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Title: Pollution Control Mechanisms When Abatement Costs Are Private Knowledge

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Abstract Approved: ______________________________

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This dissertation addresses two issues in pollution control (i) determining the optimal level of emissions, and (ii) the design of a system to induce compliance with this emission level at minimum costs. The starting points for this research are that the regulatory agency does not know the individual firm's pollution abatement costs and that firms are generally reluctant to reveal these costs.

The optimal emission level of a particular pollutant is found by creating a market for emission permits for this pollutant. By comparing the resulting cost for emission permits with the inferred price from the known damage function of that pollutant at a particular aggregate level of emissions, the optimal aggregate emission level can be determined. The cost for emission permits equals the market price for emission permits times the competitive interest rate. The resulting aggregate emission level is shown to be a second-best Pareto-optimal allocation.

Pollution Control Mechanisms When Abatement Costs Are Private Knowledge

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4.4 Issues Related to the Proposed Scheme 54
4.4.1 The Adjustment of Aggregate Quotas 55
4.4.2 Initial Allocation of Firm Quotas 57
4.4.3 Firm Entry and Exit 58
4.5 Conclusions 59

5 INDUCING INDIVIDUAL FIRM COMPLIANCE TO EMISSION QUOTAS WHEN ABATEMENT COSTS ARE PRIVATE KNOWLEDGE 62

5.1 An Outline of the Proposed Model for Pollution Control 64
5.2 A Single-Period Principal-Agent Model for Inducing Compliance to Environmental Standards 66
5.3 A Dynamic Model of Firm Behavior and Regulatory Agency Response 72
5.3.1 Single-Period Compliance in Group Three 76
5.3.2 Multi-Period Compliance in Group Two 77
5.3.3 Multi-Period Compliance in Group One 79
5.3.4 Obtaining the Fractions of Firms in the Various Groups 81
5.4 An Evaluation of the Suggested Monitoring System as a RAM 82
5.4.1 Individual Rationality 82
5.4.2 Informational Viability and Efficiency 83
5.4.3 Incentive Compatibility 84
5.4.4 Second-Best Pareto-Optimality 84
5.4.4.1 Comparison of the Expected Monitoring Costs: The Single-Group Model 86
5.4.4.2 The Expected Societal Welfare for a Given Vector of the Agency's Choice Variables 86
5.4.5 Balancing the Budget for the Regulatory Agency 89
5.5 The Optimality of Emission Quotas 89
5.6 Conclusions 90

6 SUMMARY AND CONCLUSIONS 92

BIBLIOGRAPHY 97

APPENDIX: EXPLANATION OF NOTATION AND SYMBOLS 105
A.1 Special Characters 105
A.2 Symbols 105
A.3 Functions 106
A.4 Abbreviations 107

LIST OF FIGURES

Figure		Page
1.	The optimal emission level	3
2.	Emission level when the true marginal costs of abatement are lower than the anticipated marginal costs	12
3.	The marginal damage function	30
4.	Aggregate emissions under transferable quotas	44
5.	The market price for pollution permits and the confidence interval of the marginal damage function	56
6.	The decision tree of the single-period principal-agent model	69

marginal costs are decreasing.

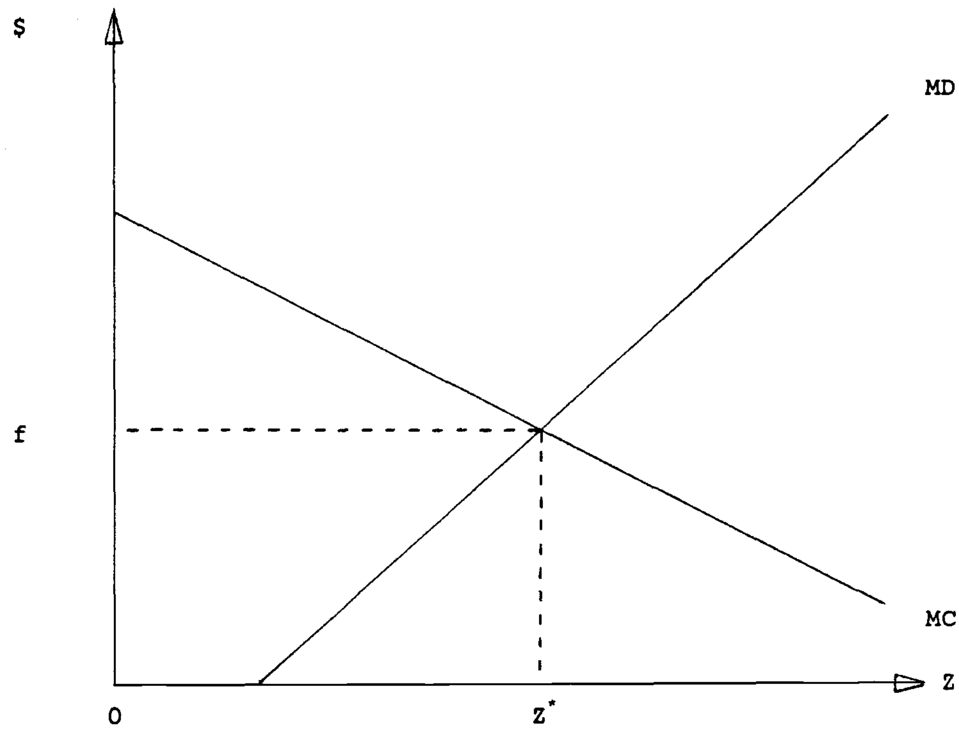

Figure 1: The optimal emission level. MC: marginal costs of abatement, MD: marginal damages, Z^* : optimal quantity, f: Pigouvian tax (fee).

The problem with Pigouvian taxes is that the firms are generally reluctant to disclose their true cost functions for abatement. Therefore the MC curve in figure 1 may not be publicly known, and the regulatory agency[1] is not able to set the correct Pigouvian tax (denoted f in Figure 1). By overstating their abatement costs, firms can increase their profits.

The first objective of this research is to show how transferable

[1] The regulatory agency (also denoted as the planner or just the "agency") represents the public's interests and seeks to maximize societal welfare.

marginal costs. The converse holds if the true costs of pollution reduction are higher than the anticipated costs. It is assumed that the marginal costs of pollution abatement is everywhere increasing. Expressed in terms of emission levels, the marginal costs are decreasing. The magnitude of these distortions depends upon the shapes of the marginal damage and cost curves and is treated in detail by Baumol and Oates (1988) for the atemporal case. Figure 2 shows the resulting emission level when the true costs of pollution abatement are lower than the anticipated marginal costs.

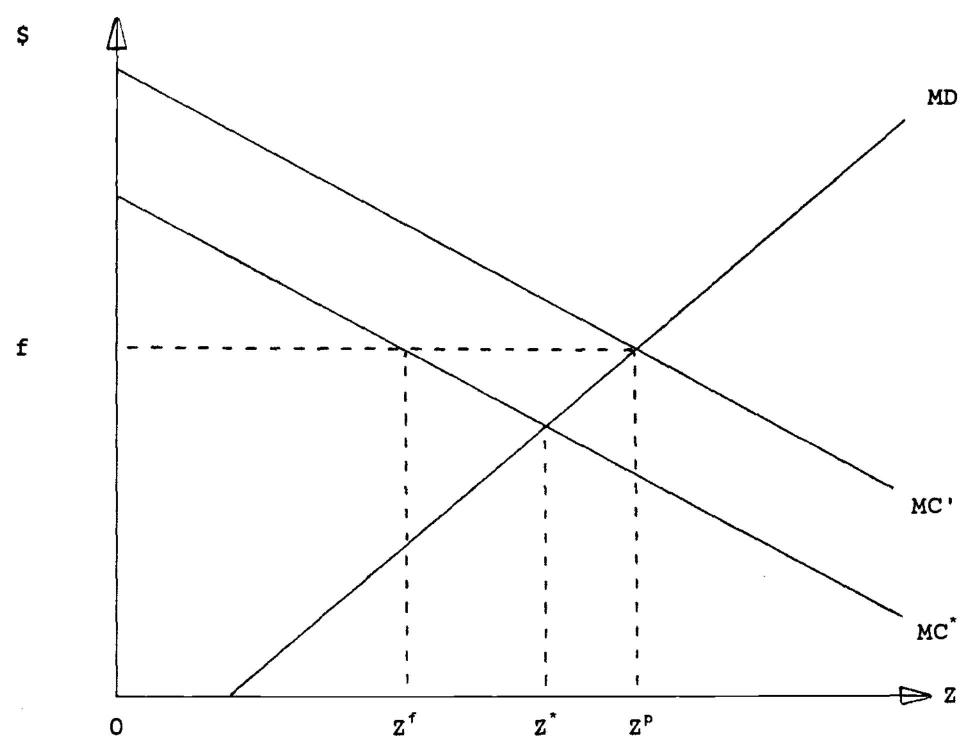

Figure 2: Emission level when the true marginal costs of abatement (MC*) are lower than the expected marginal costs (MC'). Z^* : optimal quantity, Z^P : emissions under permits, Z^f : emissions under fees, MD: marginal damage, f: Pigouvian tax.

LEMMA 3.1: Suppose that a firm has an input-regular production possibility set with a producible set Y^* and input requirement set $Q(\mathbf{y})$ for $\mathbf{y} \in Y^*$. Suppose the firm is a price taker in the input markets with a non-negative input price vector v. Then the cost function (3.1) exists for all $\mathbf{y} \in Y^*$ and all non-negative v. Further, for each $\mathbf{y} \in Y^*$, the cost function as a function of v is non-negative, non-decreasing, positively linear homogenous, concave and continuous.

By McFadden's (1978, p. 82-83) duality theorem the profit function exists uniquely:

$$\pi_n(\mathbf{p},\mathbf{v}) = \sup_{\mathbf{y}_n \geq 0} \{\mathbf{p}\cdot\mathbf{y}_n - c_n(\mathbf{v},\mathbf{y}_n)\} \tag{3.2}$$

where SUP denotes the supremum or the smaller upper bound.[11]

It also follows from the duality theorem that the profit function satisfies the following conditions (Hanoch, 1978):

CONDITION 3.1:

(i) $\pi_n(\mathbf{p},\mathbf{v})$ is a real, non-negative function of the price vector $(\mathbf{p},\mathbf{v}) \geq \mathbf{0}$ with $\pi_n(\mathbf{0},\mathbf{0}) = 0$ and $\pi_n(\mathbf{p},\mathbf{v}) > 0$ for $(\mathbf{p},\mathbf{v}) \gg 0$.

(ii) $\pi_n(\mathbf{p},\mathbf{v})$ is non-increasing in v and non-decreasing in p.

(iii) If $\mathbf{v} \gg \mathbf{0}$, $\lim_{d\to 0} \pi_n(\mathbf{p},(1/d)\mathbf{v}) \leq \mathbf{p}'\mathbf{a}$, where **a** is a vector of fixed finite values.

(iv) $\pi_n(\mathbf{p},\mathbf{v})$ is a convex, closed function for $(\mathbf{p},\mathbf{v}) \geq \mathbf{0}$.

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[11] Provided strictly positive output prices (p) and input prices (v), SUP in (3.2) can be replaced with MAX.

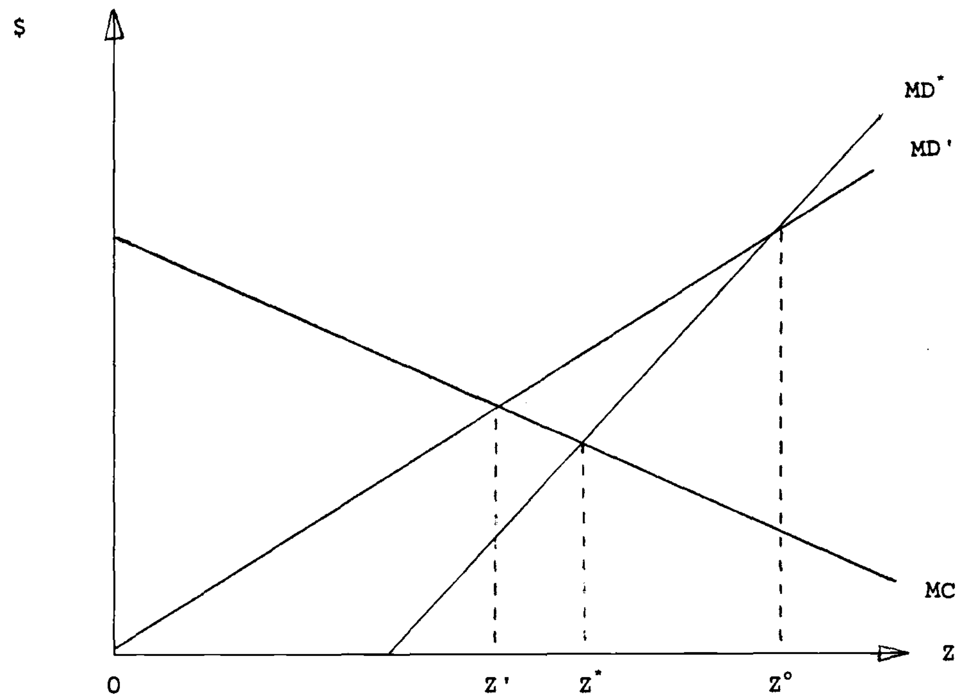

Figure 3: The marginal damage function. MD': marginal damage function including only direct effects, MD^* : marginal damage function including both direct and indirect effects, Z° : initial emission level, Z': "optimal" emission level when only direct effects are incorporated, Z^* : optimal emission level when both direct and indirect effects are incorporated.

For the remainder it is assumed that the marginal damage function captures both the direct and indirect effects, and thus represents the true marginal social damage function needed for the regulatory agency to make optimal decisions. The general specification of the benefit function becomes:

$$B(Z,\mathbf{p},\mathbf{X};\mathbf{p}^\circ,Z^\circ) \tag{3.11}$$

such that: $\partial B/\partial Z < 0$,

$\partial B/\partial p_m < 0$, where $p_m \in \mathbf{p}$ as $m \in M$, and

$\partial B/\partial X_i < 0$, for all $i \in I$.

agents better off. Then by the definition of SBPO, the RAM R' is not SBPO. Q.E.D.

Informational viability and efficiency and incentive compatibility are required for the proposed RAM to yield a predictable outcome. Individual rationality is important to facilitate the implementation of the RAM. To evaluate any RAM, a welfare indicator is needed. SBPO is chosen as the welfare indicator because it does not require the RAM to correct for all inefficiencies in the economy and it does not require individual utilities to be comparable.

The modified desireable properties of a RAM are therefore;

(i) individual rationality,

(ii) informational viability and efficiency,

(iii) incentive compatibility, and

(iv) second-best Pareto-optimality.

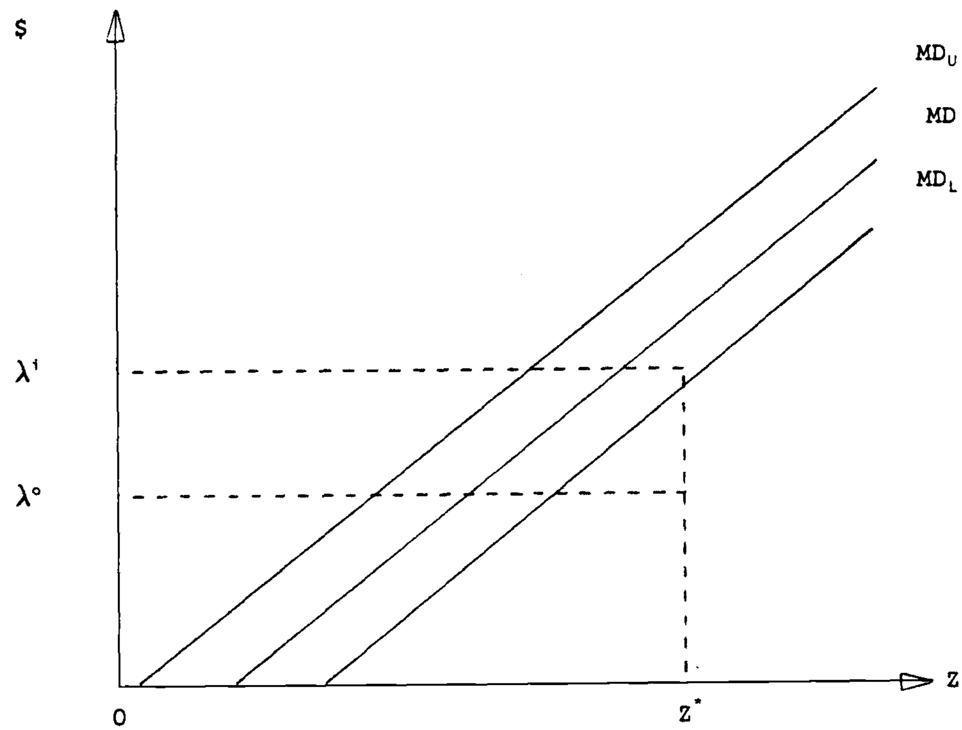

Figure 5: The market price for pollution permits times the interest rate is inside (λ^1) or outside (λ°) the 1-α/2 confidence intervals of the estimated damage function (MD).

Thus one may conclude that the agency should only seek to adjust the aggregate emission level if λ_t is significantly different from the inferred price from the damage function.

In an intertemporal model, one must also allow for the marginal costs of abatement or the public's valuation of environmental amenities to change over time. For instance, due to technological progress, the firms' cost of pollution abatement may decrease. Keeping in mind the statistical variability in the estimated damage function, this once again means that the regulatory agency should buy permits for retirement if λ_t falls below the inferred price given by the damage function, $D_t(Z_t)$.

In the process of showing that the proposed system is incentive compatible with respect to participation in the emission permit market, additional insights have been gained regarding emission permit prices. Given a particular environment, the emission permit price, p_t°, is the price consistent with firms maximizing their expected profits.

The proposed system does not ensure that firms comply with their assigned or ex-trade quotas. This is a necessary criterion for the system to satisfy the desired properties. Several mechanisms exist to ensure compliance on the average. Some of these mechanisms can easily be combined with this system of transferable pollution permits. One such mechanism is presented in chapter five.

where $\omega(p)$ is a constant for a certain price such that $\partial\omega/\partial p > 0$.

All the pieces in setting up a principal-agent model for the stochastic emission control problem have now been gathered. The agency seeks to maximize societal welfare subject to firms maximizing a revised profit function. The following figure illustrates the game tree of the single-period principal-agent model to the above problem:

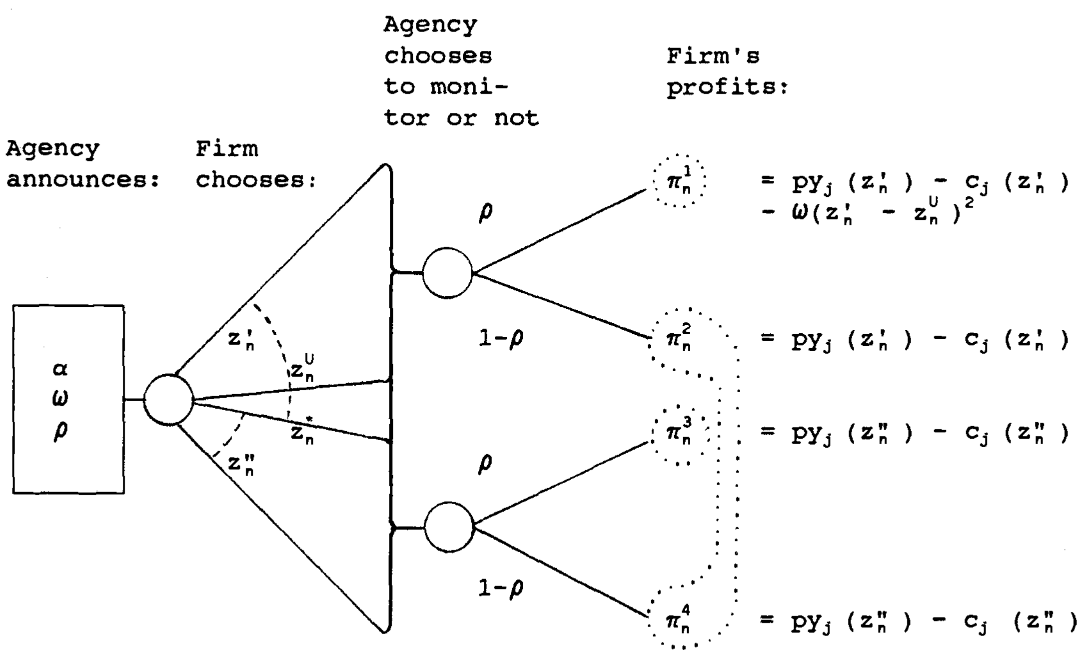

Figure 6: The game tree of the single-period principal-agent model[16], where $\pi_n^1 < \pi_n^3 = \pi_n^4 < \pi_n^2$, and

z_n' is the firm's emission level, intending not to comply

z_n'' " " " " " , intending to comply

π_n^1 profits under intended cheating when caught

π_n^2 " " " " " not caught

$\pi_n^3 = \pi_n^4$ profits under intended compliance.

[16] Areas bounded by dotted lines represents the agency's information sets.

$$\max_{z_{nt}} \pi^{g}_{jnt} = p_t y_j (z_{nt}) - C_j (z_{nt}) - \rho^g [h(\bullet) + C^g_m] \tag{5.11}$$

where C^g_m is the monitoring costs such that $C^1_m = 0$, $C^1_m > 0$ for $g = 2$ or 3, and

all other terms remain as specified in the profit function (3.4) for the single-period model presented earlier.

Let $C_\theta(\bullet)$ be the cost function for the θ technology. The single period profit function for any firm is viewed by the regulatory agency as:

$$\max_{z_{nt}} \pi^{g}_{\theta t} = p_t y_\theta (z_{nt}) - C_\theta (z_{nt}) - \rho^g [h(\bullet) + C^g_m] \tag{5.12}$$

For simplicity and without loss of generality, assume that the firm's and the agency's time horizon coincide, i.e. $t \in \{0,1,\ldots,T\}$. Denote this set T. The form of the multi-period principal-agent model does not differ much from the single-period model:

Regulatory agency:
$$\max_{\alpha,K,\omega,\rho^g} \Sigma_{t\in T}\ \beta^t\ \{B(Z_t, p_t, X_t; p^\circ \cdot Z^\circ) - \Sigma^3_{g=1} \rho^g f^g N C_m\} \tag{5.13}$$

st.

Firms
$$\left\{\begin{aligned} &\max_{\{z_{nt}\}} \Sigma_{t\in T}\ \pi_{jnt} \\ &= \Sigma_{t\in T}\ \beta^t\ \{p_t y_j (z_{nt}) - C_j (z_{nt}) \\ &- \rho\omega(p_t) \mathrm{MAX}[0, (z_{nt}(1 + e_j))^2 - (z^*_{nt}(1 + z_{1-\alpha}\sigma))^2]\} \end{aligned}\right. \tag{5.14}$$

where β $= (1 + r)^{-1}$ is the discount factor and r is a risk free nominal interest rate,

f^g is the fraction of firms in group g, $g \in G$, and

$B(\bullet)$ is defined by (3.11).

expected time without monitoring (G_2 c^m) plus its compliant profits when monitored (G_2 cm) must exceed the sum (a) through (d).

(a) the expected non-compliant profits of the expected time in group two without monitoring (G_2 n^m),

(b) the profits of detected non-compliance in the last time period in group two (G_2 nm) (before being moved to group three),

(c) the profits of compliance while in group three without being monitored (G_3 c^m), and

(d) the same profits minus the cost of being monitored in group three (G_3 cm) (before being moved to group two).

Mathematically this becomes:

$$\left.\begin{array}{ll}
\Sigma_{t=0}^{T-1} \beta^t \pi_\theta (z_{\theta t}^*) + & (G_2\ c\hat{}m) \\
\beta^T [\pi_\theta (z_{\theta T}^*) - C_m] > & (G_2\ cm) \\
\Sigma_{t=0}^{Ta} \quad \beta^t \pi_\theta (z_{\theta t}^{\prime}) + & (G_2\ n\hat{}m) \\
\beta^{Ta+1} \quad [\pi_\theta (z_{\theta Ta}^*) - C_m] + & (G_2\ nm) \\
\Sigma_{k=1}^{K} \Sigma_{t=Tb}^{Tc} \ \beta^t \pi_\theta (z_{\theta t}^*) + & (G_3\ c\hat{}m) \\
\Sigma_{k=1}^{K} \beta^{Tc+1} \quad [\pi_\theta (z_{\theta Tc+1}^*) - C_m] & (G_3\ cm)
\end{array}\right\} \qquad (5.17)$$

where Ta $= 0,1,\ldots,T_2 -1,$

Tb $= Ta + (k+1) + (k-1)T_3,$

Tc $= T_a + k(T_3 +1),$

k $= 1,2,\ldots,K$, where K is number of successive periods in group three found in compliance,

T $= Tc + 1$, where $k = K$,

T_g is defined in (5.16),

π_θ has the form of (3.4), θ replacing j, and

individual rationality, group two firms should then not pay their own monitoring costs.

5.3.4 Obtaining the Fractions of Firms in the Various Groups

The agency has already found the monitoring probabilities needed in group one, two and three for the θ technology, conditional on ω^* for various levels of α and K, $\rho_\theta^g(\alpha,\omega^*,K)$, $g \in G$.

The Markov-transition matrix for the θ technology can now be expressed as:

	G_1	G_2	G_3
G_1	$1-\phi(\alpha,z_{\theta_n})\rho_\theta^1$	$\phi(\alpha,z_{\theta_n})\rho_\theta^1$	0
G_2	$(1-\phi(\alpha,z_{\theta_n}))\rho_\theta^2$	$1-\rho_\theta^2$	$\phi(\alpha,z_{\theta_n}))\rho_\theta^2$
G_3	0	E	1-E

where G_g, $g \in G$, in the left column indicates the starting group, and the row G_g, $g \in G$, indicates resulting group, and E is the probability of escaping group three, conditional on ω and K. E becomes:

$$E = (1-\phi(\alpha,z_{\theta_n}))^K \rho_\theta^3 \tag{5.19}$$

Markov-stationarity implies that the number of firms entering and exiting between two groups must be equal. This is equivalent to solving the following system of equations:

$$\left.\begin{array}{lr} f^1\phi(\alpha,z_{\theta_n})\rho_\theta^1 = f^2(1-\phi(\alpha,z_{\theta_n}))\rho_\theta^2 & \text{exit 1 = entry 1} \\ f^2\phi(\alpha,z_{\theta_n})\rho_\theta^2 = f^3\ E\ \rho_\theta^3 & \text{exit 3 = entry 3} \\ \Sigma_{g=1}^3 f^g = 1 & \text{sum of fractions is one} \end{array}\right\} \tag{5.20}$$

Denote the solution of (5.20) $f^g(\alpha,K,\omega^*;\rho_\theta^g)$, $g \in G$.

to differ from the ex ante monitoring optimal emission level, and generally the former exceeds the latter. The model for obtaining the pre-monitoring optimal emission levels and the model for inducing compliance, are therefore constructed such that they can be used together, thus achieving a SBPO aggregate emission level, which is enforceable. Jointly these models constitute a set of new institutions for pollution control that are informationally feasible and less costly to operate than previously described approaches.

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APPENDIX

APPENDIX

EXPLANATION OF NOTATION AND SYMBOLS

A.1 Special Characters

α	the variability scale factor
$\in$	an element in a set
$\subset$	a subset of
$\succsim_i$	the ith consumer's preference ordering
ρ^g	the monitoring probability in group g, $g \in G$
θ	the technology yielding the most output per unit emissions, $\theta \subset J$
σ_M^2	the variance in the regulatory agency's emission level measurement
σ_θ^2	the variance in the emission level around the targeted emission level for technology θ
σ^2	the total variance around the targeted emission level
ω	the scale factor in the penalty function

A.2 Symbols

E	the probability of escape from group 3
f^g	the fraction of firms in group g
i	an index, indicating the ith consumer, $i \in I$
I	the index set of all consumers
j	an index, indicating the jth technology, $j \in J$
J	the index set of known technologies