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N79-27610

ECONOMIC COMPARISON OF FABRIC FILTERS AND ELECTROSTATIC PRECIPITATORS FOR PARTICULATE CONTROL ON COAL-FIRED UTILITY BOILERS

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Abstract

This paper discusses the uncertainties and associated costs involved in selecting and designing a particulate control device to meet California's air emission regulations. The basic operating principles of electrostatic precipitators and fabric filters are discussed, and design parameters are identified. The size and resulting cost of the control device as a function of design parameters is illustrated by a case study for an 800-MW coal-fired utility boiler burning a typical southwestern subbituminous coal. The cost of selecting an undersized particulate control device is compared with the cost of selecting an oversized device.

California's Particulate Emission Limits

In California, as in most states, there are many particulate emission regulations for coal-fired utility boilers. Some of the regulations applicable in California include:

(1) Federal new source performance standards.

(2) New source review requirements for non-attainment areas.

  Best available control technology.
  Lowest achievable emission rate.
  Emission offset requirements.

(3) Process weight rules.

(4) Local maximum emission rate rules.

Many of the process weight and local maximum emission rate rules are designed to prevent the construction of new coal-fired utility boilers. In fact, Scattergood Unit 3, a 309-MW gas-fired boiler owned by the Los Angeles Department of Water and Power, is just able to meet the local maximum particulate emission rate.

Kern County's process weight rule, typical of many in California, is:

$$\text{allowed emissions (lb/hr)} = 17.31P^{.16}$$

where p = coal fired in tons per hour. Under this rule, an 800-MW unit burning 350 tons per hour of a typical southwest subbituminous coal with a heating value of 10,000 Btu per pound and containing 10 percent ash would be allowed to emit only 44.4 pounds per hour of particulates. This limit, equivalent to 0.0062 pounds per million Btu, would require a particulate collection efficiency of 99.93 percent — which is clearly not within the current state of the art.

By the end of 1978, California will submit to the U.S. Environmental Protection Agency a new State Implementation Plan containing revised limits for the control of particulate emissions. It is expected that this plan will require new coal-fired plants to be equipped with the best available control technology (BACT), and that the BACT limit will be similar to the limit of 0.03 pounds per million Btu that EPA itself is considering. The California Air Resources Board expects promulgation of the new statewide limit to result in a relaxation of the numerous stricter local emission limits.

Uncertainties in the Selection and Design of Particulate Control Devices

Electrostatic Precipitators. Electrostatic precipitators (ESPs) have historically been used for the control of particulate emissions from coal-fired utility boilers. (Wet scrubbers, also historically used, are no longer usually selected: the very high operating pressure drops they need in order to achieve the collection efficiencies required by current and proposed new source performance standards result in uneconomically high operating costs.)

Electrostatic precipitators collect particulate matter by electrically charging the particles in the gas stream and then allowing the particles sufficient residence time in the ESP to migrate to the oppositely charged collecting plates. The collecting plates are periodically rapped to dislodge the collected ash, which slides into the collection hoppers. Figure 1 illustrates a typical ESP, showing the general configuration of the discharge electrodes, collecting plates, and ash hoppers. In this illustration, three stages of electrodes, plates, and hoppers are used.

The velocity at which the charged particles migrate toward the collecting plates determines the size and the resulting cost of the ESP. The higher the velocity, the smaller the size and the lower the cost. The velocity is dependent on numerous parameters, the most important of which are particle size and ash resistivity. High-resistivity ashes containing small particles are capable of accepting only relatively small electrical charges and therefore have a relatively low migration velocity. Figure 2 illustrates the resistivity of two typical coal ashes as a function of temperature. Note that medium-sulfur coal ash typically has a lower resistivity than low-sulfur coal ash. Likewise, high-sulfur coal ash usually has a lower resistivity than medium-sulfur coal ash. Note also that the ash-resistivity curve peaks at a temperature of about 400 degrees. From this curve we can see that, in order to obtain the low resistivity desired, the ESP must be located at a point in the system where temperatures are below 300°F or above 600°F. In a typical coal-fired boiler, gas temperatures are usually above 600°F upstream of the air preheater and below 300°F downstream of the air preheater, thus providing locations for hot-side and cold-side ESPs.

Both coal properties and boiler operating conditions introduce uncertainties into the design of an ESP. The primary coal properties of interest are the ash content of the coal and its resistivity. The ash content of coal from a single mine varies considerably from day to day; similarly, the resistivity may vary. If the coal source changes, as it may in the life of a coal-fired power plant, the changes in ash properties are often quite dramatic, especially if the coal sulfur content changes significantly. The primary boiler operating condition of interest is the boiler's anticipated duty. A base-load plant maintains a fairly constant exhaust gas temperature and flow rate, while a load-following plant often produces significant fluctuations in exhaust gas temperature and flow rate. These fluctuations affect the ash resistivity and velocity through the precipitator. Therefore, the designer of an ESP must consider both current and future coal supplies and plant operating conditions.

Design parameters for hot-side ESPs reported to the Federal Power Commission on FPC Form 67 are illustrated in Figure 3. The specific collector area (SCA) is an indication of the size of the ESP and is a function of the particle migration velocity and required collection efficiency. Note that, at a collection efficiency of 99.5 percent, the design SCAs vary between 260 and 740 ft 2/1000 ACFM. This threefold difference in SCAs is probably due to different design ash resistivities, but in the case of the two large SCA values it may also reflect the existence of a severe financial penalty to the vendor if the ESP does not meet strict performance guarantees.

Fabric Filters. Fabric filters, or baghouses, have only recently come into use for the collection of particulate matter from utility boilers. There are currently a few relatively small fabric filter installations on utility boilers and a few larger installations planned or under construction. Figure 4 illustrates a typical fabric filter module wherein the particle-laden gas enters the base of the filter and travels upward through the numerous bags that collect the particulate matter. The bags are periodically cleaned by diverting the gas flow to other modules and either shaking the bags or reversing the air flow through them to remove the collected ash.

The size and resulting capital cost of a fabric filter is a function of the gas velocity through the bags. This velocity is called the air-to-cloth ratio. Lower air-to-cloth ratios generally provide higher collection efficiencies at lower operating pressure drops and require larger-size installations for a given application. The design of a fabric filter involves a trade-off between the high capital cost for a low air-to-cloth ratio and the high operating (pressure drop) and maintenance (bag replacement) costs associated with a high air-to-cloth ratio. Bag material and cleaning frequency must also be included in the design trade-off.

Fabric filters are less sensitive than ESPs to variations in coal ash content and ash properties. However, uncertainties in the design of fabric filters still exist, primarily in relation to the pressure drop and resulting operating costs. Pressure drop, which depends partially on the shape and size distribution of the fly ash, can change significantly for a given fabric filter when the coal source is changed.

Performance Models for Electrostatic Precipitators

For a given application, the collection efficiency of an ESP is inversely proportional to the velocity of the gas parallel to the collecting plates, or directly proportional to the residence time of the gas in the ESP. This relationship is expressed by the Deutsch equation

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

where

η = collection efficiency

w = migration velocity of the particles

A = collecting plate area

V = gas velocity parallel to the collecting plate

The relationship $\frac{A}{V}$ is often called the specific collector area (SCA), as indicated in the preceding section. The SCA, once determined, is multiplied by the gas flow rate through the ESP to determine the total collecting plate area required for a given collection efficiency.

The migration velocity, as mentioned previously, is very sensitive to particle size and ash resistivity as well as to electrical conditions within the ESP. Most ESP designers use some form of the Deutsch equation to determine the required ESP size for a given application; and, since most designers use only one particle size instead of the particle-size distribution actually found in the gas stream, a great deal of experience is required in selecting the proper migration velocity. This design approach works fairly well when low-resistivity, high-sulfur eastern coals are used in boilers subject to relatively lenient emission limits. Unfortunately, however, the recent increase in the use of high-resistivity western coals combined with the increasingly more stringent particulate emission limits has forced the design of ESPs outside of the realm of experience of many ESP designers. This has resulted in the gross underdesign or overdesign of ESPs for western coals. Although the ESP business is very competitive, few performance guarantees have been required in the past. Consequently, most of the early ESPs for western coals were grossly underdesigned. ESP designers have subsequently modified the form of the Deutsch equation or substituted lower migration velocities in an attempt to model the performance of ESPs operating outside their realm of experience.

The SoRI Performance Model. To provide ESP designers with a better design tool, Southern Research Institute (SoRI) under contract with EPA has developed an ESP performance model that is based on the detailed physics of particle collection and considers the distribution of particle sizes (1). The SoRI model is quite complicated, and its 2,400 lines of computer code offer the designer little insight into the physical processes taking place in the ESP. While it is a vast improvement over the approach used by many ESP designers, the SoRI model calculates theoretical, or ideal, collection efficiency and still requires the designer to assume values for gas-flow maldistribution, gas leakage, rapping reentrainment, ash electrical properties, and the internal geometry of the ESP, all of which contribute to the nonideal collection efficiencies encountered in the field.

The SoRI ESP model has been simplified and programmed by Sparks (2) for use with a programmable calculator. The simplified version considers the distribution of particle sizes encountered in the ESP and should be of great value to the ESP designer. It requires the use, however, of the SoRI computer model to generate numerical values for use in calculating particle migration velocities; several typical migration velocities as a function of current density are included in the Sparks report.

The Teknekron Performance Model. Teknekron has developed a correlating function for the overall efficiency of an ESP that can be used with experimental data to predict the efficiency of an ESP of given size. A brief description of the Teknekron ESP performance model is presented here; a thorough description has recently been published and should be consulted if more detail is required (3).

The approach suggested by White (4) for handling the effects of particle-size distribution on ESP collection efficiency is

$$\eta = 1 - \int_0^\infty \exp\left(-\left(\frac{A}{V} w(x)\right)\right) P(x)\, dx \qquad (2)$$

where w(x) is the migration velocity as a function of particle size, P(x) the particle-size frequency distribution, and x the particle diameter. The functional form of w(x) is predicted by electrostatic theory to be linear with respect to particle diameter x:

$$w(x) = \frac{\epsilon_o E_c E_p x}{\theta} \qquad (3)$$

where ϵ_o is a function of the particle dielectric constant, E_c is the particle charging field strength, E_p is the strength of the precipitating field, and is the gas viscosity.

The Teknekron model assumed that migration velocity is a linear function of particle diameter, i.e.,

$$w(x) = w_o + w_1 x \qquad (4)$$

The two parameters w_o and w_1 characterize the coal used and make it possible to include the effects of thermal charging (as x goes to zero, w is finite). The resistivity of a given coal ash can be embedded in the parameters w_o and w_1, as demonstrated by Sparks (2).

The integration of collection efficiency with respect to particle size can be performed analytically for a number of functions of migration velocity if one employs semilogarithmic (or exponential) correlations for particulate loading and collection efficiency rather than the standard power law (log-log) correlations conventionally used in recording efficiency data. This method appears to entail a negligible loss of accuracy, even for 99.9-percent overall collection efficiencies. The analytical expressions for overall collection efficiency do appear to scale up reasonably well for field data, although any conclusions about the validity of the method should be reserved until more data become available.

The exponential distribution for inlet particle-size takes the form

$$P(x) = B \exp(-Bx) \qquad (5)$$

which corresponds to the cumulative distribution

$$Y(x) = \exp(-Bx) \qquad (6)$$

This cumulative distribution is defined as the mass fraction of particles having a diameter larger than or equal to x. Hence, Y(o) = 1.

The B's calculated for representative distributions of fly-ash particle size for three boiler types are as follows:

Boiler Type	B
pulverized coal	0.040
stoker	0.017
cyclone	0.10

The Deutsch equation in terms of w can be written as

$$\eta(x) = 1 - \exp\left(-\frac{A}{V} w\right) \qquad (7)$$

If $w = w_o + w_1 x$, then:

$$1 - \eta(x) = \exp\left(-\frac{A}{V} w_o - \frac{A}{V} w_1 x\right)$$

$$= \exp\left(-\frac{A}{V} w_o\right) \exp\left(-\frac{A}{V} w_1 x\right) \quad (8)$$

If the linear form of $w(x)$ is substituted into White's equation (equation 2) and integrated using an exponential particle-size distribution, we obtain *the following correlating expression for total* collection efficiency η_T:

$$1 - \eta_T = \frac{B \exp\left(-\frac{A}{V} w_o\right)}{B + w_1 \frac{A}{V}} \quad (9)$$

The new performance model has four primary features:

(1) The Deutsch equation is used as it should be used – for a given particle size.

(2) Migration velocity is characterized by two parameters, w_o and w_1, which are functions of the coal type and can be determined experimentally.

(3) Inlet particle-size distribution is characterized by a single parameter, B, which is a function of the boiler type.

(4) Overall efficiency is analytically expressed, and a closed form solution is possible.

Case Study

Particulate control costs for an 800-MW coal-fired boiler using a hot-side ESP and a fabric filter are examined in this case study. Also, the cost of selecting an improperly sized control device is discussed. The basic parameters for the case study are:

Unit size – 800 MW

Heat rate – 8800 Btu/kWh

Unit type – Pulverized coal-suspension fired

Coal type – Southwest subbituminous

Heating value – 10,000 Btu/lb

Ash content – 10%

Sulfur content – 0.8%

Emission limit – BACT of 0.03 lb/MBtu

Required particulate removal - 99/65%

Controlled emission rate – 216 lbs/hr

Hot-side ESP. Figure 5 illustrates the migration velocity as a function of particle size for a typical high-resistivity ash in a hot-side ESP. Using W_o = 0.02 m/sec and W_1 = 0.015 m/sec from figure 5 in equation 9 reveals that an A/V of 478 ft^2/1000 ACFM will provide the required 99.65 percent particle removal. This is equivalent to an average "effective" migration velocity for the entire range of particle sizes of 6 cm/sec, which is typical (5) of that reported for high-resistivity ash in a hot-side ESP.

A hot-side electrostatic precipitator operating at a temperature of 700°F in this case must treat 3,547,000 actual cubic feet per minute (ACFM) of flue gas. The ESP collecting plate area is therefore 1.7 million square feet.

The estimated turnkey capital cost for the ESP is summarized in Table 1.

The cost estimates are for an ESP delivered in late 1976. If the same system were ordered today for installation in 1981, vendor quotes would be higher to reflect almost two years of known cost inflation plus three years of estimated inflation. Also, if performance penalties are severe, the cost estimate will be higher to allow for a more conservative design and for the installation of additional collector area, if required.

Table 2 summarizes the estimated annual costs of the ESP assuming a capacity factor of 65 percent.

Table 1. Electrostatic precipitator turnkey capital cost estimate (basis: last quarter 1976 costs and dollars)

Cost item	Cost (millions of dollars)
ESP device	\$12.7
Ducting	2.8
Ash handling	2.7
Total equipment cost	\$18.2
Ash pond	3.8
Total direct cost	\$22.0
Indirect costs	8.0
Contingency and fee	7.8
Total capital investment	\$37.8
Capital investment per kW	\$47.25

Table 2. Electrostatic precipitator annual costs

Operating and maintenance (O&M)	
Labor and supervision	$ 50,000
Maintenance and supplies	2,000,000
Overhead	1,040,000
Ash disposal	200,000
Electricity @ 25 mill./kWh	1,140,000
Subtotal O&M costs	$4,430,000 = 0.97 mills/kWh
Fixed Costs	
Insurance, depreciation, taxes	$3,642,000
Capital cost	3,400,000
Subtotal fixed costs	$7,042,000 = 1.55 mills/kWh
TOTAL ANNUAL COST	$11,472,000 = 2.52 mills/kWh

Fabric Filter. A fabric filter in this case is assumed to operate at 340°F and to treat 2,446,000 ACFM of gas. An air-to-cloth ratio of 2 is typical of many fabric filters designed for utility boilers and in this case results in a filter area of 1,223,000 square feet. A design pressure drop of 4.5 inches of water is used to calculate operating electricity costs. If the pressure drop cannot be maintained at this level in practice, operating electricity costs will increase proportionately.

The estimated turnkey capital costs for the fabric filter are shown in Table 3. These costs, like the ESP capital costs, are for a fabric filter delivered in late 1976 and are subject to the same inflation rates.

Table 4 summarizes the fabric filter's estimated annual costs based on a 65 percent capacity factor. In this case, annual costs for a fabric filter are less than those for a hot-side ESP. This may not be true, however, for all applications where low-sulfur coal is burned. Each application must be evaluated separately. Still, these cost estimates do support the trend shown by some utilities toward the use of fabric filters. It should be noted that this case study does not consider the need for a flue gas desulfurization (FGD) system for sulfur dioxide control. If applicable SO_2 emission limits require the use of an FGD system, the particulate-collection capabilities of the FGD scrubber should be considered. A detailed performance and cost study may well reveal that the particulate control strategy having the lowest annual cost involves using a medium-efficiency ESP followed by a wet scrubber combining FGD and particulate control.

Fabric filters usually meet or exceed the particulate-removal requirements specified in the design, but often at the cost of unexpectedly high pressure drops. Corrective action to lower the pressure drop includes installing additional modules to lower the air-to-cloth ratio, using a different fabric type, and increasing the frequency of bag cleaning.

Table 3. Fabric filter capital cost estimates (basis: last quarter 1976 costs and dollars)

Cost item	Cost (millions of dollars)
Fabric filter device	$13.1
Ducting	0.8
Ash handling	0.5
Total equipment cost	$16.4
Ash pond	3.8
Total direct costs	$20.2
Indirect costs	6.8
Contingency and fee	7.0
Total capital investment	$34.0
Capital investment per kW	$42.50

Table 4. Fabric filter annual costs

Operating and maintenance (O&M)	
Labor and supervision	$ 50 000
Maintenance and supplies	1,000,000
Overhead	530,000
Ash disposal	200,000
Electricity	525,000
Subtotal O&M costs	$2,305,000 = 0.51 mills/kWh
Fixed costs	
Depreciation, taxes, insurance	$3,270,000
Capital cost	3,060,000
Subtotal fixed costs	$6,330,000 = 1.39 mills/kWh
TOTAL ANNUAL COST	$8,635,000 = 1.90 mills/kWh

If an ESP fails to meet the particulate-removal requirements, either the average effective migration velocity or specific collector area must be increased, or a coal of lower ash content must be used. The migration velocity can be increased by using a coal with a lower ash resistivity or by conditioning the gas to lower the resistivity. The specific collector area can be increased either by retrofitting increased collector area or by derating the boiler to reduce the gas flow rate. All these options are expensive and must be evaluated for a specific site to determine which is most cost effective.

Figure 6 illustrates the effect that an improperly sized ESP can have on the cost of generating electricity. At the design point, net generating cost exclusive of fuel is 26 mills/kWh. The right side of the curve illustrates the effect on net generating cost of selecting an ESP that is larger than required, while the left side of the curve illustrates the effect of selecting one that is smaller than required (so that the boiler must be derated to achieve emission compliance). The dashed lines represent the probable range of costs if additional collector area is retrofitted. Retrofitting, however, requires time; and the boiler must operate in a derated mode for a number of months until retrofit is completed.

References

1. McDonald, Jack R., "A Mathematical Model of Electrostatic Precipitation: Revision 1," Vol. 1, "Modeling and Programming the Electrostatic Precipitation Process," Draft Report to EPA, IERL-RTP (Birmingham, Ala.: Southern Research Institute, n.d.).

2. Sparks, Leslie E., "SR-52 Programmable Calculator Programs for Venturi Scrubbers and Electrostatic Precipitators," EPA-600/7-78-026, March 1978.

3. Edgar, T.F.; Cukor; and L. Smith, "A Simple Correlating Function for Analysis of ESP Performance in Coal-Fired Power Plants," Paper No. 78-74.6, presented at the Annual Meeting of Air Pollution Control Association, Houston, Texas, June 1978.

4. White, H.J., "Electrostatic Precipita n of Fly Ash," J. Air Poll. Control Assoc. 27 (1977):15.

5. Kiff, John W., "Hotside Electrostatic Precipitator Design and Experience," Paper presented at the Twelfth Air Pollution and Industrial Hygiene Conference, Austin, Texas, 28 January 1976.

Figure 1
ELECTROSTATIC PRECIPITATOR

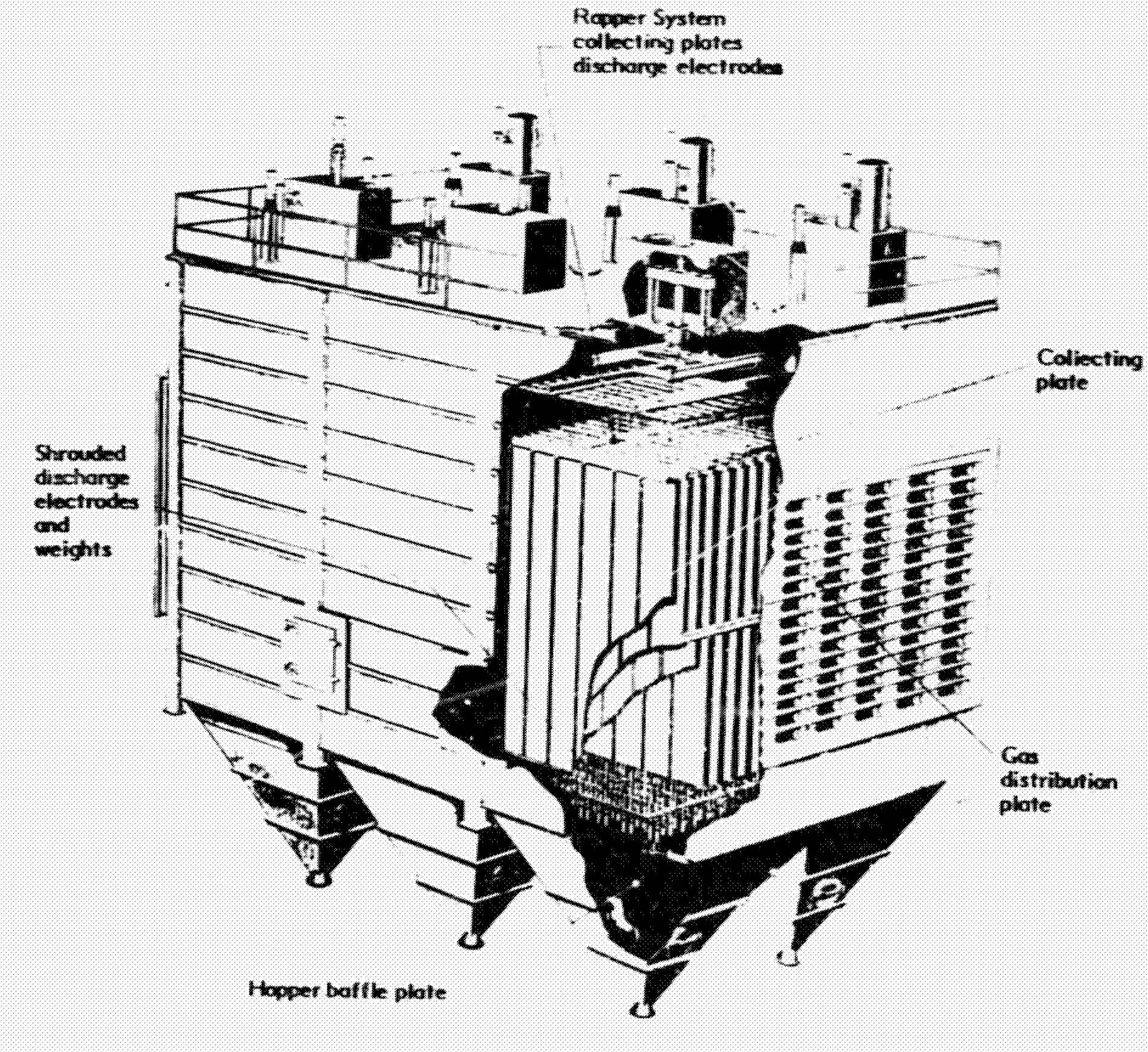

Figure 2

TYPICAL COAL ASH RESISTIVITY AS A FUNCTION OF TEMPERATURE

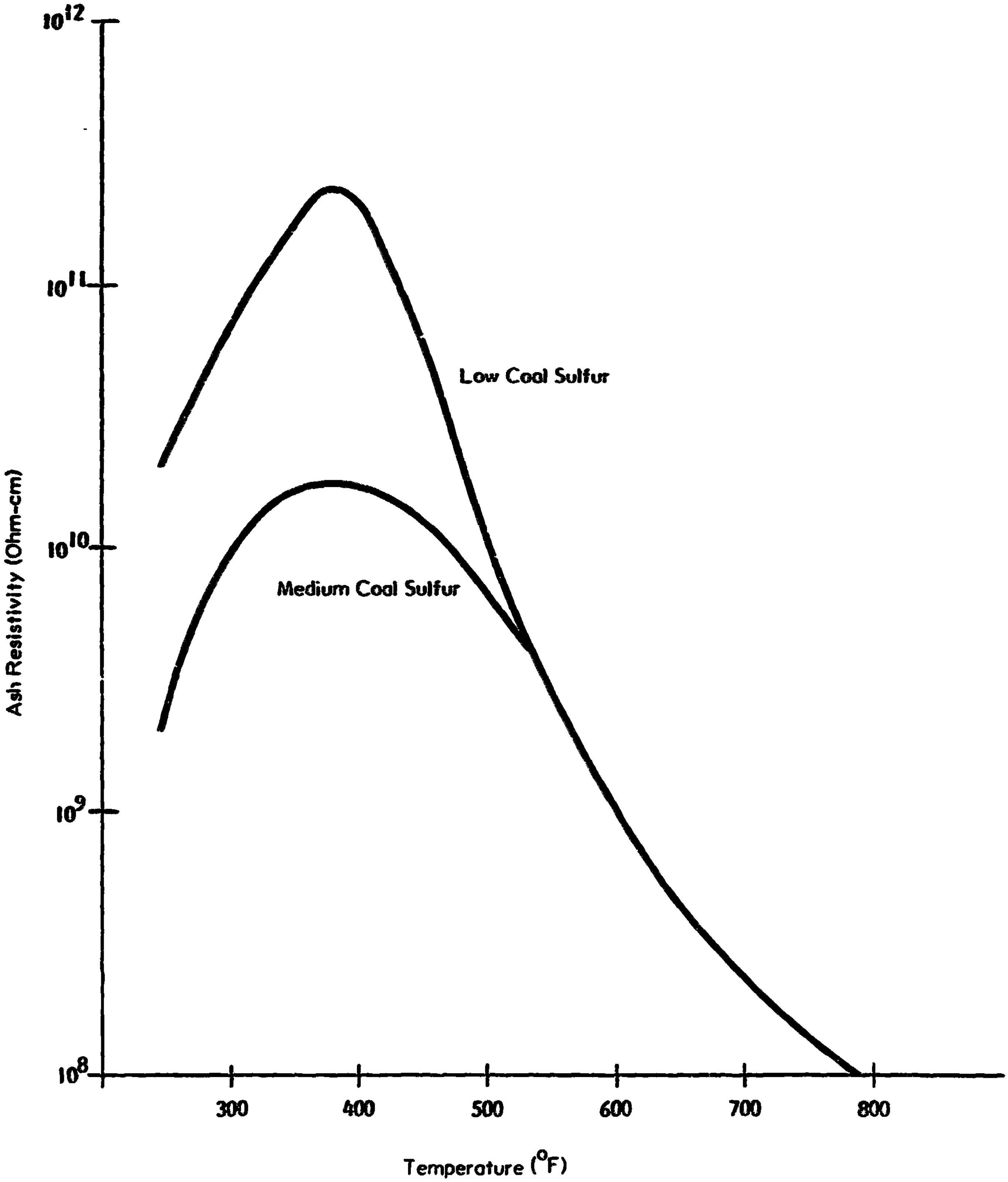

Figure 3

DESIGN PARAMETERS FOR HOT-SIDE ESP AS REPORTED TO FPC

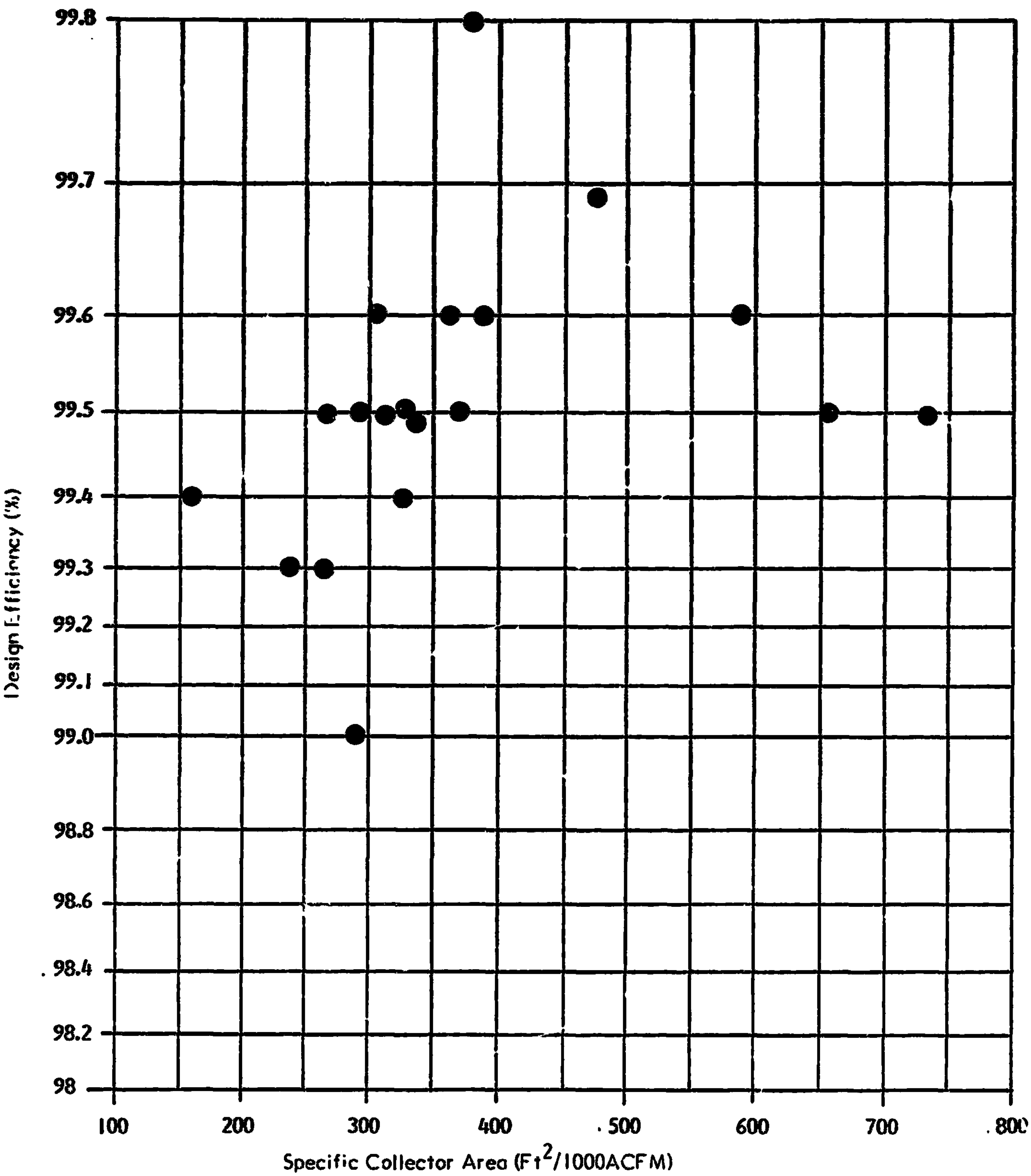

Figure 4

FABRIC FILTER MODULE

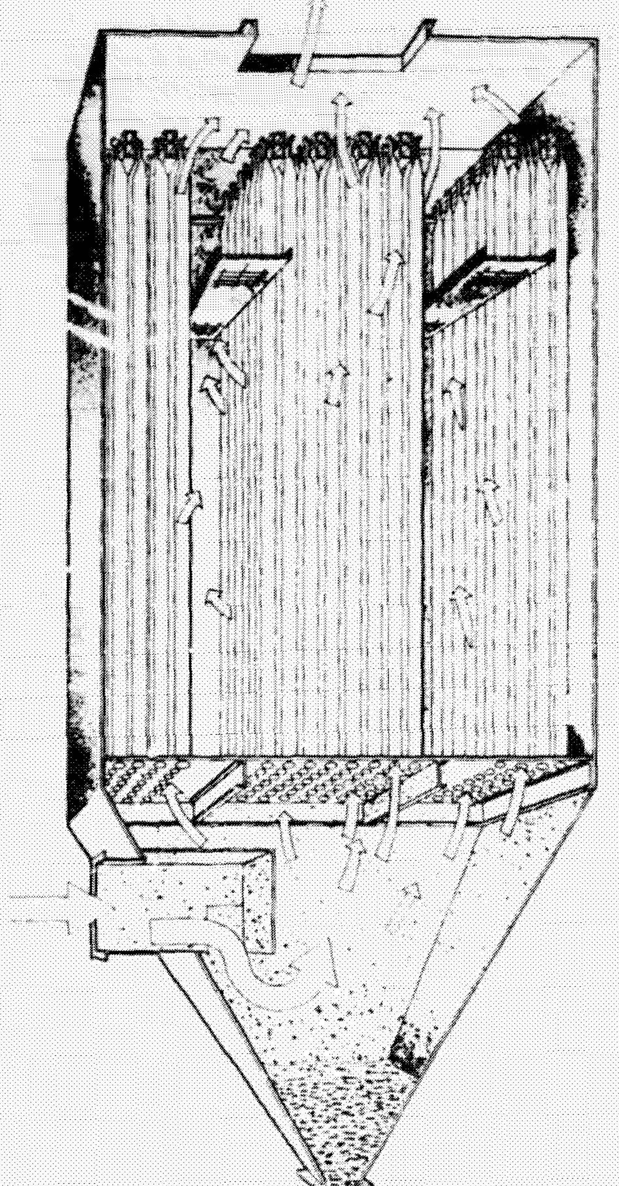

Figure 5

TYPICAL MIGRATION VELOCITY AS A FUNCTION OF PARTICLE SIZE FOR A HIGH RESISTIVITY ASH IN A HOT-SIDE ESP

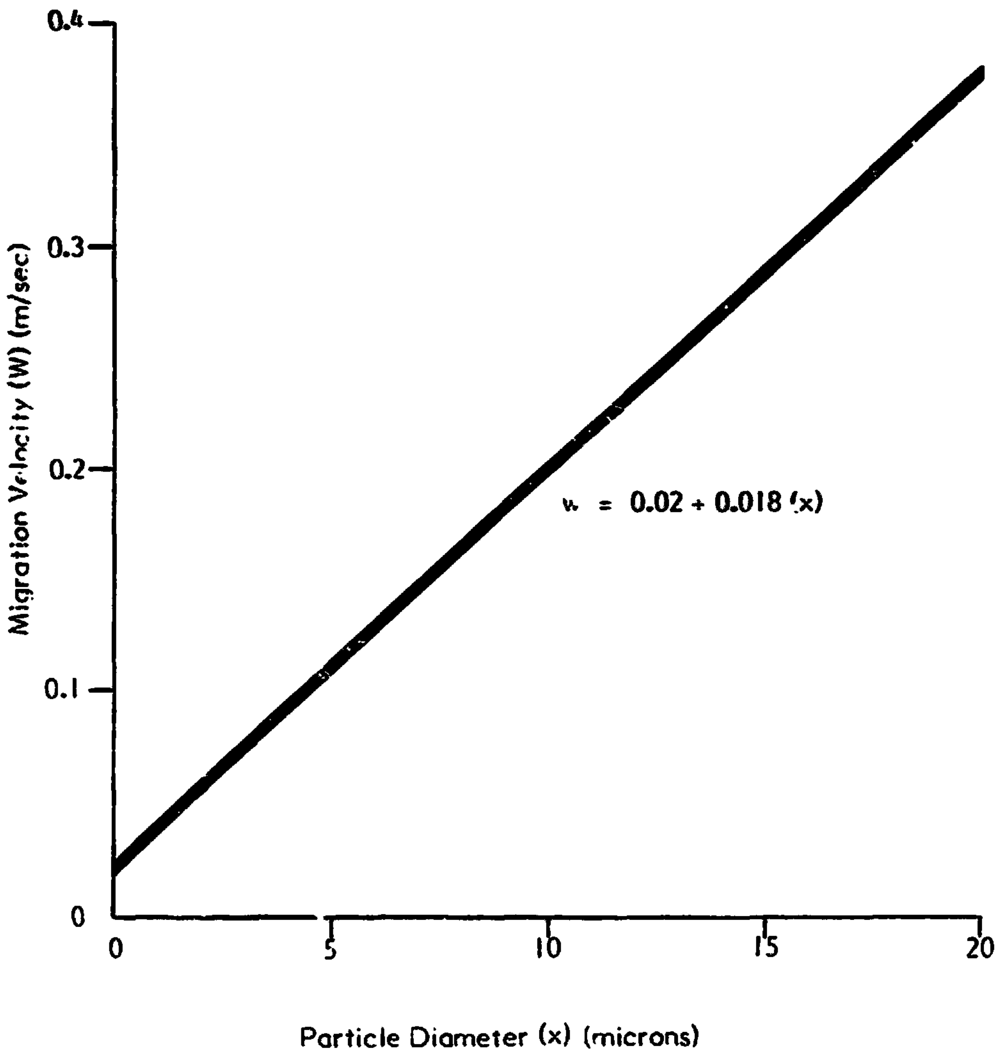

Figure 6

EFFECT OF IMPROPERLY SIZED HOT - SIDE ESP ON NET GENERATING COSTS