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COSTS AND BENEFITS OF FLY ASH CONTROL

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INTRODUCTION

The U.S. Environmental Protection Agency has recently promulgated emission standards for particulate matter discharges from fossil-fueled power plants. Emissions of particulate matter (which is mainly fly ash and unburned carbon particles) are not to exceed .10 lb per million B.t.u. heat input, maximum two hour average (Federal Register 1971, p. 24787). This standard, termed a new source performance standard, is applicable to any power plant of more than 250 million B.t.u. per hour heat input or approximately 25 MW's in capacity whose construction is commenced after August 17, 1971. Eventually, with the retirement of pre-standard plants, every plant will be subject to the standard.

To implement these new source fly ash standards, the Environmental Protection Agency has adopted a legal enforcement scheme. Firms are required to pass compliance tests on fly ash control devices before new plants go into operation. A plant is certified for operation when on the basis of prescribed stack testing procedures, discharges during the test period are no greater than the standard. During operation, opacity of stack discharges is to be continuously monitored. If the firm violates the opacity standard it can be required to modify equipment and re-pass compliance tests; if it refuses or if it repeatedly violates the standards, it can be charged in a civil action and if found guilty, fined as much as $50,000 per day of violation.

There are several loopholes in this procedure. For one thing, the opacity standard, the basis for detecting a violation, allows roughly twice the quantity of discharges as are allowed by the fly ash discharge standard. Secondly, courts in the past have usually levied fines only when violations were a factor of three or four above the standard and when there was overwhelming evidence of firm incalcitrance. Third, the firm can lower the probability of failing the compliance test by successive reruns of the compliance test. For example, if the probability of failure is .7 on a single compliance test, the probability of two failures in two tests is .49, the probability of three failures in three tests is .34, etc. These factors all point to a high likelihood that under legal enforcement, a cost-minimizing firm will not meet the fly ash standards. The obvious question which arises here is what can be done to insure compliance with the standard?

A number of economists have argued that effluent charges, relative to legal enforcement, can provide both an effective and a less costly way of implementing an environmental standard and at the same time provide economic incentives which encourage firms to adopt smaller cost control technologies.[1] However, one difficulty with effluent charges enforcement is that it may be somewhat difficult to determine an appropriate charge. On this point, Ridker (1967, pp. 1-2) states: "Economists have recommended that an effluent charge or tax be levied on emissions in order to induce behavior that will lead to acceptable levels of air pollution. Of the various arguments made against this proposal, the most telling is that no one has ventured to suggest what the magnitude of such a charge should be or even how--except at an abstract level--to determine what it should be." These same issues arise with respect to effluent charge enforcement of new source performance standards for fly ash discharges from coal-fired power plants. What level of charge will induce a power plant operator to meet the standard? Is this standard one at which marginal costs are approximately equal to marginal benefits?

The purpose of this paper is to provide qualified answers to these questions. The analysis proceeds in these steps:

1. I first show that electrostatic precipitation of fly ash is likely to be less costly than other similar available techniques for controlling fly ash discharges from coal-fired power plants.

2. Using marginal cost functions for electrostatic precipitation, I report ranges of effluent charges sufficient to induce cost minimizing power plant operators to meet new source fly ash standards.

3. Assuming achievement of new source standards, comparisons are made on a national basis between total costs and benefits and between marginal costs and benefits of fly ash control. Some caveats on the meaning of these comparisons are presented.

COSTS OF FLY ASH CONTROL

Table 1 presents 1970 data on the generation and control of particulates in the United States. Of interest are these points:

--Coal fired utility boilers account for about 23 million tons of uncontrolled particulates.

--Coal fired boilers generate over 99% of the fly ash produced by utility boilers; the remaining percentage is produced by oil-fired utility boilers.

--Of the fly ash produced in the United States in 1970 by all boilers, about 69% was produced in coal-fired utility boilers.

TABLE 1

PARTICULATE DISCHARGES TO THE ATMOSPHERE IN 1970*

Source	Type of Firing	Uncontrolled Particulates (Millions of Tons)	Collection Device**	Removal Efficiency*** (%)	Discharged Particulates (Millions of Tons)
tationary Source uel Combustion					
Utilities	Pulverized Coal (64%)	14.4	ESP/T	83	2.5
	Pulverized Coal (36%)	8.1	MDC	70	2.4
	Stoker Coal	--	--	--	--
	Cyclone Coal	0.5	ESP	80	.1
	Oil	0.06	N	0	.06
Industrial	Pulverized Coal	2.6	ESP	90	.3
	Stoker Coal	5.1	MDC	80	1.0
	Cyclone Coal	0.1	ESP	90	.01
	Oil	0.1	N	0	0.1
Residential and Commer-ial	Pulverized Coal	--	--	--	--
	Stoker Coal	2.1	MDC	60	0.8
	Cyclone Coal	--	--	--	--
	Oil	0.2	N	0	0.2
otal, Stationary ource Fuel Com-ustion					7.5***
ransportation					0.8
ndustrial Pro-esses					9.1
olid Waste isposal					1.4
iscellaneous*****					8.2
Grand Total					27.0

*Stationary source fuel combustion emissions are from Watson (1973b). All other discharge est ates are from the Environmental Protection Agency (1973).

**Electrostatic Precipitator (ESP), Tandem Mechanical Dust Collector-Precipitator (T), Mechan-cal Dust Collector (MDC), No Collector (N).

***Approximately 64% of all flue gas generated by combusting coal in electric power plants s treated in electrostatic precipitators (Southern Research Institute, undated, pp. 395-96). hese devices have average removal efficiencies of about 83% (Watson, 1970, p. 10).

****Total discharged particulates of 7.5 million tons from stationary source fuel combustion n 1970 agrees very closely with the total estimate of Spaite and Hangebrauck (1970).

****Miscellaneous includes stone and sand processing and crushing (4.2 million tons), orest fires (1.4 million tons), structural fires (.1 million tons), coal refuse burning .1 million tons), and agricultural burning (2.4 million tons).

--Non-utility boilers produced about 10 million tons of fly ash in 1970. Of this, about 75% was collected leaving 2.4 million tons of fly ash which were then discharged to the atmosphere.

--About 78% of fly ash was removed from power plant glue gases, leaving 5.1 million tons of fly ash which were then discharged to the atmosphere.

--If new source standards (approximately 99.5% removal) had been applied in 1970 to coal-fired power plants, fly ash discharges from this source would have been about .1 million tons. Total discharges from all boilers would then have been about 2.6 million tons or about 35% of what they actually were.

--Controlling particulates from coal-fired power plants in 1970 at new source levels would have reduced total particulates from all sources by about 18%.

Although it is not indicated in Table 1, coal-fired power plants (5 million tons discharged in 1970) are the largest single source of particulate matter discharges. The next largest (excluding stone crushing, a remote source) is the iron and steel industry with about 2.1 million tons discharged in 1970.

Utility plant operators currently use mechanical collectors, electrostatic precipitators, or a combination of the two to collect fly ash. Right away, mechanical collectors can be ruled out as a viable technology under the new source standards since the level of control required by these standards exceeds the capability of a mechanical dust collector. Hence, of the currently utilized devices, only mechanical collectors followed by electrostatic precipitators (so-called tandem combinations) and electrostatic precipitators alone need be considered in this analysis. This does not rule out the likely future use of other alternative devices. Air quality and emission standards for sulfur dioxide and nitrogen dioxide will probably force some power plant operators to use wet scrubbing devices which would also remove particulates. Intensive coal washing, coal gasification, and fluidized bed combustion under pressure--all process changes--are other likely future technologies which would reduce particulates. These will likely be adopted in the future if their costs are less than the costs of current particulate control technologies. Nonetheless an analysis based upon current technology--as this analysis is--may still lead to an approximate optimal particulate standard. This issue will be addressed in detail at a later point.

The following issues are of immediate concern in this section:

1. What are the minimum costs over a range of control levels of using a mechanical dust collector in tandem with an electrostatic precipitator to control fly ash?

2. What are the minimum costs of only an electrostatic precipitator?

3. Between these two, which is less costly at control levels prescribed by the new source performance standards?

An engineering-economic analysis, using Monte Carlo procedures to generalize results, will be undertaken to provide answers to these questions. It will be shown for "normal" operating temperatures (about 340°F) that electrostatic precipitation alone is less costly at "new source" control levels.

Operating temperature, itself, raises one other important consideration. One way in which a power plant can meet both fly ash and sulfur dioxide standards is by burning low sulfur coal and, in turn, precipitating its ash. Low sulfur coal, however, alters the performance of a precipitator, making it more expensive to collect a given percentage of fly ash. Two procedures for dealing with this problem are: (1) to install the precipitator at a point in the flue gas duct system where flue gas temperatures are higher (this enhances performance but increases the volume of flue gas to be treated) and (2) to alternatively enlarge the precipitator (this enhances performance by increasing treatment time). It is shown in Selzler and Watson (1973) that an enlarged precipitator at the "normal" location and hence at "normal" temperatures is less costly. The analysis of electrostatic precipitation costs in this paper is based upon operation at "normal" temperatures and it does allow for cost adjustment in relationship to the sulfur content of the coal being combusted. Consequently, it adequately covers the need for having a precipitator cost function relevant for precipitation at "normal" temperatures of fly ash from low sulfur coal. This is an important point because in the near future, as federal sulfur dioxide regulations go into effect, a number of power plants will probably be burning low sulfur western and eastern coals and desulfurized high sulfur content eastern coal (Watson (1972)).

Costs of Mechanical Fly Ash Collection

In a typical electric power plant application, a series of small diameter mechanical fly ash collectors or cyclones of the reverse-flow axial inlet type are grouped together side-by-side in a single shell and hopper chamber. Fly ash laden flue gas enters this single chamber and is distributed over and shunted through these small cyclones. Within any single cyclone, vanes impart a spinning motion to the entering gas. Fly ash particles are forced to the outside wall of the cyclone by centrifugal action and from this location fall into a dust hopper. The gas stream itself flows in a helical vortex path that reverses itself at the base of the cyclone to form an inner cone of "clean" gas which swirls up and out of each cyclone through an inner tubular guard (USDAHEW (1969) pp. 44-45).

Costs associated with the mechanical collection of fly ash include the installed cost of the mechanical collector itself, the cost of operating and maintaining the mechanical collector, the cost of installing and operating fans, and the cost of disposing of collected fly ash. In what follows, the derivation of each of these costs will be described.

I have estimated the first of these costs, the installed cost function for a mechanical collector, by performing a regression analysis using the following equation:

$$(1) \quad IK_M = d_0 \, (d_1)^J V^{d_2} E_M^{d_3} (DL)^{d_4} e^u$$

In equation (1), IK_M is the installed cost in 1000's of 1967 dollars for each of a number of observed mechanical collectors. V is the volumetric flue gas flow rate through each collector and is measured in 1000's of actual cubic feet per minute. E_M is the observed operating efficiency and is measured as the percentage by weight of fly ash collected. DL is dust loading and is measured in grains of dust per actual cubic foot of flue gas. J is a locational dummy variable which is 1 for collectors at locations having high wages and requiring inside construction, and 0 for collectors at low wage, outside construction locations. u is a random error term assumed to have mean 0, and variance, σ_u^2. An unbiased estimator of the latter is the mean square error from the regression analysis. The parameters being estimated are d_0, d_1, d_2, d_3, and d_4. The technical and cost literature on fly ash collection does not contain an explicit performance function for mechanical fly ash collection but does suggest that V, E_M, and J will be directly related and DL inversely related to IK_M (see Watson (1970) pp. 92-3)). Consequently, it is expected that the first four of these parameters will be positive, the fifth negative.

Performing the regression analysis gives the following result:

$$(2) \quad IK_M = .0714 \left[e^{\underset{(.045)}{.794}} \right]^J V^{\underset{(.036)}{.92}} E_M^{\underset{(.065)}{.38}} [DL]^{\underset{(.029)}{-.22}}, E_M \leq 85\%$$

Data are from a cross-section survey taken in 1967 by the Federal Power Commission (O'Connor and Citarella (1970)). All of the observations used in the regression analysis are on pulverized coal furnaces and mechanical fly ash collectors installed later than 1958. The number of observations is 11. R^2, corrected for degrees of freedom, = .99. The number in parentheses below each of the estimated parameters is the standard error of the estimated parameter. All of the estimated parameters are significant at a level greater than the .01 level and all have their expected signs. On the basis of an investigation of the residuals from (2), it can plausibly be assumed that u is N(0, .0004). Equation (2) holds only for values of $E_M \leq 85\%$ since 85% seems to be an approximate upper physical limit for the mechanical collection of fly ash from pulverized coal-fired furnaces.

A second category of costs, annual labor and maintenance costs (LMC), are estimated as follows (for explanation of symbols see Table 2):

$$(3)\quad LMC = .005\left(\frac{MW \cdot CF \cdot h_t \cdot 1000 \cdot HR}{HC \cdot 2000}\right)$$

Equation (3), a "best guess" estimate of labor and maintenance costs for mechanical fly ash collectors, is based upon information supplied by engineering personnel employed at the University of Minnesota, Minneapolis campus steam plant. The term in parentheses is the tons of coal combusted per year. Labor and maintenance costs are estimated, then, as the product of \$.005 per ton times the tons of coal combusted per year. In a "generalizing" sensitivity analysis which is described at a later point, Iconsider a range of unit costs centered around \$.005/ton, where the range is designed to capture the uncertainty inherent in using a single point estimate of per ton costs.

Fan operating costs are a third category of costs. Fans use electric power in moving flue gas through a mechanical fly ash collection system. These fan power costs (FPC) are given by:

$$(4)\quad FPC = \frac{\text{Pressure drop in inches of water} \cdot 5.202 \cdot 1000 \cdot V \cdot h_t \cdot \beta}{44{,}250 \cdot \text{Fan Efficiency}}$$

Equation (4) is merely a <u>definitional equation</u>: kilowatt hours times cost per kilowatt hour. The two numbers, 5.202 and 44,250, are conversion factors: 1 inch of water = 5.202 lbs/sq ft., 1kw = 44,250 ft-lbs/min. Some charges against the installed

TABLE 2

NOMENCLATURE

Symbol	Definition	Unit of Measurement
A	Collecting plate area of an electrostatic precipitator	1000's of square feet
α	Annual capital charge rate	%
AC	Average cost of disposing of collected fly ash	\$/ton in 1967 dollars
Ah	Percent ash by weight of combusted coal	%
β	Costs of a kilowatt-hour of electric power	\$/KW-Hr in 1967 dollars
CF	Capacity factor of associated generator during operating hours	Average load in megawatts/capacity load in megawatts
DL	Dust loading of flue gas	Grains/cubic foot*
E	Weight by fly ash collected divided by weight of fly ash entering an electrostatic precipitator, multiplied by 100	%
ξ_{T-R}	Average efficiency of the transformer-rectifier sets in a precipitator	Pure number
EBS	Electric bus sections in an electrostatic precipitator	The number of EBS's
h_t	Number of coal burning hours of associated boiler in year t	Hours/year t
HC	Average heat content of combusted coal	BTU/lb. of coal
HR	Average heat rate of associated generator	BTU/KW-Hr

* A grain equals 1/7000th of a lb.

TABLE 2 (Continued)

NOMENCLATURE

Symbol	Definition	Unit of Measurement
KW	Power input to the discharge electrodes of an electrostatic precipitator	Kilowatts
MF	Method of firing coal or equivalent effect in relation to size distribution of fly ash	1 for pulverized coal furnaces, 0 for cyclone furnaces or for precipitators preceded by mechanical collectors
MW	Output rating at full capacity of associated generator	Megawatts
S	Percent sulfur by weight of combusted coal	%
ΣF_{FA}	Fly ash emission factor for combusted coal	Tons of fly ash generated from 1% ash coal per ton of combusted coal
V	Volumetric flue gas flow rate through a precipitator	1000's of cubic feet/minute

capital costs of fans should also be made to account for the larger fans needed when a coal-fired electric power plant has a mechanical fly ash collection system. These charges should represent the capital costs of the fan "fraction" used by the fly ash collection system alone as distinct from the remaining fan "fraction" used to move the flue gas through the usual flue gas duct system. An estimate from industry sources of these capital costs is about $\alpha \cdot 25 \cdot MW$ per year. This charge is computed as $\alpha \cdot 1/5 \cdot 125MW$ where α is an annual capital charge rate, 1/5 is a "best guess" fraction for allocating fan costs to the fly ash collection system, and 125MW is an estimated installed cost in 1967 dollars, for electric power plant fans. The source of this latter cost is Danker (1970). [In a later sensitivity analysis, a range of values will be considered in computing "fractional" fan capital costs.] Adding the annualized capital costs to FPC gives total annual fan operating costs (FOC) as

$$(5) \quad FOC = \frac{\text{Pressure drop} \cdot 5.202 \cdot 1000 \cdot V \cdot h_t \cdot \beta}{44{,}250 \cdot \text{Fan Efficiency}} + \alpha \cdot 25 \cdot MW$$

A final category of costs are fly ash disposal costs (FADC):

$$(6) \quad FADC = \left(\frac{MW \cdot CF \cdot h_t \cdot 1000 \cdot HR}{HC \cdot 2000} \right) \cdot \left(\Sigma F_{FA} \cdot AH \cdot \frac{E_M}{100} \right) \cdot AC$$

Equation (6) is a <u>definitional equation</u>: tons of fly ash collected times disposal costs per ton. The 1st term in parentheses is tons of coal combusted; the second converts this to tons of fly ash collected. The term AC is the cost of disposing of one ton of collected fly ash.

The sum of LMC, FOC, FADC, and annualized installation costs which equal $\alpha \cdot 1000 \cdot IK_M$, gives total annual costs for a mechanical fly ash collection system. In order to insure that annualized installation costs are covered, loosely speaking, with a probability of .95, e^u in the equation for IK_M has been set equal to 1.034 $(= e^{.02 \cdot 1.65})$.[2] By substituting from Table 3, and by discounting total annual costs over a 30-year period at 8%, one can then derive representative discounted mechanical fly ash collection costs (DMC) in 1967 dollars for a 1000 MW power plant as

(7) $DMC = 279{,}184\ E_M^{.38} + 21{,}130\ E_M + 646{,}691,\ E_M \leq 85\%$

Electrostatic Precipitation Costs

The separation of fly ash from a gas stream by an electrostatic precipitator requires three basic steps: electrical charging of the fly ash, attraction of the charged fly ash to grounded collecting plates, and periodic vibration of these plates so that agglomerated fly ash can fall into a collection hopper (White (1963) p. 33).

The electrical charging is usually accomplished by passing fly ash laden flue gas through a negative, high voltage, direct-current corona. The corona (an ionization of air-gas molecules) is established between wire discharge electrodes maintained at a high voltage and grounded collecting plates. The collecting plates are typically situated in a vertical position and extend parallel to the direction of gas flow and are spaced from 6 to 12 inches apart. The wire discharge electrodes are suspended midway between the collecting plates. As the flue gas enters the precipitator, the ash particles are bombarded by the negative corona ions that flow from the high-voltage electrodes to the grounded collecting plates. Within a fraction of a second, the ash particles become highly charged and may begin migrating towards the grounded collecting surface. This electrical attraction is opposed by inertial and friction forces but may be reinforced by electric wind effects.

The ash after precipitation upon the collection plates, is periodically loosened by vibrating the plates. After loosening, most of the fly ash falls into a hopper from which it is removed to a storage area. Most power plants then

TABLE 3

REPRESENTATIVE NUMBERICAL PARAMETERS
FOR A 1000 MW POWER GENERATING UNIT

EMPIRICALLY DETERMINED PARAMETERS*	ASSUMED PARAMETERS	
$a_0 = e^{\overset{5.06}{(.43)}} = 157.6$	MW = 1000	CF = .9
$a_1 = 1.4\ (.165)$	V = 2605	AC = \$1
$a_2 = .6\ (.1)$	$\alpha = 14\%$	$\Sigma F_{FA} = .008$****
$a_3 = .22\ (.0975)$	$\beta = .004$	Fan Efficiency = .60
$a_4 = e^{\overset{.252}{(.1477)}} = 1.29$	h_t = *** 7,440 yrs. 1-12	Pressure Drop (Precipitator) = .5
$b_0 = 180{,}000\ (360{,}000)$**	5,200 yrs. 13-17	Pressure Drop (Mechanical) = 3.5
$b_1 = 4{,}710\ (2{,}100)$	2,160 yrs. 18-25	$\xi_{T-R} = .65$
$c_0 = 7{,}600\ (220)$	880 yrs. 26-30	J = 1
$c_1 = 120\ (16)$	S = 3.3%	HR = 9,000
	Ah = 11%	HC = 11,500
		DL = 3
		EBS = 24

* The numbers in parentheses are standard errors.

** The above values for b_0 and b_1 are for a precipitator at a location having high wages and requiring inside construction. For precipitators at low wage, outside construction locations, $b_0 = 130{,}000\ (55{,}000)$ and $b_1 = 2{,}960\ (340)$ (Watson (1970)).

*** This is a typical utilization pattern. Source is Slack et al. (1969).

**** .008 are the tons of fly ash generated by combusting in a pulverized-coal boiler, one ton of coal containing 1% ash by weight (see U.S. Department of Health, Education and Welfare (1969), p. 150) dispose of this waste material by transporting it to a landfill at a cost of from \$.50 to \$2.00 per ton, depending mainly on geographic location. A small tonnage of fly ash is sold by some power plants for use as road and construction fill and as an additive to concrete.

Obviously, one category of electrostatic precipitation costs are the installed costs and the power operating costs of the precipitator itself. To derive these, I have:

1. econometrically estimated a precipitator efficiency function;
2. formulated a structure and power input accounting cost equation in terms of the variables which appear in the efficiency function, and then
3. minimized these accounting costs subject to the estimated efficiency function to obtain the desired cost function.[3]

In the following paragraphs, I briefly discuss each of these steps.

A stochastic electrostatic precipitator efficiency function (E_p) written in parametric form is given by

(8) $E_p = 100\,[1 - \exp(-ze^u)]$

where $z = a_0(A/V)^{a_1}\,(KW/V)^{a_2}\,(S/Ah)^{a_3}\,(a_4)^{MF}$, A is collecting plate area in 1000's of square feet, V is flue gas flow rate in 1000's of actual cubic feet per minute, KW is power input in kilowatts to the discharge electrodes of the precipitator, S/Ah is the sulfur-to-ash ratio (by weight) of the coal combusted in the associated boiler, and MF is a dummy variable, being 1 for precipitators preceded by pulverized-coal boilers and 0 for precipitators preceded by mechanical fly ash collectors or cyclone boilders. Equation (8), a "Deutsch-type" efficiency equation, is based upon well known particle migration theory (see White (1963)). A double log transformation of this equation provides a linear equation for determining the parameters a_0, a_1, a_2, a_3, and a_4, via regression analysis. In accordance with well known precipitation theory it is expected that all of these parameters will be positive (White (1963)). In performing the regression, I have used data from four sources: The Federal Power Commission (O'Connor and Citarella (1970)), Northern States Power Company, the National Air Pollution Control Administration, and a questionnaire sent to a number of U.S. utility companies. All of the data are for precipitator systems (37 in number) installed after January, 1958 and for precipitator operations under continuous full load conditions. The estimated parameters along with their standard errors are reported in Table 3. R^2=.80. The signs of the estimated parameters all conform to prior expectations.

The parameter u in equation (8) can be interpreted as the error term in the regression analysis. It is plausible to assume based upon a plot of residuals from this regression analysis, that u is normally distributed with mean 0 and estimated variance of .12 (this latter being the mean square error from the regression analysis). Therefore, a 90% confidence interval for us is

(9) $-1.65 \leqq u/.347 \leqq 1.65$

or

$-.57 \leqq u \leqq .57$

It follows that a 90% confidence interval for ze^u is

(10) $.57z \leqq ze^u \leqq 1.77z$

This means, intuitively speaking, that 5% of the time the absolute value of the exponent in (8) will with certainty be less than .57z. In other words to guarantee that at least some specified percentage (as determined by z) of fly ash will be collected at all times with odds of 95 to 5, the absolute value of the exponent of the efficiency function can be no less than .57z.[4] On this basis, a "95 to 5 confidence efficiency" function for precipitating fly ash is

(11) $E_p = 100[1 - \exp(-.57z)]$

Structure and power accounting costs in year t ($SPAC_t$) are given by

$$(12)\quad SPAC_t = (\alpha b_1)A+(\beta h_t/\xi_{T-R}+\alpha c_1)\ KW+\alpha(b_0+c_0 EBS)$$

where α is a charge for converting installation costs to annualized costs, β= cost of a kilowatt-hour of electric power, h_t are the hours of precipitator operation in year t, ξ_{T-R} is the efficiency of the precipitator transformer-rectifiers in converting alternating current to direct current, and EBS is the number of individually energized precipitator sections. The cost parameters b_0, b_1, c_0, and c_1 have been estimated via regression analysis (Watson (1970)); their values are recorded in Table 2. Structure and power accounting costs are, then, the sum of annualized collecting plate costs, discharge electrode power <u>operating</u> costs, annualized precipitator power system costs and <u>fixed</u> costs associated with collecting plates and the precipitator power system.

Minimizing $SPAC_t$ (discounted over 30 years at 8%) subject to (11) (A and KW are variable) with substitution of appropriate parameter values from Table 3, gives total discounted structure and power costs (DSPC) for a precipitator in a representative 1000 MW power plant as follows:

$$(13)\ DSPC = 1{,}794{,}110\ [\ln(100/100-E_p)]^{1/2} + 571{,}296$$

A detailed description of this derivation is found in Watson (1970).

Other electrostatic precipitation costs include maintenance and labor costs (MLC), additional fan operating costs for moving the flue gas through the precipitator (FPC), and fly ash disposal costs (FADC). FPC and FADC for a precipitator are exactly the same as those given for a mechanical collector, namely, equations (4) and (6) above.[5] MLC have been estimated using regression analysis and are given by

$$(14)\quad MLC = 2{,}317 + \underset{(.000003)}{.000033}(V\cdot h_t\cdot 60)$$

Discounting MLC, FPC, and FADC (over a 30-year period at 8%, with appropriate values substituted from Table 3) and adding these to DSPC gives total discounted costs in 1967 dollars of precipitating fly ash (with 95 to 5 odds) from a representative 1000 MW unit as

(15) $DPC = 1,794,110[\ln(100/100-E_P)]^{1/2}+21,130E_P+1,018,656$

Cost Comparisons, A Tandem Combination Versus a Precipitator

Now consider a tandem combination, that is, a mechanical collector followed by a precipitator. The percent of fly ash to be collected by the mechanical collector is E_M. Hence the fraction of fly ash remaining in the flue gas which leaves the mechanical collector and enters the precipitator is $(1-E_M/100)$. This gives the precipitator a realized collection efficiency of $(1-E_M/100)E_P$. Combining the collection efficiencies of the two operations gives an overall collection efficiency of

(16) $E_T = E_M - .01E_ME_P + E_P$

The cost function of the combined operation is given as follows by the sum of the mechanical collector cost function (Equation 7) and the appropriate electrostatic precipitator cost function (Equation (15)):[6]

(17) $DC_T=2,036,447[\ln(100/100-E_P)]^{1/2}+279,184(E_M)^{.38}+21,130E_T+1,665,347$

For a given overall efficiency level, say E_T^*, equation (16) can be solved for E_P in terms of E_M:

(18) $E_P = (E_T^* - E_M)/(1 - .01E_M)$

Substituting E_P into equation (17) gives:

(19) $DC_T=2,036,447[\ln\{(100-E_M)/(100-E_T^*)\}]^{1/2}+279,184(E_M)^{.38}+21,130E_T^*+1,665,347$

Taking the derivative of DC_T with respect to E_M and setting the result equal to zero gives the first order conditions for either maximum or minimum costs:

$$(20)\quad dDC_T/dE_M = 1,018,224[\ln\{(100-E_M)/(100-E_T^*)\}]^{-1/2}[-1/(100-E_M)] + 106,090(E_M)^{-.62} = 0$$

Second order conditions are given by

$$(21)\quad d^2DC_T/dE_M^2 = -509,112[\ln\{(100-E_M)/(100-E_T^*)\}]^{-3/2}(1/100-E_M)^2$$
$$+1,018,224[\ln\{(100-E_M)/(100-E_T^*)\}]^{-1/2}[-1/(100-E_M)^2]$$
$$-65,775.8(E_M)^{-1.62} < 0$$

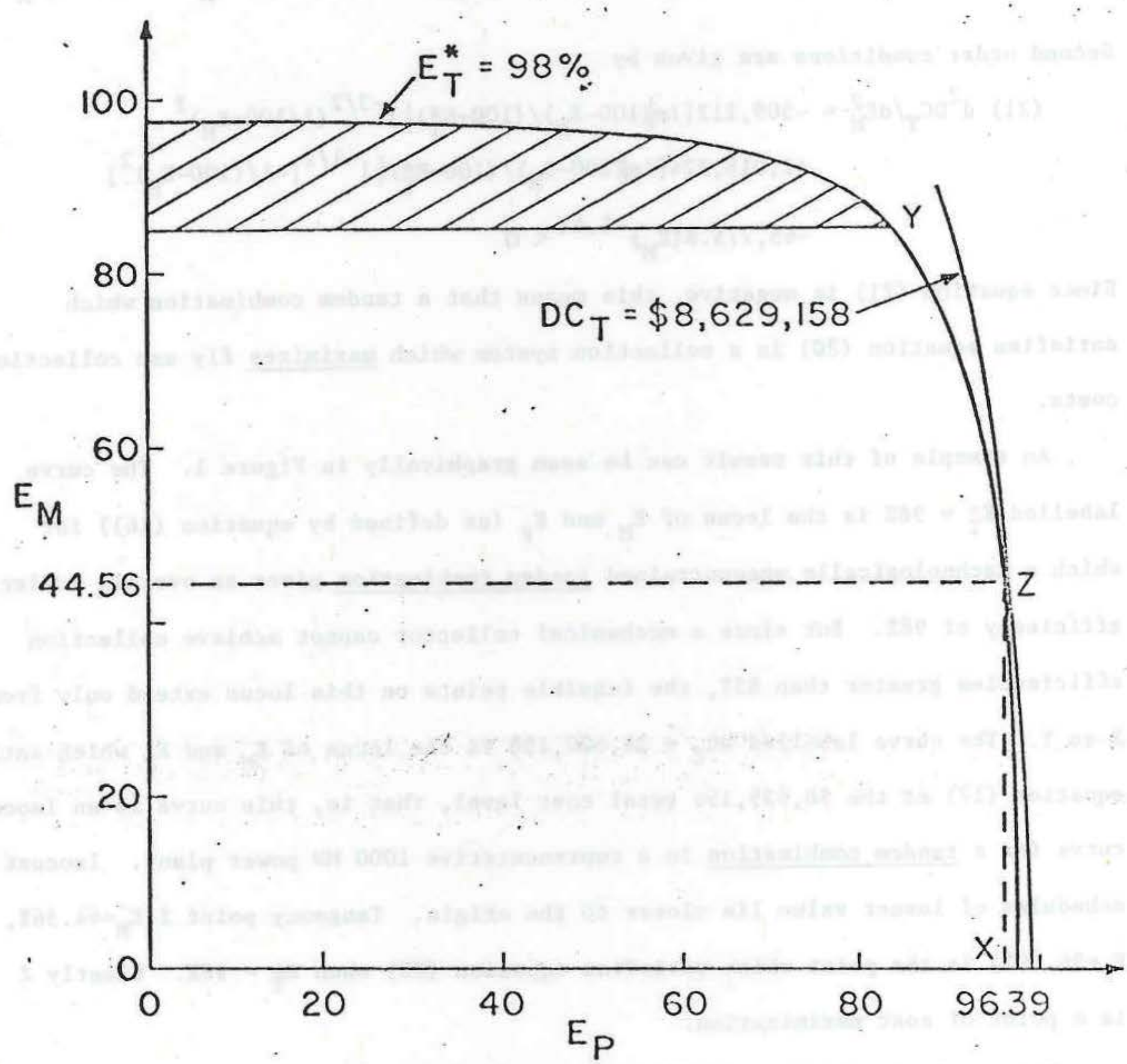
Since equation (21) is negative, this means that a tandem combination which satisfies equation (20) is a collection system which <u>maximizes</u> fly ash collection costs.

An example of this result can be seen graphically in Figure 1. The curve labelled $E_T^* = 98\%$ is the locus of E_M and E_P (as defined by equation (16)) for which a technologically unconstrained <u>tandem combination</u> gives an overall collection efficiency of 98%. But since a mechanical collector cannot achieve collection efficiencies greater than 85%, the feasible points on this locus extend only from X to Y. The curve labelled DC_T = \$8,629,158 is the locus of E_M and E_P which satisfy equation (17) at the \$8,629,158 total cost level, that is, this curve is an isocost curve for a <u>tandem combination</u> in a representative 1000 MW power plant. Isocost schedules of lesser value lie closer to the origin. Tangency point Z(E_M=44.56%, E_P=96.39%) is the point which satisfies equation (20) when $E_T^* = 98\%$. Clearly Z is a point of cost maximization.

This analysis which is generally applicable, eliminates all possible combinations except "corner combinations." For example in Figure 1, both point X and Y lie on isocost schedules of smaller value than the isocost schedule passing through Z. But which point has the smallest associated collection costs? This question can be answered by considering the total cost curves in Figure 2.

FIGURE 1

COST MAXIMIZATION
FOR A TANDEM COLLECTION SYSTEM



In Figure 2, the curve labelled DC_{M+P} is the total discounted cost curve for a mechanical fly ash collector up to an 85% collection efficiency level and then a mechanical at 85% in tandem with an electrostatic precipitator for collection efficiency levels beyond 85%. More specifically, the DC_{M+P} curve is a graph of the following equation:

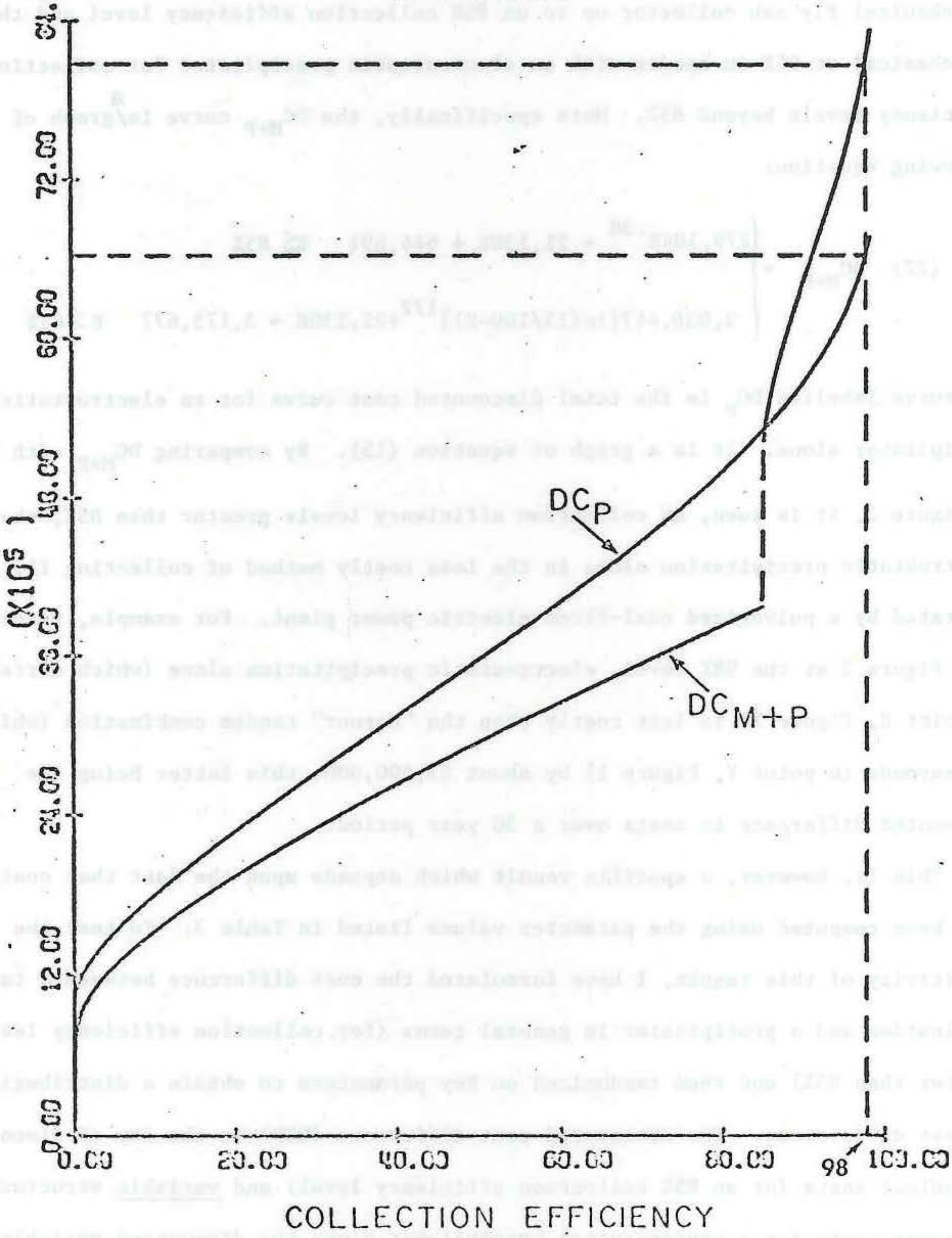
$$(22)\quad DC_{M+P} = \begin{cases} 279{,}184E^{.38} + 21{,}130E + 646{,}691 & E \leqq 85\% \\ 2{,}036{,}447[\ln(15/100-E)]^{1/2} + 21{,}130E + 3{,}175{,}677 & E > 85\% \end{cases}$$

The curve labelled DC_P is the total discounted cost curve for an electrostatic precipitator alone. It is a graph of equation (15). By comparing DC_{M+P} with DC_P in Figure 2, it is seen, at collection efficiency levels greater than 85%, that electrostatic precipitation alone is the less costly method of collecting fly ash generated by a pulverized coal-fired electric power plant. For example, reading from Figure 2 at the 98% level, electrostatic precipitation alone (which corresponds to point X, Figure 1) is less costly than the "corner" tandem combination (which corresponds to point Y, Figure 1) by about \$1,500,000, this latter being the discounted difference in costs over a 30 year period.

This is, however, a specific result which depends upon the fact that costs have been computed using the parameter values listed in Table 3. To test the sensitivity of this result, I have formulated the cost difference between a tandem combination and a precipitator in general terms (for collection efficiency levels greater than 85%) and then randomized on key parameters to obtain a distribution of cost differences. The discounted cost difference (DCD) is the sum of discounted mechanical costs (at an 85% collection efficiency level) and <u>variable</u> structure and power costs for a tandem-system precipitator minus the discounted <u>variable</u> structure and power costs for a precipitator alone. It is given as follows:

FIGURE 2

TOTAL DISCOUNTED COSTS OF A TANDEM
COMBINATION VERSUS TOTAL DISCOUNTED COSTS OF A PRECIPITATOR
(1967 DOLLARS)



(23) $DCD = M1 + M2 + M3 + M4 - M5$, where

(24) $M1 = 157.08\cdot\alpha\cdot V^{.92}(85)^{.38}(DL)^{-.22}\cdot F1$

(25) $M2 = K1\cdot\left(\frac{MW\cdot CF\cdot 1000\cdot HR}{HC\cdot 2000}\right)\cdot F2$

(26) $M3 = \left(\frac{DM\cdot 5.202\cdot 1000\cdot V\cdot\beta}{44{,}250\cdot FE}\right)\cdot F2 + \alpha\cdot K2\cdot MW\cdot F1$

(27) $M4 = 2V[1.77\ln(15/100-E)]^{1/2}(1/157.6)^{1/2}\left[\frac{F1\cdot\alpha\cdot b_1}{1.4}\right]^{.7}$

$$\cdot\left[\frac{\frac{\beta\cdot F2}{\xi_{T-R}} + F1\cdot\alpha\cdot c_1}{.6}\right]^{.3}\left[\frac{S}{Ah}\right]^{-.11}$$

(28) $M5 = 2V[1.77\ln(100/100-E)]^{1/2}[1/203]^{1/2}\left[\frac{F1\cdot\alpha\cdot b_1}{1.4}\right]^{.7}$

$$\cdot\left[\frac{\frac{\beta\cdot F2}{\xi_{T-R}} + F1\cdot\alpha\cdot c_1}{.6}\right]^{.3}\left[\frac{S}{Ah}\right]^{-.11}$$

The following definitions have been employed in the immediately preceding equations:

$DL = (3/11)\cdot Ah$ (this is a proxy for dust loading).

$F1 = (1/r)[1-(1+r)^{-30}]$

K1 = maintenance and labor costs for a mechanical collector per ton of combusted coal (e.g., equal to .005 in equation (3)).

$F2 = \sum_{t=1}^{30} h_t/(1+r)^t$

DM = pressure drop in the mechanical collector

FE = fan efficiency

K2 = installed cost of fans per megawatt capacity of the associated generator (e.g., equal to 25 in equation (5)).

Note also that the following parameters have been retained in algebraic form in equations (24) through (28) to facilitate the "generalizing" sensitivity analysis which is undertaken below:

α - capital charge rate for converting precipitator installed costs to annualized costs

Ah - average ash content of combusted coal

b_1 - installed cost per 1000 square feet of collecting plate area

β - the dollar cost of a kilowatt-hour of electric power

c_1 - installed cost per each kilowatt of power input capacity to the discharge electrodes

HC - average heat content of combusted coal

HR - average heat rate of the associated generator

K1 - maintenance and labor costs for a mechanical collector per ton of combusted coal

K2 - installed cost of fans per megawatt capacity of the associated generator

r - discount rate

S - average sulfur content of combusted coal.

Since they will vary depending upon circumstance and geographic location, I have considered a range of values for these parameters. The low, modal, and high values which I utilize are reported in Table 4.

In the actual computation of discounted cost differences I have used the following Monte Carlo scheme (based upon Dienemann (1966)):

1. Establish probability density functions (based upon the beta function) for α, Ah, b_1, β, c_1, HC, HR, K1, K2, r, and S which run over the ranges of values specified in Table 4. This procedure allows one, as well, to specify symmetry or skewness and variance spread for these distributions. My choices are indicated in columns 5 and 6 of Table 4.

2. Designate (except for MW, V, and E) appropriate values, as follows, for the remaining parameters which appear in equations (24) through (28):

TABLE 4

CHARACTERISTICS OF COST PARAMETER DISTRIBUTIONS*

(1) COST PARAMETER**	(2) LOW VALUE	(3) MODAL VALUE	(4) HIGH VALUE	(5) SYMMETRICAL OR SKEWED	(6) VARIANCE SPREAD
α	.08	.14	.18	Skewed Left	Low
Ah	6	12	24	Skewed Right	Medium
b_1	500	4,700	8,900	Symmetric	High
β	.002	.004	.008	Skewed Right	Low
c_1	80	120	160	Symmetric	Low
HC	7,000	12,000	15,000	Skewed Left	Medium
HR	8,400	9,200	10,000	Symmetric	Low
K1	.001	.005	.009	Symmetric	Medium
K2	10	25	40	Symmetric	Low
r	.04	.08	.12	Symmetric	Low
S	.3	3.3	6.3	Symmetric	Medium

* For parameters measured in dollars, low, modal and high values are in 1967 dollars.

** Characteristics for b_1 and c_1 are based upon regression analysis (Watson (1970)). Characteristics for the remaining parameters are representative of known estimates.

TABLE 5

REPRESENTATIVE FLUE GAS VOLUMES AND PRECIPITATOR SECTIONALIZATION FOR DIFFERENT SIZED POWER PLANTS*

MW (Megawatts)	V (1000's of Actual Cubic Feet per Minute)	EBS (Electrical Bus Sections)
25	131	4
100	402	6
200	706	6
300	981	6
400	1,239	10
500	1,484	12
600	1,721	18
700	1,950	18
800	2,173	18
900	2,391	24
1,000	2,605	24
1,100	2,813	30
1,200	3,019	36
1,300	3,221	36

*Flue gas volumes have been computed using an equation developed in Watson (1970, p. 80). Flue gas temperatures are assumed to be equal to 340°F.

$$CF = .9 \qquad DM = 3.5 \qquad FE = .60 \qquad \xi_{T-R} = .65$$

$$h_t = \begin{cases} 7{,}440 & \text{yrs. 1-12} \\ 5{,}200 & \text{yrs. 13-17} \\ 2{,}160 & \text{yrs. 18-25} \\ 880 & \text{yrs. 26-30} \end{cases}$$

3. Designate values for MW and V, starting with the first entries in Table 5.

4. Designate a value for E. For example, I consider, in turn, these efficiency values: 90%, 92%, 94%, 96%, 98%, 99%, 99.5%, and 99.8%.

5. Randomly pick values for α, Ah, b_1, β, c_1, HC, HR, K1, K2, r, and S from each of their respective cumulative distribution functions (these having been derived from the corresponding density functions).

6. Plug the values specified or determined in steps 2 through 5 into equation (23) and compute the discounted cost difference between a tandem combination and a precipitator.

7. Repeat steps 5 and 6, 1000 times.

8. From these 1000 reiterations determine the minimum, mean, and maximum values for the discounted cost difference.

9. Return to step 4, select the next value for E and proceed. Continue looping back to step 4 until all efficiency values have been used.

10. Return to step 3, select the next MW-V pair and proceed. Continue looping back to step 3 until all MW-V values have been used.

This provides 104 "randomly" computed sets of minimum, mean, and maximum, discounted cost differences between a tandem combination and a precipitator. To summarize this Monte Carlo experiment, I have listed in Table 6 (for each MW-V pair) the lowest collection efficiency level -- from among the 8 efficiency levels used in the computation -- for which the <u>minimum</u> discounted cost difference is positive. Hence for fly ash collection at efficiency levels above the lowest level, a precipitator installed in a power plant with the specified MW and V has a very high likelihood of being less costly than an equally efficient tandem system. It should be evident from Table 6 that this occurs at efficiency levels greater than 96% -- this being the largest of the approximate breakeven efficiencies. These breakeven efficiencies occur, of course, when the Monte Carlo procedure picks the combination of parameter values least favorable for a precipitator in comparison with a tandem combination.

In the real world, such events would occur only very infrequently. Therefore, in a great number of cases, precipitators are likely to be cheaper than tandem systems even when the levels of fly ash collection efficiency are less than the levels specified in Table 6. Nonetheless, as Table 6 indicates, at high collection levels, for example, 96% and up, which is within the range required by the new source performance standards, a precipitator alone is almost certainly going to be less costly than a tandem combination.

EFFLUENT CHARGES AND POLLUTION CONTROL EFFORT

In this section, I investigate firm behavior assuming effluent charges are levied on fly ash discharges. This analysis will be based upon electrostatic precipitator cost functions since the analysis in the previous section and in Selzler and Watson (1973) indicates that a "normal temperature" precipitator, in comparison with other available fly ash control technologies, is less costly at relatively high efficiency control levels.

It can be safely assumed that deviations in precipitator performance are of sufficiently short duration so that expected efficiency adequately describes precipitator performance within a two hour averaging period. (Recall that new source emission standards require that emissions of particulate matter not exceed

TABLE 6

MINIMUM APPROXIMATE BREAKEVEN
COLLECTION EFFICIENCY LEVELS

MW	E
25	94
100	94
200	94
300	94
400	96
500	94
600	94
700	94
800	94
900	94
1,000	96
1,100	94
1,200	94
1,300	96

.10 lb per million B.t.u. input, <u>averaged</u> over a two hour period).

From previous analysis a stochastic precipitator efficiency function, assuming pulverized coal firing, can be written as

(29) $E = 100\ [1-\exp(-ze^{u})]$, where

(30) $z = 203(A/V)^{1.4}(KW/V)^{.6}(S/Ah)^{.22}$, and where

(31) u is $N(0, .12)$.

Minimizing accounting costs of A and KW over a 30 year period subject to z (as defined by equation (30)), for given values of V, S, and Ah, would provide a discounted structure and power cost function for achieving given expected collection efficiency levels of fly ash control. In this case, structure and power accounting costs of A and KW over a 30 year period (SPAC) are written as

$$(32)\quad SPAC = d\alpha b_1 A+[(\beta/\xi_{T-R})(\sum_{t=1}^{30} k_t h_t/(1+r)^t)+d\alpha c_1]KW+d\alpha(b_0+c_0 EBS)+200MW$$

where d (the discount factor) = $(1/r)[1-(1+r)^{-30}]$ and $k_t = 1$ for all t. The other parameters in equation (32) retain their previous definitions.

It is assumed, because it is less costly, that power input to the discharge electrodes is varied so that during operation, corona discharge density is maintained at optimal operating levels. During operation, collection efficiency can decline because less power, from a steady flow of power, is available for precipitation. The main reasons are that discharge electrodes break, become grounded, or become encased in excessive layers of fly ash (Greco and Wynot (1971)). This can be overcome by having sufficient power input capacity and instrumentation so that increasing power input to functioning electrodes can maintain collection efficiency. The term 200MW in equation (32) is the discounted cost of the required instrumentation; it is based upon engineering judgment. The factor k_t (=1), indicates full utilization of power input capacity.

Expected collection efficiency is computed as follows:

(33) $\mathcal{E}E = \mathcal{E}\{100[1-\exp(-ze^{u})]\}$ where (during base load years)

(34) "First day" z=z and "last day" $z=(.808)^{.6}\cdot z$

The deterioration factor, .808, is from Greco and Wynot (1971); the exponent .6 appears because it is deterioration in power input which causes expected efficiency to fall (see the KW/V term in equation (30)).

Discounted fly ash disposal costs are the same as equation (6) except that E_M is computed as the average of first and last day expected efficiencies using equations (33) and (34) and costs are discounted. Similarly, total discounted effluent charges are the same as equation (6) except that E_M is replaced by one minus average expected efficiency (as determined by equations (33 and 34)), AC is replaced by effluent charge per ton and costs are discounted over a 30 year period.[7] The remaining precipitation costs, namely discounted labor and maintenance costs and discounted fan power costs are the same as equations (14) and (4) except that costs are now appropriately discounted. A final expense, discounted stack monitoring costs, are based upon engineering judgment and are assumed to range from \$5,000 to \$30,000 per year discounted over a 30 year period; these include annualized costs of equipment for monitoring particulate matter (not opacity) plus labor costs for recording and reporting data as required by the new source performance standards.

These cost equations provide the basis for determining the discounted marginal cost schedule. As before, Monte Carlo procedures are used to generalize results. The following programming scheme is utilized.

1. Randomly select values from beta distributions for the parameters listed in Table 7.

2. Set effluent charge = \$10N per ton of discharged fly ash where initially N=1.

3. Compute total discounted precipitation costs (including effluent charges) using the randomly selected parameter values from step 1, using the values in Tables 5, 7 and 8, and by setting z = 1.

4. Successively increment z by 1 and recompute total discounted precipitation costs. Continue through z=10.

5. Find the value of z at which total discounted precipitation costs are a minimum. Call this value z*.

6. Successively increment z*-1 by .1 and recompute precipitation costs. Continue through z*+1.

7. Find the value of [z*-1+.1J](J=1,20) at which total discounted precipitation costs are a minimum. Call this value z**.

8. Increment N by 1. Return to step 2. Continue through N=10.

9. From among z** greater than 7.32, find the minimum z**. Call this value z***. A value of z** = 7.32 provides, in accordance with equations (33) and (34), an average expected collection efficiency of 99.5% and a last day collection efficiency (base load years) of 98.33% even assuming peak load operating conditions. Operation of a precipitator at this efficiency level would satisfy the new source performance standard of .1 lb of emitted particulates per million B.t.u. heat input.

10. Determine the effluent charge associated with z***. Call this value t***.

11. Set effluent charge = (t*** - $10) + $1M where initially M = 1. Repeat steps 3 through 7. Continue through M = 20.

12. Repeat steps 9 and 10.

13. Return to step 1. Continue until 100 Monte Carlo runs have been completed.[8]

This procedure, in effect, generates the discounted marginal precipitation cost curve above minimum discounted average costs and then finds the point on this curve where average expected collection efficiency during base load years is just slightly greater than 99.5%. The marginal cost at this point is, of course, also the effluent charge which would induce a cost minimizing power plant operator to

TABLE 7

CHARACTERISTICS OF COST PARAMETER DISTRIBUTIONS*

(1) Cost Parameter	(2) Low Value	(3) Modal Value	(4) High Value	(5) Symmetrical or Skewed	(6) Variance Spread
α	.08	.14	.18	Skewed Left	Low
AC	.5	1	3	Skewed Right	High
b_0	70,000	180,000	290,000	Symmetric	High
b_1	500	4,700	8,900	Symmetric	High
β	.002	.004	.008	Skewed Right	Medium
c_0	7,200	7,600	8,000	Symmetric	Low
c_1	80	120	160	Symmetric	Low
HR	8,800	9,400	10,000	Symmetric	Medium
m_0**	1,817	2,317	2,817	Symmetric	Low
m_1***	.000027	.000033	.000039	Symmetric	Low
MC****	5,000	10,000	30,000	Skewed Right	Medium
r	.05	.09	.13	Symmetric	Low

* For parameters measured in dollars, low, modal, and high values are in 1967 dollars.

** Fixed labor and maintenance cost.

***Variable labor and maintenance cost parameter.

****Monitoring cost.

TABLE 8

"COSTING" PARAMETERS

$$h_t = \begin{cases} 7{,}440 & \text{yrs. } 1\text{-}12 \\ 5{,}200 & \text{yrs. } 13\text{-}17 \\ 2{,}160 & \text{yrs. } 18\text{-}15 \\ 880 & \text{yrs. } 26\text{-}30 \end{cases}$$

$CF = .9$

$\Sigma F_{FA} = .0085$

Fan Efficiency = .6

Pressure Drop = .5

$\xi_{T-R} = .65$

$S = .5\%$ *

$Ah = 6\%$

$HC = 8500$

* This value, representative of a low sulfur western coal and a desulfurized eastern coal, satisfies new source performance standards for sulfur dioxide emissions.

install and operate a slightly-greater-than 99.5% efficient precipitator. Furthermore, this programming routine produces unique minimums since the effluent charge per ton is a constant and the discounted marginal cost curve above minimum average cost is concave upwards.

Various estimates from this procedure are reported in Table 9. The figures in column (2) are the average per ton charges for different sized power plants needed to induce a cost minimizing power plant operator to meet new source fly ash standards. The range of charges runs from about \$53 to \$109 per ton of fly ash discharged. Total discounted precipitation costs which includes effluent charges, and effluent charges as a separate cost are reported in columns (3) and (4) respectively; except for relatively small plants the latter is about 5 to 5.4% of the former (see column (5)). The entries in column (6) are the average percentage increases in the delivered price of electric power needed to cover total precipitation costs including effluent charges. These percentages decline as power plant size increases due to economies of scale in precipitation.

A tax of about \$75 per ton would induce all but very small plants to meet new source performance standards. If coal-fired plants had been designed to meet new source standards in 1970, total effluent charge revenues at this rate would have been at the most, \$8.6 million (= 23 million tons of generated fly ash x .005 x \$75). To levy this tax it would be necessary to continuously monitor particulate matter discharges, not opacity as is currently required. However, under effluent charge enforcement the start-up compliance tests required by current legal enforcement regulation would no longer be necessary. Hence, if the Environmental Protection Agency chose to use effluent charge enforcement of new source particulate matter standards for coal-fired power plants, it should (1) require "new source" coal-fired power plants to continuously monitor and report particulate matter discharges; (2) announce a tax on particulate matter

TABLE 9

SIMULATED EFFLUENT TAX ENFORCEMENT OF PARTICULATE MATTER STANDARDS*

(1) Plant Size (MW)	(2) Effluent Charge** ($/Ton)	(3) Total Discounted Precipitation Costs** (1967 $)	(4) Total Discounted Effluent Charge** (1967 $)	(5) Charge/Cost** (%)	(6) Price Effect (%)
25	109	716,000	20,000	2.8	4.8
	(37)	(141,000)	(3,000)	(0.8)	(.9)
200	74	2,111,000	108,000	5.0	1.61
	(25)	(487,000)	(40,000)	(1.0)	(.35)
400	65	3,497,000	191,000	5.3	1.30
	(22)	(852,000)	(69,000)	(1.1)	(.30)
800	58	6,098,000	336,000	5.4	1.11
	(20)	(1,523,000)	(122,000)	(1.1)	(.27)
1,000	55	7,321,000	403,000	5.4	1.07
	(19)	(1,842,000)	(147,000)	(1.1)	(.26)
1,300	53	9,069,000	500,000	5.4	1.01
	(18)	(2,301,000)	(180,000)	(1.1)	(.25)

* For each plant size estimates are based upon 100 Monte Carlo iterations.

** Numbers in parentheses are standard errors.

discharges from these plants of about \$75/ton (in 1967 dollars); and (3) establish a precipitation cost index so that the 1967 base tax can be converted into current dollars.

COSTS VERSUS BENEFITS

The remaining issue is whether or not new source performance standards under effluent tax enforcement are economically efficient. Specifically:

1. Are total new source fly ash control benefits likely to be greater than total costs?

2. Are <u>marginal</u> new source fly ash control benefits likely to be equal to <u>marginal</u> costs?

3. Is a single emission tax sufficient or should regional differences be taken into account?

4. Are effluent taxes based upon current technology and current benefit estimates sufficient to guarantee efficiency over time?

Total Benefits and Total Costs

Estimates of the total benefits of reducing particulate matter discharges from all but miscellaneous sources are listed in Table 10. These estimates assume an overall reduction of about 87% or in terms of fly ash discharges from stationary source fuel combustion a reduction from the current level of 7.5 million tons per year to about 1 million tons per year. They have been derived by estimating benefits for the U.S. of controlling all types of air pollution and by allocating benefits to specific pollutants in proportion to the emitted tonnage of these pollutants (Waddell (1973)). Allocation by tonnage implies that benefits from controlling a ton of fly ash are equal to the benefits from controlling a ton of any other type of air pollutant. A literature search was undertaken to determine whether or not this was a reasonable basis for allocation. Only one bit of evidence was uncovered. This was a paper by Lave and Seskin (1970) linking human mortality

TABLE 10

TOTAL 1970 BENEFITS FROM CONTROLLING PARTICULATE MATTER DISCHARGES*
(1967 DOLLARS)**

Benefit Category	Low-Range Estimate (Billion $)	Mid-Range Estimate (Billion $)	High-Range Estim (Billion $)
	Amount		
Health	.9	2.3	3.7
Materials	.1	.2	.3
Aesthetics and Soiling	1.5	2.6	3.7
TOTAL	2.5	5.1	7.7

* Source is Waddell (1973).

**The Waddell estimates are in 1970 dollars; these have been converted to 1967 dollars using the Consumer Price Index.

to particulate and sulfur dioxide exposures. Their results tentatively indicate that these two air pollutants have roughly equivalent impacts on human mortality. In general, however, little is known quantitatively about the differential impacts of different air pollutants and so this allocation of benefits by tonnage must be regarded as only a very crude first approximation to actual relationships.

Not all of the benefits in Table 10, however, can be allocated to particulate matter discharges from coal-fired power plants. Table 1 indicates that coal-fired power plants contribute only about 27% of total fly ash discharges by tonnage excluding miscellaneous discharges. Miscellaneous particulates (mainly from remote sources--see Table 1) are excluded on the basis that their control would contribute very little to the benefits listed in Table 10 (Waddell (1973)). Furthermore, power plants are usually located in remote areas and they usually discharge fly ash from tall stacks. Consequently their impact on ambient air quality in populated areas is probably much less than fly ash discharged from industrial sources and from commercial and residential fuel combustion. Indeed a study by Lewis (1971) of St. Louis which adjusts for stack heights and location of emission sources and population impacted, provides a set of weights for determining exposure units per ton of fly ash discharged from different emission sources. In the Lewis study, power plants receive a proportional weight of .10, industrial sources including solid waste disposal receive a weight of .~~52~~38 and area sources (residential and commercial fuel combustion and transportation) receive a weight of .~~38~~52. In other words, a ton of fly ash discharged from a power plant has only about one-fifth the exposure impact as a ton of fly ash discharged from an ~~industrial~~ AREA source where exposure impact is measured in persons-micrograms of particulate matter/cubic meter of air per ton of fly ash. In another study (Krajeski et. al. (1972)), similar weights of about the same relative magnitude have been determined for New York City and Philadelphia.

For the purposes of this study the Lewis weights have been combined with national tonnage allocations to arrive at a benefit weighting factor of 9% for fly ash discharges from coal fired power plants. There are two implicit assumptions here. One is that stack heights, meteorological conditions, and relative locations of emission sources and population in St. Louis, New York City, and Philadelphia are representative of other U.S. urban areas. A second factor (for a fixed persons times ambient concentration) is that impacts upon a small number of people at a high ambient concentration of fly ash are equal to the impacts upon a large number of people at a low concentration.

Applying this factor, .09, to the totals in Table 10 gives a range of benefits from $225 million per year to $700 million with a mid or "best" estimate of $460 million per year.

The price effect percentages in column (6) of Table 9 are used to estimate total precipitation costs. ~~including effluent taxes~~. Assuming that all coal-fired power plants had met new source performance standards in 1970, their revenues would have been about 1.2% greater than they were to cover precipitation costs. Total coal-fired power revenues were about $11 billion in 1970. Multiplying by 1.2% gives a total precipitation cost of $132 million per year. Clearly, total benefits of the new source fly ash performance standards for coal-fired power plants are likely to be greater than total costs. Net benefits range from a low of about $93 million per year to a high of $568 million with a mid or "best" estimate of $328 million per year.

Marginal Benefits and Marginal Costs

In 1970 fly ash discharges from coal-fired power plants would have been reduced by 4.9 million tons, from 5 million to .1 million tons, if existing plants had been designed to meet new source performance standards. Dividing this reduction in tonnage into the previously cited total benefits ($225 million, $460 million, and $700 million) gives average benefits per ton removed ranging from $46/ton to $143/ton with a "best" average benefit estimate of $94/ton. Since total benefits are likely to be increasing at a decreasing rate, marginal benefits will be less than average benefits. In fact, marginal benefits must be at least one-half of average benefits--namely $23 to $72 per ton--in order to provide marginal benefits which at the upper limit approximately match the previously estimated marginal control cost of $75 per ton. But unfortunately there is no existing evidence as to the relationship between average and marginal benefit and so this limiting condition may or may not be true.

Another major qualification is in order at this point. The total benefit figures in Table 10 upon which my crude marginal benefit estimate is based are incomplete. Recent studies indicate that very fine particulates stay airborne for a considerable length of time and can be especially damaging to human health (Electrical World (1973)). Unfortunately, health effects associated with fine particulates have only recently received serious attention. Consequently avoided health damages, that is health benefits from controlling fine particulates (and a substantial percentage of these would be controlled at new source levels), have not been fully quantified and hence they are not fully reflected in the Table 10 benefit estimates. But, if they were, marginal benefit estimates might be substantially greater. Furthermore, the estimates in Table 10 exclude benefits which (using existing evaluation techniques) cannot reasonably be measured in dollars such as psychic benefits and the benefits of higher health standards for low income individuals (see Waddell (1973)).

In the absence of data, only subjective evaluations can be made in weighing these qualifying factors. On this basis, it is tentatively concluded that the new source fly ash standard for coal-fired power plants (if enforced) is probably close to being economically efficient, although the standard may be too strict if fine particulates do not have rather high marginal damages. In terms of emission taxes, this implies that a tax of between \$50 and \$75 per ton (in 1967 dollars) would be a reasonable "limited information" estimate of an efficient emission tax. However, to provide a stronger base for settting optimal standards and effluent charges, studies should be undertaken to quantify excluded benefits and to estimate an entire benefit curve as a function of control level.[9]

In Figure 3, I have plotted a reaction curve (that is, a discounted marginal cost curve) over a range of effluent charges. This curve is based upon a 200MW plant. This curve indicates a "lower bound" fly ash removal efficiency which would be achieved by almost all but small coal-fired plants. At taxes of \$50 and \$75 per ton, removal efficiencies for almost all plants (if operators are cost minimizers) would be at least 99.3% and 99.5% respectively. Assuming that existing coal-fired power plants in 1970 had been designed to remove these percentages of fly ash, total effluent charge revenues in the two cases would have been at the most, \$8.1 million and \$8.6 million respectively.

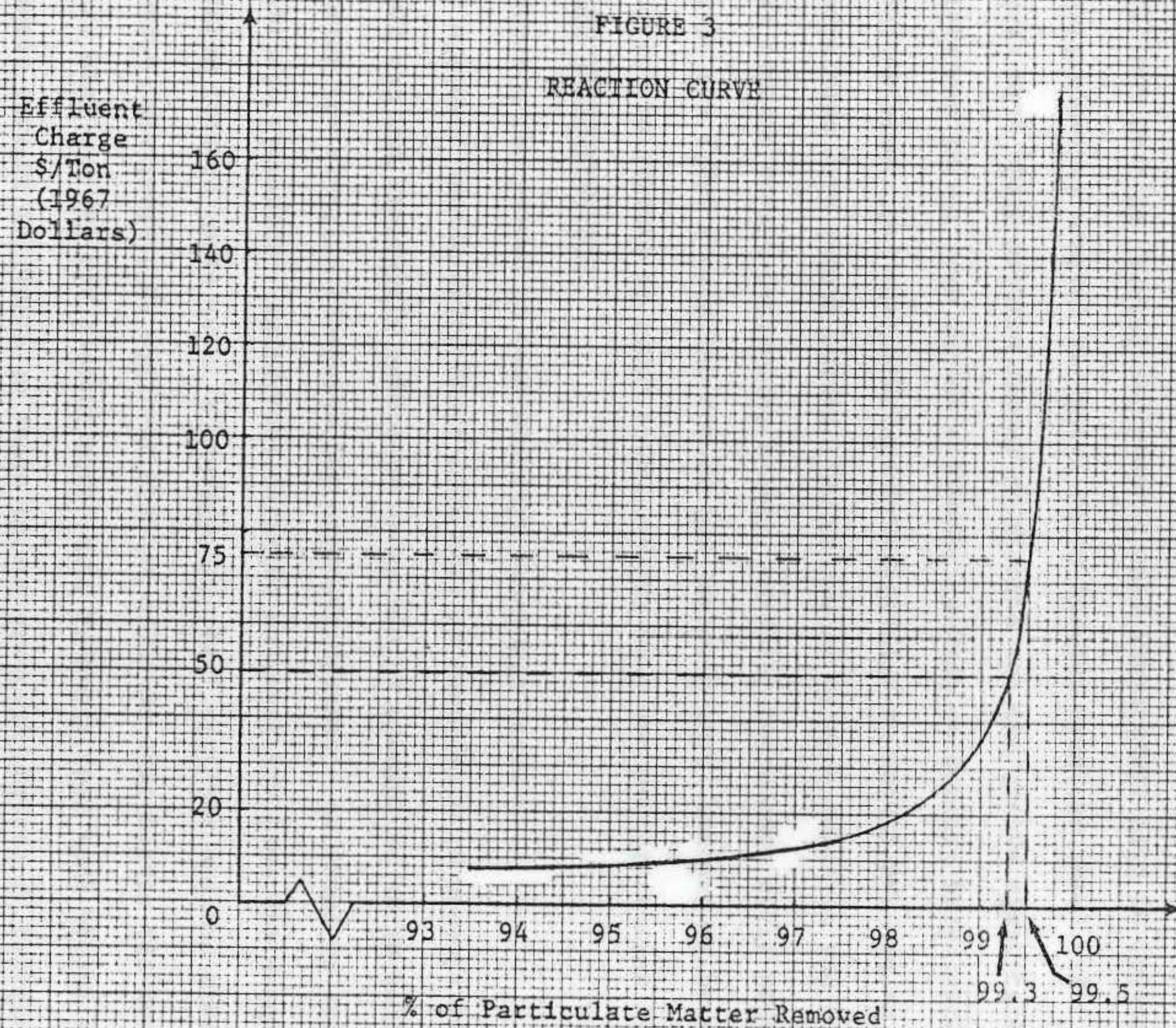
Regional Considerations

The analysis to this point has been based upon aggregate U.S. estimates of costs and benefits. This is merely a matter of convenience: it is easier to estimate national costs and benefits than it is to perform a series of regional analyses. This does not, however, obviate the need for detailed regional analyses. As Ridker states (1967, p. 9):

> "(Cost/benefit studies) should be made within a specific air shed and on specific pollutants. Each pollutant has its own characteristics and each community faces different meteorological, topological, and economic conditions. The appropriate standard, therefore, will vary with the pollutant and the community being studied."

FIGURE 3

REACTION CURVE



The total benefit estimates in Table 10 are directly related to particulate matter impacts upon man and his possessions. This suggests that very strict standards and hence relatively high effluent charges might be appropriate for densely populated regions while lower standards and lower effluent charges might be appropriate elsewhere. Additional detailed regional analyses are needed to determine the specific standards and effluent charges. In light of this, the \$50 and \$75 per ton charge suggested above can be thought of as an average national effluent charge which could very well be inadequate in densely populated regions and too severe in some sparsely populated areas.

Dynamic Considerations

With the passage of time, both marginal cost and benefit curves will tend to shift to the right (costs per ton on the vertical axis, percent of particulate matter removed on the horizontal axis). Marginal costs will shift because costs of collection will likely become less expensive as more research and development on devices other than electrostatic precipitators is undertaken and as process modification rather than add-on equipment is used to control pollutants. Marginal benefits will shift because income is growing and the income elasticity of demand for environmental quality is likely to be greater than one (see, e.g., Harris, Tolley, and Harrell (1968)) and because more individuals will be impacted by pollution as population grows. The latter, however, will be offset to some degree by remote siting of power plants. If both shifts occur at the same rate, then effluent charges based upon current comprehensive cost/benefit tradeoffs will be approximately efficient over time. However, it is not currently known whether or not the two rates are the same and so further research must be undertaken to analyze such dynamic factors.

SUMMARY AND CONCLUSIONS

In this paper, I have attempted to show that an effluent charge of between \$50 and \$75 per ton (in 1967 dollars) on fly ash discharged from new source coal-fired power plants is a reasonable "limited information" estimate of an economically efficient emission tax. Dynamic and regional studies should, however, be undertaken on the costs and benefits of controlling particulate matter with special emphasis given on the benefit side to the health effects of fine particulates and on the cost side to process modification. Such studies may indicate that other levels of fly ash effluent charges are more efficient for specific conditions and for specific regions.

The analysis in this paper also indicates that effluent tax enforcement of new source standards for particulate matter discharges from coal-fired power plants would have little financial impact on the electric utility industry. At the same time, since the industry is easily delineated and since reaction curves can be estimated--as they are in this paper--it is fairly straightforward to implement effluent tax enforcement. This will probably save substantial enforcement expense--such as the costs of compliance testing, time in court, and lawyers fees--which would likely arise under an <u>effective</u> legal enforcement strategy. Furthermore, if economists are right, effluent fee enforcement will probably encourage a relatively faster rate of process modification. Firms cannot easily escape effluent fees, but they can escape legal standards by challenging them in court. Indeed, differential savings in control expense from accelerated process modification may well be the largest economic payoff to effluent tax enforcement of environmental standards.

FOOTNOTES

[1] See, for example, Solow (1971) and Freeman and Haveman (1972).

[2] The value .02 is the standard error of u; 1.65 is the .45 zeta value from the standardized normal distribution. A 95% upper confidence limit for u is $(u-0)/.02 = 1.65$ or $u=.02 \cdot 1.65$. It should be noted that this procedure does not account for uncertainty introduced by errors in estimating the parameters in equation (2).

[3] An advantage of this methodology, in comparison with traditional purely statistical cost analysis, is that it brings more information to the analysis, thereby allowing more efficient estimation of model parameters (Anderson (1970)). Note that in estimating the installed costs for a mechanical collector, I used statistical cost analysis rather than this more "efficient" procedure. The reason for this is that in the former case, unlike the present precipitator case, there was no functional form for comprehensively describing multi-cyclone collector performance.

[4] It should be noted that this procedure does not account for uncertainty introduced by errors in estimating the parameters in equation (8).

[5] Charges against the installed costs of fans are not levied in the case of an electrostatic precipitator since very little additional fan capacity, beyond that used to move the flue gas through the normal duct system, is needed to move the flue gas through a precipitator. The pressure drop across a precipitator is not likely to ever be much greater than 0.5 inches of water.

[6] Equation (15) has, however, been slightly altered. As derived, (15) is for a precipitator preceded by a pulverized coal furnace and hence MF equals 1. But a precipitator in tandem with a mechanical collector has MF equal to 0. This alteration which makes tandem costs higher, is reflected in equation (17).

[7] Computation of discounted effluent charges and fly ash disposal costs requires evaluation of equation (33). Under the assumption that u is normally distributed with mean 0 and variance .12, equation (33) can be solved for given values of z using computerized numerical integration (see Watson (1973).

[8] Computation was performed on an IBM 370/165 system. Run time for 100 iterations exceeded 3 minutes with charges in excess of $200. A least squares approximation was substituted for numerical integration of equation (33) otherwise charges would have been about 10 times larger. Check computations indicated little loss in accuracy as a result of this substitution.

FOOTNOTES (Continued)

9 On the cost side, I have ignored marginal monitoring and enforcement costs. Under effluent tax enforcement, these are likely to be very small relative to marginal control costs and hence can probably be safely ignored.

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