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OPTIMAL ENVIRONMENTAL REGULATION
UNDER ASYMMETRIC INFORMATION

DANIEL F. SPULBER

MRG WORKING PAPER #M8706

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ABSTRACT

A model of environmental regulation with interdependent production and pollution abatement costs and heterogeneous firms is developed. Firms have private information about costs which have a quadratic form. A budget-balancing problem is shown to exist even with Bayes-Nash strategies. The full information optimum cannot be attained unless gains from trade in the product market net of external damages exceed the information rents earned by firms.

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1. Introduction.

An important issue in environmental regulation is the tradeoff between the benefits of pollution abatement and the benefits from the economic activity which generates that pollution as an unwanted by-product. If the costs of production and pollution abatement are interdependent, optimal regulation of pollution must take into account the final output market, see for example Spulber (1985) and the references therein. In the presence of asymmetric information about firm costs, interaction between environmental regulation and the output market is of particular significance as output levels are not known when regulations are designed.

This paper addresses the problem of the design of regulatory mechanisms which maximize welfare with explicit attention to the final output market. For tractability we assume quadratic firm costs. We allow firms to be heterogeneous in terms of the probability distributions of their cost parameters which are unknown both to the regulator and to other firms. The product market is assumed to be competitive. We consider a regulatory game in which firms pursue Bayes-Nash strategies in communication with the regulator. We characterize the optimal incentive compatible regulatory mechanism by which firms are assigned effluent levels and damage payments.

The principal result obtained is a characterization of a necessary and sufficient condition for optimal regulation under asymmetric information to achieve the full information optimal effluent levels. The condition is that, at the full information optimum, net benefits from the product market (consumer surplus minus total production costs and minus pollution damages) must exceed the costs of inducing truth-telling by firms. The costs of providing incentives for truth-telling are referred to as the *information rents* obtained by firms. The full information optimum is feasible, therefore, if and only if net social welfare exceeds firm information rents. Thus, net benefits from the product market may constrain the set of feasible regulations in an interesting manner.

The requirement for achieving the full information optimum is similar to the budget

balancing condition in dominant strategy frameworks. Environmental regulation is studied in a dominant strategy setting by Dasgupta, Hammond and Maskin (1980). They show that the full information optimum is attainable using dominant strategies but the government's budget does not balance. This approach is in the tradition of Groves (1973), Groves and Loeb (1975), Green and Laffont (1977) and Groves and Ledyard (1977). In d'Aspremont and Gérard-Varet (1979) it is shown that a Bayes-Nash mechanism can attain the full-information optimum but they do not give explicit attention to individual rationality. Spulber (1986) gives an example of rate regulation with a representative consumer and firm, in which the full information outcome is attained by an individually rational, and incentive compatible mechanism. The present analysis extends these results to a multifirm setting with a product market and effluent regulation.

The paper is organized as follows. The market model is presented in section 2. The set of feasible mechanisms is characterized in section 3 and the optimal mechanism is obtained in section 4. Properties of the regulated equilibrium are derived in section 5. An alternative regulatory setting is briefly examined in section 6. Conclusions are given in section 7.

2. The Model.

2.1 Basic framework

We examine a competitive market for a good Q supplied by m firms. Firms are indexed by $j = 1, \dots, m$. Each firm j produces output q^j and discharges effluents e^j . Market inverse demand is given by $P = P(Q)$ where Q is total output. External damages are $D(E)$ where E is total effluents discharged by firms. Market inverse demand, P , is continuously differentiable, positive and downward-sloping. The damage cost function, D , is twice differentiable, positive, increasing and convex for $E > 0$. Let $D'(E) \equiv \partial D / \partial E$ and $P'(Q) \equiv \partial P / \partial Q$. Note that the problem is not interesting if the damage function is separable, otherwise each firm may be charged for its marginal damages. The present analysis may be easily generalized to allow damages to be firm-specific, $D(e^1, \dots, e^m)$.

A firm of type j has a cost function $C(q^j, e^j, \theta^j)$ where θ^j is a technology parameter which takes values in the interval $[0, 1]$. For ease of presentation we assume that costs have the following *quadratic* form:

$$C(q, e, \theta^j) = (\alpha/2)(e^2 + q^2) - \gamma eq - \theta^j e, \quad (1)$$

for $j = 1, \dots, m$. Thus, marginal production costs are increasing in q . Output and pollution are cost complements, $C_{12} = -\gamma < 0$. Since $C_2 = \alpha e - \gamma q - \theta^j$, increased effluent generation lowers costs if $e \leq (\gamma q + \theta^j)/\alpha$ and raises costs otherwise. To assure convexity of costs in (q, e) , assume that $\alpha > \gamma$. Finally, note that $C_3 = -e$. Thus, the costs of reducing pollution (abatement) increase with the technology parameter θ^j .

The cost parameter θ^j represents firm j 's private information. For ease of discussion, we assume that the *a priori* beliefs of the regulator and firms about the distribution of the θ^j parameters may be represented by the cumulative distribution functions $F^j(\theta^j)$, $j = 1, \dots, m$, which are common knowledge. That is, the regulator takes the θ^j parameters to be independently but not necessarily identically distributed. The problem may be generalized to allow the θ^j parameters to be jointly distributed according to $F(\theta^1, \dots, \theta^m)$. Let $F(0) = 0$, $F(1) = 1$, $f(\theta) \equiv dF(\theta)/d\theta > 0$. Also, let $F^n(\theta) = \prod_{i=1}^n F^i(\theta^i)$.

2.2 Market equilibrium

Firms behave competitively, taking the product price p as given. Thus, each firm's marginal cost equals the product price, $p = C_1(q^j, e^j, \theta^j)$,

$$p = \alpha q^j - \gamma e^j, \quad j = 1, \dots, m. \quad (2)$$

Note that by the form of costs as given in equation (1), each firm's supply curve does not depend directly on the technology parameter θ^j , so that $q^j = q(p, e^j)$. As we will see, the firm's private information will affect its choice of pollution e^j and so will indirectly determine its market supply.

Define firm profits as a function of p, e^j and θ^j ,

$$\pi(p, e^j, \theta^j) \equiv pq(p, e^j) - C(q(p, e^j), e^j, \theta^j), \quad j = 1, \dots, m. \quad (3)$$

Applying equation (2) and the envelope theorem, we note that $\pi_2(p, e^j, \theta^j) = -C_2 = -\alpha e^j + \gamma q^j + \theta^j$, and $\pi_3(p, e^j, \theta^j) = \theta^j$.

Combining demand, $p = P(\sum_{i=1}^m q^i)$, with the supply equations (2), we can solve for the market equilibrium outputs as a function of effluent levels, $q^j = q^j(e^1, \dots, e^m)$, $j = 1, \dots, m$. It will be useful to calculate the effects of effluents on market outputs. From $p = P(\sum_{i=1}^m q^i)$ and (2) we have

$$P'(\sum_{i=1}^m q^i) \sum_{i=1}^m (\partial q^i / \partial e^\ell) = \alpha (\partial q^j / \partial e^\ell) - \gamma \delta_{j\ell}, \quad (4)$$

where $\delta_{j\ell} = 1$ if $j = \ell$ and zero otherwise. Summing over j and rearranging terms yields

$$\sum_{i=1}^m (\partial q^i / \partial e^\ell) = \gamma / (\alpha - P'(\sum_{i=1}^m q^i)). \quad (5)$$

Substituting from equation (5) into equation (4) and rearranging terms, we have

$$\partial q^j / \partial e^\ell = \left[(\gamma / \alpha) P'(\sum_{i=1}^m q^i) / (\alpha - P'(\sum_{i=1}^m q^i)) \right] + (\gamma / \alpha) \delta_{j\ell}. \quad (6)$$

Thus, we have shown that a firm's market equilibrium output is increasing in its own effluent level but decreasing in the effluent levels of other firms, $\partial q^j / \partial e^j > 0$ and $\partial q^j / \partial e^\ell < 0$, $\ell \neq j$. Since total output is increasing in the effluents generated by any individual firm, by equation (5), pollution abatement lowers total output thereby raising the market price. Hence, the benefits of reduced pollution must be balanced against both higher product prices and abatement costs.

3. Feasibility.

Consider a regulatory game in which m firms send messages s^j to a regulator.¹ Based on the messages received, the regulator assigns effluent levels e^j and penalties t^j to each firm,²

$$e^j = e^j(s^1, \dots, s^m), \quad t^j = t^j(s^1, \dots, s^m).$$

Firms do not know each other's private information θ^j , so that each follows a Bayes-Nash strategy in choosing their message. The Bayes-Nash equilibrium strategies $\tilde{s}^j = \tilde{s}^j(\theta^j)$ depend only on each firm's private information.

By standard revelation principle arguments,³ we may represent the regulatory mechanism (e^j, t^j) by a *direct mechanism* which assigns effluent levels and penalties depending upon that firm's announced parameter value. Thus, the firm's message is a reported parameter value.⁴ The direct mechanism is represented as $E^j(\theta^j, \theta^{(j)}), T^j(\theta^j, \theta^{(j)})$, $j = 1, \dots, m$, where $\theta^{(j)} = (\theta^1, \dots, \theta^{j-1}, \theta^{j+1}, \dots, \theta^m)$. Firms play a Bayes-Nash game given the direct mechanism. Each firm chooses its parameter report $\hat{\theta}^j$ under the belief that truth-telling is the Bayes-Nash equilibrium strategy for all other firms.

Let $I^n = \prod_{j=1}^n [0, 1]$ and $dF^{(j)} = dF^1(\theta^1) \dots dF^{j-1}(\theta^{j-1}) dF^{j+1}(\theta^{j+1}) \dots dF^m(\theta^m)$.

Also, let

$$t^j(\theta^j) \equiv \int_{I^{m-1}} T^j(\theta^j, \theta^{(j)}) dF^{(j)} \quad (7)$$

represent the expected payment made by firm j if it announces parameter value θ^j given that other firms pursue a truth-telling strategy. Similarly, $e^j(\theta^j) \equiv \int_{I^{m-1}} E^j(\theta^j, \theta^{(j)}) dF^{(j)}$ represents firm j 's expected effluent level.

Each firm takes the market price as given in announcing its parameter value to the regulator. The particular value of the market price is not important in determining firm j 's parameter report. Firm j 's profit from reporting parameter value $\hat{\theta}$ when its true parameter is θ is given by

$$\Pi^j(\theta, \hat{\theta}) = \int_{I^{m-1}} \pi(p, E^j(\hat{\theta}, \theta^{(j)}), \theta) dF^{(j)} - t^j(\hat{\theta}), \quad j = 1, \dots, m. \quad (8)$$

Incentive compatibility requires $\Pi^j(\theta, \theta) \geq \Pi^j(\theta, \hat{\theta})$ for all $\theta, \hat{\theta}$ in $[0, 1]$. Let $\Pi^j(\theta) \equiv \Pi^j(\theta, \theta)$. *Individual rationality* requires $\Pi^j(\theta) \geq 0$ for all θ in $[0, 1]$, $j = 1, \dots, m$.

The mechanism must also yield an allocation which is *individually rational* for consumers. There must be nonnegative gains from trade for consumers. Gains from trade, $V \geq 0$, are defined to equal gains from consuming output, net of external damages plus

effluent taxes paid by firms which are given to consumers as a lump sum payment. Define $S(\sum_{j=1}^m q^j) = \int \sum_{j=1}^m q^j P(Q) dQ$ as gross consumers' surplus. Then, net gains from trade for consumers equals

$$V = \int_{I^m} [S(\sum_{j=1}^m q^j) - p \sum_{j=1}^m q^j - D(\sum_{j=1}^m E^j) + \sum_{j=1}^m T^j] dF. \quad (9)$$

A mechanism (E^j, T^j) , $j = 1, \dots, m$ is said to be *feasible* if it is incentive compatible for firms and individually rational for both consumers and firms.

In the welfare analysis which follows, we view pollution taxes T^j as pure transfers from consumers to firms, with no welfare effects. Social welfare is defined as consumer surplus, net of damages from pollution and production costs.⁵ Since market equilibrium outputs are dependent on effluent levels we write expected net benefits as

$$B(E^1, \dots, E^m) \equiv \int_{I^m} [S(\sum_{j=1}^m q^j) - D(\sum_{j=1}^m E^j) - \sum_{j=1}^m C(q^j, E^j, \theta^j)] dF \quad (10)$$

To induce truth-telling, the regulator must compensate the firm. Thus, the regulated firm earns rents from private information. Higher values of the parameter θ^j lower total cost but raise the marginal costs of pollution abatement since $\partial^2 C / \partial e \partial \theta < 0$. For truth telling to be optimal for the firm, we require $\Pi_2^j(\theta, \theta) = 0$ or

$$\int_{I^{m-1}} \pi_2(p, E^j, \theta) (\partial E^j / \partial \theta) dF^{(j)} - \partial t^j(\theta) / \partial \theta = 0, \quad (11)$$

where $\pi_2 = -\alpha E^j + \gamma q^j + \theta^j$. By the envelope theorem $\Pi^{j'}(\theta) \equiv \Pi_2^j(\theta, \theta) = e^j(\theta)$. By integration we obtain

$$\Pi^j(\theta) = \Pi^j(0) + \int_0^\theta e^j(x) dx. \quad (12)$$

Since $\Pi^j(0)$ is nondecreasing in θ , individual rationality is satisfied for all firms if $\Pi^j(0) \geq 0$, $j = 1, \dots, m$. The profit earned by the firm with the lowest cost parameter represents the minimum return for a regulated firm. Thus, any gains earned by firms with higher cost parameter values may be characterized as returns to their private information, that is,

$\Pi^j(\theta) - \Pi^j(0) = \int_0^\theta e^j(x)dx$. Taking the expectation of this term, and applying integration by parts, we define *ex ante* rents to private information for a type j firm by

$$R^j(E^j) \equiv \int_{I^m} E^j \left((1 - F^j(\theta^j)) / f^j(\theta^j) \right) dF. \quad (13)$$

We now characterize the set of feasible mechanisms.

PROPOSITION 1: A direct mechanism $(E^j(\theta^j, \theta^{(j)}), T^j(\theta^j, \theta^{(j)}))$, $j = 1, \dots, m$ is feasible if and only if

$$\partial e^j(\theta) / \partial \theta \geq 0, \quad j = 1, \dots, m, \quad (14)$$

$$B(E^1, \dots, E^m) \geq \sum_{j=1}^m R^j(E^j). \quad (15)$$

The proof is given in the appendix. For related derivations see Guesnerie and Laffont (1984) for the one parameter setting and Myerson and Satterthwaite (1983) and Spulber (1986) for the multiple parameter setting. The difference in the present analysis is the emphasis on the comparison of expected welfare with the information rents earned by firms. The constraint in equation (15) is primarily due to *individual rationality* requirements. This is a "budget-balancing" condition which has important implications for the attainment of optimal externality levels under asymmetric information. As will be seen, efficiency may not be attained due to the costs of inducing truth-telling.

4. Efficiency.

The regulator's objective is to maximize expected social welfare $B(E^1, \dots, E^m)$. By Proposition 1, the optimal mechanism (E^j, T^j) solves the following problem, $\max_{(E^1, \dots, E^m)} B(E^1, \dots, E^m)$ subject to conditions (14) and (15). Let η be the multiplier associated with the inequality constraint (15). For now we do not explicitly include the monotonicity constraint (14). The regulator's objective function is then

$$W = (1 + \eta)B(E^1, \dots, E^m) - \eta \sum_{j=1}^m R^j(E^j). \quad (16)$$

where $\eta(B - \sum R^j) = 0$, $(B - \sum R^j) \geq 0$.

Define $H^j(\theta^j) \equiv \theta^j - (\eta/(1+\eta))((1 - F(\theta^\ell))/f^\ell(\theta^\ell))$. Let $h^j(\theta^j) \equiv dH^j(\theta^j)/d\theta^j$.

We introduce a *monotonicity condition* on H^j for ease of presentation,

$$\underline{H}. \quad h^j(\theta^j) \geq 0, \quad j = 1, \dots, m.$$

This monotonicity condition is satisfied by a number of familiar distributions including the uniform, $F^j(\theta) = \theta$, and the exponential, $F^j(\theta) = (1 - e^{-\xi\theta})/(1 - e^{-\xi})$. The monotonicity condition will be shown to guarantee that the optimal mechanism yields a fully separating equilibrium. It is possible to relax the condition by allowing $h^j(\theta^j)$ to change sign a finite number of times, see Guesnerie and Laffont (1984) and also Spulber (1986). Relaxing the condition in this manner allows pooling across firm types but does not significantly add to the present analysis.

Consider the pointwise maximum of W with respect to E^ℓ ,

$$\begin{aligned} (1+\eta) \sum_{j=1}^m \left[\left[P\left(\sum_{j=1}^m q^j\right) - C_1(q^j, E^j, \theta^j) \right] (\partial q^j / \partial E^\ell) \right] \\ - (1+\eta) D'\left(\sum_{j=1}^m E^j\right) - (1+\eta) C_2(q^\ell, E^\ell, \theta^\ell) \\ - \eta((1 - F^\ell(\theta^\ell))/f^\ell(\theta^\ell)) = 0, \quad \ell = 1, \dots, m. \end{aligned} \quad (17)$$

At the market equilibrium, price equals marginal cost for each firm. Also, since $C_2(q^\ell, E^\ell, \theta^\ell) = \alpha E^\ell - \gamma q^\ell - \theta^\ell$, equation (17), implies

$$D'\left(\sum_{j=1}^m E^j\right) = -\alpha E^\ell + \gamma q^\ell + \theta^\ell - (\eta/(1+\eta)) \left((1 - F^\ell(\theta^\ell))/f^\ell(\theta^\ell) \right), \quad \ell = 1, \dots, m. \quad (18)$$

We verify that equation (18) characterizes the optimal solution.

PROPOSITION 2: *Given the monotonicity condition H , the optimal mechanism (E^j, T^j) satisfies equation (18).*

PROOF: We first verify that the pointwise maximum of W is well defined. Then, we show that $\partial E^j / \partial \theta^j \geq 0$. Since $R^j(E^j)$ is linear in E^j for all j , it is sufficient to show that B is strictly concave. Let $B(E^1, \dots, E^m) = \int_{I^m} b(E^1, \dots, E^m) dF$ where

$$b(E^1, \dots, E^m) \equiv \int_0^{\sum_{j=1}^m q^j} P(Q) dQ - D\left(\sum_{j=1}^m E^j\right) - \sum_{j=1}^m C(q^j, E^j, \theta^j). \quad (19)$$

By the definition of the market equilibrium and the form of the cost function, note that $\partial b/E^\ell = -D'(\sum_{j=1}^m E^j) - \alpha E^\ell + \gamma q^\ell - \theta^\ell$. Recalling $\partial q^j/\partial e^\ell$ from equation (6) we have

$$\partial^2 b/\partial E^\ell \partial E^k = -D'' + \gamma[(\gamma/\alpha)P'/(\alpha - P')], \quad \ell \neq k \quad (20a)$$

$$\partial^2 b/\partial E^\ell \partial E^\ell = -D'' + \gamma[(\gamma/\alpha)P'/(\alpha - P')] - \alpha + \gamma^2/\alpha. \quad (20b)$$

Thus, the matrix $M \equiv [\partial^2 b/\partial E^\ell \partial E^k]$ has the form $M = [A - \lambda I]$ where all of the elements of A equal $a = [-D'' + \gamma(\gamma/\alpha)P'/(\alpha - P')]$, $\lambda = (\alpha^2 - \gamma^2)/\alpha$ and I is the identity matrix. Note that $D'' > 0$, $P' < 0$ and $\alpha^2 - \gamma^2 > 0$. Thus, M is a (symmetric) matrix with negative diagonal terms. Furthermore, it can be shown that the n th leading principal minor of m is equal to

$$M_n = (-1)^n [\lambda^n - na\lambda^{n-1}].$$

Since $\lambda > 0$, $a < 0$, $[\lambda^n - na\lambda^{n-1}] > 0$. Thus, the leading principal minors of M alternate in sign. So, M is negative definite and b is strictly concave.

Differentiate both sides of equation (18) with respect to θ^i .

$$\begin{aligned} D'' \sum_{j=1}^m (\partial E^j / \partial \theta^i) &= -\alpha \partial E^\ell / \partial \theta^i + \gamma \sum_{j=1}^m (\partial q^\ell / \partial E^j) (\partial E^j / \partial \theta^i) \\ &\quad + \delta_{i\ell} h^\ell(\theta^\ell), \quad \ell = 1, \dots, m, \end{aligned} \quad (21)$$

where $\delta_{i\ell} = 1$ if $i = \ell$ and $\delta_{i\ell} = 0$ otherwise. Substituting for $\partial q^\ell / \partial E^j$ from equation (6) we have

$$\begin{aligned} D'' \sum_{j=1}^m (\partial E^j / \partial \theta^i) &= -\alpha \partial E^\ell / \partial \theta^i + (\gamma^2/\alpha) (\partial E^\ell / \partial \theta^i) \\ &\quad + [(\gamma^2/\alpha)P'/(\alpha - P')] \sum_{j=1}^m (\partial E^j / \partial \theta^i) \\ &\quad + \delta_{i\ell} h^\ell(\theta^\ell), \quad \ell = 1, \dots, m. \end{aligned} \quad (22)$$

Sum both sides over ℓ and rearrange terms to obtain

$$\sum_{j=1}^m (\partial E^j / \partial \theta^i) = h^i(\theta^i) [mD'' + ((\alpha^2 - \gamma^2)/\alpha) - m(\gamma^2/\alpha)P'/(\alpha - P')]. \quad (23)$$

Using equation (23) to eliminate $\sum_{j=1}^m (\partial E^j / \partial \theta^i)$ from equation (22), we have for $i = \ell, i = 1, \dots, m$

$$(\partial E^i / \partial \theta^i) = h^i(\theta^i) [\alpha / (\alpha^2 - \gamma^2)] [(m-1)D'' + (m-1)(\gamma^2/\alpha)(-P')/(\alpha - P') + (\alpha^2 - \gamma^2)/\alpha] / [mD'' + m(\gamma^2/\alpha)(-P')/(\alpha - P') + (\alpha^2 - \gamma^2)/\alpha]. \quad (24)$$

Thus, $\partial E^i / \partial \theta^i \geq 0$ for all $(\theta^1, \dots, \theta^m)$ since the bracketed terms are positive and $h^i(\theta^i) \geq 0$. Therefore, the constraint $\partial e^i(\theta^i) / \partial \theta^i \geq 0$ is nonbinding. By Proposition 1, a mechanism is feasible if conditions (14) and (15) are satisfied. Therefore E^j is a feasible mechanism. Q.E.D.

Since $\partial E^i / \partial \theta^i > 0$ for all $E^i > 0$, note also that the equilibrium under optimal regulation is fully separating.

Since $\partial E^i / \partial \theta^i \geq 0$ for $\eta \geq 0$, it follows that the full information optimum, $(\bar{E}^1, \dots, \bar{E}^m)$ which solves $D'(\sum_{j=1}^m \bar{E}^j) = -C_2(q^i, \bar{E}^i, \theta^i)$, $i = 1, \dots, m$, also satisfies $\partial E^i / \partial \theta^i > 0$. This yields the following corollary.

COROLLARY 1: *The full information optimum $(\bar{E}^1, \dots, \bar{E}^m)$ coincides with the asymmetric information equilibrium if and only if the budget-balancing condition (15) is nonbinding at $(\bar{E}^1, \dots, \bar{E}^m)$.*

5. Characterization of Optimal Regulation.

Consider now the policy implications of the optimality condition (18). By convexity, marginal damages $D'(\sum_{j=1}^m E^j)$ are increasing in E^i . Marginal abatement costs, $-C_2$, are decreasing in E^i , since

$$\frac{-\partial^2 C(q^i, e^i, \theta^i)}{\partial e^{i2}} = -\alpha + \gamma(\partial q^i / \partial e^i) = -((\alpha^2 - \gamma^2)/\alpha) + (\gamma^2/\alpha)P' / (\alpha - P'). \quad (25)$$

Thus, the optimality condition (18) may be represented as in Figure 1. If the feasibility condition $B > \sum_{j=1}^m R^j$ is binding and η is nonzero, then marginal damages from environmental pollution, D' , are less than marginal abatement costs for firms, $-C_2$, by a positive

Figure 1

factor $(\eta/(1+\eta))((1-F^1)/f^1)$. Thus, for any given set of output vectors, $(q^1, \dots, q^m)$, the optimal effluent level, E^{j*} , is less than the level which equates marginal damages to marginal abatement costs, $\bar{E}^j$. So, *ceteris paribus*, asymmetric information drives a wedge between social and private costs such that per firm pollution levels are *less* than optimal.

If the feasibility condition is nonbinding and $\eta = 0$, then the full information optimum, is attained and $D'(\sum_{j=1}^m \bar{E}^j) = -C_2(q^1, \bar{E}^1, \theta^1)$, $\ell = 1, \dots, m$. Therefore, a key determinant of whether the full information optimum can be achieved is whether the net benefits from production at the full information optimum, $B(\bar{E}^1, \dots, \bar{E}^m)$, cover the expected information rents earned by firms, $\sum_{j=1}^m \bar{R}^j(\bar{E}^j)$. It is generally likely that the budget balancing condition will be binding.

The result that, *ceteris paribus*, pollution levels are lower under asymmetric information is counter-intuitive. One would expect that since firms wish to overstate the value of their private information parameter θ to exaggerate abatement costs, effluents would exceed

optimal levels, However, higher reports of θ are met with greater taxes since $\partial t/\partial \theta \geq 0$. Also, higher θ firms discharge greater levels of pollutants. To reward higher θ firms for revealing their private information, the welfare benefits from pollution reduction must be *positive* at the margin, that is, $-D' - C_2 > 0$. Clearly, for firms with the highest θ values, $\theta^\ell = 1$, $D'(\sum_{j=1}^m E^j) = -C_2(q^\ell, E^\ell, \theta^\ell)$ so that $E^{\ell*} = \bar{E}^*$. For firms with lower θ values to obtain tax reductions requires marginal damages to be less than marginal abatement costs so that $E^{\ell*} < \bar{E}^*$.

Let $(\bar{Q}, \bar{E})$ represent total market output and externality levels under full information and let (Q^*, E^*) represent total market output and externality levels under asymmetric information. Summing both sides of the price equals marginal cost equation, the set of market equilibrium output and effluent levels is given by the function $Q^1(E)$ which solves

$$Q^1(E) : mP(Q) = \alpha Q - \gamma E. \quad (26)$$

Clearly, $\partial Q^1(E)/\partial E = \gamma/(\alpha - mP'(Q)) > 0$. Summing both sides of $D'(\sum_{j=1}^m e^j) = -C_2$, let $Q^2(E)$ be the set of total outputs for which E is the socially optimal total effluent level under full information,

$$Q^2(E) : mD'(E) = -\alpha E + \gamma Q + \sum_{j=1}^m \theta^j. \quad (27)$$

Note that $\partial Q^2(E)/\partial E = (mD''(E) + \alpha)/\gamma > \partial Q^1(E)/\partial E$. Now define the set of total outputs for which E is the optimal total effluent level under asymmetric information by summing over both sides of equation (18),

$$\tilde{Q}^2(E) : mD'(E) = -\alpha E + \gamma Q + \sum_{j=1}^m \theta^j - (\eta/(1+\eta)) \sum_{j=1}^m ((1 - F^j)/f^j). \quad (28)$$

It follows that $\tilde{Q}^2(E) \geq Q^2(E)$ for all $(\theta^1, \dots, \theta^m)$. These curves are represented in Figure 2. Figure 2 implies the following.

PROPOSITION 3: *Total output and effluent levels are lower under asymmetric information than at the full information optimum, $\bar{Q} > Q^*$ and $\bar{E} > E^*$.*

Figure 2

We can show that output per firm is lower under asymmetric information, $\bar{q}^j > q^{j*}$ if $(1 - F^j(\theta^j))/f^j(\theta^j) > (1/m) \sum_{i=1}^m (1 - F^i(\theta^i))/f^i(\theta^i)$. Also, $\bar{e}^j > e^{j*}$ if $1 - F^j(\theta^j)/f^j(\theta^j) < (1/m) \sum_{i=1}^m (1 - F^i(\theta^i))/f^i(\theta^i)$. A complete ranking cannot be obtained.

6. An Alternative Setting.

If the regulatory game does not allow an exchange of messages between the regulator and firms, the regulator must design the tax rule before any inference about firm costs can be made. Suppose that the regulator may tax firms on the basis of all observed pollution levels, $T^j = T^j(e^1, \dots, e^m)$. Actual firm choices of pollution levels will then provide a signal to the regulator about firm costs, as well as determining a firm's tax payments. Firms will choose effluent levels according to a Bayes-Nash strategy. The vector $(\bar{e}^1, \dots, \bar{e}^m)$ will be a Bayes-Nash equilibrium if $\bar{e}^j(\theta^j)$ solves

$$\pi(p, \bar{e}^j, \theta^j) - \int_{I^{m-1}} T^j(\bar{e}^j, \bar{e}^{(j)}) dF^{(j)} \geq \pi(p, e^j, \theta^j) - \int_{I^{m-1}} T^j(e^j, \bar{e}^{(j)}) dF^{(j)}. \quad (28)$$

This type of regulation game is referred to as "one-round communication" by Dasgupta, Hammond and Maskin (1980). By the revelation principle, the direct mechanism cor-

responding to this game has the form $E^j(\theta^j)$, $T^j(\theta^j, \theta^{(j)})$. As before define $t^j(\theta^j) \equiv \int_{I^{m-1}} T^j(\theta^j, \theta^{(j)}) dF^{(j)}$. Then, the reduced-form mechanism $(E^j(\theta^j), t^j(\theta^j))$, $j = 1, \dots, m$ depends only on each firm's own parameter.

By similar analysis, the optimal direct mechanism for the restricted regulation game, can be shown to satisfy

$$\int_{I^{m-1}} D' \left(\sum_{j=1}^m E^j \right) dF^{(\ell)} = -\alpha E^\ell + \gamma q^\ell + \theta^\ell - (\eta/(1+\eta)) \left((1 - F^\ell(\theta^\ell)) / f^\ell(\theta^\ell) \right), \quad \ell = 1, \dots, m. \quad (29)$$

We may no longer establish that the full information optimum is attainable by regulation under asymmetric information since firm effluent levels will not depend on the entire vector of cost parameters. This point is made by Dasgupta, Hammond and Maskin (1980). In our framework, note that budget-balancing ($\eta = 0$) is no longer sufficient for feasibility of a mechanism corresponding to the full information optimum.

An alternative approach is to recognize the limits of "one-stage communication" and to define a second-best optimum. The *second-best optimum* consists of a competitive equilibrium in the product market, $P(\sum_{j=1}^m q^j) = C_1(q^i, E^i, \theta^i)$ and firm marginal abatement costs equal to expected marginal damages. Thus, $\bar{E}^i(\theta^i)$ solves

$$\int_{I^{m-1}} D' \left(\sum_{j=1}^m E^j(\theta^j) \right) dF^{(j)} = -C_2(q^i, E^i, \theta^i), \quad i = 1, \dots, m. \quad (30)$$

This immediately implies the following.

PROPOSITION 4: *Optimal regulation under asymmetric information with one-round communication achieves the second-best optimum, $\bar{E}^1(\theta^1), \dots, \bar{E}^m(\theta^m)$, if and only if the budget balancing condition is nonbinding for the mechanism $(\bar{E}^1, \dots, \bar{E}^m)$.*

7. Conclusion.

We have examined a model of environmental regulation in which the trade-off between output and environmental damages is emphasized. This trade-off has important implications for regulation under asymmetric information about production costs and pollution

abatement costs. Regulated firms earn information rents which depend on the value of their privately observed cost parameter. Firms have incentive to overestimate the costs of abatement in communicating with the regulatory authority. For the regulatory mechanism to be both incentive compatible and individually rational, the expected gains from trade between consumers and firms net of environmental damages must be sufficient to cover the expected information rents which will be earned by firms.

If net gains from trade exceed expected firm information rents at the full information optimum, then the full information optimum is attainable by a direct revelation mechanism. The Bayes-Nash nature of the regulatory game does not eliminate the budget balancing problem. If the constraint that net gains from trade exceed expected information rents is strictly binding, then the well-known equal marginal cost rule is violated. Marginal costs of pollution abatement are not equal across firms, nor do these equal marginal external damages. The budget-balancing restriction implies that both effluent and output levels are lower under asymmetric information.

APPENDIX

Proof of Proposition 1.

Let (E^j, T^j) be incentive compatible and individually rational. The second order condition for truth-telling to be optimal for the firm and for equation (11) to yield a global maximum is $\Pi_{22}^j(\theta, \hat{\theta}) \leq 0$. Totally differentiating $\Pi_{22}^j(\theta, \theta) = 0$ we have $\Pi_{21}^j + \Pi_{22}^j = 0$. Thus, $\Pi_{22}^j \leq 0$ requires $\Pi_{21}^j \geq 0$. But, since $\Pi_{21}^j = \partial e^j(\theta)/\partial \theta$ we have equation (14), see Guesnerie and Laffont (1984) and Spulber (1986) for similar arguments. From equations (12) and (13), we have

$$\int_0^1 \Pi^j(\theta) dF^j(\theta) = \Pi^j(0) + R^j(E^j). \quad (A1)$$

Therefore, from equations (9), (10), (12) and (A1) we have

$$\begin{aligned} V + \sum_{j=1}^m \Pi^j(0) &= \int_{I^m} \left[\int_0^{\sum_{j=1}^m q^j} P(Q) dQ - p \sum_{j=1}^m q^j - D\left(\sum_{j=1}^m E^j\right) \right. \\ &\quad \left. + \sum_{j=1}^m T^j + \sum_{j=1}^m \Pi^j(\theta^j) \right] dF - \sum_{j=1}^m R^j(E^j) \\ &= B(E^1, \dots, E^m) - \sum_{j=1}^m R^j(E^j). \end{aligned} \quad (A2)$$

Individual rationality implies $V + \sum_{j=1}^m \Pi^j(0) \geq 0$, so that equation (A2) implies equation (15).

Now suppose that equations (14) and (15) hold. From the definition of $\Pi^j(\theta)$, we calculate the following derivative

$$\Pi^{j'}(\theta) = \int_{I^{m-1}} [\pi_2 \partial E^j / \partial \theta + \pi_3] dF^{(j)} - \partial t^j(\theta) / \partial \theta, \quad (A3)$$

where $\pi_3 = \theta^j$. If we let $\partial \Pi^j(\theta) / \partial \theta = \int_{I^{m-1}} \pi_3^j dF^{(j)}$, then

$$\int_{I^{m-1}} \pi_2^j (\partial E^j / \partial \theta) = \partial t^j(\theta) / \partial \theta. \quad (A4)$$

Let $\Pi^j(0) = 0$, $j = 1, \dots, m$ so that

$$t^j(0) = \int_{I^{m-1}} \pi^j(q^j, E^j, 0) dF^{(j)}, \quad j = 1, \dots, m, \quad (\text{A5})$$

where $q^j = q^j(p, E^j)$ and $E^j = E^j(0, \theta^{(j)})$. Define $T^j(\theta^1, \dots, \theta^m)$ by

$$\begin{aligned} T^j(\theta^1, \dots, \theta^m) &= \int_0^{\theta^j} \pi_2(p, E^j(x, \theta^{(j)}), x) (\partial E^j / \partial \theta^j) dx \\ &+ \int_{I^{m-1}} \pi^j(p, E^j(0, \theta^{(j)}), 0) dF^{(j)}, \quad j = 1, \dots, m. \end{aligned} \quad (\text{A6})$$

It is easy to verify that the tax function as constructed in equation (A6) satisfies equations (A4) and (A5). By equation (14), T^j is well defined. Therefore, given (14) and T^j as in equation (A6) the mechanism (E^j, T^j) , $j = 1, \dots, m$ is incentive compatible. Furthermore, since $\Pi^j(0) = 0$ for all j , it follows immediately that

$$V = B(E^1, \dots, E^m) - \sum_{j=1}^m R^j(E^j) \quad (\text{A7})$$

By equation (15), $V \geq 0$. So, the mechanism (E^j, T^j) , $j = 1, \dots, m$ is feasible.

Q.E.D.

FOOTNOTES

1. Kwerel (1977) considers a simple framework in which the regulator minimizes the sum of pollution damages and abatement costs. Firms communicate their entire cost function to the regulator who then issues a fixed number of pollution licenses. The present model, with product market interaction requires a more complicated mechanism.

2. Dasgupta, Hammond and Maskin (1980) refer to this type of procedure as "two-round communication."

3. Let $(s^1, \dots, s^m)$ take values in $S = S^1 \times \dots \times S^m$ where S^j is firm j 's message space. Since the market price p is a function of effluent levels, we may write profit as $\pi^j(e, \theta^j)$. Let $s^{(j)} = s^1, \dots, s^{j-1}, s^{j+1}, \dots, s^m$. Let $e = (e^1, \dots, e^m)$, $dF^{(j)} = dF^1 \dots dF^{j-1} dF^{j+1} \dots dF^m$ and $I^n = \prod_{i=1}^n [0, 1]$. Then, the Bayes-Nash equilibrium of the regulatory game in messages, $(\tilde{s}^1, \dots, \tilde{s}^m)$ is defined by $\tilde{s}^j(\theta^j)$ such that

$$\begin{aligned} & \int_{I^{m-1}} [\pi^j(e(\tilde{s}^j, \tilde{s}^{(j)}), \theta^j) - t^j(\tilde{s}^j, \tilde{s}^{(j)})] dF^{(j)} \\ & \geq \int_{I^{m-1}} [\pi^j(e(s^j, \tilde{s}^{(j)}), \theta^j) - t^j(s^j, \tilde{s}^{(j)})] dF^{(j)} \end{aligned}$$

for all messages s^j in S^j .

4. Define the direct mechanism by $E^j(\theta^j, \theta^{(j)}) = e^j(s^1(\theta^1), \dots, s^m(\theta^m))$ and $T^j \times (\theta^j, \theta^{(j)}) = t^j(s^1(\theta^1), \dots, s^m(\theta^m))$.

5. The problem can be generalized to allow the regulator to give positive weight to firm profits in the social welfare function. However, this does not add to our present discussion.

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