viewing angle, particle index of refraction, particle optical absorptivity, and particle shape, in addition to particle size. The schematic drawing in Figure 4.4 shows a system which utilizes "integrated near forward" scattering. Different viewing angles might be chosen to optimize some aspect of the counter performance. For example, near forward scattering minimizes apparent variations in the indicated particle size which are actually due to changes in the index of refraction of the particle, but for this geometry, there is a severe loss of resolution for particle diameters near 1 μm. Right angle, or 90°, scattering smooths out the response curve, but the intensity is more dependent on the particle index of refraction.

Available geometries are:

Bausch & Lomb 40-1	Near forward scattering
Royco 220	Right angle scattering
Royco 245, 225	Near forward scattering
Climet CI-201, 208	Integrated near forward scattering

Single particle counters used with dilutors have been compared with impactors for making fractional efficiency measurements on particulate control devices. In general, agreement between the inertial and optical instruments is within about a factor of two in concentration for a given particle size.

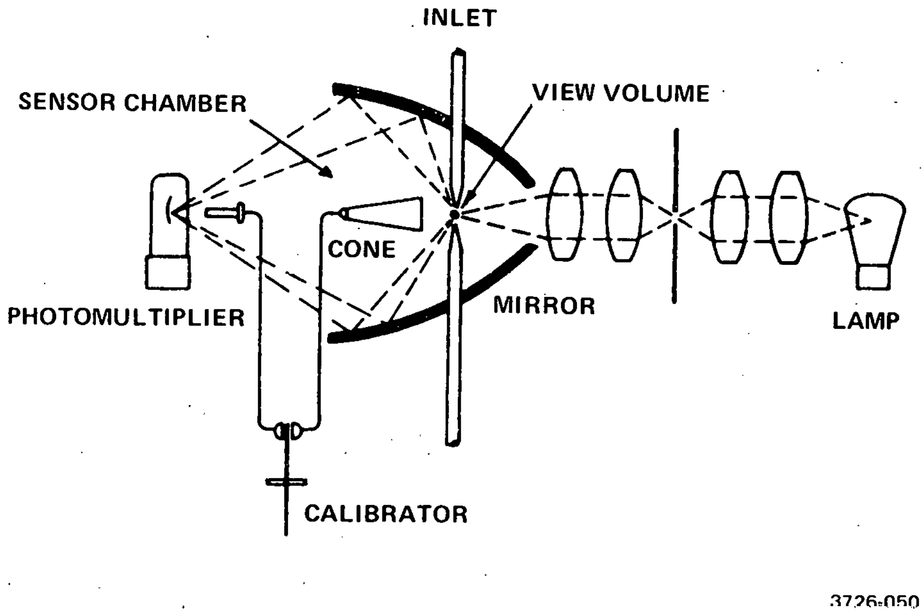

Figure 4.4 Operating principle for an optical particle counter (courtesy of Climet Instruments).

Current research is aimed at extending the concentration limits of optical particle counters, at minimizing problems due to the variation in the particulate index of refraction, and at improving the technique of using these devices for stack testing.

A suggested method for minimizing the effects of particle index of refraction in optical sizing measurements resulted from a study of the Fraunhofer diffraction formulation at small forward scattering angles.[155] The basis of this method involves measuring the intensity of light scattered by a single particle at two small scattering angles and the calculation of the ratio of these two intensities.

Prototype systems for particle sizing which are based on this concept have been developed.[156,157] One of these, the PILLS-IV instrument, is commercially available.[156] The intensities of scattered laser pulses at two small angles are normalized to a reference pulse for synchronization and to allow for fluctuations in intensity of the laser source.

The laser used in this system is a semiconductor junction diode (λ = 0.9 μm). The PILLS-IV can be used over the range of particle sizes of 0.2 to 3.0 μm. The view volume is stated to be approximately 2×10^{-7} cm^3. The upper concentration limit for single particle counters is determined by the requirement that the probability of more than one particle appearing in the view volume at a given time be much less than unity. For the PILLS-IV, this would set the concentration limit at approximately 10^6 particles/cm^3, a value much higher than those for conventional single particle counters.

Diffusion Batteries

The most widely used device for measuring the particle-size distribution of sub-micron aerosol particles is the diffusion battery, together with a condensation nuclei counter for measuring the concentrations of particles entering and leaving the diffusion battery.[158-164]

Diffusion batteries may be comprised of a number of long, narrow, parallel channels (Figure 4.5),[147] a cluster of small-bore tubes, or a series of screens (Figure 4.6).[161]

Variations in the length and number of channels (tubes or screens) and the gas flow rate are used as the means of measuring the number of particles in a selected size range. As the gas moves in streamline flow through the channels, the particles diffuse to the walls at a predictable rate, depending on the particle size and the diffusion battery geometry. It is assumed that every particle which reaches the battery wall will adhere; therefore, only a fraction of the influent particles will appear in the effluent of a battery. It is only necessary to measure the total number concentration of particles at the inlet and outlet of the diffusion battery under a number of conditions in order to calculate the particle-size distribution.

Mathematical expressions in series form for the extent of penetration by a monodisperse aerosol through a diffusion battery made with rectangular slots or parallel plates are available.[163]

When the Stokes diameter is used to describe particle size, the penetration of diffusion batteries is virtually independent of physical properties of the individual particles. The theory for diffusional sizing and data analysis is adequate, although the size resolution for the system is poor relative to other methods.

The parallel plate geometry is convenient because of ease of fabrication and the availability of suitable materials, and also because sedimentation can be ignored if the slots are vertical, while additional information can be gained through settling, if the slots are horizontal.

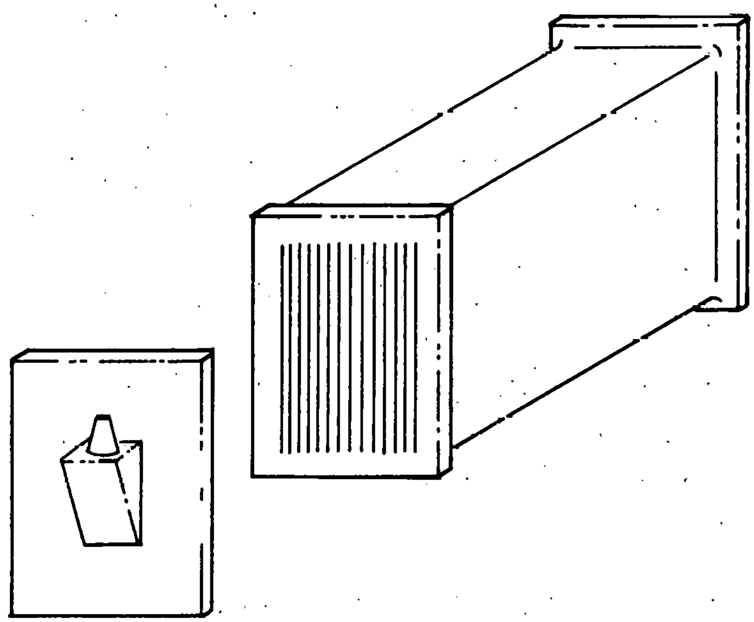

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Figure 4.5 Parallel plate diffusion battery.

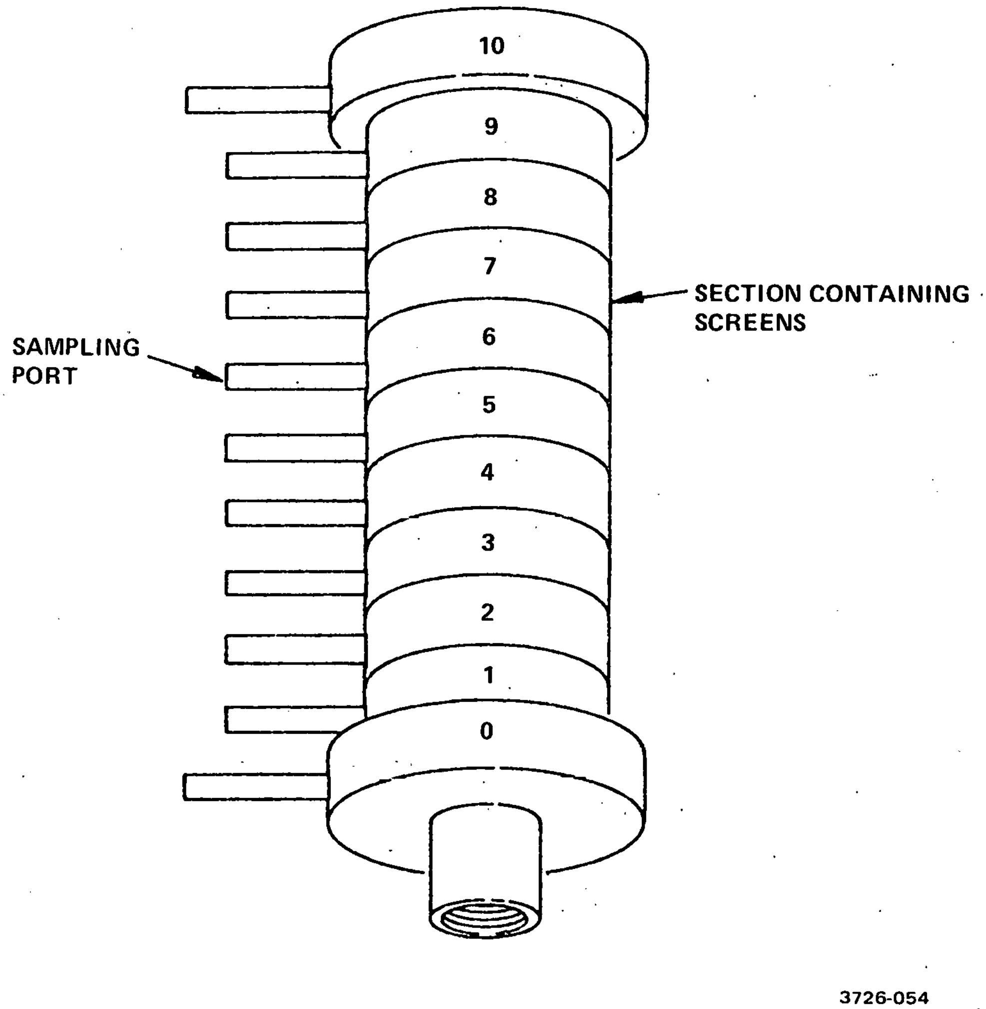

Figure 4.6 Screen type diffusion battery.

Disadvantages of this equipment are bulk and the long transport time through the battery required to measure a particle-size distribution.

When calculating the fraction of the particles which penetrate a series of diffusion batteries, the transport time for batteries must be taken into account. A complete measurement of a particle-size distribution may require 2-4 hours; thus, diffusional measurements are most applicable to stable sources where the particle-size distribution is constant in time.

Tube and screen arrangements, which are more compact than plate batteries, have been found to be suitable in laboratory studies,[161,162] Although the screen-type diffusion battery must be calibrated empirically, it offers convenience in cleaning and operation. Figure 4.6 shows the geometry. This apparatus is commercially available. The diffusion of aerosols in a battery with cylindrical tube geometry has recently been investigated.[165]

The particle-size distribution may be calculated from the data by means of a nomograph prepared using the theoretical penetration for each diffusion battery geometry and flow rate for a large number of monodisperse particle sizes and comparison of this nomograph with experimental penetration values.[160] Alternatively, it is sometimes convenient to use a cut point technique like that used for reduction of cascade impactor data.[147] Other methods have been described.[166-168]

Condensation Nuclei Counters

Condensation nuclei counters utilize the action of particles as nuclei for the condensation of water from a supersaturated vapor. This procedure is used for measurement of particles in the 0.002 to 0.3 μm range (condensation or Aitken nuclei). In most condensation nuclei counters, a sample is withdrawn from the gas stream, humidified, and brought to supersaturation by reducing the pressure. In this condition, condensation will be initiated on all particles larger than a certain critical size. The process forms a homogeneous aerosol, predominantly composed of the condensed vapor containing one drop for each original particle (condensation nucleus) with a size greater than the critical size appropriate to the degree of supersaturation obtained; a greater degree of supersaturation is used to initiate growth on smaller particles. The number of particles that are formed is estimated from the optical characteristics of the final aerosol.

Both manually operated and automated condensation nuclei counters are commercially available.[169-172] Condensation nuclei counters, like other aerosol sampling instruments, are designed for laboratory conditions. Minor modifications are usually required in the application of these instruments to sources when the particle concentration, or gas temperature and pressure, may not be within the normal operating ranges.

Electrical Mobility Analyzers

The electrical mobility analyzer is based on the concept that there is a unique charging rate for each particle size if the charging region is homogeneous with respect to space charge density and electric field.

Thus, if the particle charge and mobility are measured, the particle size can be calculated. These measurements can be made in the Electrical Aerosol Analyzer, which has recently become commercially available.[173,174] A schematic drawing of the analyzer is shown in Figure 4.7. It is used primarily on sub-micron particles, in the same range covered by condensation nuclei counters (0.002 to 0.3 μm).

The Electrical Aerosol Analyzer is being evaluated at present in field tests on industrial emission sources, which so far have included an asphalt plant, a clinker cooler for a Portland cement plant, a kraft paper mill recovery boiler, and one oil-fired and four coal-fired power boilers. The instrument performed with varying degrees of success, the main difficulty being a susceptibility to interferences in a high vibration environment.

The use of electrical mobility as a measure of particle size is sound in principle. If calibration studies and field tests show this technique to be accurate and reliable, it could become the most widely used method for measuring ultrafine particle sizes. It has the distinct advantage of very rapid data acquisition compared to diffusion batteries and condensation nuclei counters (two minutes as opposed to two hours for a single determination of particle-size distribution).[174-176]

Disadvantages of the electrical mobility technique are the difficulty of predicting the particle charge and the fraction of the particles bearing a charge with sufficient accuracy; and the requirement for sample dilution when making particle-size distribution measurements in flue gases.

Figure 4.8 shows the agreement between particle-size distribution values measured simultaneously in the field with diffusional and electrical apparatus.[147]

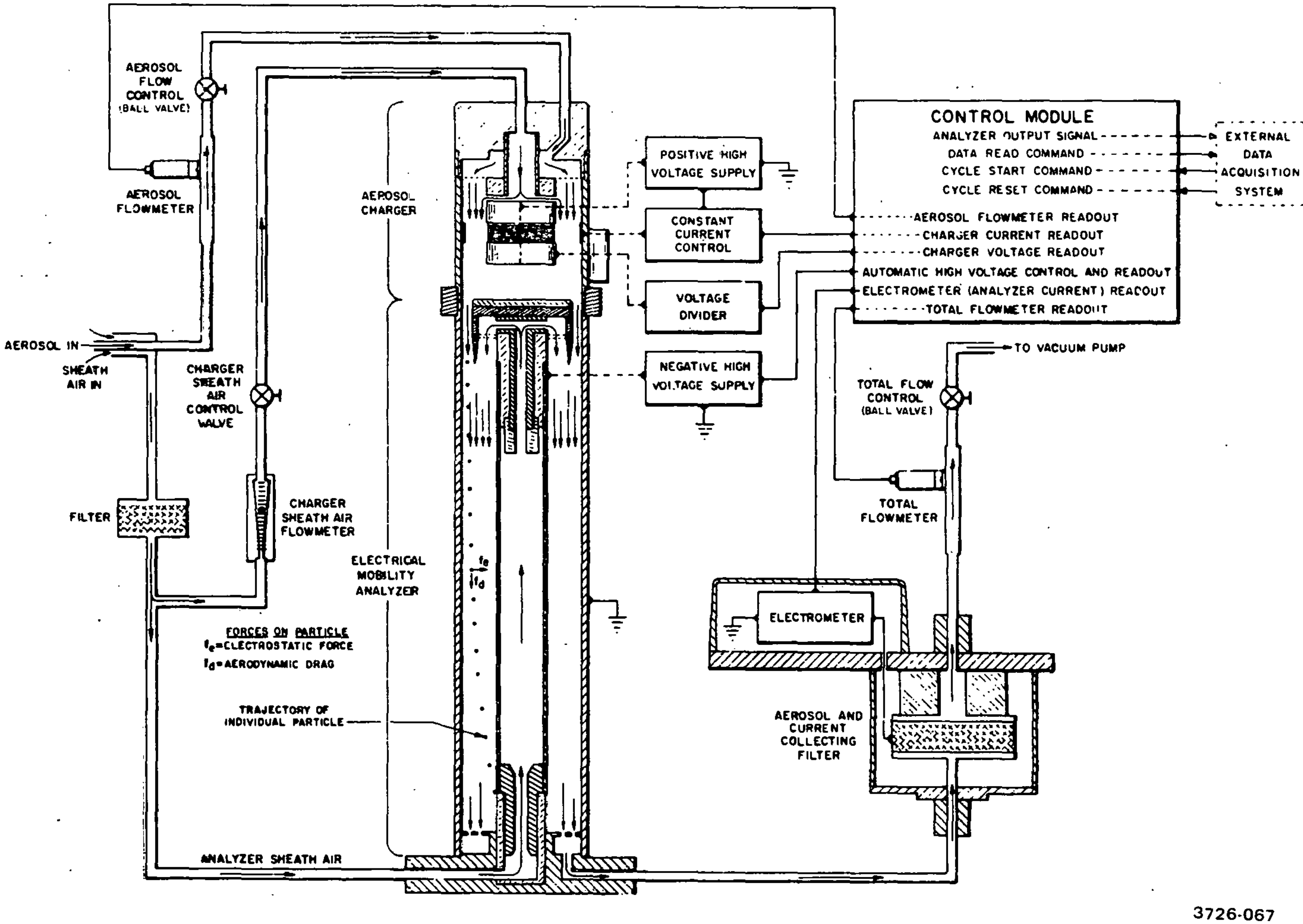

Figure 4.7 Schematic diagram of the electrical aerosol analyzer.[175]

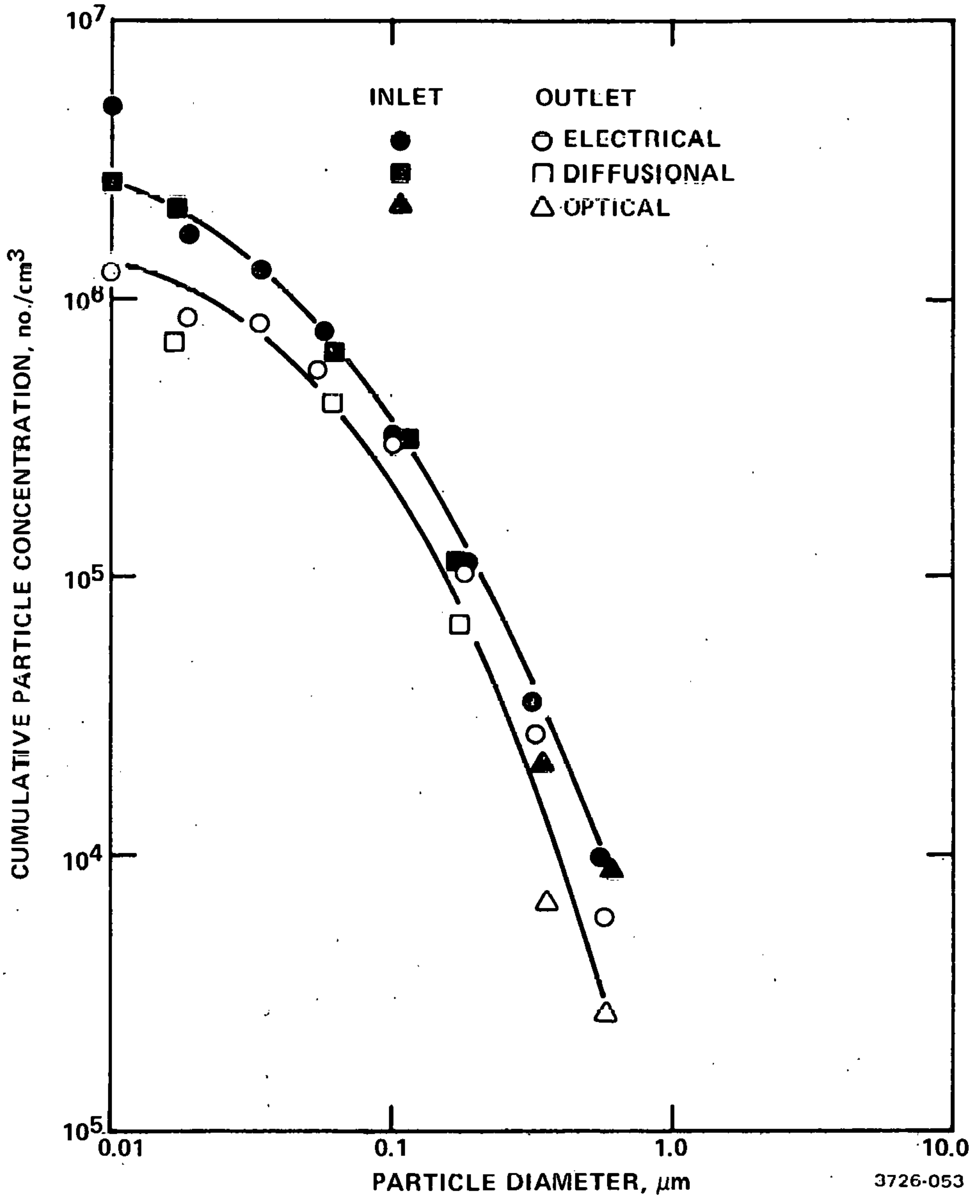

Figure 4.8 Particle size distributions measured with optical, diffusional, and electrical techniques at the inlet and outlet of an operating electrostatic precipitator.[147]

4.3 SAMPLING TECHNIQUES

When possible, in-stack sampling is preferred because it avoids problems of condensation and sample loss which occur when probes are used for extractive sampling. Unfortunately, the existing sub-micron sizing techniques (diffusional mobility analysis and electrical mobility analysis) do not lend themselves to in-stack sampling. Particulate concentrations are extremely high in an industrial flue gas and vary by orders of magnitude from one industrial process to another and from the inlet of a control device to the outlet of the same device. Temperature, pressure, moisture content, and the physical properties of the particulate also vary widely from one industrial process to another. Because of the wide variations in particle concentration and operating conditions in boiler stacks and the limited usable concentration range for sizing techniques, extensive dilution and conditioning of the sample are required.

The temperature of the gas sample must be reduced to the level at which the measuring instruments can be operated. A dilution system must be used to reduce the particle concentration to levels at which the instruments function properly. Various orifice designs can be used for dilution. Samples with high moisture content must be dried. A suitable system for extracting, conditioning, and diluting gas samples is shown in Figure 4.9.[147,158]

Problems involved in sampling include loss of particles in sample lines and condensation of materials such as sulfuric acid. Electrostatic charges on fly ash particles can interfere with measurements but can be neutralized by exposure of the sample to a radioactive source.

4.3.1 Sampling from High Temperature-High Pressure Gas Streams

Two approaches to the problem of characterizing the particulate emissions in high temperature-high pressure gas streams are

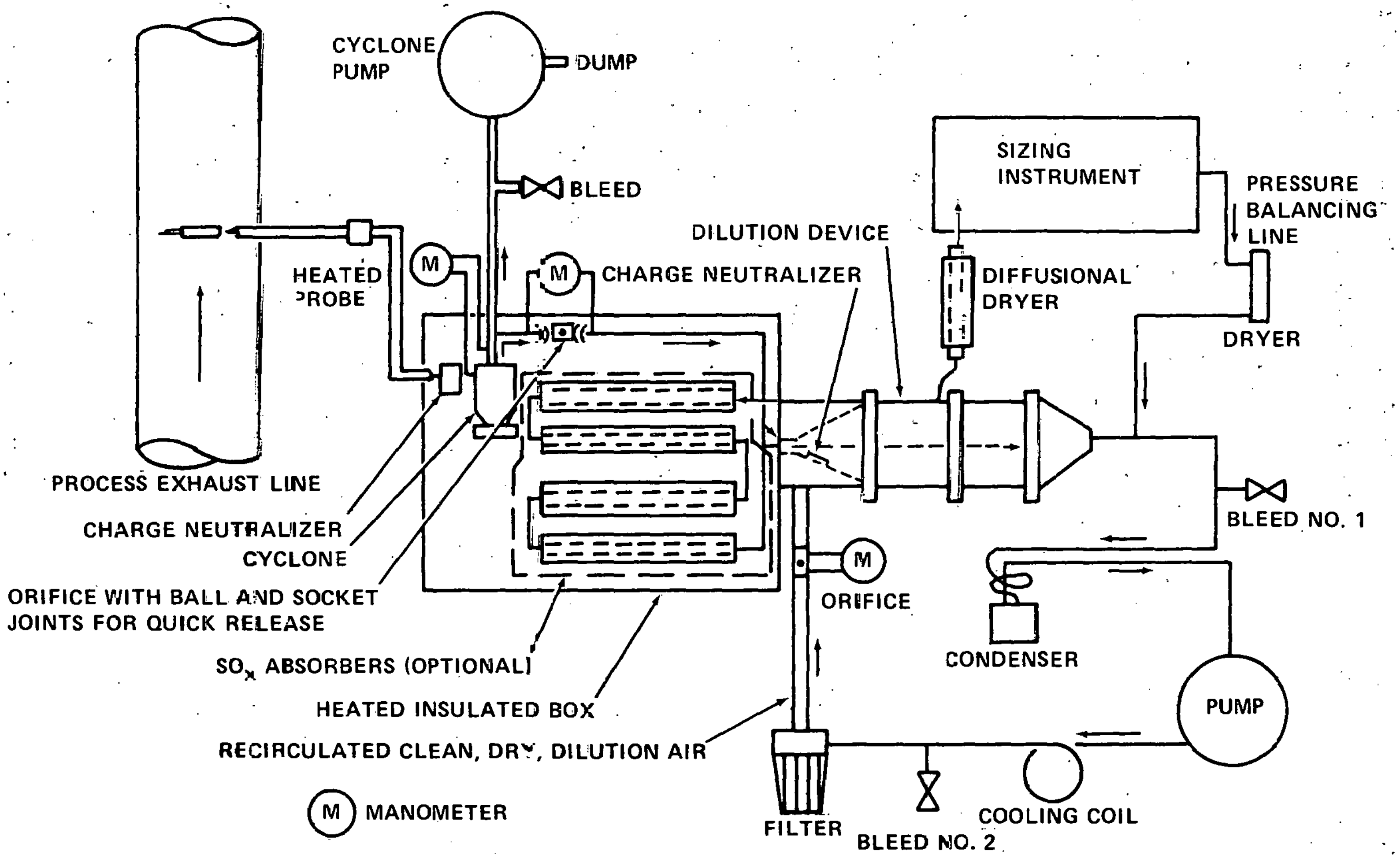

Figure 4.9 System for sample extraction and dilution.[158]

possible: (1) the instruments may be placed inside the duct to take samples under typical gas conditions, or (2) a probe may be employed to cool the sample and reduce the pressure. Each method has disadvantages. Presumably filters would be adequate means for measuring mass concentration for in-situ sampling, but there are no particle sizing instruments for which performance under conditions of high temperature and pressure has been established. If a probe is used, it is likely that the nature of the aerosol will change when the gas stream is cooled and the pressure reduced, for example, by the condensation of high boiling point organic substances.

Sampling efforts thus far have involved the use of a probe to reduce the gas temperature and pressure.[177]

4.4 LABORATORY TECHNIQUES

Several laboratory techniques are used for determining the particle-size distribution of dusts. They are not as suitable for analysis of micron and sub-micron particle-size dusts as the field test methods discussed above. The size distribution of a flue gas aerosol is continually changing as the result of agglomeration, settling, and condensation. It is impossible to re-disperse the particulate matter exactly as it was in the gas or to calculate the original size distribution from laboratory data.

Methods that are used for the measurement of particle size are optical and electron microscopy, sedimentation, centrifugation, elutriation, and electrical conductivity.

A commercially available centrifugal particle classifier (Bahco) is routinely used to measure the size distribution of powders down to a particle diameter of about 2 μm. It is the instrument specified in the American Society of Mechanical Engineers Standard Method for determining the particle-size distribution of powders.

Various spiral centrifuges that are more sensitive to smaller particles (down to 0.05 μm) have been developed, but none is commercially available yet.[178-181]

Air elutriation is the basis of the Roller particle-size analyzer, which is used for particles down to 5 μm in diameter.

A sedimentation device is available which measures particle size by the rate at which the particles settle from a liquid suspension.

The size distribution of a powder that can be suspended in a solution of an electrolyte can be measured by electrical conductivity modulation (Coulter Counter).

In spite of their limitations, laboratory methods are the only methods available for determining particle shape and surface features, particle density and chemical composition, and the extent of particle agglomeration.

Research on sampling and measurement techniques by the Environmental Protection Agency is described in the preceding pages. Other research programs on these topics include the following, supported by the Electric Power Research Institute.[27]

The Denver Research Institute is developing laboratory apparatus and procedures for the measurement of electrical resistivity of fine particulate matter (RP 464).

Instrumentation for use with low-pressure cascade impactors in measuring the size distribution of particles in the range of 0.03 to 30 μm emitted from coal-fired utility boilers is being developed at the University of Washington (RP 414).

An impactor-precipitator for in-stack measurement of the particle-size distribution of fly ash in the 0.03-30 μm size range is being developed by Meteorology Research, Inc. (RP 463).

Auger electron spectroscopy is used for measuring the concentrations of elements on the surface of fly ash particles that may be responsible for the electrical resistivity characteristics of fly ash, in a project at Stanford University (RP 631).

A portable instrument containing a novel diffusion battery for measurement of size distribution of sub-micron particles is being developed by Air Pollution Technology. The diffusion battery uses wire screens instead of the customary parallel channels (RP 723).

A comparison of techniques for measurements of fine particulate matter is being made in order to provide the utility industry with procedures to use in emission source testing (RP 781).

5. CONCLUSIONS

The types of equipment used at present for control of fly ash emissions from power plants that burn coal are electrostatic precipitators, fabric filter baghouses, and wet scrubbers. Mechanical collectors (cyclones) are installed in some power plants ahead of these collectors for removal of the larger ash particles.

Electrostatic precipitators are by far the most widely used device for fly ash control; they were introduced in this application in 1930. Fabric filter baghouses and wet scrubbers were introduced in electrical utility power plants only within the past several years.

Two environmental problems faced by the electric utility industry are resulting in changes in the technology of controlling fly ash emissions. The amount of western low-sulfur coal used in the production of electricity is increasing; by 1985, according to a recent estimate, low-sulfur coal from western sources will account for about 1/4 of the total production of coal in the United States. The fly ash from low-sulfur coal usually has a high electrical resistivity that causes problems in collecting it in an electrostatic precipitator.

Also, there is general concern about the possibility of fine particle emissions of fly ash and other industrial dusts with particle diameters below about 3 μm. These particles contribute little to the total mass of the emissions, but they add disproportionately to atmospheric haze. They are also potentially hazardous to human health because of their high respirability. Control of fine particle emissions will require improved performance of all types of collection equipment.

In electrostatic precipitators, increased control has been obtained by designing the equipment to have a larger unit capacity or to operate at a higher temperature than usual, or in some existing installations, by adding chemical agents to the coal or flue gas to increase collectability.

The effects of the fine particle problem on the techniques of fabric filtration or wet scrubbing have not yet been well defined. Only within the last few years have measurements been made that show the collection efficiency of fabric filters for sub-micron particles to be adequate. As for wet scrubbers, their overall collection efficiencies are also satisfactory, but, because of the problems inherent in obtaining valid samples from the scrubber outlet, fractional collection efficiencies for sub-micron particles have not yet been measured with sufficient accuracy.

It is not practical to make precise statements regarding the comparative costs of the collection devices. The available data indicate that installed fabric filter baghouses are the most expensive. However, electrostatic precipitators designed for efficient collection of fly ash from low-sulfur coal can cost considerably more than precipitators used in collecting fly ash from coal containing moderate sulfur contents. The high cost can be enough that fabric filters become competitive. The paucity of data on the costs of wet scrubbers for fly ash removal (as distinct from sulfur dioxide removal) does not permit direct comparison.

The power requirements of equipment for collecting fly ash vary from 0.3 to 6% of the output of the electric power plant. Electrostatic precipitators require about 0.3% of the plant output, depending on the properties of the fly ash. Energization of the precipitator uses about 3/4 of this power. Fabric filter baghouses require 0.5% of the plant output. Wet scrubbers use the largest amount of power, 5-6% of the plant output, with half of the power being required to overcome the relatively high pressure drop in the scrubber.

The most common maintenance problems in electrostatic precipitators are mechanical failure of the discharge electrodes, due mostly to arcing and corrosion, and rapper malfunction. In fabric filter baghouses, limited experience with installations collecting fly ash indicates that the chief maintenance problem is bag failure due to the occasional development of a high pressure drop, usually due to failure of timers and other equipment. Wet scrubbers have problems of scaling and deposition of solids (mainly calcium sulfate) that accumulate in pipe lines or regions of low flow rates.

High-energy wet scrubbers have some advantages over the other devices used for collecting fly ash, *e.g.*, they can be used to collect sulfur dioxide simultaneously. However, the problems with scaling and build-up of solids have almost removed them from competition for fly ash collection only. The prevalent attitude in electric utilities appears to favor electrostatic precipitators and fabric filter baghouses, with scrubbers downstream if needed for removing sulfur dioxide.

Research and development efforts aimed at increasing the effectiveness of fly ash control equipment have produced several modifications that appear to be useful. In electrostatic precipitators, these modified processes include precharging the fly ash suspended in the flue gas before it enters the precipitator. This is an attempt to separate the components of the electrostatic precipitation process so that particle charging and collection can be carried out separately under conditions most favorable for each.

In fabric filtration, new developments include fabrics of metal fibers for high-temperature service and non-woven supported fabrics with fine fibers designed for improved collection of fine particles and higher filtration velocities.

The limitations of conventional collection devices have also resulted in new devices or techniques that combine two or more mechanisms of particle collection. Devices based on hybrid techniques that appear worth further study and development are charged-droplet scrubbers, wet electrostatic precipitators, and granular bed filters.

Charged-droplet scrubbers do not yet appear to have a high enough collection efficiency for the fine particle fractions of fly ash to make them economically competitive with conventional collection devices. Wet electrostatic precipitators can operate with a collection plate area lower than that of a dry precipitator, but the resulting savings would be largely used in an increased materials cost.

Granular-bed filters, including fixed-bed filters and dry scrubbers, can be effectively used for the collection of particles large enough to be captured by impaction, but they are less efficient in collecting sub-micron particles. They can be operated effectively at high temperatures, but whether the pressure drops involved in the efficient collection of fine particles will be prohibitively high remains to be determined.

Adequate sampling and measurement techniques for determining the concentration of fly ash and its particle-size distribution in flue gases have become available only in the past few years, and there is still no complete agreement among those who use the techniques on how to interpret some of the results.

Overall particulate mass concentrations of fly ash are determined by weighing samples extracted from flue ducts, although in-stack opacity measurements can be used to a limited extent.

Particle size and size distribution are measured in the stack by an impactor for particles 0.5-1 μm in diameter; by an optical particle counter on an extracted gas sample for particles 0.3 - 1.5 μm in diameter; and by diffusion batteries coupled with condensation nuclei counters operating on an extracted gas sample for particles 0.002-0.3 μm in diameter. Electrical mobility measurement is a new technique that may displace diffusion measurements for sizing fine particles.

Improved sampling techniques are especially needed for measurements downstream from wet scrubbers.

Cascade impactors and cyclones designed in various combinations for collecting specific particle-size fractions are in an active stage of development.

New instruments being developed for continuous measurement of particle-size distribution and particulate mass concentration are based on light scattering or attenuation, beta radiation attenuation, and electrical charge effects, operated in-stack or on extracted flue gas samples.

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