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The Economics of Enforcing Air Pollution Controls[1]

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The goal of this paper is to determine the likely effect on a firm's control actions of alternative implementation and enforcement policies available to the control agency. Three alternatives are studied, legal enforcement through the new source performance standards set forth by EPA, and two effluent fee enforcement alternatives. First, a generalized model of the effects of implementation and enforcement policies on the firm's control actions is developed. This model assumes that the firm is an expected cost minimizer. The model is then applied to the case of particulate matter discharges from coal-fired power plants in order to estimate empirically the effect of policy alternatives on the firm's control efforts. Finally, the results of the model and its empirical application are used to develop policy functions which relate control to the values of various policy parameters. These results lead us to several policy recommendations.

INTRODUCTION

The use of the environment by a firm can impose uncompensated costs on other firms or on individuals. There are two general methods which may be employed to internalize these costs to the polluting firm: namely, emission standards and emission charges.[2] In assessing the cost of pollution control typical studies look only at the cost of the control device or process change without concern for the institutional constraints placed on the firm by the control agency and the legislature. Yet it is clear that the firm incurs differential expenses in addition to (or instead of) the actual installation and operation costs of the control device or process change itself. These additional expenses can include compliance testing or other certification expenses, legal expenses, fines, and other enforcement costs. These expenses are a function of the implementa-

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[2] Other possible control instruments such as subsidies and marketable permits have been neglected in this study.

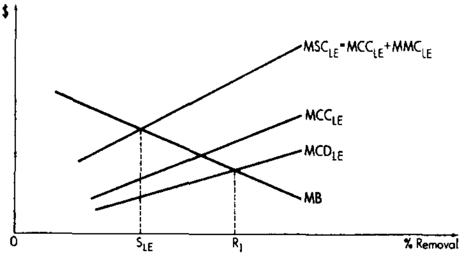

FIG. 1. Standards enforcement.

tion and enforcement rules employed by the control agency. Hence they are likely to vary with the method of internalization (policy instrument) chosen.

Optimal Emission Standards

Before we proceed with the development of our model, a general framework is provided by investigating how the cost to the firm of complying with control requirements and the cost to society of insuring that the firm complies affect the optimal level of pollution control.[3] It is likely that both these costs will differ between the two implementation and enforcement alternatives. Let us first investigate legal enforcement (LE) and then turn our attention to effluent fee (EF) enforcement. In Fig. 1 we plot increasing percent removal of a pollutant (R) on the horizontal axis and dollar costs on the vertical axis. The marginal cost of a control device (MCD_{LE}) increases as removal increases. This is the cost function measured in the usual control cost study. However, the cost of the device is not the full cost born by the firm. Depending upon the form of legal enforcement the firm may have to conduct compliance tests, incur monitoring costs, keep records and meet other requirements imposed by the control agency. Interpreting these curves as planning horizon cost curves it is clear that at least some of these compliance costs vary with R. Thus, the marginal cost of control for legal enforcement (MCC_{LE}) which the firm actually faces includes both MCD_{LE} and these other costs and lies above MCD_{LE}.

The marginal social cost of control using legal enforcement (MCS_{LE}) includes the cost to the firm (MCC_{LE}) and the cost to the control agency of carrying out enforcement activities in an attempt to insure that its rules and regulations are carried out (MMC_{LE}). The control agency must inspect the site to determine that the firm has the required controls installed and operating and that it does not cheat by turning the devices off when the control agency personnel are not around. It is reasonable to assume that at least some of these costs vary with the level of removal. This is because it is likely that the payoff to cheating will increase as the required level of control increases. Control agency enforcement efforts should increase in an attempt to counteract this incentive.

Assuming the usual declining marginal benefit function (MB), the optimal level of control for this set of control instruments would be where $MSC_{LE} = MB$ or S_{LE} in Fig. 1. Note that when it is recognized that social control costs are greater than the cost of the device itself, the optimal level of control of pollution is less than the level usually determined in empirical studies (R_1). The neglect of these costs would lead to the setting of a standard which is inefficiently stringent.

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[3] Anderson and Crocker (1971) suggest that these issues are of vital importance in control instrument decisions but do not cite any literature which explores their effects on control.

The same conceptual set of control cost functions hold for the effluent fee enforcement case. However, each of these functions may differ from their legal enforcement equivalents in their actual location on the graph. There are compliance costs for the effluent fee enforcement system as well. The firm must record emissions, pay the fee, deal with periodic checks by control agency personnel, etc. It is reasonable to assume that these compliance costs would increase with the level of removal. Likewise, the marginal management costs to the control agency are likely to increase with the level of removal. This is because higher removal and consequently greater effluent fees makes cheating more profitable to the firm. This in turn necessitates greater checking by the control agency.

If society's goal is to control pollution at least cost (and if it wished to neglect distributional issues), it should pick that institutional form which is least costly. Economists have often argued that the best institutional form for pollution control is the effluent fee. For this to be true it is necessary that the net social benefit of control for the effluent fee enforcement system be greater than the net social benefit of control for the legal enforcement system where each is at its optimal level (i.e., MSC = MB).

In order to determine if the economists' argument is correct it is necessary to know both MCC and MMC under legal enforcement and effluent fee enforcement. While logical arguments can be made to support the economist's argument, the other side also has merit. The determination will probably rest on empirical evidence yet to our knowledge no such estimates exist. This paper attempts to fill part of this gap by determining the firm's cost functions under alternative enforcement policies. The determination of the control agency's cost functions are left for future research.

AN ENFORCEMENT MODEL OF THE FIRM'S CONTROL BEHAVIOR

In this section we derive a model of the firm's reactions to enforcement strategies. We then explore various cases to determine the likely reaction of the firm to alternative values of the policy variables under differing technological and time frame assumptions. In the following section this model is applied to the case of new source performance standards for fly ash discharge from coal-fired power plants.

Becker (1968) developed a model of the economics of crime and punishment which consists of a damages function, an enforcement cost function, a supply of offenses function, and a punishment function. Becker's supply of offenses function can be interpreted in terms of air pollution control. The polluter's supply of offenses (the number of times he exceeds the standard) are assumed to be a function of the probability of his being convicted, the fine he pays per conviction, and what Becker calls "a portmanteau variable" representing the sum of all other influences It is this supply of offenses (emissions) function that we explore for the air pollution case in this paper. Specifically stated, our goal is to intestigate the reactions of an individual firm to alternative standards, conviction probabilities, and fines (the policy variables) under different implementation schemes.

Cost of Pollution Control to the Firm

It is assumed for the purposes of this paper that the firm seeks to minimize the expected cost of control of pollutants [E(CC)].[4] These expected costs are the sum of

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[4] While our model does not specifically consider the tradeoffs involved in the interrelationships between control costs and total product output of the firm, the conclusions reached here do hold in the general case. For a model which relates pollution control costs to the optimal output of the firm see Fan and Froehlich (1972).

the expected cost of control devices [E(CD)] and the expected cost of compliance and enforcement actions imposed on the firm for compliance or noncompliance with required controls or standards [E(EC)]. The firm's objective function[5] is then

$$\min E(CC) = E(CD) + E(EC), \tag{1}$$

given a fixed set of control regulations (the policy variables). Both CD and EC are stochastic in this formulation. Device costs include both capital and installation costs (KC) and operation and maintenance costs (OM). For many devices OM will have some distribution about an expected value because the device might partially or fully fail during the period (as when a catalytic reactor gets poisoned). Enforcement costs are stochastic because the control efficiency of the device is stochastic causing the incidence of violation to be uncertain. A complete analysis of E(CD) is not necessary for our purposes. It is assumed here (and has been shown for the electrostatic precipitator case we explore empirically) that:

$$\partial E(CD)/\partial R > 0$$

and

$$\partial^2 E(CD)/\partial R^2 > 0$$

The arguments in the E(EC) function are somewhat different depending upon the implementation and enforcement method used. For the legal enforcement method now employed for new sources by EPA the expected enforcement and compliance costs are a function of the expected number of days the firm is detected to be in noncompliance during the year [E(N)] times the expected penalty imposed on the firm for each violation [E(P)].

$$E(EC) = f[E(N) \cdot E(P)]. \tag{2}$$

E(N) is a function of the expected control efficiency of the device installed by the firm [E(R)] given the various rules and regulations imposed upon the firm by the control agency and/or the legislature.

$$E(N) = g[E(R) \mid I, S, C], \tag{3}$$

where

I = the frequency, accuracy, and form of the inspection and monitoring actions of the control agency,
S = the emission standard set by the control agency,
C = the requirements set by the control agency for certification of the effectiveness of the firm's control device (usually through some sort of compliance testing procedure).

That is, for any given set of control agency policies, the higher E(R) the lower E(N). If the control agency were to increase its enforcement efforts by increasing the frequency of inspections, improving the accuracy of monitoring, or making compliance tests more strict, any given E(R) would imply a larger E(N). Likewise, a more stringent emission standard would increase E(N).

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[5] This objective function can easily be translated into Becker's supply of offenses function. However, it is stated in stochastic form rather than deterministic form since many of the terms are stochastic in nature. The first derivative of this function represents the value to the firm of a violation and hence under perfectly competitive conditions the opportunity cost to society of pollution control.

The expected penalty is a function of the probability of being convicted of being in violation (PC), the money fine imposed on the firm by the courts if convicted of being a polluter (F), the damages to the firm's image if convicted (DI) and the possible shutdown time (ST) for required repairs or construction if found in violation by either the control agency or the courts.

$$E(P) = h(PC, F, DI, ST). \tag{4}$$

PC is a function of the legal costs incurred by the firm to defend itself against the control agency (LC). The effectiveness of a dollar spent on defense demands upon the control agency's prosecution efforts (CAP).

$$PC = k(LC\ CAP). \tag{5}$$

The firm will minimize its cost where

$$\partial E(CC)/\partial R = \partial E(CD)/\partial R + \partial E(EC)/\partial R = 0. \tag{6}$$

Since enforcement costs decline as removal increases, this condition can be satisfied. For a set of policy parameter values Eq. 6 defines the values of MCC_{LE} and MCD_{LE} as equal to the values of $\partial E(CC)/\partial R$ and $\partial E(CD)/\partial R$, respectively.

In the case of pure effluent fee enforcement the E(EC) function is less complex. Expected enforcement costs are simply a function of R and the level of the effluent fee (EF) per unit of emissions given some monitoring and inspection system and possibly some certification of the control device as well.

$$E(EC) = m(R, EF \mid I, C), \tag{7}$$

where under usual circumstances

$$\partial E(EC)/\partial R < 0,$$

and

$$\partial^2 E(EC)/\partial EF^2 > 0.$$

Alternative Enforcement Strategies

Having discussed the factors which affect the firm's expected cost of environmental control, we turn our attention to the effects of alternative enforcement strageties on their expected cost and the firm's reaction in terms of pollution control.

Let us assume that the control agency has an air quality goal which it is attempting to reach using the legal enforcement method. It has several policy tools available by which it can effect the control efforts of the firm. It can set higher or lower emission standards, change penalties for noncompliance, make court actions more prompt, and impose external pressures on the firm through public statements.

Standard. The firm will react to higher standards by installing more effective devices, but only if the expected penalties and court costs are higher than the cost of control. It will delay as long as the court cost of delaying actions is less than the interest on the cost of control devices and savings in operation and maintenance expenses. For a given envorcement effort against the firm, a higher standard will cause the firm to attempt more delaying actions.

Monitoring. The lack of any monitoring of the control actions of the firm will make any standard set by the control agency ineffective. The frequency and type of monitoring will also affect the firm's compliance.[6]

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[6] For an investigation of monitoring alternatives applied to automotive emissions see Downing (1974).

There are two stages of our legal enforcement model. One for the situation before the firm takes any control action and another for the situation after the installation of control equipment. This is because control and enforcement costs differ in the two cases. To make this distinction clear, Eq. (1) is rewritten as follows.

$$\min E(\mathrm{CC}) = [\mathrm{KC} + \mathrm{E}(\mathrm{EC_B})] + [E(\mathrm{OM}) + \mathrm{E}(\mathrm{EC_A})], \tag{8}$$

where

$\mathrm{E}(\mathrm{EC_B})$ = expected enforcement cost before installation of a control device,

$\mathrm{E}(\mathrm{EC_A})$ = expected enforcement cost after installation of a control device (i.e., during operation).

In the before installation case all of Eq. (8) holds although it is possible that the firm will perceive $\mathrm{E}(\mathrm{EC_A})$ as zero in which case the last two terms drop out.

After installation of the required devices the first two terms on the right hand side of Eq. (8) are inoperative. The firm is faced with the choice of operating the device or not and its decision clearly depends upon $\mathrm{E}(\mathrm{EC_A})$. This in turn depends upon $\mathrm{I_A}$. Assuming that each violation detected by an inspection is a separate offense (the usual case in control legislation), an increase in monitoring frequency will *ceteris paribus* yield more control. The device will be operated more effectively and more often. But the form as well as the frequency of inspection will affect this result. Unannounced inspections will be more effective in stimulating proper operation and maintenance of devices. Indeed it has been observed that when control authority personnel go home at night firms take the opportunity to plow the accumulated fly ash out of the stack. This can be safely done because, in effect the control agency has announced noninspection.

Penalty. It is perhaps obvious that increasing the level of penalty imposed (rather than threatened) will increase compliance by the firm. The timing of the imposition of a penalty can also have a substantial effect on the firm's control effort. If the expected value of the penalty is constant, it will induce firms to employ legal delaying actions if the legal costs are less than the interest on the expected value of the penalty. If the penalty were made a fee and hence payable upon release of the pollution, its present value would be increased. Thus, an effluent tax is more effective than an equivalent penalty per pound because it is payable on release rather than after court action. As a corrollary to this result, the control agency can make the effective penalty larger by increasing the speed of bringing accused violators into court. There is another reason to believe that an effluent fee will be more effective than a penalty. The direct payoff for cheating 10% on reporting emissions in the effluent fee case saves the firm 10% of the fee. In the penalty case, because of the zero/one nature of the violation definition, this level of cheating may save 100% of the penalty. It pays more to cheat in the legal enforcement system than in the effluent fee system.

In addition to the above policy alternatives, the control agency has two more options. First, it can try to obtain more tightly written laws which would increase the probability of obtaining a conviction (make the penalty more certain) and/or improve their preparation to the same end.[7] Second, the control agency can increase the damage to the firm's image by publicly announcing violations.[8]

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[7] Tittle (1969) as shown that greater certainty of punishment for a crime is associated statistically with lower offense rates.

[8] It has another opion—to shift to an alternative enforcement scheme. This may be preferable since in the current legal enforcement scheme noncompliance is "... enforced by criminal process, probably the most cumbersome coercive tool we have. The violator is protected by all the constitutional protections which apply to any criminal trial. He can demand a trial by jury and unanimous verdict (and this against the heavy burden of proof faced by the prosecution)." (Krier, 1970, pp. 5–29.)

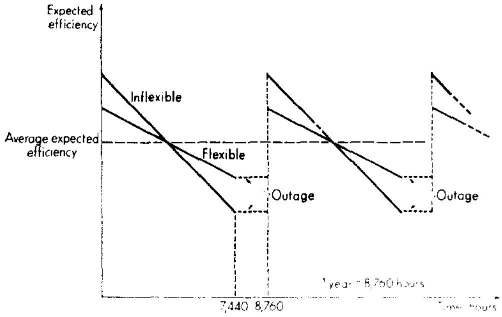

FIG. 2. Precipitator operating curves.

A SIMULATION OF ENFORCEMENT ALTERNATIVES

We have presented a general theory of a firm's reactions to environmental control implementation and enforcement alternatives. In order to demonstrate some of these propositions and determine their empirical significance a simulation study was conducted for enforcing the federal new source performance standards for particulate matter discharges from coal-fired power plants. The simulation model employed allows us to determine the likely control actions of the firm (and related costs) resulting from alternative levels of enforcement policy parameters and implementation schemes. In effect, via this analysis we will be examining a variety of enforcement "experiments."[9]

Ideally it is desirable to find the set of enforcement policy parameters which minimize the sum of costs for both firms and enforcement agencies. This analysis, however, covers only costs to firms since data and information on enforcement agency costs are almost nonexistent. Nonetheless it will be seen that the partial results reported here are rich in policy implications.[10]

The Simulation Model

We have simulated six policy scenarios:

	Inflexible technology	Flexible technology
Compliance test with fine for violating an opacity standard	S1	S2
Compliance test with tax on emitted fly ash	S3	S4
Emission tax only	S5	S6

Our model describes the firm's least-cost effort to control fly ash discharges given each of the three enforcement policy sets listed above and two variants of electrostatic precipitator technology: inflexible and flexible.

Figure 2 demonstrates the difference between flexible and inflexible precipitator technology. Expected collection efficiency is measured on the vertical axis; operating hours are measured on the horizontal axis. A typical base loaded power plant will operate about 7440 hours per year, the remaining hours in that year will be outage hours when normal maintenance is performed on generating equipment and pollution control devices. The two curves labelled "inflexible" and "flexible" show that precipi-

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[9] A detailed explanation of the simulation model can be found in Downing and Watson (1973).

[10] It is assumed throughout that managers of coal-fired power plants attempt to minimize expected costs over their planning horizons and that available cost effective fly ash control technology is electrostatic precipitation (see Watson (1974)).

tator efficiency declines over operating hours. This occurs because precipitator discharge electrodes fail, lowering the filtering capacity of the precipitator (Greco and Wynot (1971)). The dashed-line sections of the operating curves represent precipitator maintenance time during scheduled outages of the power plant. On restart, precipitators again perform at top efficiency. By comparing the two performance curves it is seen that a flexible precipitator's efficiency declines less rapidly during an operating cycle. This results from having power shunting electonic instrumentation which optimizes precipitator filtering capacity as discharge electrodes fail. In comparison with a larger inflexible precipitator, a smaller sized flexible precipitator can produce the same average collection efficiency over an operating cycle.

The Legal Enforcement Model

Equation 8 is used as the starting point for our simulations of the firm's reaction to alternative values of the control agency's policy parameters. The firm is assumed to be minimizing its expected costs of control subject to the constraints placed on it by control agency policy. A wide range of policy options are explored. For each set of policy parameters the legal enforcement simulation model considers a number of precipitators of different sizes and consequently different expected collection efficiencies. For each precipitator the model computes the probability of passing a start-up compliance test at some specified compliance test standard. It also computes the expected number of days per year when each precipitator would violate a specified opacity standard. Using these two pieces of information it then computes and sums costs in order to determine total expected costs.

The model begins by computing and summing precipitator installation costs and compliance test costs. Using the probability of passing the compliance test as a weighting factor it then adds in operating, maintenance and stack monitoring costs plus fines for violating the opacity standard, all of these costs, of course, having been computed for a precipitator of the originally specified size. A given precipitator, however, may fail the compliance test. If it fails the model assumes that the precipitator is enlarged to a size which has virtually no probability of failing a subsequent compliance test. In such cases, a power plant would then incur the installation and penalty costs[11] for an enlarged precipitator and its operating, maintenance and stack monitoring costs plus fines for violating a specified opacity standard during operation of the enlarged precipitator. The model sums these costs and uses the probability of failing the compliance test (1-probability of passing) as a weighting factor. The sum of the expected costs yields total expected out-of-pocket costs for a precipitator of some specified size, for a specified compliance test standard and opacity standard, and for a single compliance test.[12] The model then allows successive runs of the compliance test. This changes the probability of passing and failing the compliance test and changes the weighting factors in computing total expected costs. At this stage, the model finds the number of compliance tests at which total expected out-of-pocket costs are a minimum. It then goes on to successively larger sized precipitators, computing costs in exactly the same

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[11] Penalty costs in this case are the increased costs of producing the power from alternative sources and the interest on investment in the plant during the six months that would be required to complete the expansion.

[12] Two very computationally complicated variants of this model were investigated. One was least cost selection of load shedding or fines when the opacity standard was violated. Another was least cost selection of serial enlargement or a single state enlargement. In a sensitivity analysis, both variants in combination produced results approximately equal to those of the simpler basic model.

fashion for the given set of compliance test and opacity standards. It also holds constant throughout, the flue gas flow rate, the number of averaged stack samples taken during a compliance test and the expected fine for violating the opacity standard. As a final step it finds the precipitator size or efficiency which minimizes total expected out-of-pocket costs to the firm for the given set of enforcement policy parameters. The set of exogenous enforcement policy parameters is then changed and the model rerun.

The only difference between policy scenarios S1 and S2 (similarly S3 and S4) is the selection of precipitator technology. In going from S1 to S2 (and S3 to S4) everything else is held constant in running the model including the exogenous enforcement policy parameters.

Federally promulgated regulations require that the average of at least three separate stack samples must provide a reading which satisfies the compliance test standard before a power plant is allowed to begin full time operation. The model simulates this by repeated sampling from the appropriate density functions, averaging of the sample efficiencies, and computation of pass and fail probabilities. As the number of averaged stack samples is increased, cost minimizing power plants will tend to pick more efficient precipitators.

The probability density functions associated with the compliance tests are also affected by boiler load conditions during compliance tests. When boilers are loaded at peaking levels, the flue gas flow rate through a precipitator can be about 15% above the normal level. Clearly the probability of failing is less under normal load conditions. On the other hand, compliance tests under high load conditions make the compliance test more effective in enforcing a given fly ash emission standard. The model allows for flue gas flow rate variations in simulating compliance tests and hence in computing probabilities of pass and fail.

The Emission Tax Model

For a precipitator of given size and for a given emission tax per ton of fly ash discharged, the emission tax cost model computes total emission taxes. To these it adds installation costs, operating, maintenance and stack monitoring costs to obtain total expected out-ot-pocket costs. Precipitator size is then incremented and total costs recomputed. Computation is truncated when the model finds the precipitator size or efficiency which minimizes the sum of precipitator costs and total taxes for the given emission tax. The emission tax, which is a constant value per ton, is then incremented and the model rerun. Unit emission taxes which vary over time with meterorological conditions for example, and unit taxes which increase as total emission increase, are not specifically considered. However, such emission taxes would not change our basic results.

Simulation Results

The objective of the simulation model is to provide cost and performance functions for each of the policy scenarios. The following functions are of interest: expected out-of-pocket costs to the firm as a function of enforcement policy parameters; expected precipitator efficiency as a function of enforcement policy parameters; and expected out-of-pocket costs to the firm as a function of removal efficiency.

The following ranges of enforcement policy parameters are covered in the simulated scenarios:

Before installation parameters	Range
Compliance test standard (S_{LEB})	0.04–0.14 lb/million (Btu discharge rate)
Compliance test conditions (C)	
No. of averaged stack samples (N)	3–50 stack samples
No. of successive compliance tests (M)	3–15 tests
Flue gas flow rate (FR)	1 V–1.15 V (V is the normal load flue gas flow rate)
After installation parameters	
Opacity standard (S_{LEA})	5–40%
Fine/day of violation (F_A)	\$500–\$50,000/day
Probability of conviction (PC_A)	0–1
Emission tax parameter	
Tax/ton of fly ash (T)	\$5–\$180/ton

Scenarios S1 through S4 use of combination of structured and randomly chosen enforcement policy parameters. Our objective was to uniformly cover a relatively wide range of enforcement policy combinations. In all, 50 different policy combinations were selected for these simulations. These policy combinations allow for variations in the above policy parameters only. Several options available to the firm and/or the control agency were not included because of inability to observe and quantify relevant parameter values. Thus, we assume that the firm will attempt to comply with the control agency's requirements rather than carry on a prolonged legal battle although the latter is possible or perhaps likely. Delay of the payment of a penalty through legal action is also assumed to be zero as is damage to the corporate image (DI). While we do allow for variations in the probability of conviction, we do not explicitly investigate the trade-offs implicit in Eq. 5. These regretable but necessary omissions in the assessment of the firm's reaction to policy alternatives result in a bias toward overly optimistic estimates of control. Firms may, and often have in the past, take the legal delay alternative we exclude from our analysis. In the case of the emission-tax-only scenarios, the model was run for only a maximum of 10 different tax rates since each emission tax produces a unique least-cost response. For each set of enforcement policy parameters the model computes expected precipitator efficiency, expected least-costs of fly ash control and expected fines or emission taxes paid. Furthermore, in order to provide for differential response due mainly to economies of scale, the model considers four different plant sizes, 1300 MW, 800 MW, 200 MW, and 25 MW. That is, for each power plant size per scenario, the simulation experiments provide 50 observations (scenarios S1 through S4) or a maximum of 10 observations (scenarios S5 and S6) on firm least-cost behavior as a function of enforcement policy parameters.

Since the model is too complex to solve analytically regression analysis has been used to summarize these "experimental" data. In effect, this "solves" the model. The following functions have been fitted.

Scenarios S1 through S4:

$$C = A(S_{LEB})^{a_1}(N)^{a_2}e^{MD\cdot a_3}(FR)^{a_4}(S_{LEA})^{a_5}(FT)^{a_6}; \tag{9}$$

$$E = 100 - 100\cdot \mathrm{EXP}[-B(S_{LEB})^{b_1}(N)^{b_2}e^{MD\cdot b_3}(FR)^{b_4}(S_{LEA})^{b_5}(FT)^{b_6}], \tag{10}$$

Scenarios S5 and S6:

$$C = A(T)^{a_6}; \tag{11}$$

TABLE I

CURRENT ENFORCEMENT PRACTICE

Plant Size (MW)	Expected average efficiency[a] (%, inflexible technology)	Expected cost (1000's of 1967 dollars, discounted)	Expected time in violation[a] (%)
25	99.1%	$ 720	0%
200	98.0	1,900	61
800	97.7	5,200	70
1300	97.7	7,800	70

[a] During base load year at normal flue gas flow rates. Time in violation would be higher and average efficiency lower to the extent that plants are operated above normal loads, for example, under peak load demand conditions.

All scenarios:

$$E = 100 - 100 \cdot \mathrm{EXP}[-B(T)^{b_6}]. \tag{12}$$

$$C = D(\ln(100/(100 - E)))^{d_1}(N)^{d_2}; \tag{13}$$

$$C - FT = G(\ln(100/(100 - E)))^{g_1}(N)^{g_2}. \tag{14}$$

C is total expected discounted cost. It includes out-of-pocket firm pollution control costs, associated firm management costs, and total fines or emission taxes. E is average expected precipitator collection efficiency (%) during base-load years. FT is total expected discounted fine or emission tax. MD is a dummy variable which is 1 when the maximum number of allowable successive compliance tests is 3, and 0 when greater than 3.

Individual enforcement policy coefficients within the indicated functional forms are not constrained in the simulation model. They may or may not be significant depending upon least cost tradeoffs. Therefore in "solving" the model the regressions can help to determine which enforcement policy coefficients are significant and therefore exert an influence on the firm's control efforts. The results of the regressions were consistent with prior expectations.[13] The regression coefficients for the compliance test standard (S_{LEB}) and the opacity standard (S_{LEA}) were negative and the remaining coefficients were positive.

The role of effective fine in scenarios S1 and S2 needs further elaboration. The fine appears to be an insignificant determinant of behavior in scenarios S1 and S2. This is misleading. In the model itself, costs (excluding effective fines) are nearly constant over a wide range of precipitator sizes. Consequently, the impact of any positive effective fine is to usually induce a cost minimizing firm to pick a fine-avoiding precipitator. Furthermore, increasing the dollar fine per conviction usually makes the cost curve more steep around the least cost precipitator size, but does not shift the least cost point. Hence, the impact of effective fine on firm behavior is a zero–one effect. If the effective fine is any positive value (fine positive, probability of conviction positive) then the promulgated opacity standard is operative (i.e., the opacity standard impacts firm behavior in relationship to its specified value). A positive effective fine, of course, also promotes maintenance of pollution control devices since even very lax opacity standards would be violated if firms did not maintain their control devices.

One final result of our simulation analysis is of interest. Our best assessment of EPA's

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[13] For greater detail on the regression models and results see Downing and Watson (1973).

current choice of policy parameters for the enforcement of the new source performance standards for coal-fired power plants is[14]

Compliance test standard	0.1 lb/million Btu
No. of successive compliance tests	15 or less
No. of averaged stack samples	3
Flue gas flow rate	1.1 V
Opacity standard	30%
Fine/day of violation	\$500–\$50,000/day

Using these values in the model, we find that most plants will control to less than the standard and almost never be cited for a violation. In fact, plants larger than 100 MW will be in violation from 50 to 70% of the time depending upon plant size (see Table I). The reason why plants are not cited for a violation is that the enforced opacity standard allows about three times the emission of the compliance test standard. We also find that small plants control to a higher percent removal than large plants even though it is relatively more expensive for them to do so. This is because large plants enjoy economies of scale which allow them (relative to small plants) to make more favorable cost-reducing tradeoffs against enforcement policy parameters. Furthermore, all firms choose inflexible technology since its out-of-pocket cost to the firm is less than flexible technology. This is an inefficient choice for society, however, since the real resource cost of the same level of average control using flexible technology is less (see below). In fact, savings in the resource costs of control are probably an underestimate of the societal savings since flexible technology has a higher last day efficiency than inflexible technology. Thus, if marginal damages decline with control as is usually the case, then the increased damages due to a lower first day efficiency for the flexible

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[14] The final new source performance standard rules and regulations particulate matter discharges from fossil-fueled steam generators were issued by the U.S. Environmental Protection Agency on December 23, 1971 (*Fed. Reg*, December 23, 1971, pp. 24876–24895). Particulate matter discharges (which are mainly fly ash and unburned carbon particles) are not to exceed 0.1 lb/million Btu heat input maximum 2-hr average. This standard is applicable to any power plant unit of more than 250 million Btu/hr input or approximately 25 MW in capacity whose construction is commenced after August 17, 1971. Eventually, with the retirement of prestandard plants, every plant will be subject to the standard.

Under these regulations, 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 by the firm at its expense and reported to EPA. If the firm violates the opacity standard (20% opacity) it can be charged in a civil action under the provisions of the Clean Air Act and if convicted, fined as much as \$50,000/day of violation.

These regulations have several peculiar features. For one thing, the start-up compliance test can be run an unlimited number of times. Secondly, the conditions under which compliance tests are to be conducted are not clearly defined. Beyond some general stipulations, the rules and regulations do not specify test conditions. Presumably EPA technical personnel will be on hand to check test conditions. The tests, themselves, will be conducted by utility company personnel. A strong fraternity of engineering interests is likely to pervade compliance testing activities with liberal interpretations of test conditions "being understood" by the participants. A third feature is that the average of as few as three compliance test stack samples is the measurement for comparison with the promulgated standard. As demonstrated, the number of successive compliance tests, the stringency of test conditions, and the number of averaged compliance test stack samples markedly influence firm behavior.

A peculiar feature of the federally promulgated opacity standard the basis or detecting a violation during operation, is that it allows roughly twice the quantity of discharges as are allowed by the particulate matter discharge standard. This too influences firm pollution control effort.

device are more than off-set by the higher damage savings due to its greater last day efficiency.

POLICY ANALYSIS

Cost Comparisons

We can now use our simulation results, summarized by our regression equations, to investigate tradeoffs among the alternative enforcement schemes.

Four straightforward results evolve from a comparison of out-of-pocket cost to the firm over the different enforcement schemes and from a comparison of resource costs (cost minus total fine or total tax) over the different enforcement schemes.

First, at high collection efficiencies the expected resource costs of flexible technology are generally less than those of inflexible technology at all plant sizes and for each of the three enforcement schemes. Figures 3a–3c show some representative curves for a 1300 MW plant. Under enforcement schemes using compliance tests, firms will incur enlargement costs weighted by the probability of failing the compliance test. These enlargement costs tend to be quite large while their weighting factors—the probabilities of compliance test failure—tend to decline at high efficiencies. This produces relatively small expected enlargement costs at high collection efficiencies. Hence at high efficiencies flexible devices have smaller expected resource costs than inflexible devices (for the same average efficiency) because the saving from their smaller original-size costs exceed the sum of their extra instrumentation costs, their higher power input costs, and their larger (but relatively small) enlargement costs. This is demonstrated by Fig. 3a and b: flexible costs are less than inflexible when collection efficiency is approximately 95% or greater. Under emission-tax-only enforcement and at high collection efficiencies a flexible precipitator also has smaller expected resource costs than an inflexible precipitator (see Fig. 3c). The reason is that the smaller original-size costs for flexible

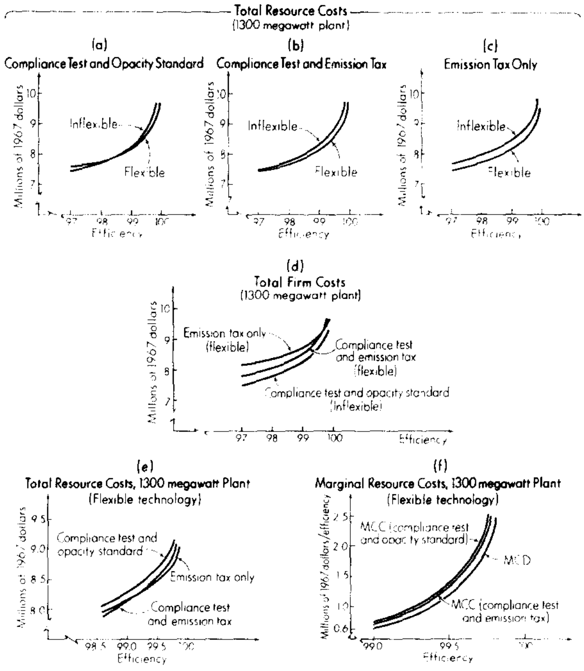

FIG. 3. Cost comparisons.

precipitators provide savings which exceed their extra instrumentation and power costs. In this case there is no question of a plant failing a compliance test and incurring enlargement costs. Therefore, since enlargement costs need not be overcome by flexible cost savings, flexible precipitators enjoy an even greater cost advantage over inflexible under emission-tax-only enforcement then they do under compliance test (with an opacity standard or emission tax) enforcement. This is demonstrated by the relatively larger cost advantage for flexible technology in Fig. 3c; in Fig. 3a and b flexible technology enjoys a relatively smaller cost advantage.

Second, the lowest out-of-pocket cost to the firm occurs with enforcement via a compliance test and opacity standard (with inflexible technology), the next from the lowest is a compliance test with emission tax (with flexible technology), and the third from the lowest is the emission tax only (with flexible technology). Out-of-pocket costs, of course, include fines and emission taxes paid under each of the enforcement schemes. Figure 3d presents each of these costs for a 1300-MW plant. On the other hand, a comparison of resource costs (all for flexible technology) gives the exact opposite ordering (see Fig. 3e). Hence the enforcement schemes which use emission taxes and resource-saving flexible technology and which consequently are attractive to a cost-minimizing resource manager are unattractive to the firms being regulated and vice versa. An implication is that there will be some resistance by firms to a shift toward enforcement schemes which use emission taxes even though this is desirable from the viewpoint of resource cost minimization.

In our earlier discussion of efficient enforcement a distinction was made between resource costs of control only (MCD) and marginal resource costs of control including marginal firm management costs (MCC). We now have quantitative measures of these costs (see Fig. 3f). On the average (at high efficiency levels) there is about 6% difference between MCC and MCD under compliance-test-with-emission-tax enforcement and about a 6.6% difference under compliance-test-with-opacity-standard enforcement.[15] It would appear that if a marginal benefit curve crosses these cost curves at high efficiency levels, using one or the other to determine efficient control levels results in approximately the same control level. It is well to recall however, that the proper inclusion of marginal enforcement agency costs could significantly impact determination of efficient control levels.

Policy Frontiers

Particular technologies were deliberately specified in the above ordering of preferred costs by the firm. This is necessary because the firm in reacting to enforcement policy parameters chooses the precipitator size and *technology* which minimizes its costs. Indeed, different mixes of enforcement policy parameters will induce it to pick flexible technology in some cases and inflexible technology in others. We proceed now to investigate the conditions governing technology selection.

The curve labeled AA in Fig. 4 is the locus of compliance test standards and opacity standards for which flexible technology and inflexible technology are equal in our-of-pocket costs. This locus is determined by setting costs as a function of enforcement policy parameters from scenarios S1 and S2, equal to each other. The dashed perpendiculars and the area to the northeast of these perpendiculars indicate approximate feasible choices for the compliance test and opacity standards. The crossed area to

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[15] Cost differences of about the same relative magnitude occur at other plant sizes. Note that we have assumed that record keeping and fee playing costs do not vary with the removal rate.

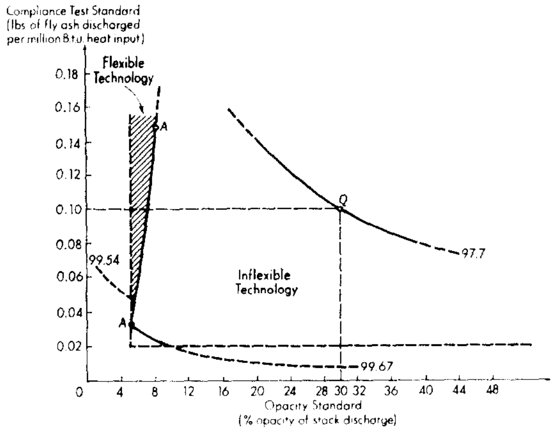

FIG. 4. Enforcement by compliance test and opacity standard, 1300-MW plant. An average of three stack samples ($N = 3$), no limits on the number of successive compliance tests (MD = 0), and an intermediate level for the flue gas flow rate (1.1V) are representative of current enforcement practice. (similar tradeoffs occur at other plant sizes.)

the left of AA is the policy area within which flexible technology is cheaper in out-of-pocket costs. To the right, inflexible technology is cheaper. The curve labeled 99.54 is the locus of compliance test and opacity standards (given flexible technology) which would induce a cost minimizing firm to select a 99.54% efficient precipitator (in effect an isoquant). The curve labeled 99.67 is a similar locus given inflexible technology. Note that the iso-efficiency curves are only relevant for the policy areas where their technologies are less costly. A 99.54% efficient flexible precipitator and a 99.67% efficient inflexible precipitator are devices which would meet the new source fly ash discharge standard even on the last day of their operating cycles at peak load flue gas flow rates (1.15 V).Current legal enforcement practice is somewhere in the vicinity of the point labeled *Q*.[16] As indicated by the iso-efficiency curve passing through Q, a cost minimizing 1300-MW plant would install a precipitator having a base-load efficiency of about 97.7%. This is substantially below 99.67%, the base-load efficiency needed to meet the federally promulgated new source fly ash standard.

Furthermore, as is clearly indicated, current legal enforcement practice induces the firm to pick inflexible technology even though resource costs are greater than flexible technology. This can be explained as follows. For a relatively tight compliance test standard a cost minimizing firm will pick roughly the same sizes of flexible and inflexible precipitators to avoid high enlargement costs. Therefore the "first day" efficiencies of the two devices will be approximately the same while the installation costs of the equivalent size flexible precipitator will be higher because of extra flexible instrumentation costs. Moreover, the flexible precipitator will have a higher average operating efficiency and consequently higher operating costs. Thus, for a given set of S1 and S2 enforcement parameters (and specifically a relatively tight compliance test standard) a cost minimizing firm would pick an inflexible precipitator of lower average operating efficiency but the same first day efficiency.

Similar analysis has been carried out for scenarios S3, S4, S5, and S6. The results are summarized in Fig. 5. FF is the locus of compliance standards and emission taxes

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[16] The enforced opacity standard is likely to be 30% or higher, rather than the promulgated 20%. In the past courts have levied fines only when violations were considerably greater than the relevant standards and when firms were uncooperative and recalcitrant.

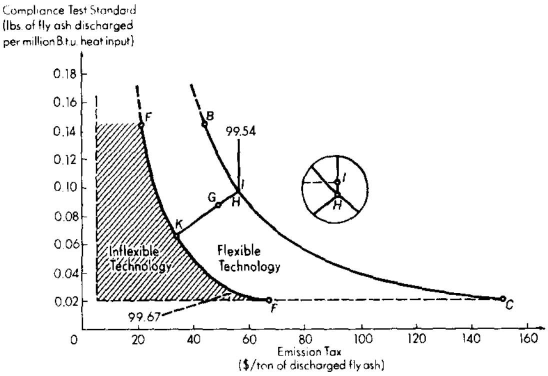

Fig. 5. Enforcement by compliance test and emission tax, 1300-MW plant. An average of three stack samples (N = 3), no limits on the number of successive compliance tests (MD = 0), and an intermediate level for the flue gas flow rate (1.1V) are representative of current enforcement practice. (Similar tradeoffs occur at other plant sizes.)

for which total flexible and inflexible precipitator out-of-pocket costs for a 1300-MW plant are equal. This locus or policy frontier is determined by setting 1300-MW costs as a function of enforcement policy parameters from scenarios S3 and S4, equal to each other. In the crossed area to the left of FF, inflexible technology is cheaper. To the right, flexible is less costly. BC is the locus of compliance test standards and emission taxes using compliance-test-with-emission-tax enforcement and emission-tax-only enforcement for which precipitator efficiency is equal in a comparison of these two alternative enforcement schemes. The curves labeled 99.54 and 99.67 are iso-efficiency curves for a flexible precipitator under emission tax enforcement and an inflexible precipitator under compliance-test-tax enforcement. The point labeled G is the compliance test standard and emission tax combination where total expected costs to the firm for a 99.54% efficient precipitator are equal to tax-only enforcement at H. To the left of G on the 99.54% iso-efficiency curve, the test-tax policy combinations result in smaller costs to the firm while to the right of G they are more expensive than tax only enforcement (indicated by point H). At point I, a compliance standard of 0.1 (the current EPA standard) combined with an emission tax of $56/ton would induce a cost minimizing firm to pick a law-abiding 99.54% efficient precipitator. However, note that an emission tax alone of the same amount would produce the same level of control at less expected cost to the firm. Point K is the least cost point for the firm under compliance-test-tax enforcement.

Figure 5 also indicates that flexible technology enjoys a relative policy advantage under emission tax enforcement. This occurs because increased flexibility allows the firm, for a given precipitator size, to reduce total emission taxes. Loosely speaking, flexible technology will cost less than inflexible as long as this emission tax savings (offset by some additional fly ash disposal costs) exceeds the additional flexible instrumentation costs. This may, of course, not occur if the emission tax rate is relatively small or if the compliance test standard is relatively tight. In these cases enlargement costs dominate technology selection and inflexible technology clearly has a cost advantage over flexible technology.

Enforcement Policy and Technology Development

The model contains two "types" (really degrees) of precipitator technology, labeled, for convenience flexible and inflexible. These particular variants were modeled because they are feasible choices in today's technology choice set. Over time though, one would expect that precipitators even more efficiency-flexible than these could be developed. This raises an important issue, namely, do different enforcement schemes either encourage or discourage the development and adoption of efficiency-enhancing technology?

The answer is that emission tax enforcement schemes encourage such developments while enforcement by compliance test and opacity standard discourages them.

The crux of the matter is that enforcement by compliance test and opacity standards tends, for the most part, to encourage good first day performance by firms. Hence, flexible technology development which improves over-the-operating-cycle efficiency is not cost effective for the firm under these enforcement circumstances. Moreover, improving flexibility generally shrinks the relevant policy area within which flexible technology would be adopted under such an enforcement scheme. In comparison, emission tax enforcement rewards over-the-operating-cycle performance. Hence, costs to the firm tend to fall as flexibility increases, given emission tax enforcement of environmental standards. This is true over a wide policy range even when emission taxes are combined with compliance tests. Or in terms of Fig. 5, gains in precipitator flexibility would cause the technology policy frontier, FF, to shift toward the origin.

The important conclusion is that the resource costs of pollution control as well as potential damages for a given average removal efficiency fall as technology is made more flexible and so it is important to devise enforcement schemes which encourage firms in this direction. We have seen that compliance-test-opacity-standard enforcement will usually fail in this regard while emission tax enforcement schemes will generally suceed.

SUMMARY AND CONCLUSIONS

The optimal level of control and emissions has been shown to depend upon the cost of the control devices and process changes, the management costs imposed on the firm by the control agency, and the management cost of the control agency itself (and, of course, the benefits of control). These costs differ among alternative implementation and enforcement schemes. In order to determine the optimal implementation and enforcement scheme it is necessary to determine the optimal control level, and hence values of policy parameters, for each alternative. The net benefit of control for each alternative could then be compared and the scheme with the largest net benefit chosen. While we cannot prove it without further research, the evidence we present indicates that an effluent fee enforcement scheme would be optimal in controlling fly ash emissions from coal-fired power plants. However, we do not expect this result to apply universally. Some form of legal enforcement may be preferred in many cases. This is especially true in cases where continuous monitoring of emissions is technically difficult and expensive.

Assuming that firms are expected cost minimizers we find that different implementation and enforcement techniques imply different reactions to control agency policy. Under a legal enforcement system the relevant policy parameters are inspection and monitoring techniques, emission standards, device certification procedures, probability of conviction if accused of a violation, fines and shutdown penalties, and damage to the corporate image. For example, in our simulation of fly ash control we find that stricter compliance tests and less stringent opacity standards can yield the same level of control. The model indicates that a higher marginal fine or penalty would yield greater control. In our empirical case, however, we find that any positive effective fine will have the same effect on the firm's control decision. This probably is not a general result.

In effluent fee enforcement the relevant policy parameters are the marginal fee, the device certification process if any, and the inspection and monitoring system employed. As expected, higher effluent fees yield greater control. When a certification procedure is added to the effluent fee we find that a tradeoff between the certification standard and the effluent fee exists. This is born out in our empirical test. However, there is a range of effluent fees for which any feasible compliance test will have no effect on the firm's control efforts.

Under current enforcement practice, most coal-fired power plants will not meet the federal new source fly ash standard being in violation as much as 70% of the year. We suspect that this noncompliance result holds for most enforcement schemes currently employed by various control agencies. Our analysis indicates that owners of power plants, especially large ones, have a strong incentive to seek relaxations in compliance test conditions. We also find that smaller plants are relatively more costly to control and, therefore, should be subject to relatively less tsringent penalties or standards.[17] It should be noted that our simulations assume that firms comply with the letter (if not the spirit) of the law rather than fight its implementation. If firms were to take advantage of all the legal delaying tactics available to them, emission reductions such as we determine in this study will be optimistic both as to amount and timing.

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[17] Becker (1968, pp. 189 and 196) derived a similar result on theoretical grounds. He argues that penalties (or standards) should be less for smaller violators (plants) and that high income firms should be prosecuted more thoroughly rather than less thoroughly as we have found in our analysis.

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