Using Markets to Allocate Pollution Permits and Other Scarce Resource Rights Under Limited Information

by

Tracy R. Lewis* and David E. M. Sappington*

Revised July 1993

* University of Florida.

We are grateful to the National Science Foundation and the Public Utilities Research Center at The University of Florida for financial support. We also thank Sanford Berg, Rob Feenstra, Robert Hahn, Chris James, Roger Noll, and seminar participants at The University of California - Davis for helpful comments.

ABSTRACT

We consider the design of government policy to ration such scarce resources as water or pollution permits in the presence of limited information. When government policy is formulated, some informed agents (e.g., established public utilities) know how highly they value the resource. Other uninformed agents (e.g., potential independent power producers) only learn their valuations at some later date. The government allows uninformed agents to trade the resource rights they receive on a competitive market. Informed agents may or may not have the same privilege. The optimal initial distribution of resource rights is shown to differ significantly according to whether informed agents can trade the rights they receive.

1. Introduction.

State and Federal governments are currently grappling with the issue of how best to ration such scarce resources as water, pollution rights, and the broadcast spectrum. One allocation procedure that has been afforded considerable attention in recent years involves the creation of markets for tradeable rights to the resource. The Clean Air Act Amendments of 1990 have created a market for tradeable pollution permits. Firms can buy and sell rights to emit pollutants on Chicago's Board of Trade.[1] The state of California is considering a similar market-based plan whereby firms can buy and sell rights to consume water.[2]

It is well documented that markets for scarce resource rights can promote economic efficiency by ensuring the resource is employed in its highest-value use.[3] However, many important questions about the design of market-based systems have not yet been answered. For instance, how should resource rights be allocated initially when some potential users with political clout have private information about how highly they value the resource?[4] Furthermore, should all recipients of resource rights be permitted to participate in the market for resource rights that ultimately develops, or should some recipients be denied access to this market?

Some insights related to the first of these questions have been derived in the auction literature under the assumption that all relevant parties have perfect private information about how highly they value the resource, and that communication between the government and all parties is costless. (See, for example, Wilson (1979), Palfrey (1980), Harris and Raviv (1981), and Myerson (1981).) In practice, though, governments often have to implement long-run resource policies before all parties who may be affected by the policy discover their valuations of the resource. For instance, although the large, established public utilities may have known their private valuations of pollution permits in 1990 when the Clean Air Act Amendments were passed, potential independent power producers that had not yet begun to generate electricity were unlikely to have been so informed. Certainly, it would have been prohibitively costly for the government to attempt to solicit valuations from all parties who would eventually be affected by the government's policy.[5]

To address the complications introduced by limited information and costly communication, we develop a stylized model in which some politically powerful agents are perfectly informed about their valuations of the resource when the government designs its resource policy. Other agents share the government's imperfect knowledge of likely valuations. The government sets aside a large number of resource rights for eventual use by the many agents who are initially uninformed. In doing so, the government creates a competitive market for resource rights which operates after all agents become informed. Taking the existence of this competitive market as given, we investigate how resource rights are optimally allocated initially. In allocating rights, the government seeks to limit the information rents of the informed agents and maximize the revenues collected from these agents in order to meet other budgetary obligations, including the provision of compensation to parties who suffer from restricted access to the resource.[6] We find that through strategic initial allocation of resource rights, the government can mitigate the usual incentive an informed agent has to understate his valuation of the resource, in an attempt to secure a smaller financial assessment for the resource rights he is allocated. Consequently, information rents are reduced. The government achieves this rent reduction by creating a countervailing incentive for agents to exaggerate their true valuations of the resource.

To illustrate how this countervailing incentive can be created, suppose the valuation of a particular informed agent is positively correlated with the valuations of uninformed agents, and thus with the final market price for resource rights. If the government allocates relatively few resource rights to the informed agent in this setting, the agent will have an incentive to exaggerate his private valuation of the resource. This incentive arises because the exaggeration amounts to a prediction that the final market price at which the agent will have to purchase additional resource rights will be particularly high, and so the agent needs to be compensated now for the large costs he will incur in the future.

Although the government can create this beneficial countervailing incentive when informed agents are permitted to trade the resource rights they are allocated, there is a drawback to such unrestricted trade. Trade enables agents to rearrange the allocation of resource rights the government might otherwise impose to limit the rents that informed agents command from their private information.[7] In settings where the potential for creating countervailing incentives is small (due to limited correlation between the private valuations of informed agents and the final market price for resource rights, for example), the government may prefer to prohibit informed agents from trading the resource rights they are allocated. When such trading is prohibited, the optimal initial allocation of resource rights is shown to depend critically on the agents' production technologies and the nature of their private information.

Our formal analysis of these issues begins in section 2, where we describe the model under consideration and derive the optimal government policy in the setting of primary interest where informed agents are permitted to trade the resource rights they are initially allocated. For the purpose of comparison, we briefly consider the optimal government policy when such trade is prohibited in section 3. Conclusions are drawn in section 4, and extensions of our analysis are discussed. All formal proofs are relegated to the Appendix.

It is important to note at the outset that our formal analysis incorporates some important simplifications. For instance, we do not explicitly model market interactions. We simply take as given the fact that a competitive market for resource rights eventually develops. This approach enables us to focus on questions about how the government can best employ competitive markets to achieve its goals. It also allows us to avoid some delicate theoretical issues concerning the operation of markets in the presence of asymmetric information.[8] We also ignore the complications caused by such considerations as externalities across resource users.[9] Furthermore, we introduce a strong distinction between informed firms (who know how highly they value resource rights at the time the government designs its policy) and uninformed firms (who do not discover their valuations until after government policy has been formulated). In addition, we assume the government can commit itself not to renege on its announced resource policy, even though some constituents may suffer under the policy. Some thoughts on these issues are offered in section 4.

2. Unrestricted Trading Regime.

In this section, we analyze the setting of primary interest, where resource rights can be traded freely by all agents. Our analysis starts at the point where the maximum number of rights (to pollute, to produce, to consume a scarce resource, etc.) has been determined. Our concern is with how to best distribute the selected number of rights, A, among potential users of the rights.[10] At the time the government formulates its policy, there are N agents, who we will call firms, who already know how highly they value resource rights. As noted above, these firms might be large public utilities that have been producing electricity for many years, for example. There are an additional M firms who are not so informed. These M uninformed firms can include firms (such as independent power producers in the electric generation industry) that have not yet begun operations, but will eventually be operating in industries affected by the government's policy on resource rights. The uninformed firms share the government's imperfect knowledge about their likely valuations for resource rights. It is common knowledge whether a particular agent is informed or uninformed, but only an informed firm knows its valuation of resource rights.[11]

The benefit an informed firm derives from the scarce resource is determined by the firm's valuation parameter, θ_i. Denote by $R(q, \theta_i)$ the net revenue firm i can secure when it consumes q units of the scarce resource and its valuation parameter is θ_i. Higher values of q lead to higher net revenues for each firm at a decreasing rate, i.e., $R_1(q, \theta_i) > 0$ and $R_{11}(q, \theta_i) < 0 \; \forall \; q, \theta_i$, where numerical subscripts denote the obvious partial derivatives. Net revenue for each informed firm increases with the firm's valuation parameter, i.e., $R_2(q, \theta_i) > 0 \; \forall \; i$. Two distinct relationships between a firm's valuation parameter and the marginal impact of the resource on the firm's net revenues will be considered in the ensuing analysis. When θ_i and q are complements, and higher realizations of the firm's valuation parameter increase the rate at which the firm's net revenues increase with the amount of the resource it employs. When $R_{12}(q, \theta_i) < 0$, θ_i and q are substitutes, and higher θ_i valuations reduce the rate at which net revenues increase with q.

To illustrate these two cases, suppose q represents the level of pollution a firm emits in the course of production. When it is costly to reduce expelled pollutants, higher levels of q will be associated with higher profit levels for the firm, and so the right to pollute will be a valuable resource for producers. Now suppose θ reflects the efficacy of scrubbers in reducing the pollution (e.g., sulfur dioxide emissions) associated with production. As this efficacy increases, additional rights to emit pollutants will enhance the firm's profits less dramatically, so $R_{12}(q, \theta_i) < 0$, and θ_i and q will be substitutes. In contrast, θ_i and q can be complements when, for example, θ_i indexes demand for the final product manufactured by the firm. As final demand increases, so can the marginal profitability of increased production and the associated increase in pollution.

In the ensuing discussion, we will focus on this interpretation of q as the level of pollution expelled by a firm. We will refer to $a_i \geq 0$ as the number of pollution allowances allocated to informed firm i. Each allowance entitles its bearer to emit one unit of a homogeneous pollutant.[12] A firm cannot emit more units of pollution than the number of allowances it holds.

Of central importance in our model are the firms' valuation parameters, $\theta \equiv (\theta_1,...,\theta_N)$. These valuations for the N informed firms are modeled as realizations of N independent random variables.[13] $f_i(\theta_i) > 0 \ \forall \ \theta_i \in [\underline{\theta},\overline{\theta}]$ will denote the density function for θ_i, and $F_i(\theta_i)$ will denote the corresponding distribution function. $h_i(\theta_i) \equiv \dfrac{1 - F(\theta_i)}{f_i(\theta_i)}$ is assumed to be nonincreasing in θ_i for all $i = 1,...,N$.[14] The realization of θ_i is known only to informed firm i.

The government's task of achieving the targeted level of pollution (A) most effectively is complicated by two factors. First, the government does not know how costly it is for firms to reduce the pollutants they expel in the course of production. Formally, informed firm i knows the exact realization of θ_i, but the government cannot observe this realization. Second, there are limits on the reduction in profit from pollution abatement that informed firms can be forced to bear. These limits can have financial and/or political origins. Firms that know they will suffer large reductions in profit under a pollution abatement plan will often mount strong political opposition to the plan. Re-election concerns (along with legal restrictions against confiscatory legislation) will prompt politicians to respect what we term *political consensus* or *participation constraints* when resource policies are formulated. These constraints require that informed firms anticipate net losses that are not too pronounced (i.e., each informed firm's expected profit must exceed some lower bound, $\underline{\pi}$).[15]

To write the government's problem formally, we analyze direct mechanisms wherein all informed firms simultaneously announce their valuations of the resource to the government. The government commits in advance to allocate $a_i(\hat{\theta})$ pollution rights to informed firm i and to collect $T_i(\hat{\theta})$ dollars from that firm when the vector of valuations reported by all informed firms is $\hat{\theta} \equiv (\hat{\theta}_1,...,\hat{\theta}_N)$. Negative values of $T_i(\hat{\theta})$ reflect compensatory payments to firm i. Using the revelation principle, we focus on the government policy that induces each informed firm to truthfully reveal its valuation as a best response to truthful revelation by all other informed firms.[16] Allowances that are not allocated to informed firms are sold to uninformed firms (or to market agents such as traders or to the public at large) at their expected market value, given the vector of valuations reported by informed firms. Formally, $A_u(\hat{\theta}) = A - \sum_{i=1}^{N} a_i(\hat{\theta})$ will denote the number of allowances sold to the uninformed firms when informed firms report valuations $\hat{\theta}$.[17] The equilibrium expected revenues from the sale of allowances to uninformed firms when θ is the vector of valuation parameters for the N informed firms is denoted $T_u(\theta) = A_u(\theta)p^E(\theta)$. In this expression, $p^E(\theta)$ denotes the expected price for an allowance on the Walrasian market in which all firms eventually participate, given θ. The actual price in this market, $p(\theta,\theta^u)$, will depend on the valuation parameters of all informed (θ) and uninformed (θ^u) firms.[18]

The market for resource rights is assumed to be a perfect Walrasian market in which no firm or group believes it can influence the (single) market clearing price, $p(\cdot)$, at which all resource rights are bought and sold.[19] Each firm that participates in this market takes as given the market-clearing price that is established after all firms learn their valuation parameters. Each firm buys (respectively, sells) allowances as long as the marginal contribution of the allowances to net revenue exceeds (respectively, falls short of) $p(\cdot)$. This process ensures that, in equilibrium in this unrestricted trading regime, the marginal contribution to net revenue of a unit of the resource is the same for all firms, i.e.,

$$p(\theta, \theta^u) = R_1(q_i, \theta_i) = \tilde{S}_1(Q_u, \theta^u) \quad \forall\, i = 1, ..., N, \tag{2.1}$$

where q_i is the number of units of the resource consumed by informed firm i, and thus the final number of allowances firm i holds. For simplicity, we treat all uninformed firms as a single competitive sector, and take θ^u to be a scalar with positive support on the interval $[\underline{\theta}, \overline{\theta}]$. $\tilde{S}(Q_u, \theta^u)$ in (2.1) denotes the aggregate (post-trading) realized surplus of the uninformed sector that ends up with Q_u units of the resource when its valuation parameter is θ^u.

In the ensuing analysis, $S^E(A_u, \theta)$ will denote the expected value of *net* surplus in the uninformed sector when the sector is awarded A_u resource rights, and when $\theta = (\theta_1, ..., \theta_N)$ is the vector of valuation parameters for the informed firms. This surplus measure is defined to be net of payments by the uninformed sector, $T_u(\theta)$, for resource rights. $S^E(A_u, \theta)$ is assumed to be a strictly increasing, strictly concave function of A_u. $S_1^E(\cdot)$ will denote the partial derivative of $S^E(\cdot)$ with respect to its first argument, A_u. To calculate the expected net surplus for uninformed firms, the government relies on its knowledge of how the competitive market operates, and on its knowledge of $g(\theta^u|\theta)$, the conditional density of θ^u given $\theta \equiv (\theta_1, ..., \theta_N)$.[20]

Before providing a formal statement of the government's problem in this regime of unrestricted trading, we briefly review the timing in the model, and then discuss the government's objective. The timing is as follows. First, each of the N informed firms observes privately the realization of its valuation parameter. Second, the government announces its policy. Third, the informed firms simultaneously report their valuation parameters to the government. These reports determine how the A resource rights are allocated. Fourth, firms that were initially uninformed learn their valuation parameters. Fifth, the Walrasian market for resource rights clears. Finally, firms produce.

The government wishes to maximize the expected welfare of informed and uninformed firms. However, due to the social costs of distortionary taxes that must be imposed to finance government projects, the government also values revenues collected from these firms.[21] This latter government preference is captured by introducing the parameter $\alpha \geq 0$ in the following formal statement of the government's problem in this regime of unrestricted trading, [G-U]:

$$\underset{a_i,\, A_u(\cdot),\, T_i(\cdot)}{\text{Maximize}} \quad E \left\{ \sum_{i=1}^{N} \pi_i(\theta) + S^E\left(A_u(\theta),\, \theta\right) + p^E(\theta)\left[A_u(\theta) - Q_u(\theta)\right] \right.$$

$$\left. + \, [1+\alpha]\left[\sum_{i=1}^{N} T_i(\theta) + T_u(\theta) \right] \right\}$$

subject to, $\forall\, \theta$ and $\forall\, i = 1,\ldots,N$:

$$p(\theta,\, \theta^u) = R_1(q_i, \theta_i) = \tilde{S}_1(Q_u,\, \theta^u)\ ; \tag{2.1}$$

$$\pi_i(\theta) \;\geq\; \underline{\pi}\ ; \tag{2.2}$$

$$\pi_i(\theta) \;\geq\; \pi_i(\hat{\theta}_i, \theta_{-i}) \qquad \forall\, \hat{\theta}_i \neq \theta_i\ ; \tag{2.3}$$

$$A \;=\; \sum_{i=1}^{N} a_i(\theta) \;+\; A_u(\theta) \;=\; \sum_{i=1}^{N} q_i \;+\; Q_u\;; \quad \text{and} \tag{2.4}$$

$$a_i(\theta) \in [\underline{a},\, \overline{a}]\,; \tag{2.5}$$

where $\pi_i(\hat{\theta}_i,\theta_{-i}) \;=\; E_{-i,\theta^u}\{R(q_i,\theta_i) - T_i(\hat{\theta}_i,\theta_{-i}) + p(\theta,\theta^u)[a_i(\hat{\theta}_i,\theta_{-i}) - q_i]\}$, (2.6)

$T_u(\theta) \equiv p^E(\theta)\,A_u(\theta)$, $\quad \pi_i(\theta) \equiv \pi_i(\theta_i,\theta_{-i})$, $\quad p^E(\theta) = \int_{\theta^u} p(\theta,\theta^u)\,g(\theta^u|\theta)\,d\theta^u$, and

$Q_u(\theta)$ is the expected equilibrium resource use by all uninformed firms, given θ.

In the statement of [G-U], E denotes the expectations operator over $\theta \equiv (\theta_1,\ldots,\theta_N)$. E_{-i,θ^u} is the expectations operator over $\theta_{-i} \equiv (\theta_1,\ldots,\theta_{i-1},\theta_{i+1},\ldots,\theta_N)$ and θ^u, given θ_i. The objective function in [G-U] reflects the government's concern with the welfare of informed and uninformed firms, and with the revenues collected from these firms. The higher the value of α, the higher the costs of distortionary taxes, and thus the more highly the government values the revenues collected directly from firms. Only in the limiting case of $\alpha = 0$ does the government place no premium on revenue collection. Equation (2.1) again defines the final allocation of the resource rights after all trading has taken place. Inequality (2.2) defines the participation constraint for informed firm i. Recall that informed firms will participate in the government's program only if they anticipate profit of at least $\underline{\pi}$. Notice from equation (2.6) that the realized profit of an informed firm is the sum of: (i) direct net revenues, $R(\cdot)$, less transfer payments to the government, $T(\cdot)$; and (ii) proceeds from the sale of any excess of allowances, $a(\cdot)$, over final consumption of the resource, $q(\cdot)$. The corresponding expected profit for uninformed firms is reflected in the objective function in [G-U]. Inequality (2.3) captures the incentive compatibility constraints for informed firm i. The inequality ensures the firm will truthfully report its valuation as a Nash response to truthful revelation by all other informed firms. As defined in equation

(2.6), $\pi_i(\hat{\theta}_i, \theta_{-i})$ is the profit informed firm i would expect to earn if it misrepresented its valuation as $\hat{\theta}_i$, while all other informed firms reported their private information truthfully. Equality (2.4) ensures the total number of allowances assigned to both informed and uninformed firms is equal to the mandated level, A.

Relation (2.5) captures an additional restriction that is placed on feasible initial allocations of allowances in this regime of unrestricted trading. The number of allowances each informed firm receives is bounded above by $\overline{a}$ and below by $\underline{a}$. The bounds are structured to ensure that a perfect Walrasian market for allowances ultimately operates. If all allowances were distributed to a single firm, for example, the assumption that all firms eventually act as price takers would be less palatable. The restriction is also useful from a technical perspective, because it helps avoid troubling corner solutions.[22]

Lemma 1 is helpful in understanding the solution to [G-U].

Lemma 1. $$\frac{\partial p^E(\theta)}{\partial \theta_i} = \int_{\theta^u} \left[p_i(\theta, \theta^u)\, g(\theta^u | \theta) - p_{\theta^u}(\theta, \theta^u)\; G_i(\theta^u | \theta) \right] d\theta^u, \tag{2.7}$$

where $$p_i(\theta, \theta^u) \equiv \frac{\partial p(\theta, \theta^u)}{\partial \theta_i} = R_{12}(q_i(\theta), \theta_i) \left[\sum_{\ell=1}^{N} \frac{R_{11}(q_i, \theta_i)}{R_{11}(q_\ell, \theta_\ell)} + \frac{R_{11}(q_i, \theta_i)}{S_{11}^E(A_u, \theta)} \right]^{-1}, \tag{2.8}$$

$$p_{\theta^u}(\theta, \theta^u) = \frac{\partial p(\theta, \theta^u)}{\partial \theta^u}, \quad G(\theta^u \mid \theta) = \int_{\underline{\theta}}^{\theta^u} g(\xi | \theta) d\xi, \quad \text{and} \quad G_i(\theta^u | \theta) = \frac{\partial G(\theta^u | \theta)}{\partial \theta_i}.$$

Lemma 1 identifies the impact of an increase in the valuation parameter of firm i on the expected equilibrium price in this regime of unrestricted trading. There are two distinct effects reflected in (2.7). The first effect $(p_i(\cdot)g(\cdot))$ captures the direct impact of firm i's higher valuation on the equilibrium price, holding constant the valuations (θ_{-i}, θ^u) of other firms. From

(2.1), this first effect is positive when $R_{12}(\cdot) > 0$, since higher valuations for the resource drive the market price higher.[23] The second effect captures the impact of a higher θ_i on the expected equilibrium price due to altered beliefs about the valuations of uninformed firms. If an increase in firm i's valuation implies that the valuations of the uninformed firms are relatively more likely to be high, for example (so that $G_i(\theta''|\theta) < 0$), then an additional upward force on the expected equilibrium price is introduced, provided $p_{\theta''}(\cdot) > 0$.

As Lemma 2 reports, the net effect of an increase in the valuation parameter (θ_i) of an informed firm on the expected equilibrium price ($p^E(\theta)$) for the resource determines how many allowances the firm is allocated. When an increase in θ_i raises $p^E(\theta)$, the government allocates the minimum number of allowances it can to firm i. The maximum possible number of allowance is awarded to firm i when an increase in θ_i reduces $p^E(\theta)$.

Lemma 2. At the solution to [G-U]:

$$a_i(\theta) = \begin{cases} \underline{a} & \text{if } p_i^E(\theta) > 0 \\ \overline{a} & \text{if } p_i^E(\theta) < 0. \end{cases}$$

The intuition that underlies Lemma 2 is critical for understanding how the government allocates resource rights initially to better limit the information rents of informed firms. Informed firms have a natural incentive to understate their valuation of the resource. Such understatement amounts to a claim that they will derive little profit from use of the resource, and thus are not willing to pay much for resource rights. When informed firms are permitted to trade allowances, the government can create a countervailing incentive for firms to overstate their true valuations of the resource.[24] A firm that receives few resource rights directly from the government will tend to purchase additional rights in the marketplace. Such a net buyer of resource rights will wish to exaggerate the market price at which it will be forced to purchase the rights, thereby making a case for initial government subsidies to compensate for large subsequent costs. When $p_i^E(\cdot) > 0$, the expected equilibrium price of the resource varies directly with the valuation of firm i. Thus, to exaggerate the final market price at which it will have to purchase resource rights, firm i will have an incentive to exaggerate its valuation of the resource. By enhancing this countervailing incentive to exaggerate valuations, the government is better able to mitigate the usual incentive firms have to understate their valuations of the resource. The result is reduced information rents for the informed firms.

Lemma 2 explains how the government acts to maximize the strength of this countervailing incentive. The government allocates the fewest (respectively, the most) allowances it can to those informed firms for whom higher valuations lead to a higher (respectively, a lower) expected equilibrium price. The minimal number of allowances the firm receives when $p_i^E(\cdot) > 0$, for example, provides the strongest possible encouragement for the firm to exaggerate θ_i, since the firm is most likely to be a net buyer of the resource. This fact and the other central features of the government's optimal policy in the unrestricted trading regime are summarized in Proposition 1.

Proposition 1. At the solution to [G-U], $\forall\, i = 1,\dots, N$:

(i) $$R_1(q_i,\theta_i) = p(\theta, \theta^u) = \tilde{S}_1(Q_u, \theta^u); \tag{2.9}$$

(ii) $$a_i(\theta) = \begin{cases} \underline{a} & \text{if } p_i^E(\theta) > 0 \\ \overline{a} & \text{if } p_i^E(\theta) < 0; \end{cases} \tag{2.10}$$

(iii) $\sum_{t=1}^{N} a_t(\theta) + A_u(\theta) = A$; and (2.11)

(iv) $$\frac{\partial}{\partial \theta_i}\pi_i(\theta) = E_{-i,\theta^u}\left\{R_2(q_i, \theta_i) + \left[p_i(\theta, \theta^u) - p_{\theta^u}(\theta, \theta^u)\frac{G_i(\theta^u \mid \theta)}{g(\theta^u \mid \theta)}\right][a_i(\theta) - q_i]\right\}, \tag{2.12}$$

provided $\overline{a} - \underline{a}$ is sufficiently small.

Property (i) of proposition 1 reflects the efficient final resource consumption ensured by the competitive market. Property (ii) records the optimal initial allocation of resource rights to maximize the strength of countervailing incentives. Property (iii) simply states that all allowances are distributed, as required. Property (iv) indicates how equilibrium expected profits of informed firm i vary with its valuation parameter. The terms in square brackets on the right-hand side of (2.12) captures the strength of the countervailing incentive created for firm i in this unrestricted trading regime.

3. Limited Trading Regime.

Traditionally, governments have employed "command and control" strategies to limit pollution. Firms have been told the maximum amount of pollutants they are permitted to emit, and no trading of allowances has been allowed. When informed firms are not permitted to trade resource rights, the optimal initial allocation of resource rights can differ significantly from the optimal allocation of rights in the unrestricted trading regime. To demonstrate this fact, we now briefly examine the government's optimal policy when uninformed firms can trade their resource rights on a competitive market, but informed firms are prohibited from such trade.

The formal statement of the government's problem in this regime of limited trading is denoted [G-L], and is given in the Appendix. [G-L] is analogous to [G-U], except that the counterparts to constraints (2.1) and (2.5) are not imposed, and the profits of informed firms do not include revenues from sales of allowances, since no such sales are permitted. In the ensuing discussion, the superscript "L" will denote variables in the solution to [G-L]. With this exception, all notation is as defined above.[25]

Proposition 2 reports standard observations about the solution to [G-L]. The Proposition refers to $p^{LE}(A_u^L, \theta)$, which is the expected equilibrium price on the Walrasian market in this limited trading regime when the informed firms' valuation parameters are given by θ, and the uninformed firms receive $A_u^L \in (0, A]$ allowances.

Proposition 2. At the solution to [G-L], $\forall$ $i,j = 1,..., N$ and $\forall$ θ:

(i) $$m(q_i^L(\theta), \theta_i) = m(q_j^L(\theta), \theta_j) = p^{LE}(A_u^L, \theta) + \frac{\alpha}{1+\alpha} A_u^L p_1^{LE}(A_u^L, \theta), \quad (3.1)$$

where $$m(q, \theta_i) = R_1(q, \theta_i) - \frac{\alpha}{1+\alpha} R_{12}(q, \theta_i) h_i(\theta_i); \quad (3.2)$$

(ii) $$\frac{\partial}{\partial \theta_i} \pi_i^L(\theta) = E_{-i}\{R_2(q_i^L(\theta), \theta_i)\}; \quad (3.3)$$

(iii) $q_i^L(\theta) = a_i^L(\theta)$; and (iv) $A_u^L(\theta) = A - \sum_{i=1}^{N} a_i^L(\theta)$.

Condition (i) of Proposition 2 provides a *modified efficiency rule* for allocating resources among users. The rule requires modified marginal net benefits, $m(\cdot)$, rather than direct marginal net benefits, $R_1(\cdot)$, to be equated across all informed firms. Modified marginal net benefits are the difference between direct marginal net benefits, $R_1(\cdot)$, and marginal information rents, as indicated in (3.2).[26] Deviations from the surplus-maximizing allocation are implemented to limit the information rents that informed firms command from their private information when these rents are costly to the government (i.e., when $\alpha > 0$).[27] These rents for informed firm i increase with θ_i at the rate identified in equation (3.3). In the case where q and θ_i are complements, so $R_{12}(q, \theta_i) > 0$, a given reduction in the resource input, q, lowers the net revenues of a firm by a greater amount the higher its valuation of the resource. Therefore, to limit the potential gain in profit from understating the value of the resource, the government will grant fewer than the surplus-maximizing number of allowances to informed firms who claim to have smaller valuations of the resource. Informed firms that admit to having higher valuations will be awarded a greater number of allowances, but will be charged a relatively large amount for the allowances.

In contrast, when q and θ_i are substitutes, so $R_{12}(q, \theta_i) < 0$, a given increase in q raises the net revenues of a firm by a greater amount the smaller is θ_i. Hence, to limit incentives to understate θ_i, the government delivers more than the surplus-maximizing number of allowances to informed firms that claim to have low realizations of θ_i. In turn, these firms are charged for the relatively large number of allowances they receive according to the relatively high marginal valuation of the resource rights implied by a claim that θ_i is small. These charges will outweigh the true marginal valuation of the resource rights for a firm whose θ_i realization is higher than claimed, so incentives to understate θ_i are mitigated.

Notice from (3.1) that uninformed firms receive fewer than the number of allowances that would equate the expected marginal value of the resource to uninformed firms and the modified marginal net benefits to informed firms. The reduction in A_u^L results in a higher equilibrium price for resource rights, which in turn allows the government to collect more revenues from uninformed firms. In essence, the government exploits its position as the monopoly supplier of resource rights to enhance the revenues it collects directly from firms.

Thus, the optimal distribution of permits can be very different in the limited trading regime than in the unrestricted trading regime. Before concluding, note that although we have taken the number of allowances to be fixed, our formulation of [G-L] allows us to consider how asymmetric information and political participation constraints affect the marginal cost of meeting a more stringent environmental standard. These added restrictions will increase the social cost of marginal pollution reductions when the mandated reductions interfere with the government's ability to limit the rents that accrue to informed firms. Recall that when the resource (q) and the valuation parameter (θ_i) are substitutes (so $R_{12}(q, \theta_i) < 0$), information rents are best reduced in the limited trading regime by distributing more than the surplus-maximizing number of allowances. Thus, a reduction in the number of available allowances (A) places a particular burden on the government. Not only does the reduction in A reduce the net revenues of firms directly, it also increases the rents of informed firms. In contrast, when information rents decline as fewer resource rights are allocated (as when $R_{12}(\cdot) > 0$), the direct reduction in net revenues caused by a decline in A is offset in part by the associated reduction in information rents. Consequently, when $R_{12}(\cdot) > 0$ the marginal social cost of a tightened resource constraint (i.e., of reducing A) at the solution to [G-C] is less than the corresponding marginal social cost at the solution to the government's problem in the limited trading regime where the valuations (θ) of all informed firms are common knowledge. These observations are recorded formally as Proposition 3. In the statement of the Proposition, $\lambda(\theta)$ is the value of the Lagrange multiplier associated with the resource constraint ($A_u^L + \sum_{i=1}^{N} a_i^L = A$) at the solution to [G-L], and $\lambda^*(\theta)$

is the value of the corresponding multiplier in the setting where there is no information asymmetry.

Proposition 3. Assume $p_{11}^{LE}(A_u^L, \theta) \leq 0 \quad \forall\, \theta$ and $\forall\, A_u^L > 0$.[28] (i) If $R_{12}(q, \theta_i) > 0$ then $\lambda(\theta) \leq \lambda^*(\theta)$ (ii) If $R_{12}(q, \theta_i) < 0$ then $\lambda(\theta) \geq \lambda^*(\theta)$. The inequalities in (i) and (ii) will be strict if $\alpha > 0$ and $\theta \neq (\overline{\theta}_1,\ldots,\overline{\theta}_N)$.[29]

4. Conclusions and Extensions

We have contrasted the optimal manner in which to distribute resource rights in two distinct settings: the unrestricted trading regime and the limited trading regime. Important differences (summarized in Propositions 1 and 2) were shown to emerge in the two settings, mainly due to the potential for creating countervailing incentives in the unrestricted trading regime.

Both regimes were argued to have their advantages. In the limited trading regime, the government can dictate the final allocation of resource rights among informed firms. In the unrestricted trading regime, an efficient allocation of resource rights is ensured (given a competitive market for resource rights), and countervailing incentives can be created. In choosing between these regimes, a government would have to carefully weigh the advantages of each regime.

In a setting where the government's budget constraint is not very binding (i.e., where α is close to zero, so the government is largely concerned with maximizing total surplus), the government will prefer the unrestricted trading regime to the limited trading regime.[30] This preference arises because the unrestricted regime leads to efficient resource consumption (and thus surplus maximization) and allows the government to limit the information rents of informed firms by creating countervailing incentives.

The government will also tend to favor the unrestricted trading regime when considerable uncertainty about the uninformed firms' demand for the resource exists even when the valuations of informed firms are known. In this case, final consumption of the resource may be far from efficient if the final resource consumption of informed firms is established in the limited trading regime before all relevant information arrives.

The government's preference between regimes is less obvious when θ^u and θ are highly correlated. In this case, little residual uncertainty will exist about the resource demand of uninformed firms after informed firms report their valuations. Thus, the additional gains from trade of resource rights on a competitive market need not be great. However, when the valuation of informed firm i is highly correlated with the ultimate valuation of the uninformed sector (and thus with the final market price), the potential for creating countervailing incentives is particularly pronounced. A detailed specification of the conditions under which the government prefers one trading regime over another awaits future research.[31]

Since our model has a variety of special features, additional research on at least the following five dimensions is recommended. First, alternative formulations of the market for resource rights should be developed. Absent a perfect Walrasian market, individual firms may have some influence on the prices at which resource rights are traded. This influence could result in a final allocation of the resource that is not efficient. Furthermore, additional incentives might arise for firms to misrepresent their true valuations of the resource in order to secure a more favorable trading position.[32]

Second, alternative government policies should be investigated. We have explored two extreme regimes: one where informed firms can trade resource rights freely, and another where informed firms cannot trade at all. Conceivably, intermediate regimes where limited trading by informed firms is permitted might be preferred by the government. Different policy instruments might also be considered. For instance, the government might adopt a different fee structure when transferring resource rights to uninformed firms. Conceivably, the government might also retain a sizeable supply of resource rights in order to remain an active player in the market for these rights.

Third, different treatments of "the resource" are warranted in some settings. In the pollution context, for example, an additional ton of sulfur dioxide emissions in a heavily polluted airshed may entail a higher social cost than the same ton of pollutants in an area with very little air pollution. Conceivably, the optimal policy in such settings might impose limits on the ability of firms to trade pollution rights across geographic regions.[33]

Fourth, dynamic elements warrant careful treatment. The dynamic evolution of the market for resource rights deserves careful analysis. The fact that market participants update their resource demands continually over time, even as markets for resource rights operate, should be modeled formally. The assumption of perfect government commitment abilities also warrants further consideration. In practice, governments are unable to commit themselves completely to future policies. Legislation can always be passed that alters the mandates of the Clean Air Act, for example.[34] Recognizing this fact, firms may act strategically. For example, firms may not undertake the level of pollution abatement they are instructed to implement, believing announced abatement standards will be relaxed if compliance is not forthcoming.

Finally, interactions among regulatory regimes deserve explicit consideration. If state public utility commissions treat expenditures on pollution allowances differently from expenditures on pollution abatement investments when calculating a utility's allowed rate of return, regulated firms' choices among methods for complying with the Clean Air Act may be distorted. For some useful thoughts on this issue and related issues, see Bohi and Burtraw (1990), Hahn (1993), Rose and Burns (1991), and Tschirhart (1984).[35]

FOOTNOTES

1. See the *Wall Street Journal* (1991).

2. See the Bay Area Economic Forum Report (1991).

3. For example, Hahn and Noll (1990) suggest that $200 million was saved each year in the EPA's market-based program to phase out lead in gasoline. The authors also estimate that billions of dollars will be saved through the use of market trading to meet the pollution requirements of the Clean Air Act. Tietenberg (1985) estimates that it may be as much as twenty times cheaper to use a market permit system rather than direct controls to satisfy certain requirements of the Clean Air Act.

4. See Hahn and Noll (1983) for a discussion of political and distributional problems which may preclude the use of marketable pollution certificates.

5. Similarly, when it sells securities, the U.S. Treasury generally solicits bids from a relatively small number of large buyers, who in turn resell the securities to other small buyers. The government does not solicit bids directly from all potential buyers because of the prohibitive costs of doing so. (See Reinhart (1992).)

6. When information rents, and thus government taxation, are not socially costly, Groves-type schemes can be employed to elicit private valuation information from resource users. See Kwerel (1977) and Dasgupta, Hammond, and Maskin (1980).

7. See Arnott and Stiglitz (1991) and Varian (1990) for additional thoughts on different settings where recontracting by agents can be either beneficial or detrimental to the principal.

8. See Bikhchandani and Huang (1989) and Harris and Raviv (1992) for careful treatments of these issues. Because we avoid these issues, our analysis should be viewed as a pedagogical benchmark that might serve as a point of departure for further research. Our intent is not to undertake a detailed theoretical investigation of how markets operate in the presence of asymmetric information. Our more modest goal is to examine how well-functioning markets might best be employed by the government to achieve its resource allocation objectives.

9. See Tietenberg (1985) for a comprehensive treatment of pollution markets and the complications arising from externality effects, seasonal and spatial variation in damages, multi-media damages, and other relevant complications. Bowes et al. (1991) provide an insightful treatment of other important considerations in the regulation of toxic substances.

10. In practice, the magnitude of A is often determined largely by political considerations. The ensuing analysis can be viewed as deriving the minimum cost of achieving the identified political goal. Of course, the initial choice of A can be a complex and controversial matter (see Hahn and Hester (1989)).

11. We do not allow informed firms to masquerade as uninformed firms, or vice versa. Such a possibility gives rise to the additional complications addressed in Lewis and Sappington (1993a, b).

12. Under the 1990 Clean Air Act Amendments, one pollution allowance entitles its bearer to emit one ton of sulfur dioxide annually. (See Rose and Burns (1991).)

13. There may be systematic components of the value of the resource that affect all firms symmetrically. These components are assumed known to the government and all firms, and are captured directly in the net revenue function, $R(q, \theta_i)$. Variations in θ_i reflect the idiosyncratic deviations of firm i from known industry norms.

14. This assumption is standard in the literature. Technically, it helps to avoid bunching or pooling in the optimal incentive policy.

15. $\underline{\pi}$ could represent the opportunity profit of firms in the industry. In this case, the participation constraints simply state that firms always have the option of deploying their assets in alternative ventures. One interpretation of our formal analysis is that while there may be $\tilde{N} > N$ informed firms that would participate in the industry absent resource rationing, only the N most productive informed firms operate in equilibrium.

    There are plausible alternative formulations of the participation constraint. For example, an environmental proposal might become law only if the welfare of a *majority* of affected agents is improved by the proposal. A formal model along these lines is developed in Lewis et al. (1991).

16. See Myerson (1979). Also see Ma (1988) and Mookherjee and Reichelstein (1990) for thoughts on how to ensure implementation of the preferred equilibrium when multiple Nash equilibria are possible.

17. For expositional simplicity, we will describe the A_u allowances as being sold to uninformed firms. When these firms are not readily identified by the government, though

(perhaps because they have not yet begun to operate), the other possibilities of selling to speculators, market makers, traders, or other uninformed individuals or groups should be kept in mind. By assuming that allowances are sold at their expected value, we abstract from any ability the government might have to tax future potential market participants. This ability may be limited, for example, because of participants' real wealth constraints, or because of the latitude future participants may have to feign wealth constraints by arranging to repurchase allowances from individuals with limited wealth who purchase allowances directly from the government. We assume throughout that A_u is sufficiently large that a well-functioning market for allowances ultimately operates.

18. Of course, the equilibrium price will also depend on the number of available allowances, A.

19. See Hahn (1984) for an analysis of a setting with unrestricted trading where some firms may have the ability to influence the market price of resource rights. In practice, steps are being taken to ensure a well-functioning market for pollution allowances. The government has a reserve of pollution allowances it can employ to bolster future supplies of allowances. (See Rose and Burns (1991).) Trading on the Chicago Board of Trade will also facilitate ready exchange of allowances. Recall, too, that recent theoretical and empirical work suggests that competitive equilibria will be closely approximated with double auctions even when there are very few buyers and sellers. (See Smith (1982) and Satterthwaite and Williams (1989). Also see Maddison (1993) for an application to markets for sulfur dioxide emissions.)

20. If $\tilde{g}(\theta, \theta^u)$ denotes the joint density of $\theta = (\theta_1, ..., \theta_N)$ and θ^u, then $g(\theta^u|\theta) = \tilde{g}(\theta, \theta^u)/[f_1(\theta_1) ... f_N(\theta_N)]$, since the θ_i's are independent random variables.

21. See Laffont and Tirole (1986). The government may also value this revenue if it can be employed to compensate individuals who are harmed by pollution (see Burtraw (1991)).

22. As is evident in the proof of Proposition 1, the government's objective function turns out to be linear in allowances. The simplifying assumption that $\underline{a}$ and $\overline{a}$ are identical for all firms is not crucial to our findings.

23. This first effect is negative when $R_{12}(\cdot)$ is negative.

24. See Lewis and Sappington (1989a,b) for formal treatments of countervailing incentives.

25. In [G-L], as in [G-U], the allowances, $A_u^L(\cdot)$, sold to uninformed firms are sold at their expected market value. Furthermore, the taxes, $T^L(\cdot)$, imposed on informed firms depend only on the vector of valuation parameters, $\hat{\theta}$, reported by the informed firms. If the government could base these taxes on both $\hat{\theta}$ and the final equilibrium price for resource rights, then it could create countervailing incentives in the limited trading regime, much as it could in the unrestricted trading regime. This restriction on feasible taxes reflects our concern with settings where ongoing government involvement in the financial aspects of its resource policy is not feasible.

26. Only in the extreme cases where the government places no premium on collected revenues (i.e., where $\alpha = 0$) or where the valuation parameter of each informed firm takes on its highest conceivable value will the resource be distributed to maximize expected

aggregate surplus. More generally, the resource will not be distributed to ensure equal marginal profitability of the resource across informed firms.

27. These distortions are analogous to the distortions that arise in a variety of models where an uninformed "principal" designs on incentive scheme for informed "agents".

28. This assumption ensures concavity of the aggregate demand curve in the uninformed sector. $\tilde{S}_{111}(A_u, \theta^u) \leq 0$ is sufficient to ensure $p_{11}^{LE}(A_u^L, \theta) \leq 0$.

29. Of course, if $R_{12}(\cdot) = 0$ so that marginal net revenues for all informed firms are independent of θ_i, then $\lambda(\theta) = \lambda^*(\theta)$, since information rents are not affected by the level of the resource consumed.

30. This conclusion is proved formally in Lewis and Sappington (1992).

31. Comparisons with other popular policies are more straightforward. For instance, the optimal policy in the unrestricted trading regime will generally dominate a simple linear tax on pollution for three reasons. First, by excluding tradeable resource allowances, the linear tax policy does not admit the creation of countervailing incentives. Thus, eliciting information from informed firms to inform optimal tax policy will be more costly for the government. Second, linear taxes are generally not optimal, even within the restricted class of policies that only allow for pollution taxes. Third, a linear tax policy will generally not ensure the desired level of emissions. (See Besanko (1987), Kwerel (1977), and Roberts and Spence (1976) for related discussions.)

32. This issue is discussed by Bikhchandani and Huang (1989) in the context of treasury bill auctions.

33. See Montgomery (1972) for a useful analysis along these lines.

34. For some thoughts on this issue, see Hahn and Hester (1989). In fact, efforts are already underway to extend the period of time certain utilities have to comply with the Amendments. See Gutfield (1991).

35. Some additional extensions of our analysis are reported in Lewis and Sappington (1992). For instance, following Besanko (1985) and Besanko and Sibley (1991) among others, the government is presumed able to control the use of multiple productive resources (e.g., pollution allowances and the number of industrial scrubbers to reduce airborne pollutants). Distortions in the use of these additional inputs are generally implemented to better limit the information rents of informed firms. An additional extension recognizes the costs of monitoring resource consumption (e.g., how much pollution a firm produces). Following Maskin and Riley (1985), conditions are derived under which government welfare is higher when the government can monitor (only) the final output of firms than when (only) their resource consumption can be observed. A third extension allows informed firms to have private information about consumer demand for the final product they produce, rather than about their production technologies. Following Lewis and Sappington (1988), conditions are derived under which efficient use of the resource can be ensured in the limited trading regime without yielding any rents to the informed firms. One implication of this fact is that the qualitative features of the optimal policy to allocate a scarce

resource may be sensitive to the exact nature of the information asymmetry between the government and resource users.

APPENDIX

Proof of Lemma 1.

Recall that $p^E(\theta) = \int_{\theta^u} p(\theta, \theta^u)\, g(\theta^u \mid \theta)\, d\theta^u$. Differentiating this expression with respect to θ_i and integrating by parts yields equation (2.7). Equation (2.8) follows from a straightforward but tedious comparative static exercise. First equalities (2.1) and (2.4) are differentiated totally. Then Cramer's rule is applied. Some manipulation of the resulting expression yields equation (2.8).

■

Lemma 2 is proved as part of the proof of Proposition 1.

Proof of Proposition 1.

From (2.6) and the revelation principle, the incentive compatibility constraints (2.3) require

$$\frac{\partial}{\partial\theta_i}\pi_i(\theta) = \frac{\partial}{\partial\theta_i} E_{-i} \int_{\theta^u} \Big\{R(q_i, \theta_i) + p(\theta, \theta^u)[a_i(\theta) - q_i] - T(\theta)\Big\}\, dG(\theta^u \mid \theta)$$

$$= E_{-i} \int_{\theta^u} \{ R_2(q_i, \theta_i) + p_i(\theta, \theta^u)[a_i(\theta) - q_i]$$

$$+ R(q_i, \theta_i) + p(\theta, \theta^u)[a_i(\theta) - q_i] - T(\theta)\}\, dG_i(\theta^u \mid \theta)$$

$$= E_{-i} \int_{\theta^u} \left[R_2(q_i, \theta_i) + \{p_i(\theta, \theta^u) - p_{\theta^u}(\theta, \theta^u)\frac{G_i(\theta^u \mid \theta)}{g(\theta^u \mid \theta)}\}\,[a_i(\theta) - q_i] \right] dG(\cdot)$$

$$= E_{-i,\theta^u} \left[R_2(q_i, \theta_i) + \{p_i(\theta, \theta^u) - p_{\theta^u}(\theta, \theta^u)\frac{G_i(\theta^u \mid \theta)}{g(\theta^u \mid \theta)}\}\,[a_i(\theta) - q_i] \right],$$

where the second line follows from the envelope theorem, the third line follows from integrating by parts, and the last line, which coincides with equation (2.12), is obtained by consolidating terms under the expectations operator.

The global incentive compatibility constraints will be satisfied if

$$E_{-i,\theta^u}\left\{ p_i(\theta,\theta^u)\,\frac{\partial a_i(\theta)}{\partial \theta_i} \right\} \geq 0. \tag{A1.1}$$

It will become clear shortly that (A1.1) will hold.

From (2.12) and the fact that constraint (2.2) binds only for the smallest realization of θ_i, integration by parts reveals:

$$\pi_i(\theta) = \underline{\pi} + \int_{\underline{\theta}}^{\bar{\theta}} E_{-i,\theta^u}\left\{R_2(q_i,\theta_i) + p_i(\theta,\theta^u)\,[a_i(\theta) - q_i]\right\} h(\theta_i)\,dF_i(\theta_i). \tag{A1.2}$$

Substituting from (A1.2) into the objective function in [G-U], and letting $\lambda(\theta)$ represent the Lagrange multiplier associated with the resource constraint (2.4), the government's objective function can be written as:

$$\begin{aligned}
\underset{a_i(\bullet),\,A^u(\bullet)}{Maximize}\quad E_\theta \Bigg[\int_{\theta^u} & [1+\alpha] \sum_{i=1}^{N} \left(R(q_i,\theta_i) + p(\theta,\theta^u)\,[a_i(\theta) - q_i]\right) \\
& + S^E(A_u(\theta),\theta) + p^E(\theta)[A_u(\theta) - Q_u(\theta)] + [1+\alpha]\,p^E(\theta)\,A_u(\theta) \\
& - \alpha \sum_{i=1}^{N} \left\{\underline{\pi} + R_2(q_i,\theta_i) + p_i(\theta,\theta^u)[a_i(\theta) - q_i]\right\} h_i(\theta_i)\,g(\theta^u \mid \theta)\,d\theta^u \\
& + \lambda(\theta)\,[A - \sum_{i=1}^{N} a_i(\theta) - A_u(\theta)] \Bigg].
\end{aligned} \tag{A1.3}$$

Pointwise maximization of (A1.3) provides

$$[1+\alpha]\,p(\theta,\theta^u) - \lambda(\theta) - \alpha\, p_i(\theta,\theta^u)\, h_i(\theta_i) \left\{ \begin{matrix} \leq \\ = \\ \geq \end{matrix} \right\} 0 \text{ as } a_i(\theta) \left\{ \begin{matrix} = & \underline{a} \\ \in & (\underline{a}, \overline{a}) \\ = & \overline{a} \end{matrix} \right. \quad ; \text{ and} \tag{A1.4}$$

$$[1+\alpha]\,p^E(\theta) - \lambda(\theta) = 0. \tag{A1.5}$$

Together, (A1.4) and (A1.5) imply the conditions stated in Lemma 2 and equation (2.10).

Finally, provided $p_i(\theta,\theta^u)$ has the same sign for all θ_i, (A1.4) implies that $\frac{\partial a_i(\theta)}{\partial \theta_i} = 0$ for all θ_i, so that (A1.1) is trivially satisfied. This completes the proof of Lemma 2 and Proposition 1.

■

Proof of Proposition 2.

The formal statement of [G-L] is

$$\underset{a_i^L(\cdot),A_u^L(\cdot),T_i^L(\cdot)}{Maximize} \quad E\left\{ \sum_{i=1}^{N} \pi_i^L(\theta) + S^E(A_u^L(\theta),\theta^u) + [1+\alpha]\left[\sum_{i=1}^{N} T_i^L(\theta) + T_u^L(\theta) \right] \right\} \tag{A2.1}$$

subject to, $\forall\ \theta$ and $\forall\ i = 1, \ldots, N$:

$$\pi_i^L(\theta) \geq \underline{\pi}; \tag{A2.2}$$

$$\pi_i^L(\theta) \geq \pi_i^L(\hat{\theta}_i,\theta_{-i}) \quad \forall\ \hat{\theta}_i \neq \theta_i; \text{ and} \tag{A2.3}$$

$$A = \sum_{i=1}^{N} a_i^L(\theta) + A_u^L(\theta); \tag{A2.4}$$

where $\pi_i^L(\hat{\theta}_i,\theta_{-i}) = E_{-i}\{R(a_i^L(\hat{\theta}_i,\theta_{-i}) - T_i(\hat{\theta}_i,\theta_{-i})\}$, (A2.5)

$$\pi_i^L(\theta) \equiv \pi_i^L(\theta_i,\theta_{-i}), \text{ and } q_i^L(\theta) = a_i^L(\theta).$$

From (A2.5) and the revelation principle, local incentive compatibility requires

$$\frac{\partial}{\partial \theta_i} \pi_i^L(\theta) = E_{-i}\{R_2(q_i^L(\theta),\theta)\} \quad \forall\ i=1,\dots N. \tag{A2.6}$$

The global incentive compatibility constraints will also be satisfied at the identified solution provided $\dfrac{\partial q_i^L(\theta)}{\partial \theta_i} \geq 0 \ \ \forall\ i$, which can be readily verified. (See the proof of Proposition 3 in Lewis and Sappington (1992).) Using (A2.6) and integrating by parts,

$$\pi_i(\theta) = \underline{\pi} + \int_{\underline{\theta}}^{\bar{\theta}} E_{-i}\{R_2(q_i(\theta),\theta_i)\} h(\theta_i) dF_i(\theta_i) \quad \forall\ i = 1, \dots N. \tag{A2.7}$$

Substituting from equation (A2.7) into the objective function in [G-L] and letting $\lambda^L(\theta)$ represent the Lagrange multiplier associated with the resource constraint (A2.4), the government's objective can be rewritten as:

$$\begin{aligned} \underset{a_i^L(\cdot),A_u^L(\cdot)}{Maximize}\ E \Bigg[\int_{\theta_u} & \Big\{[1+\alpha] \sum_{i=1}^{N} R(q_i^L, \theta_i) + S^E(A_u^L(\theta), \theta_u) + [1+\alpha]\, p^{LE}(A_u^L,\theta)\, A_u^L(\theta) \\ & - \alpha \sum_{i=1}^{N} [\underline{\pi} + R_2(q_i^L(\theta),\theta_i)] h_i(\theta_i) \Big\} g(\theta^u \mid \theta) d\theta^u \\ & + \lambda^L(\theta)[A - \sum_{i=1}^{N} a_i(\theta) - A_u(\theta)] \Bigg] . \end{aligned} \tag{A2.8}$$

Pointwise maximization of (A2.8) with respect to $a_i^L(\cdot)$ and $A_u^L(\cdot)$ yields:

$$R_1(q_i,\theta_i) - \frac{\alpha}{1+\alpha} R_{12}(q_i^L,\theta_i) h_i(\theta_i) - \frac{\lambda^L(\theta)}{1+\alpha} = 0 \quad \forall\ i=1,\dots N; \text{ and} \tag{A2.9}$$

$$p^{LE}(A_u^L,\theta) + \frac{\alpha}{1+\alpha} p_1^{LE}(A_u^L,\theta)\, A_u^L - \frac{\lambda^L(\theta)}{1+\alpha} = 0, \tag{A2.10}$$

which implies equations (3.1) and (3.2) in Proposition 2.

■

Proof of Proposition 3.

Consider the case where $R_{12}(\cdot) > 0$. Suppose $\lambda(\theta) \geq \lambda^*(\theta)$. In the absence of information asymmetry, $\lambda^*(\theta)$ satisfies:

$$\lambda^*(\theta) = [1+\alpha]R_1(q_i^*, \theta_i) \leq \lambda(\theta) = [1+\alpha]R_1(q_i^L, \theta_i) - \alpha\, R_{12}(q_i^L, \theta_i)h_i(\theta_i); \tag{A3.1}$$

$$\lambda^*(\theta) = [1+\alpha]p^{LE}(A_u^*, \theta) + \alpha\, p_1^{LE}(A_u^*, \theta)\, A_u^* \leq \lambda(\theta) = [1+\alpha]p^{LE}(A_u^L, \theta) + \alpha\, p_1^{LE}(A_u^L, \theta)\, A_u^L, \tag{A3.2}$$

where "*" refers to levels in the setting with no information asymmetry. But (A3.1) implies

$$q_i^* > q_i^L \quad \forall\ i=1, \ldots N \text{ whenever } \theta_i \neq \bar{\theta}. \tag{A3.3}$$

Furthermore, (A3.2), together with $p_{11}^{LE}(\cdot) \leq 0$, implies

$$A_u^* \geq A_u^L \quad \forall\ i=1, \ldots N. \tag{A3.4}$$

Together (A3.3) and (A3.4) imply a violation of the resource constraint. Hence $\lambda(\theta) < \lambda^*(\theta)$. The proof for the case of $R_{12}(\cdot) < 0$ is similar, and so is omitted.

■

REFERENCES

Arnott, Richard and Joseph Stiglitz, "Moral Hazard and Non-Market Institutions: Dysfunctional Crowding Out or Peer Monitoring?", *American Economic Review*, 81(1), March 1991, 179-190.

Baron, David and Roger Myerson, "Regulating a Monopolist with Unknown Costs", *Econometrica*, 50(4), July 1982, 911-930.

Bay Area Economic Forum report, "Using Water Better: A Market-Based Approach to California's Water Crisis", September 1991.

Besanko, David, "On the Use of Revenue Requirements Under Imperfect Information", in Michael Crew (ed.), *Analyzing the Impact of Regulatory Change in Public Utilities*. Lexington, Mass.: Lexington Books, 1985.

Besanko, David, "Performance Versus Design Standards in the Regulation of Pollution", *Journal of Public Economics*, 34(1), October 1987, 19-44.

Besanko, David and David Sibley, "Compensation and Transfer Pricing in a Principal-Agent Model", *International Economic Review*, 32(1), February 1991, 55-68.

Bikhchandani, Sushil and Chi-fu Huang, "Auctions with Resale Markets: An Exploratory Model of Treasury Bill Markets," *Review of Financial Studies*, 2(3), July 1989, 311-59.

Bohi, Douglas and Dallas Burtraw, "Utility Investment Behavior and the Emissions Trading Market", Resources for the Future mimeo, 1990.

Bowes, Michael, Molly Macauley, and Karen Palmer, "Incentive Based Approaches to Regulating Toxic Substances", Resources for the Future mimeo, September 1991.

Burtraw, Dallas, "Compensating Losers When Cost-Effective Environmental Policies are Adopted", *Resources*, 104, Summer 1991, 1-4.

Dasgupta, Partha, Peter Hammond and Eric Maskin, "On Imperfect Information and Optimal Pollution Control", *Review of Economic Studies*, 47(5), October 1980, 857-860.

Gutfield, Ruth, "Possible Revision of Clean Air Rules Would Give Some Utilities More Time", *The Wall Street Journal*, October 11, 1991, p. A4.

Hahn, Robert, "Market Power and Transferable Property Rights", *Quarterly Journal of Economics*, 99(4), November 1984, 753-765.

Hahn, Robert, "Government Markets and the Theory of the N'th Best," American Enterprise mimeo, March 1993.

Hahn, Robert and Gordon Hester, "Where Did All The Markets Go?: An Analysis of EPA's Trading Program", *Yale Journal on Regulation*, 6(1), Winter 1989, 109-153.

Hahn, Robert and Roger Noll, "Barriers to Implementing Tradable Air Pollution Permits: Problems of Regulatory Interactions", *Yale Journal on Regulation*, 1(1), 1983, 63-91.

Hahn, Robert and Roger Noll, "Environmental Markets in the Year 2000", *Journal of Risk and Uncertainty*, 3(3), 1990, 347-363.

Harris, Milton and Artur Raviv, "Allocation Mechanisms and the Design of Auctions", *Econometrica*, 49(6), November 1981, 1477-1499.

Harris, Milton and Artur Raviv, "Differences of Opinion Make A Horse Race", Northwestern University mimeo, June 1992.

Kwerel, Evan, "To Tell the Truth: Imperfect Information and Optimal Pollution Control", *Review of Economic Studies*, 44(3), October 1977, 595-602.

Laffont, Jean-Jacques and Jean Tirole, "Using Cost Observation to Regulate Firms", *Journal of Political Economy*, 94(3), June 1986, 614-641.

Lewis, Tracy and David Sappington, "Regulating a Monopolist with Unknown Demand", *American Economic Review*, 78(5), December 1988, 986-998.

Lewis, Tracy and David Sappington, "Inflexible Rules in Incentive Problems", *American Economic Review*, 79(1), March 1989a, 69-84.

Lewis, Tracy and David Sappington, "Countervailing Incentives in Agency Problems", *Journal of Economic Theory*, 49(2), December 1989b, 294-313.

Lewis, Tracy and David Sappington, "Allocating Resource Rights Under Limited Information", unpublished mimeo at the University of Florida, June 1992.

Lewis, Tracy and David Sappington, "Ignorance in Agency Problems", *Journal of Economic Theory*, forthcoming in 1993a.

Lewis, Tracy and David Sappington, "Insurance, Adverse Selection, and Cream-Skimming", University of Florida mimeo, March 1993b.

Lewis, Tracy, Roger Ware and Robert Feenstra, "Eliminating Price Supports: A Political Economy Perspective", *Journal of Public Economics*, 40(2), November 1989, 159-185.

Ma, Ching-to, "Unique Implementation of Incentive Contracts with Many Agents", *Review of Economic Studies*, 55(4), October 1988, 555-572.

Maddison, David, "Imperfect Competition Need Not Undo the Benefits of a Permit System," *Oxford Energy Forum*, May 1993, 12-14.

Maskin, Eric and John Riley, "Input Versus Output Incentive Schemes", *Journal of Public Economics*, 28(1), October 1985, 1-23.

Montgomery, W. David, "Markets in Licenses and Efficient Pollution Control Programs", *Journal of Economic Theory*, 5, 1972, 395-418.

Mookherjee, Dilip and Stefan Reichelstein, "Implementation via Augmented Revelation Mechanisms", *Review of Economic Studies*, 57(3), July 1990, 453-476.

Myerson, Roger, "Incentive Compatibility and the Bargaining Problem", *Econometrica*, 47(1) January 1979, 61-74.

Myerson, Roger, "Optimal Auction Design", *Mathematics of Operations Research*, 6(1), February 1981, 58-73.

Palfrey, Thomas, "Multiple-Object, Discriminatory Auctions with Bidding Constraints: A Game-Theoretic Analysis", *Management Science*, 26(9), September 1980, 935-946.

Reinhart, Vincent, "An Analysis of Potential Treasury Auction Techniques", *Federal Reserve Board Bulletin*, June 1992, 403-413.

Roberts, Marc and Michael Spence, "Effluent Charges and Licenses Under Uncertainty", *Journal of Public Economics*, 5(3,4), April-May 1976, 193-208.

Rose, Kenneth and Robert Burns, "Overview and Discussion of the Key Regulatory Issues in Implementing the Electric Utility Provisions of the Clean Air Act Amendments of 1990", The National Regulatory Research Institute Interim Report #91-10, June 1991.

Satterthwaite, Mark and Steven Williams, "The Rate of Convergence to Efficiency in the Buyer's Bid Double Auction as the Market Becomes Large", *Review of Economic Studies*, 56(4), October 1989, 477-498.

Smith, Vernon, "Microeconomic Systems as an Experimental Science", *American Economic Review*, 72(5), December 1982, 923-955.

Teitenberg, Thomas, *Emissions Trading: An Exercise in Reforming Pollution Policy*. Washington, D.C.: Resources for the Future, 1985.

Tschirhart, John, "Transferable Discharge Permits and Profit-Maximizing Behavior", in Thomas Crocker (ed.), *Economic Perspectives on Acid Deposition Control*. Stoneham, Mass.: Butterworth Publishers, 1984.

Varian, Hal, "Monitoring Agents with Other Agents", *Journal of Institutional and Theoretical Economics*, 146(1), March 1990, 153-174.

Wall Street Journal, "CBOT Approves Contract on Utility Pollution Risk", July 17, 1991.

Wilson, Robert, "Auctions of Shares", *Quarterly Journal of Economics*, 94(4), November 1979, 675-689.