Budget Balancing Incentive Mechanisms

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Abstract

Xepapadeas [10] develops a pollution abatement incentive mechanism that both reduces the information requirements of regulator and is "budget balancing", drawing only on the social gains from pollution abatement to encourage firm compliance. This paper demonstrates that, contrary to Xepapadeas [10], the budget balancing system of random penalties cannot be used induce compliance with the regulator's objectives if firms are risk neutral. However, the mechanism can be successfully applied if firms are sufficiently risk averse (Rasmusen [9]) . Second, the paper explores the optimal design of the random fine system, including the choice of fines, penalty probabilities, and team size.

Budget Balancing Incentive Mechanisms

The information requirements associated with many nonpoint source pollution control mechanisms represent a significant barrier to their practical implementation. It is typically not enough to measure the ambient concentration of a pollutant at a receptor site. One must also understand and monitor the stochastic fate and transport mechanisms that link sources of pollution to the receptor site of interest.[1] This information can be costly, potentially offsetting the gains to society from the pollution control itself. In addition, traditional control devices, such as Pigouvian taxes and subsidies, require that *each* polluting agent incur the marginal damage associate with the regulatory agency's target level of pollution. The result is that these mechanisms are typically not "budget balancing," collecting a multiple of damage costs from firms as a whole when taxes are employed and requiring the regulatory agency to pay a multiple of the avoided damage costs to firms in the case of Pigouvian subsidies.[2]

Recent work by Xepapadeas [13] offers a promising approach to resolving both the monitoring and budget balancing problems. Drawing on the moral hazard literature for dealing with shirking within the firm (e.g., Holmström [6], Rasmusen [11]), Xepapadeas develops a budget balancing incentive scheme that relies upon a combination of subsidies and random fines. A random fine is assessed against at least one polluter in the event that the regulator's pollution target is violated.[3] Budget balancing is achieved by then returning this fine, minus the damages to society from non-compliance, to the remaining firms. The regulator need not observe the actual emissions or abatement efforts of the individual firms. Properly designed, this system of random fines induces firms to adopt the targeted level of abatement effort.

The purpose of this paper is twofold. First, it demonstrates that, contrary to Xepapadeas [13], the budget balancing system of subsidies and random penalties cannot be used induce compliance with the regulator's objectives if firms are risk neutral.[4] However, the mechanism can be successfully applied if firms are sufficiently risk averse (Rasmusen [11]) . Second, the paper explores the optimal design of the random penalty mechanism. We show that the mechanism will be effective for a wider range of firms if program parameters are differentiated according to the firms' risk preferences. The paper also considers the optimal number of firms to include in the regulatory pool.

2. THE BASIC MECHANISM

The random penalty mechanism developed in Xepapadeas [13] represents an adaptation to the environmental arena of the budget balancing contracts developed in Rasmusen [11]. Whereas [11] is concerned with avoiding shirking among agents producing a shared output, the agents in [13] share the gains to society from reductions in the ambient concentration of pollution. A key distinguishing feature between the two articles lies in Xepapadeas's assumption that the agents are risk neutral. This section reviews the system of subsidies and random penalties developed in Xepapadeas [13] and extends its application to the case in which firms are risk averse along the lines of Rasmusen [11]. The notation of [13] is followed with only minor modifications.[5]

2.1 Notation

Consider an economy consisting of n firms (i=1,...,n) which in the course of their production processes contribute to the ambient concentration of pollution in a region. Pollution abatement effort is assumed to be costly, with the cost to the i^{th} firm determined by the function $C_i(A_i)$, where A_i denotes the level of the firm's abatement effort, $C_i(0) = 0$, $\partial C_i/\partial A_i > 0$, and $\partial^2 C_i/\partial A_i^2 > 0$. In the absence of government intervention, the cost minimizing firm sets its abatement effort to zero and earns a profit of Π_i^0. The resulting ambient concentration is given by $W_0 \equiv W(0)$, where $W(A)$ is the single-valued function linking the ambient concentration of pollution to the vector of firm abatement efforts $\mathbf{A} \equiv (A_1, A_2, \ldots, A_n)$. Assume that $\partial W/\partial A_i \leq 0$. The regulatory agency's problem is to reduce this concentration to the socially optimal level of $\hat{W} \equiv W(\hat{A})$, where $\hat{A}_i$ denotes the optimal level of abatement effort by firm i. Xepapadeas [13] derives $\hat{W}$ and $\hat{A}$ as the result of the social planner's maximization of an Arrow type [1] felicity function. The familiar first order conditions result, equating the marginal benefits and marginal costs of abatement effort. Formally,

$$-\lambda \partial W(\hat{A})/\partial A_i = \partial C_i/\partial A_i \qquad \forall\, i=1, \ldots, n, \tag{1}$$

where λ denotes the shadow cost of pollution concentration.

2.2 Budget Balancing with Risk Neutrality

Let $\Psi = \Psi[W(A)]$ denote the welfare gains to society resulting from abatement effort **A** and the corresponding reduction in ambient concentration from W_0 to $W(A)$.[6] Under Xepapadeas' [13] budget balancing contract B, if the target level of ambient concentration is met (i.e., $W \leq \hat{W}$), the regulator allocates the gains to society ($\hat{\Psi} \equiv \Psi(\hat{W})$) among the firms. Formally, firm i receives the subsidy $\hat{b}_i = \phi_i \hat{\Psi}$, where $\Sigma_i \phi_i = 1$.[7]

In the event that the target concentration level is not met, one firm is randomly selected and penalized. The penalty has two components: (1) the firm loses its subsidy, $\hat{b}_i$, and (2) an additional fine, F_i, is assessed against the firm.[8] In order to maintain the budget balancing nature of the contract, these penalties, minus the welfare loss to society due to the higher ambient concentration, are redistributed among the remaining firms.

The random penalty mechanism can be summarized in terms of the firm's subsidy, b_i, under the program:

$$b_i(A) = \begin{cases} \hat{b}_i = \phi_i \hat{\Psi} & W \le \hat{W} \\ -F_i & W > \hat{W}\text{ , with probability } \xi_i \\ \hat{b}_i + \phi_{ij}[\hat{b}_j + F_j + \Gamma(W)] & W > \hat{W}\text{ , with probability } \xi_j\ ;\ j \neq i \end{cases} \tag{2}$$

where $\xi_i \in [0,1]$ denotes the probability that firm i is penalized (with $\Sigma_i\, \xi_i = 1$), $\Gamma(\mathbf{A}) \equiv \Psi[W(\mathbf{A})] - \hat{\Psi}$ denotes the change in social welfare from the level targeted by the regulator (with $\Gamma[W(\mathbf{A})] < 0$ for $W(\mathbf{A}) > \hat{W}$), and $\phi_{ij} \equiv \phi_i/\Sigma_{k\neq j}\phi_k$ denotes the share of firm j's penalty that is allocated to firm i.

The contract in (2) establishes a noncooperative game among the firms sharing in the societal gains from pollution abatement. Firm i's total profit is conditioned on its own level of abatement effort, as well as the abatement effort put forth by the other firms, denoted $\mathbf{A}_{-i} \equiv (A_1, \ldots, A_{i-1}, A_{i+1}, \ldots, A_n)$. That is,

$$\Pi_i(A_i, A_{-i}) = \Pi_i^0 + b_i(A) - C_i(A_i) \qquad \forall i = 1, 2, \ldots n. \tag{3}$$

The question is whether the contract parameters can be designed so that there exists a Nash equilibrium with each firm voluntarily choosing the targeted level of abatement effort and yielding the targeted ambient concentration.

Following Xepapadeas [13] and Rasmusen [11], assume that each firm treats the other firms as being in compliance (i.e., $\mathbf{A}_{-i} = \hat{\mathbf{A}}_{-i}$). Let $A_i^* \in [0, \hat{A}_i)$ denote the i$^{\text{th}}$ firm's optimal "cheating abatement level." Assuming firms are risk neutral, A_i^* is given by

$$A_i^* = \underset{A_i \in [0, \hat{A}_i)}{argmax}\ E[\Pi_i(A_i, \hat{A}_{-i})] \tag{4}$$

where

$$E[\Pi_i(A_i, A_{-i})] = \Pi_i^0 - C_i(A_i) - \xi_i F_i + \sum_{j \neq i} \xi_j \{\hat{b}_i + \phi_{ij}[\hat{b}_j + F_j + \Gamma(W)]\} \tag{5}$$

denotes firm i's expected profits. The firm will choose the Pareto optimal abatement effort, $\hat{A}_i$, if cheating is on average less profitable than compliance. That is, if [9]

$$\begin{aligned}\Omega_i &\equiv E[\Pi_i(A_i^*, \hat{A}_{-i})] - E[\Pi_i(\hat{A}_i, \hat{A}_{-i})] \\ &= -\xi_i F_i + \sum_{j \neq i} \xi_j \{\hat{b}_i + \phi_{ij}[\hat{b}_j + F_j + \Gamma(W)]\} - \hat{b}_i + [C_i(\hat{A}_i) - C_i(A_i^*)] \\ &< 0 \qquad\qquad \forall\, i = 1, \ldots, n\end{aligned} \tag{6}$$

Xepapadeas [13, p. 123] notes that because ". . . Ω_i is a strictly decreasing function of F_i, there should exist a fine $\hat{F}_i \in (0, +\infty)$ such that $\Omega_i(\hat{F}_i) < 0$." While this statement is true, it is not sufficient to ensure that the required *series* of inequalities in (6) holds simultaneously. The problem is that, while increasing F_i will decrease Ω_i, it will also increase Ω_j (i.e., $\partial\Omega_j/\partial F_i > 0$) and potentially encourage another firm to cheat. In fact, Holmström's [6, p. 326] Theorem 1 establishes that this cheating effect will dominate, so that $\mathbf{A} = \hat{\mathbf{A}}$ will not be a Nash equilibrium under contract B of Xepapadeas [13]. Rewriting this theorem in the current notation, we have:

THEOREM 1. *Assuming risk neutral firms, there does not exist a set of fines, shares, and penalty probabilities (i.e., $\{F_i, \phi_i, \xi_i\}$) that will yield the Pareto optimal Nash equilibrium of $\mathbf{A} = \hat{\mathbf{A}}$ satisfying the inequality constraints in (6).*

PROOF: Holmström [6], Theorem 1. Whereas Holmström's agents share output from the production process (i.e., x(a)), agents in the current application share output from the abatement process plus the pool of exogenous fines (i.e., $[\Psi(A) + \Sigma_i F_i]$). Holmström's private cost function, $v_i(a_i)$, corresponds to the abatement cost function $C_i(A_i)$. Fibnally, whereas Holmström's theorem 1 applies for a general sharing rule, $\{s_i[x(a)]\}$, the random penalty mechanism relies upon specific shares $[b_i(\mathbf{A}) + F_i]$.

Altering the parameters of the random penalty mechanism (i.e., $\{F_i, \phi_i, \xi_i\}$) simply represents different ways to alter the "size of the pie" (i.e., x(a)) and the sharing rule used (i.e., s[x(a)]). Theorem 1 of Holmström still applies. Q.E.D.

2.3. Budget Balancing with Risk Aversion

As noted by Rasmusen [11], the limitation of optimal sharing rules when firms are risk neutral lies in the linearity of the agent's objective function with respect to money. Even with random penalties for shirking, a profit maximizing firm will equate the marginal benefits from shirking and the expected marginal penalty. Pareto optimality requires that this expected marginal penalty equal the marginal damage of pollution concentration for each firm (equation (1)). The budget balancing restriction, however, prohibits this, since the marginal damage to society must be shared. The insight of Rasmusen [11] is that random penalties, *when agents are sufficiently risk averse*, can provide the extra "kick" to each agent's share of the marginal damage that is needed to insure compliance. The addition of risk to the firm's returns can be used to leverage what is otherwise an insufficient incentive to comply. Conceptually, the firm can comply and receive a certain return or cheat and be forced to participate in a lottery. The greater the firm's risk aversion, the more they will wish to comply, thereby avoiding the lottery.

Risk aversion is incorporated into the analysis by assuming firms maximize the expected utility received from their profits, where utility is represented by the function $U_i(\Pi_i)$ with $U' > 0$ and $U'' < 0$. The firm's cheating abatement level, A_i^*, is then determined by

$$A_i^* = \underset{A_i \in [0, \hat{A})}{argmax} \; E\{U[\Pi_i(A_i, \hat{A}_{-i})]\} \tag{7}$$

where

$$E[\Pi_i(A_i, A_{-i})] = \xi_i U[\Pi_i^0 - C_i(A_i) - F_i\ ] + \sum_{j \neq i} \xi_j \{U[\Pi_i^0 - C_i(A_i) + \hat{b}_i + \phi_{ij}(\hat{b}_j + F_j + \Gamma(W))]\} \tag{8}$$

As in Rasmusen [11], we assume agents exhibit constant absolute risk aversion, providing a convenient parameterization of risk preferences.[10] In particular, $U_i(\Pi_i)$ is given by

$$U_i(\Pi_i) = -\exp(-\theta_i \Pi_i) \tag{9}$$

where $\theta_i = -U''/U' > 0$ measures the agent's constant absolute risk aversion.

With risk averse firms, the system of subsidies and random penalties in (2) will yield the Pareto optimal Nash equilibrium if

$$\begin{aligned} \Omega_i &\equiv E\{U[\Pi_i(A_i^*, \hat{A}_{-i})]\} - E\{U[\Pi_i(\hat{A}_i, \hat{A}_{-i})]\} \\ &= -\xi_i \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) - F_i\ ]\} \\ &\quad -\sum_{j \neq i} \xi_j \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) + \hat{b}_i + \phi_{ij}(\hat{b}_j + F_j + \Gamma(W))]\} \\ &\quad + \exp\{-\theta_i[\Pi_i^0 - C_i(\hat{A}_i) + \hat{b}_i\ ]\} \\ &< 0 \qquad \forall\, i = 1, \ldots, n \end{aligned} \tag{10}$$

Rasmusen's [11, p. 431] Proposition 2 can be written in the current context as the following theorem.

THEOREM 2. *Assuming risk averse firms, then for any set of positive fines and penalty probabilities (i.e.,* $\{F_i, \xi_i \mid F_i > 0$ *and* $\xi_i > 0\}$*) there exists at least one sharing rule* $\{\phi_{ij}\}$ *such that the Pareto optimal level of abatement effort,* $\mathbf{A} = \hat{\mathbf{A}}$*, is also a Nash equilibrium satisfying the inequality constraints in (10) provided (a) firms are sufficiently risk averse (i.e.,* θ_i *is large enough for all i) or (b) the fines are set high enough for all firms (i.e.,* F_i *is large enough for all i)* .

PROOF: The proof of part (a) parallels Rasmusen [11, p. 431] and proceeds in two steps. First, we establish that there exists at least one sharing rule $\{\phi_i\}$ such that:

$$\hat{b}_i - C_i(\hat{A}_i) + C_i(A_i^*) \geq 0 \qquad \forall\, i = 1, \ldots, n \tag{11}$$

This inequality follows through a proof by contradiction. Suppose that a sharing rule satisfying the inequalities in (11) cannot be found, then $\hat{b}_i - C_i(\hat{A}_i) < -C(A_i^*) < 0$. Summing this inequality over all i yields $\hat{\Psi} < \Sigma_i C(\hat{A}_i)$; i.e., the total costs of optimal pollution abatement exceed the social benefits received from that level of abatement effort. This contradicts the Pareto optimality of abatement effort $\hat{A}$. Therefore, there exists at least one sharing rule satisfying equation (10).

The second step in the proof requires establishing that Ω_i is negative for a sufficiently large θ_i. Rewriting equation (10) yields:

$$\Omega_i = [-\xi_i \exp(\theta_i F_i) - \sum_{j \neq i} \xi_j \exp\{-\theta_i(\hat{b}_i + \phi_{ij}\{\hat{b}_j + F_j + \Gamma(W)\})\} + \exp(-\theta_i\{\hat{b}_i - C_i(\hat{A}_i) + C_i(A_i^*)\})]$$
$$\cdot \exp(-\theta_i\{\Pi_i^0 - C_i(A_i^*)\}) \tag{12}$$

The last term, outside of the square brackets, is strictly positive. As θ_i increases, the second and third terms inside the square brackets go to zero if the sharing rule satisfies the inequality constraint in equation (11). However, the first term has a positive exponent and goes to negative infinity as θ_i increases. Therefore, $\Omega_i < 0$ for θ_i sufficiently large. Q.E.D.

The proof of Part (b) of Theorem 2 is left to the appendix. Intuitively, the simultaneous increase in the fines for all firms encourages compliance by increasing the variability of firms' cheating returns. As long as firms are risk averse, this increased variability eventually provides enough disutility to lead firms into compliance. A potential problem with employing larger and larger fines to insure compliance is that firms may begin to face liquidity constraints, effectively creating an upper bound on F_i.

Theorem 2 deviates from Rasmusen's [11] Proposition 2 in two respects. First, Theorem 2 identifies minimum shares that must be allocated to an individual agent. Specifically, the shares must satisfy

$$\hat{b}_i > C_i(\hat{A}_i) - C_i(A_i^*) \qquad \forall\, i = 1, ..., n. \tag{13}$$

That is, each agent must be allocated enough of the social gains from optimal abatement to offset the cost savings from cheating. This condition is not contained in [11] because Rasmusen assumed that the agent's utility function was separable in money and effort.[11] This eliminates the interaction between θ_i and $[C_i(\hat{A}_i) - C_i(A_i^*)]$. Second, the proof of Theorem 2b corrects an oversight in Rasmusen's proof of Proposition 2(b). Rasmusen's [11] argument in the current application would correspond to noting that Ω_i is strictly decreasing in F_i (i.e., $\partial\Omega_i/\partial F_i < 0$). Increasing F_i will indeed decrease the first term in the square brackets of equation (12). Unfortunately, this proof has the same incentive problem as in the previous section. While increasing the fine to firm i can be used to induce compliance of that firm, it will, at the same time, encourage other firms to cheat ($\partial\Omega_j/\partial F_i > 0$). However, as shown in the appendix, *simultaneous* increases in all of the fines can induce compliance by increasing the variability of the firm's returns under cheating.

3. EXTENSIONS

Theorem 2 insures that a budget balancing system of subsidies and random penalties can be used to encourage compliance with the socially optimal abatement objectives if firms are sufficiently risk averse. But the theorem itself provides no guidance in terms of mechanism design. Rasmusen [11] and Xepapadeas [13] are similarly quiet on the choice of program parameters. For example, agents are given an equal probability of being penalized (i.e., $\xi_i = 1/n$) in [11], despite varying levels of compliance costs and risk preferences. While the penalty probabilities are allowed to vary in [13], the author does not explore how they should be assigned to individual firms. This section extends the balanced budget incentive mechanism in two directions. First, we consider how program parameters should be differentiated among agents with different risk preferences and abatement cost characteristics. Second, we detail how the number of firms in the regulatory pool impacts program efficacy.

3.1 Risk Preferences and Program Design

Risk aversion is key to achieving compliance in the random penalty scheme detailed above. It is, therefore, natural to explore how the incentive mechanism's efficacy can be improved by targeting the program parameters according to the risk preferences of individual firms. In order to simplify the exposition, consider a world with two types of firms distinguished only in terms of their risk aversion. Specifically, n_H firms are designated as highly risk averse firms, with a risk aversion coefficient $\theta^H > 0$. The remaining $n_L \equiv n - n_H$ firms have a lower level of risk aversion, with $0 < \theta^L < \theta^H$. In all other regards firms are assumed to be identical, with $C_i(A_i) = C(A_i)$, $\hat{A}_i = \hat{A}$, and $\Pi_i^0 = \Pi^0$ $\forall$ i=1, ..., n.

Let ξ^g, F^g, and ϕ^g denote the penalty probabilities, fines, and compliance shares allocated to individual firms within group g (g = H,L). Initially, assume that the regulator treats the two groups identically, with $\xi^g = \xi$, $F^g = F$, and $\phi^g = \phi$. The question is how compliance can be improved by moving away from this set of symmetric program parameters. We focus here on changes in the penalty probabilities. We show that compliance with the regulator's objective can be improved by shifting the penalty probability towards less risk averse firms and away from high risk averse firms. Intuitively, the highly risk averse firms need to face a relatively small chance of being penalized in order to insure that they will choose compliance. Reducing their penalty probability (ξ^H) allows us to increase ξ^L for the low risk aversion firms, who focus more on expected returns and less on the variability of returns.

To see this result, first consider the impact that a change in the penalty probability has on a firm's compliance. One would expect that an increase in the probability of being penalized would push firms towards compliance. This is in fact the case. Let Ω^g denote the value of Ω_i for firms in group g. Using (10), we have:

$$\begin{aligned}\Omega^g = &-\xi^g \exp\{-\theta_g[\Pi^0 - C(A_g^*) - F\ ]\} \\ &-(1-\xi^g)\exp\{-\theta_g[\Pi^0 - C(A_g^*) + \hat{b} + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\} \\ &+ \exp\{-\theta_g[\Pi^0 - C(\hat{A}_g) + \hat{b}\ ]\} \qquad \forall\, g = H,L.\end{aligned} \tag{14}$$

Taking the derivative of Ω^g with respect to ξ^g yields:

$$\begin{aligned}\partial\Omega^g/\partial\xi^g = &-\exp\{-\theta_g[\Pi^0 - C(A_g^*) - F\ ]\} \\ &+\exp\{-\theta_g[\Pi^0 - C(A_g^*) + \hat{b} + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\} \\ <\ & 0 \qquad \forall\, g = H,L.\end{aligned} \tag{15}$$

Since the right-hand side of equation (15) is independent of ξ^g, we also have $\partial^2\Omega^g/(\partial\xi^g)^2 = 0$. This suggests that, if only one of the two groups is noncompliant, increasing the penalty probability for the noncompliant group will push them in the desired direction.[12]

The next step is to establish the likely identity of this noncompliant group. Intuitively, one would expect compliance to increase with risk aversion. The random penalty scheme offers firms the choice between a certain outcome (with compliance) and a lottery (when cheating has occurred). If firms with low risk aversion have chosen to comply and avoid the "cheating" lottery, one would expect firms with a higher level of risk aversion to do the same. The reverse need not be true. Theorem 3 formalizes this intuition.

THEOREM 3: *Let $\Omega(\theta;\xi,F,\phi)$ represent the value of Ω for a given set of program parameters and level of firm risk aversion. Then (a) $\Omega(\theta^L;\xi,F,\phi) \leq 0 \Rightarrow \Omega(\theta^H;\xi,F,\phi) < 0$ for $\theta^L < \theta^H$ and (b) there exists a unique θ^* such that $\Omega(\theta^*;\xi,F,\phi)=0$.*

PROOF: See Appendix.

Note that Theorem 3 does not establish that $\partial\Omega/\partial\theta < 0$. This need not be the case. For example, Figure 1 illustrates the shape of $\Omega(\theta)$ for the negative exponential utility function. θ^* merely establishes the boundary between non-compliance and compliance.

Theorem 3 can be used to establish the basic conclusion of this subsection; i.e., that non-compliance with the regulator's optimal abatement objective can be reduced by shifting the penalty probability towards firms with lower levels of risk aversion. Consider any two risk aversion coefficients, with $\theta^H > \theta^L > 0$. Four potential compliance scenarios can arise when $\xi^H = \xi^L$:

- **Case 1: $\Omega^H < 0$ and $\Omega^L < 0$ (Complete Compliance).** In this situation, no changes in the penalty probabilities are required to achieve compliance.

- **Case 2: $\Omega^H \geq 0$ and $\Omega^L \geq 0$ (Complete Noncompliance).** In this situations, no changes in the penalty probabilities can be made to achieve compliance. Both risk aversion groups require increases in ξ, but ξ^H and ξ^L are constrained by the relationship: $n_H\xi^H + n_L\xi^L = 1$.

- **Case 3: $\Omega^H \geq 0$ and $\Omega^L < 0$.** Theorem 3 rules out this alternative.

- **Case 4: $\Omega^H < 0$ and $\Omega^L \geq 0$.** In this case, compliance may be achieved by shifting some of the penalty probability towards the low risk aversion firms. If this shift is small enough (i.e., so as not to induce noncompliance on the part of the high risk aversion firms), then the budget balancing incentive mechanism may be successfully applied.

Figure 2a illustrates the potential gains for a two-firm example. With $\xi^L = \xi^H = .5$, only the highly risk averse firm is in compliance (i.e., $\Omega^H < 0$ and $\Omega^L > 0$). A reduction in ξ^H to within the range of (ξ^*,ξ^{**}), with the corresponding increase in ξ^L, moves the low risk aversion firm into compliance ($\Omega^L < 0$), while maintaining compliance for the high risk aversion firm. However, if the

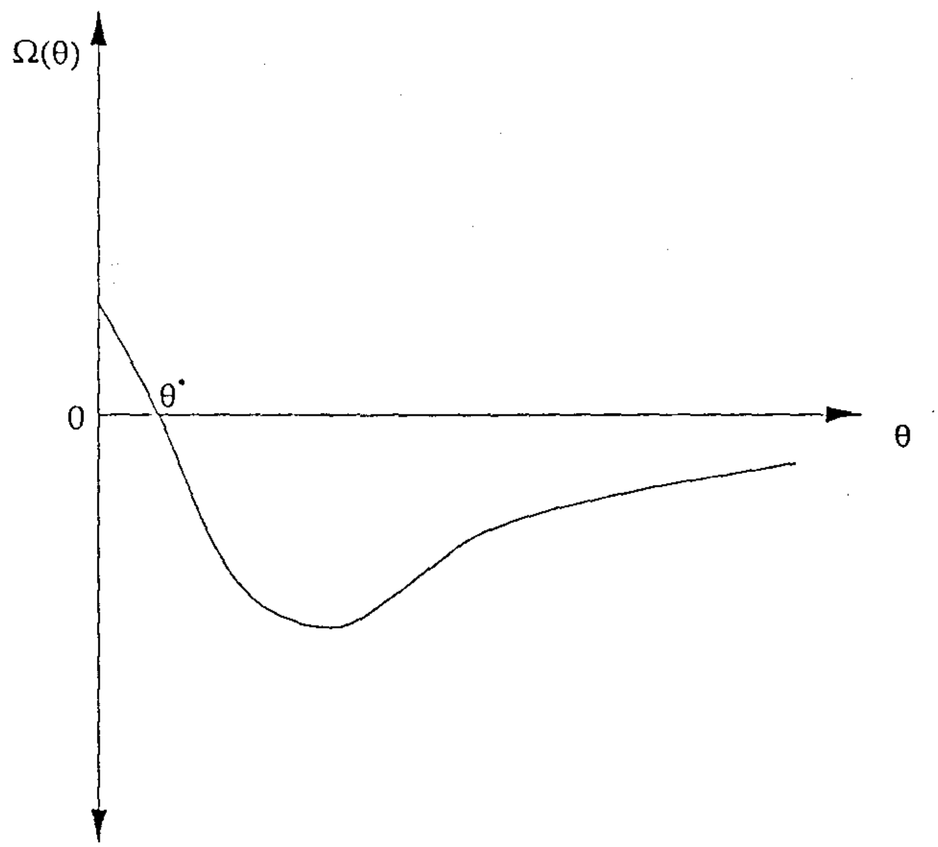

Figure 1. Compliance Curve for the Constant Absolute Risk Aversion Model

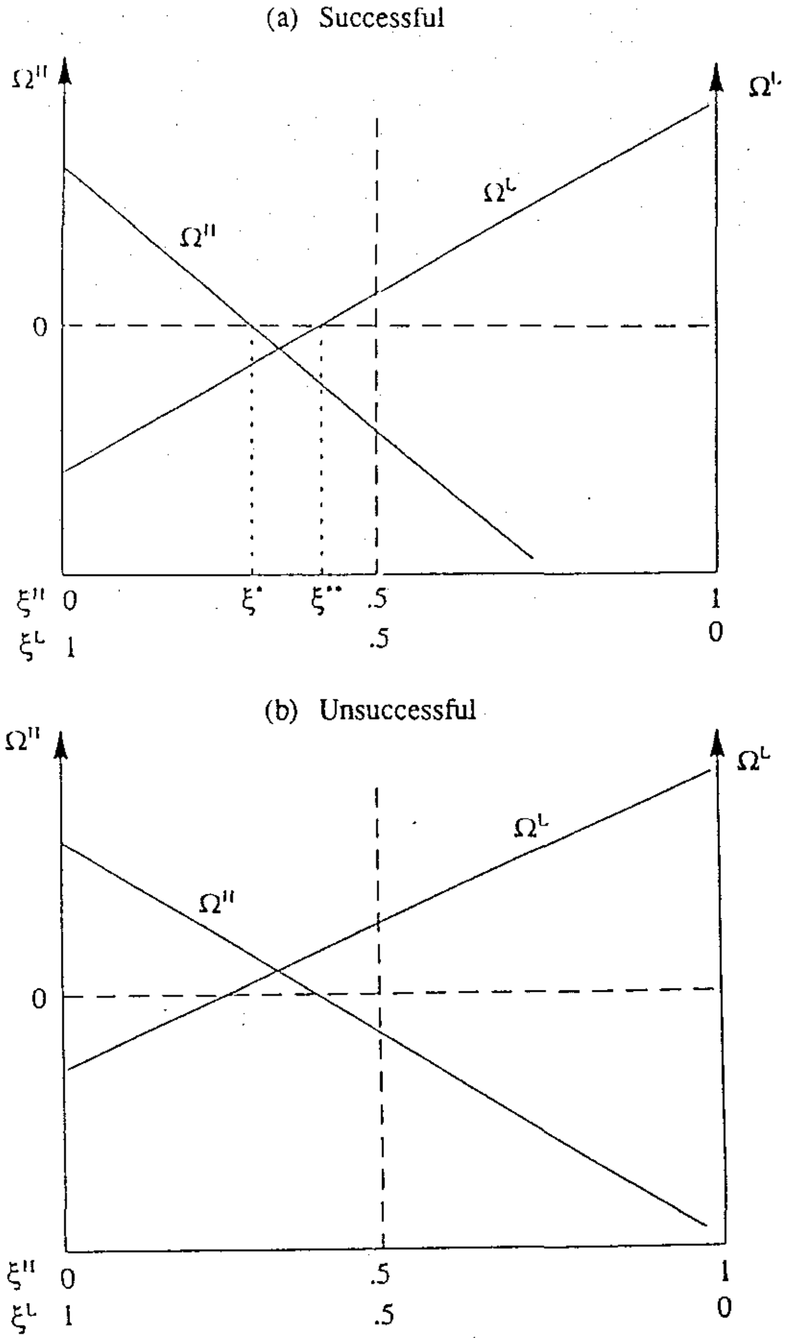

Figure 2. Probability Adjustments

overall level of risk aversion is not high enough, the shift in probabilities will be unsuccessful, as illustrated in Figure 2b.

3.2 Team Size

The results of the previous subsection illustrate how the regulator can enhance compliance by exploiting the diversity of firms within the targeted group. Another tool available to the regulator is the choice of how many firms to group together in applying the random penalty mechanism. For example, in its efforts to control the use of agricultural chemicals, the regulator can choose to treat all farms within a region as a single group or to divide them into several "teams." The advantage of the single team approach is that it requires the monitoring of a single emissions or concentration threshold for the region. Subdividing the region requires the establishment and monitoring of additional thresholds and, hence, entails additional information costs.[13] On the other hand, including a large number of firms on a single regulatory team may adversely affect the random penalty incentive. A firm's chances of being penalized for noncompliance decrease as the number of firms on the team increases. This subsection determines the impact of team size on compliance.

In order to simplify the exposition, consider an economy with n identical firms. With $\xi_i = 1/n$, $F_i = F$, and $\phi_i = \phi$, the compliance conditions of equation (10) reduce to:

$$\begin{aligned}\Omega = & -(1/n)\exp\{-\theta[\Pi^0 - C(A^*) - F\ ]\} \\ & -[(n-1)/n]\exp\{-\theta[\Pi^0 - C(A^*) + \hat{b} + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\} \\ & + \exp\{-\theta[\Pi^0 - C(\hat{A}) + \hat{b}\ ]\} \\ & < 0.\end{aligned} \tag{16}$$

The impact of team size on compliance can be seen by differentiating (16) with respect to n yielding:

$$\partial\Omega/\partial n = (1/n^2)[\exp\{-\theta[\Pi^0 - C(A^*) - F\ ]\} - \exp\{-\theta[\Pi^0 - C(A^*) + \hat{b} + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\}]$$
$$+ \{-\theta[\hat{b} + F + \Gamma(W)]/[n(n-1)]\}\exp\{-\theta[\Pi^0 - C(A^*) + \hat{b} + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\}] \quad (17)$$

The two lines of equation (17) reflect the two competing effects that result from a change in n. The first line is strictly positive and reflects the fact that an increase in n decreases the firm's probability of being penalized. This encourages the firm to cheat (i.e., increases Ω). Offsetting this effect is the fact that, when the firm cheats and is not caught, a larger n means that the firm must share the penalty (i.e., $\hat{b} + F + \Gamma(W)$) with more agents. This reduces the incentive to cheat (i.e., decreases Ω), as reflected in the strictly negative term on line two of equation (17). However, it is the first effect that dominates, yielding the following theorem.

THEOREM 4: *Compliance is a strictly decreasing function of team size (i.e., $\partial\Omega/\partial n > 0$).*

PROOF: Factoring $\partial\Omega/\partial n$ into two terms, equation (17) can be rewritten as

$$\partial\Omega/\partial n = \rho\,\sigma \quad (18)$$

where

$$\rho \equiv n^{-2}\exp\{-\theta[\Pi^0 - C(A^*) + \hat{b} + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\} \quad (19)$$

and

$$\sigma \equiv \exp\{\theta[\hat{b} + F + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\} - 1 - \theta[\hat{b} + F + \Gamma(W)][n/(n-1)]\ . \quad (20)$$

Since $\rho > 0$, it is the sign of σ that determines the sign of $\partial\Omega/\partial n$. Using the fact that $\Gamma(W) < 0$, equation (20) implies

$$\begin{aligned}\sigma &> \exp\{\theta[\hat{b} + F + \Gamma(W) + \{\hat{b} + F + \Gamma(W)\}/(n-1)]\} - 1 - \theta[\hat{b} + F + \Gamma(W)][n/(n-1)] \\ &= \exp\{\theta[\hat{b} + F + \Gamma(W)][n/(n-1)]\} - 1 - \theta[\hat{b} + F + \Gamma(W)][n/(n-1)] \\ &= g(\theta[\hat{b} + F + \Gamma(W)][n/(n-1)])\end{aligned} \tag{21}$$

where $g(x) \equiv \exp(x) - 1 - x$. Since $g(0) = 0$ and $g'(x) = \exp(x) - 1 > 0$ for $x > 0$, then $g(x) > 0$ for $x > 0$. With $\theta[\hat{b} + F + \Gamma]n/(n-1) > 0$, it immediately follows from equation (21) that $\sigma > 0$, which in turn implies that $\partial\Omega/\partial n > 0$. Q.E.D.

Theorem 4 suggests that, from the perspective of compliance, it is desirable for the regulator to keep the number of team members as small as possible. This must be weighed against the additional monitoring costs associated with having numerous small teams, as well as the additional potential for collusion. Large teams may still be effectively controlled, provided that risk aversion within the team is large enough or that the regulator has set large enough fines to offset the negative effects of team size.

4. CONCLUDING REMARKS

The combination of subsidies and random penalties, originally proposed in Rasmusen [11] and adapted to the environmental arena by Xepapadeas [13], provides a potentially promising alternative to more traditional approaches to pollution control. By eliminating the need for firm level monitoring of emissions or abatement effort, the mechanism can significantly lower the regulator's administration costs. In addition, the budget balancing aspect of the control device eliminates the need for the regulator to contribute incentives to the firms, beyond the welfare gains generated by abatement. In an era of significant budgetary constraints, this feature of the random penalty mechanism is particularly appealing.

There are, however, limits to the use of random penalties. Contrary to the original claim in Xepapadeas [13], random penalties cannot be used to achieve compliance if firms are risk neutral. Budget balancing still requires that each firm pay, on average, only a fraction of the damages associated with pollution emissions. This will not be enough to offset the cost savings that they fully capture by shirking.[14] However, if firms are risk averse, Theorem 2 demonstrates that the introduction of random penalties can be used to leverage each firm's portion of the marginal damages and achieve compliance with the regulator's objective. If risk aversion among the firms is small, increasing the level of fines for all firms can be used to insure compliance, as long as liquidity constraints are not binding.

The random penalty mechanism may face a second problem in both the political and legal arenas due to the random assignment of the penalty in the event of shirking. Firms that consistently comply with their assigned abatement objective can still be penalized. This may make random penalties difficult to legislate and to uphold in a court of law.

Finally, this paper has extended the research into random penalties by considering ways in which the regulator can improve compliance by targeting program parameters according to the risk preferences of individual firms and by choosing the optimal team size. One limitation of using risk preferences to target program characteristics is that information on risk attitudes may itself be costly to acquire, potentially offsetting the reduced monitoring costs associated with the random penalty approach. An area of future research is to consider alternative targeting criteria, such as the size or abatement cost structure of the firms.

5. APPENDIX

5.1 Proof of Theorem 2(b)

Consider a set of fines, where $F_i = a_i F$. The compliance variable Ω_i in equation (10) becomes:

$$\begin{aligned}\Omega_i = & -\xi_i \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) - a_i F\ ]\} \\ & -\sum_{j\neq i} \xi_j \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) + \hat{b}_i + \phi_{ij}\{\hat{b}_j + a_j F + \Gamma(W)\}]\} \\ & + \exp\{-\theta_i[\Pi_i^0 - C_i(\hat{A}_i) + \hat{b}_i\ ]\}\end{aligned} \tag{22}$$

Differentiating Ω_i with respect to F yields:

$$\begin{aligned}\partial\Omega_i/\partial F = & -\theta_i a_i \xi_i \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) - a_i F\ ]\} \\ & + \sum_{j\neq i} \theta_i a_j \xi_j \phi_{ij} \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) + \hat{b}_i + \phi_{ij}\{\hat{b}_j + a_j F_j + \Gamma(W)\}]\} \\ < & -\theta_i a_i \xi_i [\exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) - a_i F\ ]\} \\ & - \sum_{j\neq i} a_j \xi_j \phi_{ij} \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) - a_i F\ ]\}] \\ = & -\theta_i \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) - a_i F\ ]\}[a_i\xi_i - \sum_{j\neq i}(a_j \xi_j \phi_{ij})]\,.\end{aligned} \tag{23}$$

The regulator can choose the a_i's to solve the system of n equations:

$$a_i\xi_i - \sum_{j\neq i}(a_j\xi_j\phi_{ij}) = 0 \qquad i = 1, \ldots, n \tag{24}$$

The second derivative of Ω_i with respect to F yields:

$$\partial^2\Omega_i/\partial F^2 = -(\theta_i a_i)^2\xi_i \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) - a_i F\ ]\}$$
$$- \sum_{j\neq i} (\theta_i a_j \phi_{ij})^2 \xi_i \exp\{-\theta_i[\Pi_i^0 - C_i(A_i^*) + \hat{b}_i + \phi_{ij}\{\hat{b}_j + a_j F + \Gamma(W)\}]\} \tag{25}$$
$$< 0\ .$$

Equations (23) and (25) insure that, for a sufficiently large F, $\Omega_i < 0\ \forall$ i. Q.E.D.

5.2 Proof of Theorem 3

<u>Part a</u>

Let $\Omega_i(\theta) = \Omega_i(\theta;\xi,F,\phi)$ denote the value of Ω_i for a given set of program parameters and level of firm risk aversion. Furthermore, let $R_i(\theta)$ denotes the risk premium that firm i associates with the cheating solution. That is, $R_i(\theta)$ is defined implicitly by:

$$U\{E[\Pi_i(A_i^*, \hat{A}_{-i})] - R_i(\theta)\} = E\{U[\Pi_i(A_i^*, \hat{A}_{-i})]\}\ . \tag{26}$$

Theorem 1 of Pratt [9, p. 128] establishes that this risk premium is monotonically increasing with risk aversion; i.e., $\partial R_i(\theta)/\partial\theta > 0$. Using $R_i(\theta)$, $\Omega_i(\theta)$ in equation (14) can be rewritten as:

$$\Omega_i(\theta) = U\{E[\Pi_i(A_i^*, \hat{A}_{-i})] - R_i(\theta)\} - U[\Pi_i(\hat{A}_i, \hat{A}_{-i})]\ . \tag{27}$$

The term $\{E[\Pi_i(A_i^*, \hat{A}_{-i})] - R_i(\theta)\}$ denotes the certainty equivalent profit of the cheating option, as perceived by a firm with a risk aversion coefficient of θ.

Now consider two risk aversion levels θ^L and θ^H, with $\theta^L < \theta^H$ and $\Omega_i(\theta^L) \leq 0$. Since U is a monotonically increasing function, $\Omega_i(\theta^L) \leq 0$ implies that

$$E[\Pi_i(A_i^*, \hat{A}_{-i})] - R_i(\theta^L) \leq \Pi_i(\hat{A}_i, \hat{A}_{-i}) \ . \tag{28}$$

With $\partial R_i(\theta)/\partial\theta > 0$, this in turn implies that

$$E[\Pi_i(A_i^*, \hat{A}_{-i})] - R_i(\theta^H) < \Pi_i(\hat{A}_i, \hat{A}_{-i}) \ . \tag{29}$$

Again using the fact that U is a strictly increasing function, equation (29) implies

$$\Omega_i(\theta^H) = U\{E[\Pi_i(A_i^*, \hat{A}_{-i})] - R_i(\theta^H)\} - U[\Pi_i(\hat{A}_i, \hat{A}_{-i})] < 0 \ . \tag{30}$$

Part b

The second half of Theorem 3 follows immediately from combining Theorems 1, 2, and 3(a). From Theorem 1 we have $\Omega_i(0) > 0$. Theorem 2 establishes that $\Omega_i(\theta) < 0$ for θ sufficiently large. Since Ω_i is a continuous function of θ, there therefore exists at least one θ^* such that $\Omega_i(\theta^*) = 0$. The fact that θ^* is unique follows from the first half of Theorem 3, since $\Omega_i(\theta^*) = 0$ implies that $\Omega_i(\theta) < 0$ for all $\theta > \theta^*$. Q.E.D.

6. FOOTNOTES

1. See Cabe and Herriges [4].

2. Xepapadeas [13, p. 114] defines budget balancing incentive mechanisms in the environmental arena as contracts that allocate "...to the members of the discharges' group the total amount of subsidy that corresponds to any given deviation between desired and 'measured' ambient concentration levels."

3. Related research on dealing with moral hazard in the multiple agent setting includes Baiman and Demski [3], Lazear and Rosen [7], Radner [10], Atkinson and Feltham [2], Green and Stokey [5], and Nalebuff and Stiglitz [8].

4. This result was demonstrated earlier by Holmström [6].

5. In particular, whereas Xepapadeas [13] considers the application of the random penalty mechanism over time, we restrict our attention to a single time period. Extending the results below to multiple time periods is straightforward.

6. $\Psi[W(\hat{A})]$ corresponds to the residual social valuation of optimal abatement, RSB, in Xepapadeas [13].

7. In Xepapadeas [13], the i^{th} firm's share in the gains to society, ϕ_i, is set equal to its share of the total targeted abatement level; i.e., $\phi_i \equiv \hat{A}_i / \Sigma_j \hat{A}_j$.

8. It is important to note that the firm selected need not be the source of the excess pollution. As a result, the firm's actual abatement effort need not be monitored.

9. As noted in Xepapadeas [13], the Nash equilibrium of the game may change if the firms do not assume that their counterparts are in compliance (i.e., $\mathbf{A}_{-i} = \hat{\mathbf{A}}_{-i}$).

10. Much of the analysis below does not depend upon this specification. However, some of the results, specifically those stated in Theorems 2 and 3, use the convenient parameterization of risk in their proofs.

11. The subsidy specification in Xepapadeas [13], with $\phi_i \equiv \hat{A}_i / \Sigma_j \hat{A}_j$, need not satisfy the restriction in (13).

12. A similar argument can be made in terms of changes in the fine, F^g, since increases in the fine will also encourage compliance (i.e., $\partial\Omega^g/\partial F^g < 0$).

13. Collusion is an additional problem that is likely to increase as the number of firms on a "team" shrinks.

14. Of course, if budget balancing is not strictly required, then the random penalty may be effective. However, the basic point of this paper remains. If the government has limited resources available to provide incentives for pollution abatement, the random penalty mechanism provides a way of leveraging those resources, but only for firms who are risk averse.

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