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Environmental Regulation with Optimal Monitoring and Enforcement

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Abstract

We derive a set of optimal environmental regulations in the presence of asymmetric information about pollution abatement costs, where compliance may have to be induced through appropriate monitoring and enforcement measures. The regulator commits to monitoring of compliance with incentive compatible environmental regulations. The regulator can reveal regulations to achieve the objective of choosing the given abatement level, by proposing a menu of regulatory contracts that specify abatement levels.

Keywords. Environmental Regulation, Asymmetric Information, Incentive Compatibility, Monitoring

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1. Introduction

In the regulatory setting, it seems quite reasonable to presume that firms have better information about their productive capabilities and abatement opportunities than does the regulator. In the model of environmental regulation with asymmetric information to follow, the regulator anticipates the strategic response of a firm possessing full information about the cost of pollution abatement. In this model, it is assumed that the regulator can make a commitment to an incentive schedule from which the firm chooses a pollution abatement level and receives a corresponding subsidy (penalty). Formally, the regulator's problem can be represented as a direct revelation game in which the regulator commits to an incentive schedule assigning abatement responsibility and the level of subsidy to the firm on the basis of a subsequent message sent by the firm to the regulator about its abatement cost . The regulator may restrict attention to incentive schedules that are incentive compatible. This class of regulatory mechanisms induce the firm to truthfully reveal the value of its abatement costs.

Some papers in the optimal mechanism design literature analyze the potential benefit of monitoring or auditing when designing regulatory contracts, but none of these papers address the enforcement problem so critical to environmental regulation (Baron, 1989). For example, in Baron and Besanko (1984), ex post auditing of firm costs may occur after output is produced and, hence, after the firm has announced its costs. If the audit signal a misreport, then the agent is penalized. The ability to monitor improves upon the Baron-Myerson (1982) contract by reducing the firm's rent from private information and by increasing the efficiency of the contract by allowing the regulator to set prices closer to marginal costs. This form of auditing for cost-type is obviously different than monitoring for compliance with environmental standards.

As we showed in the case-based context of hazardous waste management (Gottinger, 1999) the essential elements of our analysis must include optimal, if costly and imperfect, monitoring and enforcement of regulations, criminal behavior, and most importantly the incentives for such behavior.

Our model is in the spirit of Swierzbinski’s model (Swierzbinsky, 1994) though more simplified and transparent, and it carries one important additional feature. It considers the case of an option to the firm of noncompliance, covering a ‚criminal behavior‘ aspect not known to the regulator. Also unlike suggested in a similar model of regulation by Jebjerg and Lando (1997) the marginal incentives necessary to effectively abate pollution may not vary according to firms‘ cost-types.

The paper is organized in the following manner. In Section 2 we provide the basic model design and notation. In Section 3 we analyze incentive compatible environmental regulations with costly monitoring and enforcement. Here we consider the possibility of corner solutions regarding monitoring probabilites and contrast the resulting distortions in the standard setting with the case of an interior solution for monitoring probabilities. Section 4 concludes this paper.

2. Structural Assumptions and Model Design

We start formulating the regulatory problem in a familiar conventional framework (Besanko and Sappington, 1987). Suppose that the firm to be regulated is one of two possible types. The types are distinguished by the cost of complying with a regulation that mandates the quantity, q, of pollution that must be abated. Let $C(q,\theta)$ represent the firm's total pollution abatement cost . The parameter θ summarizes the firm's cost-type, and its value is known by the firm and unknown to the regulator. We assume that to the regulator $\theta \varepsilon \{\theta_1,\theta_2\}$ with $\theta_2 > \theta_1$. The regulator's prior belief that $\theta = \theta_i$, for $i \varepsilon \{1,2\}$, is described by $\alpha_i \varepsilon (0,1)$ such that $\alpha_1 + \alpha_2 = 1$.

$C(q,\theta)$ is meant to include all of the abatement costs the firm incurs in meeting a standard of q. It certainly includes the cost of installing and operating pollution abatement technology, and it also includes lost profits due to any other changes in the production process (e.g., changes in output level or input mix).We make the following assumptions regarding $C(q,\theta)$:

$$C(q,\theta) > 0 \text{ for all } q > 0. \quad (2.1)$$

$$C_q(q,\theta) > 0 \text{ for all } q > 0. \quad (2.2)$$

$$C(q,\theta_2) > C(q,\theta_1) \text{ for all } q > 0,\ \theta_2 > \theta_1, \text{ and} \quad (2.3)$$

$$C_q(q,\theta_2) > C_q(q,\theta_1) \text{ for all } q > 0,\ \theta_2 > \theta_1 . \quad (2.4)$$

Also convexity on C applies.

Assumptions (2.1) and (2.2) state that abatement costs are positive and an increasing function of q. Assumptions (2.3) and (2.4) identify the role played by the abatement cost function parameter θ. Assumption (2.3) suggests that total pollution abatement costs are higher the larger is θ, and assumption (2.4) suggests that marginal pollution abatement costs are an increasing function of θ as well. Thus, if the firm is a high- cost type, we mean that it has higher total and marginal costs of pollution abatement than a low- cost type, holding constant the level of pollution abatement q.

In the regulatory game developed here, the regulator offers a menu of contracts to the firm from which the firm chooses one. Each contract is a quadruple, specifying a required level of pollution abatement, q_i , a corresponding lump-sum subsidy (penalty) to be paid to(by) the firm, S_i , a probability of inspection for compliance, p_i and a corresponding fine, F_i to be paid by the firm if inspected and found to be out of compliance with the abatement standard q_i. With only two possible abatement cost-types, the firm is presented a choice between contract

(q_1,S_1, p_1 ,F_1) and (q_2, S_2, p_2,F_2). More generally, with n possible cost-types, the firm is presented with a choice of n regulatory contracts[1].

The timing of the regulatory game is as follows. First, the regulator offers the firm the choice between (q_1,S_1,p_1,F_1,) and (q_2 ,S_2 ,p_2, F_2). Next, the firm chooses a contract, receives the appropriate subsidy, and engages in production and pollution abatement activity. The regulator cannot costlessly observe (non)compliance with the appropriate abatement standard. Instead, the regulator monitors firm compliance with the probability, p_i, specified in the contract selected by the firm. An important feature of this design is that we assume the regulator, through allocation of its monitoring and enforcement budget, credibly commits to the specified monitoring probabilities. This is done exogenously by the regulator, his committing to probabilities depends on his assessment of the likelihood of non-compliance by the firms and consequential damage. Probabilities will be high if the risk of non-compliance is high and low otherwise. If monitoring occurs, we assume the inspection is perfectly informative; monitoring reveals compliance or noncompliance without error. If a firm is not complying with the abatement standard specified in her regulatory contract (i.e., $q < q_i$), the firm pays the specified fine F_i.

In our model, the regulator anticipates the strategic response of a firm that knows about her cost of pollution abatement. When designing the contracts (q_1,S_1, p_1, F_1) and (q_2,S_2 ,p_2 ,F_2) the regulator commits to an incentive scheme for the firm which is, in the terminology of mechanism design, incentive compatible. The firm selects the contract designed for its abatement cost-type. A low -cost type firm with $\theta = \theta_i$ will find it at least as profitable to choose (q_1, S_1, p_1, F_1) as to choose(q_2, S_2, p_2 ,F_2). Similarly, a high- cost type firm will choose (q_2, S_2, p_2 ,F_2) over (q_1, S_1, p_1, F_1) because its profits are maximized by that choice. Formally, the regulator's problem can be represented as a direct revelation game in which the regulator commits to an incentive schedule assigning abatement responsibility, lump-sum transfer, monitoring probability, and fine for non-compliance on the basis of a subsequent message sent by the firm to the regulator about its abatement cost function. The regulator may restrict attention to schedules which are incentive compatible and that induces the firm to truthfully reveal her abatement cost function parameter θ.

Firm profits before environmental regulation are common knowledge and are equal to π. Profits after regulation, for a firm complying with the abatement standard q_i, are

$\Pi(\pi, q_i, S_i, \theta) = \pi - C(q_i, \theta) + S_i$, where θ is the value of the firm's abatement cost function parameter. When the firm is presented with two contracts (q_1, S_1, p_1, F_1) and (q_2, S_2, p_2 ,F_2), incentive compability requires that, for i, j ε {1,2}

$$\Pi(\pi, q_i, S_i; \theta_i) \geq \Pi(\pi, q_j, S_j; \theta_i). \quad (2.5)$$

[1] If θ is from a continuous interval such that $\theta \; \varepsilon \; \{ \underline{\theta}, \bar{\theta} \}$, then the firm is presented with a regulatory schedule ($q(\theta)$, $S(\theta)$, $p(\theta)$, $F(\theta)$) from which a particular contract is calculated based upon the firm's revelation of θ.

These incentive compatibility constraints may be rewritten as

$$- C(q_i, \theta_i) + S_i \geq - C (q_j, \theta_i) + S_j . \qquad (2.6)$$

Throughout the analysis to follow, we assume that the firm selects the regulatory contract according to the regulator's preferences if it is indifferent about alternative contract.

Subsidies play a key role in maintaining incentive compatibility. Assuming that compliance is induced with the abatement standards q_1 and q_2, a firm with low abatement costs (i.e. $\theta = \theta_1$) will only accept an abatement responsibility of q_1 instead of q_2,where $q_1 > q_2$, if $S_1 > S_2$. We also consider the economic cost of a subsidy S, as $(\beta - 1)S$. The parameter β is greater than or equal to one, and it represents the administrative costs, tax distortions, or other inefficiencies associated with the use of subsidies as an environmental policy instrument. That is, every dollar paid to the firm in the form of a subsidy is provided at an economic cost of β dollars.

To induce firm compliance with the standards, the regulator must choose the probabilities of monitoring, p_1 and p_2, as well as the fines for noncompliance, F_1 and F_2 , appropriately.We assume that the regulator will commit to monitoring with any probability so that random monitoring will be his best choice, if as we assume the fines and subsidies are exogenously given. To that end, we assume the regulator is subject to four sets of constraints. First, we assume there is a maximum fine, $\overline{F}$ which can be levied against a noncompliant firm. To regulators (from environmental protection agencies) in charge of enforcement, the maximum penalties for violation are exogenously given.

The second set of enforcement constraints are the compliance constraints. Since the regulator commits to the monitoring probabilities p_1 and p_2 , it is optimal to guarantee that the firm (which has chosen the contract designed for her abatement cost-type) will comply with the abatement standard rather than risk the punishment for noncompliance[2]. We assume the monitoring technology is without error and the probabilities of monitoring and fines for noncompliance are independent of the size of the violation with the abatement standard: therefore, if a firm decides to not comply with the standard , it will, in fact, not abate any pollution. A noncompliant firm's expected profits, if it chooses the contract designed for its cost type, will be $\pi + S_i - p_i F_i$ .The firm's profits, if it complies, will be $\pi - C(q_i , \theta_i) + S_i$. Throughout the paper, we assume that firms are risk-neutral. Consequently, the compliance constraints may be written as

$$C(q_i , \theta_i) \leq p_i F_i \text{ for } i \ \varepsilon \ \{1,2\} \qquad (2.7)$$

In other words, a firm will choose to comply with an abatement standard if the cost of compliance is less than the expected penalty for noncompliance.

[2] In a model of enforcement without commitment to monitoring probabilities,it can be optimal to allow firms to pursue a mixed strategy in which firms do not comply part of the time.

The third set of enforcement constraints to the regulator's problem are hybrid constraints. They are a combination of incentive compatibility and compliance constraints. The regulator must ensure that the firm chooses and complies with the contract designed for its abatement cost-type rather than choose and not comply with the terms of the contract designed for the other cost-type. Profits for a compliant firm choosing the appropriate regulatory contract are $\pi - C(q_i, \theta_i) + S_i$ while the expected profits for a noncompliant firm choosing the contract designed for the other cost-type will be $\pi - p_j F_j + S_j$. The hybrid constraints may be written as

$$- C(q_i, \theta_i) + S_i \geq - p_j F_j + S_j \text{ for } i, j \in \{1,2\}, i \neq j \quad (2.8)$$

The hybrid constraint will prove to be binding for a high cost-type firm who may be tempted to accept the contract designed for a low cost-type in order to obtain the relatively large subsidy S_1.

The fourth and final set of enforcement constraints is simply the requirement that p_1 and p_2 be less than or equal to one since they represent monitoring probabilities. In examining the optimal incentive compatible environmental regulations with costly monitoring, we pay careful attention to the case where one or both monitoring probabilities are optimally set to their corner solution values of one.

To complete the model, we let the environmental benefits of pollution abatement be given by the function E(q). As is standard in the environmental economics literature, environmental benefits are assumed to be an increasing but concave function of pollution abatement (i.e., $E'(q) > 0$ and $E''(q) \leq 0$). For convenience, we assume that the expected cost of monitoring for compliance is given by cp where c is the unit cost of monitoring and p is the probability of a monitoring inspection. We assume that the regulator is risk-neutral; therefore, the regulator is assumed to maximize the expected environmental benefit of abatement, less the expected cost of abatement, less the economic cost of raising and administering the expected subsidy, and less the expected cost of monitoring.

The regulator's problem is to choose (q_1, S_1, p_1, F_1) and (q_2, S_2, p_2, F_2) to maximize

$$\alpha_i \{E(q_i) - C(q_i,\theta_i) - (\beta-1)S_i - cp_i\} \text{ s.t.}$$

$$\pi - C(q_i,\theta_i) + S_i \geq 0, \text{ for } i \in (1,2) \quad (2.9)$$

$$- C(q_i,\theta_i) + S_i \geq - C(q_j,\theta_i) + S_j, \text{ for } i,j \in (1,2) \quad (2.10)$$

$$C(q_i,\theta_i) \leq p_i F_i, \text{ for } i \in (1,2) \quad (2.11)$$

$$- C(q_i,\theta_i) + S_i \geq -p_j F_j + S_j, \text{ for } i, j \in (1,2) \quad (2.12)$$

$$F_i \leq \overline{F}, \text{ for } i \in (1,2) \text{ and} \quad (2.13)$$

$$p_i \leq 1, \text{ for } i \in (1,2) \quad (2.14)$$

Recall that α_i represents the regulator's prior belief that $\theta = \theta_i$. The inequalities of (2.9) are individual rationality constraints, and they ensure that the firm enjoys a profit at least equal to its reservation level: in this model, reservation profits are zero. The individual rationality constraints guarantee that the firm will participate in the regulatory relationship. The incentive compatibility constraints of (2.10) identify (q_i, S_i, p_i, F_i) as the regulatory contract the compliant firm will choose when its abatement cost function parameter is θ_i. Constraints (2.11) through (2.14) are the aforementioned enforcement constraints.: the compliance constraints, the hybrid incentive compatibility/compliance constraints, the maximum fine constraints, and the monitoring probability constraints.

In subsequent propositions about optimal environmental regulations with costly monitoring for compliance, we find that the maximum penalty constraint is binding; that is, $F = \bar{F}$. In this model, the firm is risk-neutral. When deciding whether to comply with an abatement standard, the firm weighs the cost of abatement against the expected cost of noncompliance, pF. The firm is concerned with the magnitude of the product pF, not its individual components p and F. In this model, increasing the probability of monitoring is costly while increasing the penalty for noncompliance is not. The regulator would ideally impose infinite fines and monitor the firm with infinitesimal probabilities; however, for economic and political reasons previously discussed, we rule this possibility out. Consequently, the regulator uses the maximum fine possible, and monitors the firm with a frequency large enough to maintain compliance with the standard. Given that F is set to its maximum value $\bar{F}$, binding compliance constraints and costly monitoring results in abatement standards which are less stringent than they would otherwise be.

3. Enforcement Model

In this section, we consider standard setting and enforcement issues jointly, and we formally analyze the complete regulatory model.

Formally, the regulator's problem may be represented by the following Lagrangian, and the regulator chooses (q_1,S_1,p_1,F_1) and (q_2,S_2,p_2,F_2) as well as $\lambda_1,\lambda_2,\omega_{12},\omega_{21}$, y_1,y_2, z_{12}, z_{21}, x_1, x_2, υ_1 and υ_2 to maximize.

$$L = \sum_{i=1}^{2} \alpha_i \{ E(q_i) - (\beta - 1) S_i - C(q_i,\theta_i) - cp_i \}$$

$$+ \sum_{i=1}^{2} \lambda_i(\pi - C(q_i,\theta_i) + S_i) + \sum_{i,j=1_{ij}}^{2} \omega_{ij}(-C((q_i,\theta_i) + S_i + C((q_j,\theta_i) - S_j] \qquad (3.1)$$

$$+ \sum_{i=1}^{2} y_i[- C(q_i,\theta_i) + p_i,F_i] + \sum_{i,j=1_{ij}}^{2} z_{ij} [-C(q_i,\theta_i) + S_i + p_jF_j - S_j]$$

$$+ \sum_{i=1}^{2} x_i(\overline{F} - F_i) + \sum_{i=1}^{2} \upsilon_i(1-p_i).$$

In this formulation of the regulator's problem, λ_i, ω_{ij}, y_i, z_{ij}, x_i, and υ_i for i, j, ε {1,2}, $i \neq j$, are the nonnegative multipliers associated with the individual rationality, incentive compatibility, compliance, hybrid incentive compatibility/compliance, maximum penalty, and monitoring probability constraints, respectively. The regulator's problem can be simplified by noting that some of the constraints are redundant: they are implied by pairs of other constraints.

For instance, it can easily be shown that $z_{12} = 0$; the hybrid incentive compatibility/ compliance constraint is not binding for a low cost-type firm. Incentive compatibility requires that

$$\pi - C(q_1,\theta_1) + S_1 \geq \pi - C(q_2,\theta_1) + S_2,$$

and assumption (2.3) states that

$$\pi - C(q_2,\theta_1) + S_2 \geq \pi - C(q_2,\theta_2) + S_2 \text{ since } \theta_2 > \theta_1 .$$

Finally, the compliance constraint for a high-cost type firm requires that

$$\pi - C(q_2,\theta_2) + S_2 \geq \pi - p_2 F_2 + S_2,$$

and by transitivity

$$\pi - C(q_1,\theta_1) + S_1 \geq \pi - p_2 F_2 + S_2 : z_{12} = 0.$$

If incentive compatibility and compliance constraints are satisfied for low and high cost-type firms respectively, the hybrid incentive compatibility/compliance constraint for a low cost-type firm will be automatically satisfied.

Similarly, the compliance constraint for a low cost-type firm is redundant. Satisfaction of the constraints of incentive compatibility for a low cost-type firm and hybrid incentive compatibility/compliance for a high cost-type firm guarantee that $y_1 = 0$. Since

$$\pi - C(q_1,\theta_1) + S_1 \geq \pi - C(q_2,\theta_1) + S_2 \geq \pi - C(q_2,\theta_2) + S_2 \geq \pi - p_1 F_1 + S_1,$$

then

$$\pi - C(q_1,\theta_1) + S_1 \geq \pi - p_1 F_1 + S_1.$$

Likewise, individual rationality for a low cost-type firm is guaranteed by satisfaction of the constraints of incentive compatibility for a low cost-type and individual rationality for a high cost-type. With $\pi - C(q_1,\theta_1) + S_1 \geq \pi - C(q_2,\theta_1) + S_2 \geq \pi - C(q_2,\theta_2) + S_2 \geq 0$, we have $\pi - C(q_1,\theta_1) + S_1 \geq 0$, that is $\lambda_1 = 0$.

We first look at the interior solution of the problem before we get to the corner solution.

Proposition 3.1

The interior solution (i.e. p_1, p_2 $\varepsilon(0,1)$) to the asymmetric information/enforcement problem satisfies

(i) $E'(q_1) = \{\beta + c/\overline{F}\}\, C_q(q_1,\theta_1)$

(ii) (ii) $E'(q_2) = (\beta + c/\overline{F})\, C_q(q_2,\theta_2) + \frac{\alpha_1}{\alpha_2}[\beta - 1) + c/\overline{F}]\{C_q(q_2,\theta_2) - C_q(q_2,\theta_1\}),$

(iii) $S_1 = C(q_1,\theta_1) - C(q_2, \theta_1) + S_2.$

(iv) $S_2 = C(q_2,\theta_2) - \pi$.

(v) $$p_1 = \frac{C(q_2,\theta_2)+(S_1-S_2)}{\overline{F}} = \frac{C(q_2,\theta_2)+[C(q_1,\theta_1)-C(q_2,\theta_1)]}{\overline{F}}$$

(vi) $p_2 = \frac{C(q_2,\theta_2),}{\overline{F}}$, and

(vii) $F_1 = F_2 = \overline{F}.$

The proof is given in the appendix.

One of the more interesting features of the optimal regulations is characterized by condition (v) of Proposition 3.1. The probability of monitoring a low- cost type firm, p_1, is set at a level to satisfy the binding hybrid incentive compatibility/compliance constraint for a high cost-type firm. Condition (v) may be rewritten as $-C(q_2,\theta_2) + S_2 = p_1\overline{F} + S_1$. The probability p_1 is chosen to deter a high- cost type firm from selecting the low cost-type regulatory contract (and then not complying with the abatement requirement contained therein).

Condition (v) may also be expressed as $p_1\overline{F} = C(\alpha_1,\theta_1) + \{C(q_2,\theta_2) - C(q_2,\theta_1)\}$, and in this firm, two points emerge. First, since $\{C(q_2,\theta_2)-C(q_2,\theta_1)\} > 0$, we know that $p_1\overline{F} > C(q_1,\theta_1)$. The probability of monitoring , p_1, is set to a level which is higher than necessary to induce the low cost-type firm to comply with its abatement standard q_1; the compliance constraint is not binding for the low cost-type. The added complication of asymmetric information forces monitoring probabilities to play a more complicated role in the optimal regulatory scheme. In the case of asymmetric information, the monitoring probability p_1 must also help maintain incentive compatibility since noncompliance with regulations is a distinct possibility.

Second , since $p_1\overline{F} = C(q_1,\theta_1) + \{C(q_2,\theta_2) - C(q_2,\theta_1)\}$, we also know that the regulator commits to inspecting the low cost-type firm with greater frequency the larger its abatement requirement q_1; however, once again , this is true because the regulator must deter the high cost firm from accepting the low cost contract and cheating. It is the hybrid incentive compatibility/compliance constraint for a high cost-type firm which is binding, not the compliance constraint for a low cost-type firm: $z_{12} > 0$ and $y_1 = 0$. The cost of monitoring for compliance simultaneously influences both the optimal probabilities of monitoring and the optimal pollution abatement standards.

Conditions (i) and (iii) of Proposition 3.1 characterize the abatement standard and subsidy designed for the low cost-type firm. Condition (iii) implies that incentive compatibility is binding for a low cost firm: S_1 is chosen to make the firm indifferent between complying with the low or high cost-type regulatory contracts. This result is well known in the incentive literature relating to problems of adverse selection, and condition (iii) suggests that the result continues to hold in a regulatory context of asymmetric information in which compliance must be enforced through costly inspections. Condition (i) indicates that the abatement standard for a low cost-type firm is distorted downward from the level which equates the marginal benefit and cost of pollution abatement. If q_1 were increased from the level described by condition (i) of the proposition, S_1 would have to be increased to maintain incentive compatibility for a low cost firm. Increasing S_1 in this manner would be unacceptably costly. First, there are the direct welfare costs of raising, through distortionary means, the subsidy, summarized by the parameter β. Second, increasing S_1 to support an increase in q_1 above the optimal level described in condition (i) necessitates an increase in p_1 to maintain satisfaction of the hybrid incentive compatibility/compliance constraint for a high cost-type firm. For every dollar S_1 is increased p_1 must be increased by $1/\overline{F}$ at a unit cost of c. This accounts for the $c/\overline{F}$ term in condition (i).

As condition (ii) of Proposition 3.1 makes clear, the presence of asymmetric information about abatement costs heavily distorts the abatement standard to be met by a high cost-type firm, particularly in a model complicated by costly monitoring for compliance. Since $\{ C_q (q_2, \theta_2) - C_q (q_2,\theta_1)\} > 0$, we know that q_2 is chosen to be far below the level which would equate the marginal benefit and cost of pollution abatement. Condition (ii) may be rewritten as

$$\alpha_2[E'(q_2) - C_q (q_2,\theta_2) - (\beta - 1) C_q (q_2,\theta_2) - c/\overline{F}\, C_q (q_2,\theta_2)]$$

$$= \alpha_1 [\beta - 1) + c/\overline{F}] \{C_q (q_2,\theta_2) - C_q (q_2,\theta_1) \}. \qquad (3.1)$$

In this form, equation (3.1) yields intuition about the standard setting process for a high cost firm. From the regulator's perspective, $\theta = \theta_2$ with probability α_2. At the margin, increasing q_2 yields pollution abatement benefits of $E'(q_2)$ at a cost given by $C_q (q_2,\theta_2)$. Condition (iv) indicates that the individual rationality constraint is binding for a firm with $\theta = \theta_2$. Consequently, if q_2 is increased at the margin, S_2 must be increased by $C_q (q_2,\theta_2)$ at a welfare cost of $(\beta - 1)C_q (q_2,\theta_2)$. Condition (vi) of Proposition 3.1 indicates that the compliance constraint is also binding for a firm with $\theta = \theta_2$, so p_2 must be increased by $\frac{C_q(q_2,\theta_2)}{\overline{F}}$ at a unit cost of c if q_2 is increased marginally. The left-hand side of equation (3.1) captures the consequences of setting q_2 when $\theta = \theta_2$, and this occurs with probability α_2 from the regulator's perspective.

Moreover, setting q_2 has implications for welfare even if $\theta = \theta_1$, and the right-hand side of equation (3.1) accounts for these effects. To the regulator $\theta = \theta_1$ with probability α_1 . If q_2 is increased at the margin, S_2 must be increased as described in the preceding paragraph;

however, S_1 must also be increased to maintain incentive compatibility for a low cost-type firm. S_1 must be increased by $C_q(q_{2,}\theta_1)$ because$C_q(q_{2,}\theta_2)$ is the amount S_2 is increased and $C_q(q_{2,}\theta_1)$ is the amount abatement costs increase for a firm which accepts the $(q_2,S_2,p_2, \overline{F})$ contract, when $\theta = \theta_1$. To keep a low cost-type firm from accepting the high cost-type contract. S_1 is increased at unit costs equal to $[(\beta - 1) +c/\overline{F}]$. The $(\beta- 1)$ term is the direct welfare cost of raising the subsidy and the $c/\overline{F}$ term relates to the cost of raising p_1 to maintain satisfaction of the binding hybrid incentive compatibility/compliance constraint for a high cost-type firm when S_1 is increased. Condition (ii) of Proposition 3.1 accounts for the connection between the aspects of asymmetric information and costly enforcement so prevalent in most problems of environmental regulation.

Now we move move to a special case of corner solutions.

If the cost of monitoring is relatively low, the benefit of pollution abatement relatively high, the maximum penalty for noncompliance relatively low, it can be optimal for the regulator to choose a corner solution for one or both monitoring probabilities. There are two possible cases: (i) $p_1= 1$, $p_2 < 1$, and (ii) $p_1= p_2 = 1$. It can be shown that if $p_2 = 1$, then $p_1= 1$ as well. We will refer to the first case as a partial corner solution and the second case as a complete corner solution. In the partial corner solution $p_1= 1$, and the Lagrange multiplier associated with the monitoring probability constraint υ_1 is positive.

Proposition 3.2

The partial corner solution to the asymmetric information/enforcement problem satisfies

(i) $E'(q_1) = [\beta + \frac{c+\upsilon_1/\alpha_1}{\overline{F}}]C_q\,(q_1,\theta_1)$,

(ii) $E'(q_2) = [\beta +c/\overline{F}]C_q\,(q_2, \theta_2) + \frac{\alpha_1}{\alpha_2}\,[(\beta - 1) + \frac{c+\upsilon_1/\alpha}{\overline{F}}]\,\{C_q\,(q_2, \theta_2) - C_q\,(q_2, \theta_1)\}$

(iii) $p_1 = 1 = \frac{C_q\,(q_2,\theta_2) + (S_1 - S_2)}{\overline{F}} = \frac{C(q_2,\theta_2) + [\,C(q_1,\theta_1) - C(q_2,\theta_1)\,]}{\overline{F}}$

(iv) $p_2 = \frac{C(q_2,\theta_2)}{\overline{F}}$.

(v) $S_1= C(q_1,\theta_1) - C(q_2,\theta_1) + S_2$.

(vi) $S_2 = C(q_2, \theta_2) - \pi$. And

(vii) $F_1= F_2 = \overline{F}$.

The first three conditions of the proposition simultaneously solve for the optimal values of $q_{1,}q_2$ and υ_1.Then conditions (iv), (vi), and (v) individually determine the optimal values of $p_{2,}$ S_2, and S_1 respectively. In the partial corner solution, a margin for adjustment, p_1 , is bound. With $p_1 = 1$, the standard setting process is affected dramatically by the hybrid incentive compatibility/compliance constraint for the high cost-type firm. Increasing q_1 or q_2 requires increasing S_1 to maintain incentive compatibility for a low cost firm as before, but now $p_1$cannot be increased to maintain the hybrid constraint. The hybrid constraint must be satisfied by altering $q_{1,}q_2$ or S_2, which feeds back to the process of setting S_1. Again, conditions (i),(ii), and (iii) of the proposition must be solved simultaneously to determine the optimal abatement standards in this partial corner solution case.

In the complete corner solution case, $p_1= p_2 = 1$, and the regulator enforces a pooling equilibrium. If $p_2 = \frac{C(q_2,\theta_2)}{\overline{F}} = 1$, then $q_1 = q_2$, $S_1= S_2$, and $p_1= p_2 = 1$.By contradiction, suppose $q_1> q_2$ and $S_1 > S_2$. From the hybrid incentive compatibility/compliance constraint, $p_1 \geq \frac{C(q_2,\theta_2)+(S_1-S_2)}{\overline{F}}$, but if $p_2 = 1$ then $\overline{F} = C(q_2,\theta_2)$, and $p_1> 1$ since by supposition $S_1 = S_2$. This of course, violates the requirement that $p_1\leq 1$. In other words, if the regulator finds it optimal to choose $p_2 = 1$, then the regulator must also choose $S_1> S_2$. and $q_1 =q_2.$ However, the complete corner solution is not likely to prevail. It occurs only when the maximum penalty for noncompliance, $\overline{F}$, is so low that it is beneficial to set q_2 so that abatement costs are equal to $\overline{F}$ even when $\theta = \theta_2$. The compliance constraint, in concert with the monitoring probability constraint, defines the maximum abatement standard that can be set and enforced for a high cost-type firm. This is the level such that $C(q_2,\theta_2) = \overline{F}$. If the benefit of pollution abatement is high enough to justify setting q_2 to this level, the regulator cannot set and enforce an even higher abatement requirement for a low cost-type firm. In this rare instance, we are left with a pooling equilibrium in which $q_1=q_2$ and $S_1 = S_2$.

4. Summary and Conclusion

We have discussed the optimal design of incentive compatible environmental regulations under conditions of asymmetric information about pollution abatement costs when compliance with abatement standards can only be monitored at cost. Costly enforcement of pollution standards is shown to distort downward the optimal level of abatement required of both low and high cost firms. A hybrid incentive compatibility / compliance constraint is developed and shown to be binding for high cost firms, thereby influencing the optimal values of the regulatory variables.

This paper addresses the issues of asymmetric information and costly enforcement in a united framework which, except für very recent research had not yet been explored in the environmental economics literature. Much of the literature in environmental regulation has treated the problems of asymmetric information and costly enforcement as distinct and separate. The few papers which have explored the issues of standard setting and enforcement jointly have restricted attention to suboptimal uniform standards.

Much of the relevant work, (e.g.. Russell (1990) and Harrington (1988)), about the strategic considerations of enforcing pollution control laws take as exogenously given a uniform pollution control standard. In these papers, a repeated game framework is employed to demonstrate that when regulating firms with heterogeneous abatement costs, enforcement costs can be lowered by treating firms heterogeneously based upon their prior record of (non)compliance. The welfare gains of these sophisticated Markov models of enforcement are due, in part, to the fact that they treat, in equilibrium, firms with low costs differently than those with high costs. However, all firms are subject to the same pollution control standard. In our approach, firms with low pollution abatement costs are subjected to different pollution control standards, as well as different enforcement measures, than firms with high costs.

Appendix

Proof of Proposition 3.1

The Lagrangian for the asymmetric information/enforcement problem is contained in the text of Section 4 as are the proofs of the preliminary results that the Lagrange multipliers z_{12}, y_1, and λ_1 are all equal to zero. The first-order necessary conditions are consequently

$$\alpha_1 E'(q_1) - [\alpha_1 + \omega_{12}]C_q(q_1,\theta_1) + \omega_{21}C_q(q_1,\theta_2) = 0. \quad (A.1)$$

$$\alpha_2 E'(q_2) - [\alpha_2 + \lambda_2 + y_2 + \omega_{21} + z_{21}]C_q(q_2,\theta_2) + \omega_{12}[C_q(q_2,\theta_1)] = 0. \quad (A.2)$$

$$\alpha_1 (1 - \beta) + \omega_{12} - \omega_{21} - z_{21} = 0. \quad (A.3)$$

$$\alpha_2 (1 - \beta) + \lambda_2 + \omega_{21} - \omega_{12} + z_{21} = 0. \quad (A.4)$$

$$\alpha_1 c + z_{21} F_1 - v_1 = 0 \quad (A.5)$$

$$- \alpha_2 c + y_2 F_2 - \upsilon_2 = 0. \quad (A.6)$$

$$- x_1 + z_{21} p_1 = 0. \text{ And} \quad (A.7)$$

$$- x_2 + y_2 p_2 = 0. \quad (A.8)$$

Since $\alpha_1 c > 0$, $\alpha_2 c > 0$, $\upsilon_1 \geq 0$, $\upsilon_2 \geq 0$ $z_{21} > 0$ and $y_2 > 0$ from (A.5) and (A.6). With q_1, q_2 ε $(0,q_{max})$, from assumption (2.1), $p_1 > 0$ and $p_2 > 0$ to satisfy the compliance constraints. Consequently. $z_{21}p_1 >0$ and $y_2p_2 > 0$ so that $x_1 > 0$ and $x_2 > 0$, yielding condition (vii) of the proposition:$F_1 = F_2 = \bar{F}$. For the interior solution in monitoring probabilities p_1 and p_2 covered by this proposition, $\upsilon_1 = 0$ and $\upsilon_2 = 0$. Therefore $z_{21} = \frac{(\alpha_1 c)}{\bar{F}} > 0$ and $y_2 = \frac{(\alpha_2 c)}{\bar{F}} > 0$. The facts that hybrid incentive compatibility / compliance constraints are binding for a high cost-type firm generate conditions (v) and (vi) of the proposition.

If ω_{21}, > 0 then from (A.3), $\omega_{12} = \alpha_1 (\beta - 1) + \frac{(\alpha_1 c)}{\bar{F}} > 0$, yielding condition (iii) of the proposition. If $\omega_{21} = 0$, then $\lambda_2 = \alpha_2(\beta - 1) + \alpha_1 (\beta - 1) + \frac{(\alpha_1 c)}{\bar{F}} - \frac{(\alpha_1 c)}{\bar{F}} = (\beta - 1) > 0$ from equation (A.4), thereby generating condition (iv) of the proposition. Moreover, with $\omega_{12} = \alpha_1 (\beta - 1) + \frac{(\alpha_1 c)}{\bar{F}}$, (A.1) becomes $\alpha_1 E'(q_1) = [\alpha_1 + \alpha_1 (\beta - 1) + \frac{(\alpha_1 c)}{\bar{F}}] C_q(q_1,\theta_1)$. Dividing by α_1 and rearranging, we obtain condition (i) of the proposition. Similarly, with

$\lambda_2 = (\beta - 1), y_2 = \frac{(\alpha_2 c)}{\bar{F}}$ and $z_{21} = \frac{(\alpha_1 c)}{\bar{F}}$, (A.2) may be rewritten as condition (ii) of the proposition.

To check that $\omega_{21} = 0$, we check that profits for a firm with $\theta = \theta_2$ are larger if it accepts and complies with the (q_2,S_2,p_2,F_2) contract rather than the (q_1,S_1,p_1,F_1) contract. Profits for a high cost-type firm complying with the contract designed for a low cost-type are

$$\pi - C_q(q_1,\theta_2) + S_1$$

$$= \{\pi - C(q_1,\theta_1) + S_1\} + C(q_1,\theta_1) - C(q_1,\theta_2) \quad \text{(A.9)}$$

$$= \{\pi - C(q_2,\theta_1) + S_2\} + C(q_1,\theta_1) - C(q_1,\theta_2)$$

where $\{\pi - C(q_1,\theta_1) + S_1\} = \{\pi - C(q_2,\theta_1) + S_2\}$ since incentive compatibility is a binding constraint ($\omega_{12} > 0$) for a low cost-type firm. From (A.9) it is easy to see that profits are distinctly larger for a high cost-type firm if it complies with the contract designed for its type:

$$(\pi - C(q_2,\theta_2) + S_2) - (\pi - C(q_1,\theta_2) + S_1)$$

$$= (\pi - C(q_2,\theta_2) + S_2) - (\pi - C(q_2,\theta_1) + S_2) - C(q_1,\theta_1) + C(q_1,\theta_2) \quad \text{(A.10)}$$

$$= [C(q_1,\theta_2) - C(q_1,\theta_1)] - [C(q_2,\theta_2) - C(q_2,\theta_1)] > 0$$

given assumption (2.4) and the fact that $q_1 > q_2$. Since the incentive compatibility constraint for a high cost-type firm is not binding $\omega_{21} = 0$, and the proof is complete.

Proof of Proposition 3.2

The Lagrangian for the asymmetric information/enforcement problem is contained in the text of Section 3 as are the proofs of the preliminary results that the Lagrange multipliers z_{12}, y_1 , and λ_1 are all equal to zero. The first-order necessary conditions are (A.1) through (A.8) presented in the proof of Proposition 3.1.

Again, since $\alpha_1 c > 0$, $\alpha_2 c > 0$, $\upsilon_1 \geq 0$, and $\upsilon_2 \geq 0$, we attain $z_{21} > 0$ and $y_2 > 0$ from (A.5) and (A.6). With q_1,q_2. ε $(0,q_{max})$, assumption (2.1) states that abatement costs will be positive, necessitating the result that $p_1 > 0$ and $p_2 > 0$ to satisfy the compliance constraints. Consequently, $z_{21}\, p_1 > 0$ and $y_2 p_2 > o$ so that $x_1 > 0$ and $x_2 > 0$; that is, the maximum penalty constraints are binding, and condition (vii) of the proposition is obtained: $F_1 = F_2 = \bar{F}$.

For the partial corner solution covered by the proposition, $p_1 = 1$ and $\upsilon_1 > 0$ while $p_2 < 1$ and $\upsilon_2 = 0$. Therefore, from (A.5) we obtain $z_{21} = \frac{(\alpha_1 c + \upsilon_1)}{\bar{F}}$ and from (A.6) we have $y_2 = \frac{(\alpha_2 c)}{\bar{F}}$. With $z_{21} > 0$ and $y_2 > 0$, the hybrid incentive compatibility/compliance constraints for a high cost-type firm are binding, generating conditions (iii) and (iv) of the proposition.

If $\omega_{21} = 0$, then from (A.3), $\omega_{12} = \alpha_1 (\beta - 1) + \frac{(\alpha_1 c + \upsilon_1)}{\bar{F}} > 0$, providing condition (v) of the proposition. If $\omega_{21} = 0$, then from (A.4), $\lambda_2 = (\beta - 1) > 0$, and we obtain condition (vi). If $\omega_{21} = 0$, (A.1) and (A.2) directly imply conditions (i) and (ii) of the proposition. Finally, the proof that $\omega_{21} = 0$ is identical to the one found at the end of the proof of Proposition 3.1: profits are distinctly larger for a high cost-type firm if it complies with the contract designed for its type rather than with the low cost-type contract.

References

Baron, D.P.(1989),“Design of Regulatory Mechanisms and Institutions“, Chapt. 24 in

R. Schmalensee and R.D. Willig (eds.), Handbook of Industrial Organization, North Holland: Amsterdam 1989.

Baron, David P., and David Besanko, (1984) "Regulation, Asymmetric Information, and Auditing," Rand Journal of Economics, Vol. 15, pp. 447-470.

Baron David P., and Roger B. Myerson, (1982),"Regulating a Monopolist with Unknown Costs," Econometrica, Vol. 50, pp. 911-930.

Besanko, David and David E.M. Sappington, (1987), Designing Regulatory Policy with Limited Information, Harwood, Chur.

Gottinger, H.W. (1999), „Crime Control and Environmental Policy: The Case of Hazardous Wastes“, Metroeconomica Vol. 50 ,pp. 1-33

Harrington, Winston, (1988) "Enforcement Leverage When Penalties are Restricted." Journal of Public Economics, Vol. 37, pp. 29-53.

Jebjerg, Lars and Henrik Lando (1997), „Regulating a Pollution Firm under Asymmetric Information“, Environmental and Resource Economics 10, 267-284.

Russell, Clifford, (1980)"Game Theory Models for Structuring Monitoring and Enforcement Systems," Natural Resource Modeling.

Swierzbinski, Joseph E.V. (1994), „Guilty until Proven Innocent-Regulation with Costly and Limited Enforcement“, Jour. of Environmental Economics and Management 27, 127-146.