OXFORD INSTITUTE FOR ENERGY STUDIES

Lagged Regulation of Energy Industries

Anthony G. Heyes

Oxford Institute for Energy Studies

EV21

1995

LAGGED REGULATION OF ENERGY INDUSTRIES

Anthony G. Heyes

Abstract

In a variety of contexts regulatory agencies are legally obliged to use a cost-benefit rule (or some variant there of) to revise environmental standards to reflect improvements in pollution-control techniques, but have considerable discretion over the timing of such revision. How should the agency use this discretion? In a simple model of standard-setting under endogenous technical change we show that an agency can use implementation lags strategically to effect the supply of new 'clean' technologies. Longer lags tend to encourage more intense R&D effort by the regulated industry itself whilst discouraging parallel effort by external developers. Optimal implementation lags are characterized. The analysis calls into question the conventional view that 'foot-dragging' by agencies is necessarily evidence of incompetence and/or regulatory capture and will, in general, be an efficient strategic response by the executive agency to the need to manipulate dynamic incentives.

EV21
Oxford Institute for Energy Studies
1995

The contents of this paper
are the author's sole responsibility.
They do not necessarily represent the
views of the Oxford Institute for
Energy Studies or any of its Members

ISBN 0 948061 89 8

Anthony G. Heyes is a Research Fellow at the Oxford Institute for Energy Studies, and concurrently a Fellow of Nuffield College. He has an MA from the University of Cambridge and a Ph.D. from McGill University, Montreal. His research interests are in the regulation of the environmental impacts of energy production, transportation and usage.

CONTENTS

INTRODUCTION

In a number of environmental regulatory contexts legislation decrees that the executive agency must apply a cost-benefit (CB) or cost-efficiency criterion when setting and updating regulatory standards. The regulatory agency is obliged to set standards such as to equate marginal environmental benefits and marginal compliance costs.[2]

In the United Kingdom, the 1990 Environmental Protection Act dictated that regulatory standards should be set to be compatible with the use of the 'best available technology not entailing excessive cost' (BATNEEC), which followed the adoption of the same rule by the European Commission in its 1984 Air Quality Framework Directive. Though no statutory definition of 'excessive' was provided, and an adequate case law has yet to develop, Pearce and Brisson (1993) note that 'what little legal opinion there is on BATNEEC suggests that a cost-benefit interpretation (whereby tighter standards will be deemed appropriate if and only if the marginal benefit from tightening exceeds the marginal cost) is the most likely to be adopted'. [3]

In the US Toxic Substances Control Act 1976, to take a North American example, the Environmental Protection Agency (EPA) is instructed to seek to eliminate 'unreasonable risk', where a risk is deemed unreasonable if and only if the expected benefits from reducing it are greater than the marginal costs of so doing (see Shapiro (1990: 206-11)). Analogous provisions are included in the US Insecticide, Fungicide and Rodenticide Act of 1985. Proposals contained in the House Republican's 'Contract with America' envisage a cost-benefit basis for all regulatory decisionmaking in the environmental, health and safety fields and, if enacted, would constitute - 'the biggest regulatory reform in congressional memory' (*The Economist* (1995: 53)).[4]

In each case the executive agency is required by law to look at the range of compliance-technologies available and, by comparing the cost implications of tighter requirements with established measures of environmental benefit, formulate numerical pollution standards. Notice that the regulatory philosophy remains non-prescriptive in that the agency does not stipulate what technology the regulatee must use in order to satisfy the promulgated standards.[5]

That setting standards according to a CB-rule implies static optimality is true by construction. Many authors, however, have argued that so doing will depress the rate at which new pollution-control technologies are developed and so be dynamically inefficient (e.g., Downing and White (1986), Milliman and Prince (1989), Magat (1979)). Under a CB-regime technological advance, reducing as it does the marginal cost of compliance, induces a tightening of regulatory standards - a process for which Harrington and Krupnick (1981) coined the phrase 'regulatory ratchetting' - and part of the surplus generated by that advance is sequestered by the regulator in the form of improvements in environmental quality. This leaves (so the argument goes - though we will question it here) inadequate or even perverse incentives for private agents to expend effort and funds on R&D into pollution-control and other 'clean' technologies.

Whilst regulators may be bound by legislation to ratchet standards to their new CB-compatible level following the emergence of a new technology (or improvement of an existing one) they generally have significant discretion over the immediacy/timing of that ratchetting. Typically the agency will design the institutions and procedures by which technical advance is translated into new standards (e.g., the frequency and speed of regulatory reviews, the complexity and length of verification procedures, the length of technological assessment and demonstration periods, the rules and conventions adopted in compliance-scheduling) and, as such, will choose how promptly and/or quickly that translation occurs (see for examples, Mintz (1988)). Will the regulatory agency, operating subject to the type of legislative mandate outlined but with scope for putting 'inertia' into the implementation process want to do so? If so, how much? These are the questions addressed here in the context of a simple model in which technical change is endogenous and 'inertia' is modelled in a stylized way as a scalar 'implementation lag'. We show that the regulator can exploit his discretion over the timing of ratchetting to generate welfare improvements and in so doing call into question the conventional wisdom that 'foot-dragging', of which regulatory agencies are often criticized by environmentalists and others, is necessarily evidence of incompetence and/or regulatory capture.[6] Delays in regulatory ratchetting will, in general, be an efficient strategic response by the executive agency to the need to manipulate dynamic incentives. The analysis is argued to have significant implications for how we should think about the design of technological review and enforcement procedures by EPA' s.

The paper fits most naturally into the existing literature on the interface between environmental regulation and technical change. This includes Orr (1976), Magat (1979), Downing and White (1986), Milliman and Prince (1989), Carraro and Topa (1992) and Yao (1988), and is expertly surveyed by Moro (1993). Mendelsohn (1984) establishes, for example, that under certain types of uncertainty quantity-based regulation tends to encourage more efficient levels of R&D than does price-based regulation, whilst Laffont and Tirole (1994) show that a system of tradeable pollution permits - by offering a compliance 'technology' which competes with any engineered pollution-control device - reduces the incentive for environmental innovation below what is socially optimal. The more general literature on the incentives for R&D is, of course, voluminous (Reinganum (1989) provides an excellent survey).

The novelty of our approach is essentially twofold: (i) The regulatory choice variable: The EPA chooses the timing of implementation, rather than what is implemented (the latter being determined by legislative decree).[7] There is considerable anecdotal evidence that EPA's can and do exercise considerable discretion over the timing of implementation (see Mintz (1988), Yaeger (1991)). As Lester (1990) contends in this context: '(T)he legislature may well decide what is to be done, but it is the rules of the implementing agency which will govern when.' The critical role of such timing is emphasized in the models of Yao (1988), Malik (1991) and Cadot and Sinclair-Desagne (1994). (ii) The source of technical innovation: In our model there are two would-be innovators engaged in the R&D of pollution-control technologies - the polluting firm itself and an external entrepreneur - and the strategic interaction between these two players is modelled explicitly. Existing work has always assumed either that all R&D is done by the polluting industry (e.g., Downing and White (1986), Cadot and Sinclair-Desagne (1994), Yao (1988)) or (in a very small number of cases) that it is all done by specialist R&D firms outside of the polluting industry (e.g., Laffont and Tirole (1994)). Neither assumption is realistic and restricting the analysis in either way suppresses a rich source of strategic interdependence.[8] Under a regime of endogenous regulatory ratchetting a major spur to R&D by the polluting industry is the knowledge that outsiders are working to develop new pollution-control technologies which could provide those outsiders with a basis upon which to exact rents. At the same time a major disincentive to R&D by external developers is the knowledge that the polluting industry is engaged in parallel R&D which could render any output from its own work commercially redundant.[9] Furthermore, the prospect of regulatory-updating procedures being lagged in any way can be expected to have markedly different incentive implications for the two parties. This type of interdependence is ignored in existing analyses but is treated explicitly here.

2 MODEL

The most significant strategic aspects of what is a complex dynamic problem are distilled into a simple three-stage model involving a single polluting firm, an external engineering company (or 'entrepreneur') and an environmental regulator who is subject to a cost-benefit (CB) mandate but can commit to an implementation lag. A number of other interesting aspects of the problem do not feature in the model and some of these shortcomings are identified in Section 3.

Let s denote the regulatory standard. The marginal environmental benefit from each increase in s is b. (Think of s as being required reductions in the emission of some pollutant below some unregulated baseload and b as the (constant) marginal environmental damage caused by the pollutant in question). The cost to the regulated firm of complying with the standard is $C(s|t_i)$, where t_i denotes the technology employed. $C_s(s|t_i)$, the marginal cost of compliance, is everywhere positive and increasing in s (i.e., the marginal productivity of spending on environmental protection effort is everywhere positive but diminishing).

The timing of moves is as follows: (i) At stage one the regulator commits to an 'implementation lag', d, which represents the period that will be allowed to elapse after any advance in technological know-how before s is ratchetted to take account of that advance. (ii) At stage two (before production starts) the polluting firm and the external enterpreneur attempt to develop a better (in a sense to be defined) compliance technology. We will refer to the strategic interaction at this stage as the 'R&D game'. (iii) The outcome of the R&D game, in conjunction with the implementation lag to which the regulator has already committed, determines the profile of standards with which the polluting firm must comply during the production period (stage three) that follows.[10, 11]

The polluting firm has free access to some existing compliance technology t_L (L for 'low'). During the R&D game both the firm and the external entrepreneur try to develop a better technology (t_H - H for 'high') - the former in anticipation of being able to use it itself, the latter in the hope of being able to market it. t_H is associated with an everywhere lower marginal cost of compliance curve (i.e. $C_s(s|t_H)<C_s(s|t_L)$ for all $s>0$). Denoting the R&D efforts of the firm and the entrepreneur as r_1 and r_2, their respective probabilities of achieving t_H will be denoted $p(r_1)$ and $p(r_2)$ (where $p(0)=0$ and p approaches unity concavely from below as r_i is increased without limit). The CB-compatible standards with and without t_H being in existence will be denoted s_H and s_L respectively and are implicitly defined by $C_s(s|t_i)=b$ - the point of intersection between the marginal benefit line and the appropriate marginal cost curve in Figure [1]. If, at the end of the R&D game, the development efforts of the players have failed to turn up t_H then the regulatory standard s_L will prevail throughout the production period. If, on the other hand, t_H has been developed the regulator's mandate requires that the standard be ratchetted to s_H , but this will only occur at time d after the start of the production period where d is the implementation lag.

The set-up captures, in a stylized way, the key characteristics of the regulatory context we want to model: (i) The cost (marginal and total) of environmental protection depends upon the state of technological know-how. (ii) Technological advance occurs endogenously as a result of the R&D efforts of the polluting industry itself and/or specialist outside firms. (iii) A significant determinant of the pattern of incentives for R&D is how it is anticipated that the results of that R&D will affect the future profile of regulatory requirements. (iv) Legislative dictat routinely obliges the regulator to apply a CB-rule (or some variant there of), i.e. to update standards to maintain parity between the marginal cost and marginal benefit curves, but leaves him discretion over the speed/immediacy of that updating.

The steps we will follow in the rest of the paper are as follows: In this Section we characterize the equilibrium in the R&D game; we then establish that the equilibrium is always suboptimal and characterize that suboptimality. Next we show that the regulator can induce changes in the characteristics of that equilibrium by changing the length of the implementation lag. Finally we analyse when, and to what extent, he will wish to do so, bearing in mind the environmental costs of so doing. In Section 3 some of the implications of the analysis are discussed and possible extensions are outlined. We speculate upon the likely consequences of relaxing some of the main assumptions made in the course of setting up and developing the model.

Equilibrium in the R&D Game

The R&D game is a single-shot, simultaneous move game under perfect information. Exchange in the production period that follows is efficient in the sense that in equilibrium mutually beneficial trades are always exploited. This implies that if t_H is developed it will be adopted immediately since for any regulatory standard $C(s_i|t_L)>C(s_i|t_H)$ - total compliance costs are lower when it is used than when it is not - though the division of the gains from adoption will vary according to the identity of the developer(s). (The market for 'technological know-how', then, is assumed to 'clear': the identity of the developer(s) will impact upon the allocation of the producer surplus derived from the adoption of the new technology rather than affecting the adoption decision itself).

If neither party develops t_H then the firm's compliance costs will be C_{LL} - where we adopt the convention that $C_{ij}=C(s_i|t_j)$ - the cost of satisfying the low standard with the low technology throughout the production period. If the regulated firm has developed t_H it will install it immediately (i.e. at the start of the production period) but will not need to pay rental for its use. Before s is ratchetted upwards its compliance costs will be C_{LH} since it faces standards based on the old technology (i.e. t_L) but uses the new. This is area(032) on Figure [1]. After the ratchetting the firm's compliance costs, C_{HH}, equal the area(045). If, on the other hand, the entrepreneur is the sole successful developer of t_H it will still be installed at the start of the production period but the regulated firm will now have to pay an appropriate rental to the entrepreneur. For simplicity we will assume that the entrepreneur is able to act as a perfectly discriminating supplier which implies that before the ratchetting of standards he will be able to extract a rental equal to $(C_{LL}$-

C_{LH}) - or the area(012) - whilst after the ratchetting the rental will be $(C_{HL}-C_{HH})$ - the area(056).[12]

Since the external entrepreneur only gets a payoff from successful development of t_H if the polluting firm fails to come up with a substitute of its own there are, from his point of view, two sources of commercial risk involved in investing R&D funds in this way: (i) the 'scientific risk' that the research programme funded will fail to turn up the technological improvement (which occurs with probability $(1-p(r_2))$) and (ii) the 'redundancy risk' that the project will be successful (in the scientific sense) but that the new technology will turn out to have no commercial value because the polluting firm has developed a substitute technology which does the same job. The extent of this second type of risk depends, of course, upon the research decisions of the polluting firm and it is through this interdependence that the scope for strategic interaction arises as the polluting firm recognizes that it can influence the R&D activities of outside developers.

The firm chooses $r_1 \geq 0$ to minimize its expected loss function, $F(r_1, r_2, d)$, which is the sum of its R&D spending and expected compliance costs (to simplify notation we ignore discounting):

$$[1]\ F(r_1, r_2, d) = r_1 + p(r_1).[d.C_{LH} + (1-d).C_{HH}] + (1-p(r_1)).p(r_2).[d.C_{LL} + (1-d).C_{HL}] + (1-p(r_1)).(1-p(r_2)).C_{LL}$$

The first term in the firm's loss function is the cost of the R&D itself. The remaining terms reflect the firm's expected expenditure on regulatory compliance (including, where appropriate, payments to the external supplier) during the production phase: (i) With probability $p(r_1)$ the firm will develop t_H itself and so will face compliance costs C_{LH} before and C_{HH} after the ratchetting. (ii) With probability $p(r_2).(1-p(r_1))$ the firm does not develop t_H but the external entrepreneur does. In that case though s_H is installed immediately the firm must pay the appropriate rental to the external developer such that (a) before standards rise the firm pays compliance costs C_{LH} plus a transfer to the external developer equal to $(C_{LL}-C_{LH})$ for a total of C_{LL}; (b) after standards are ratchetted compliance costs are C_{HH} plus a transfer of $(C_{HL}-C_{HH})$ for a total of C_{HL}. (iii) With probability $(1-p(r_1)).(1-p(r_2))$ neither the firm nor the entrepreneur find t_H, standards are never ratchetted and the firm's compliance costs equal C_{LL} throughout the production period.

The first-order condition defining an interior solution to the firm's problem can be written:

$$[2]\ F_{r_1}(r_1^*, r_2, d) = p_r(r_1^*).\Psi + 1 = 0$$

where

$$\Psi = \left[(d.C_{LH} + (1-d).C_{HH}) - p(r_2).(d.C_{LL} + (1-d).C_{HL}) - (1-p(r_2)).C_{LL}\right]$$

(Note that Ψ will be negative in the neighbourhood of an interior minimum, and that the associated second-order condition will necessarily be satisfied). The firm increases its R&D expenditures up to the point at which the marginal cost of R&D equals the expected incremental reduction in compliance costs which it induces. Equation [2] implicitly defines r_1^* - the firm's privately optimal level of R&D expenditure - as a function of r_2 and d, and it is shown in Appendix [1] that the firm's reaction function is upward sloping in $\{r_1, r_2\}$-space. An increase in r_2 makes it more likely that, should it fail to find t_H itself, the firm will find itself facing s_H and ransom to the external developer in the production period rather than just continuing to meet the low standards with the existing technology (t_L), and so induces an increase in its efforts to develop t_H in-house.

The external entrepreneur's problem is to maximize $R(r_2,r_1,d)$ his expected revenues net of development outlays (again, for simplicity we abstract from discounting):

$$[3]\ R(r_2, r_1, d) = p(r_2).(1-p(r_1)).[d.(C_{LL} - C_{LH}) + (1-d).(C_{HL} - C_{HH})] - r_2$$

The only case in which the entrepreneur makes a return in the production period is when he has developed t_H but the regulated firm has not (i.e. with probability $p(r_2).(1-p(r_1))$). In that case he receives the rental payments outlined (we will return to the issue of imperfectly appropriable rents later). The associated first-order condition is:

$$[4]\ R_{r_2}(r_2^*, r_1, d) = p_r(r_2^*).(1 - p(r_1)).\mathbf{Z} - 1 = 0$$

where

$$\mathrm{Z} = d.(C_{LL} - C_{LH}) + (1 - d).(C_{HL} - C_{HH})$$

The entrepreneur's reaction function, implicitly defined by Equation [4] is downward-sloping in $\{r_1, r_2\}$-space (see Appendix [2]). An increase in r_1 increases the risk of redundancy (by making it more likely that the polluter will have developed a substitute technology of his own) and so makes spending on r_2 less attractive at the margin.

The Nash-equilibrium in the innovation game is defined by the intersection of the respective reaction functions, as shown in Figure [3], and will be denoted $\{r_1^*(d), r_2^*(d)\}$ with the respective equilibrium R&D levels expressed as functions of the regulatory instrument d.

Welfare Characteristics of Equilibrium in R&D Game

The expected social welfare gain from innovative activity (versus a benchmark in which $r_1 = r_2 = 0$), which we will call $SW(d, r_1, r_2)$, is simply the change in expected aggregate producer surplus plus expected environmental benefits and can be represented as follows:

$$[5]\ SW(d,r_1,r_2) = \Gamma(r_1,r_2).G(d) - r_1 - r_2$$

where

$$\Gamma(r_1, r_2) = [1 - (1 - p(r_1)).(1 - p(r_2))]$$

and

$$G(d) = d.(C_{LL} - C_{LH}) + (1 - d).[b.(s_H - s_H) - (C_{HH} - C_{LL})]$$

Thus $\Gamma(r_1^*(d), r_2^*(d))$, for example, is the probability that *in equilibrium* t_H is found by at least one of the players, whilst *G(d)* is the social benefit (producer surplus plus environmental benefits) from its being found. Social welfare can be seen to depend upon *d* both directly as well as through the induced R&D intensities of the two players. Armed with a welfare function it is now possible to make a normative assessment of the Nash equilibrium in the R&D game:

Proposition [1]: In any equilibrium the external entrepreneur engages in less R&D than is socially optimal. The regulated firm engages in more (less) R&D than is socially optimal when r_2 is sufficiently large (small).
Proof: See Appendix [3].

This is an interesting result, both parts of which can be understood intuitively: (i) Both the social planner and the entrepreneur only value the latter's R&D success in the event that the polluting industry's R&D programme is unsuccessful. In that case, however, whilst the entrepreneur derives a surplus equal to the change in aggregate producer surplus (all of which, by assumption, he is able to appropriate) the planner derives a benefit equal to that change *plus* the environmental benefits generated by the pursuant ratchetting of standards. Given diminishing returns to R&D effort this implies that the entrepreneur underspends *vis-a-vis* what would be socially optimal. Notice that if appropriability were imperfect (i.e., the entrepreneur anticipated being able to extract only some fraction of the producer surplus in the event of finding himself sole developer) this divergence would be even greater. (ii) A similar sort of argument can be sketched in the case of r_l. The ambiguity noted in the proposition arises because the social planner is less likely to value success of the polluting firm's R&D programme (valuing it only when the external entrepreneur is unsuccessful) but when he does he values it more highly (valuing, as before, not just the producer benefits but also the pursuant environmental benefits).

It cannot be determined in general whether total R&D spending, and therefore the expected rate of emergence of new pollution-control technologies, will be above or below what is socially optimal. This contradicts the conventional wisdom that in the absence of additional government intervention private agents will necessarily do too little 'green' R&D, adherence to which underlies the common view that such projects are necessarily worthy of encouragment by means of public subsidy, tax write-offs or other means. This conventional wisdom is based on the implicit assumption made in existing analyses that the only source of technical change is the polluting firm itself.

A lot of the qualitative ambiguity in the model arises from the fact that C_{HL} - the cost of complying with the ratchetted standard without the benefit of the new technology (upon the basis of whose existence the standard has been ratchetted) - is a significant deteminant of the expected private returns to R&D, but does not feature at all in the welfare function. Whilst it impacts significantly upon the *allocation* of post-innovation producer surplus within the private sector it has no (direct) effect whatever on the *size* of that surplus which, together with environmental amenity, is what concerns the social planner. In this way the area(1256) on Figure [2] - and hence the shape of the marginal compliance curve even outside of the range on which the firm will ever operate - matters. To remove the ambiguity in Proposition [1] would require that additional restriction be placed on the form of the cost functions.

The Incentive Impact of Lagged Ratchetting

It was established in the last section that developers outside of the polluting industry will always tend to underinvest in the R&D of new pollution-control technologies, whilst the polluting firm itself may over- or under-invest depending upon the parameters of the model. In what ways can the regulator exploit his discretion over *d* to influence these R&D levels? Firstly we characterize the partial derivatives of interest:

Proposition [2]: An increase in the length of the implementation lag induces, *ceteris paribus*, a decrease in the R&D expenditure of the external entrepreneur. It induces an increase in the R&D expenditure of the polluting firm when and only when that of the external entrepreneur is sufficiently small.

Proof: Appendix [4]

Consider Figure [4]: an increase in *d* induces a leftward shift in the reaction function of the entrepreneur and a twisting (flattening) in that of the regulated firm.

For the purposes of further analysis we will assume, as is illustrated here, that the equilibrium in the R&D game is coincident with some point on the regulated firm's reaction function to the *left* of the 'fulcrum'.[13] The Nash equilibrium moves from 0 to 1 as a result of a hypothetical increase in *d*. The following can now be said about the implications of a marginal change in *d* for the characteristics of the equilibrium:

Proposition [3]: In equilibrium a lengthening of the regulatory lag will induce a decrease in the R&D efforts of the external entrepreneur but will have an ambiguous impact upon the parallel efforts of the regulated firm.

Proof: Appendix [4].

The ambiguity of the impact on r_1 results from the fact that the direct and strategic implications of the change in d on it work in opposite directions. The equilibrium impact can be broken down in the usual way:

$$\frac{dr_1^*}{dd} = \frac{\delta r_1^*}{\delta d} + \frac{\delta r_1^*}{\delta r_2}.\frac{\delta r_2}{\delta d}$$

The first term on the left-hand side is the direct impact and is positive: for any given level of r_2 an increase in d makes in-house R&D relatively more attractive by leaving a longer interval before the regulator 'claws back' some of the pursuant surplus from technological improvement in the form of more stringent environmental requirements. The second, composite term reflects the strategic effect and is negative: an increase in d reduces the intensity with which the external entrepreneur pursues the new technology and so encourages, *ceteris paribus*, a decrease in R&D by the regulated firm itself. In the case of r_2 the direct and strategic impacts work in the same direction: not only does the longer lag make holding sole ownership less valuable by reducing the portion of the production period over which the higher post-ratchet rental can be extracted, but by inducing an increase in the R&D efforts of the polluting firm makes it more likely that scientific success by the external entrepreneur will be commercially redundant in any case.

The Optimal Implementation Lag: A Positive Theory of Regulatory Foot-dragging

By manipulating d, then, the regulatory agency is able to influence not just how much R&D is done in total, but who does it (i.e. the extent to which it is 'in-house' research by the polluting industry versus external research by engineering companies outside). The regulatory problem is to choose $d \geq 0$ to maximize the expected social welfare function specified above ($\tilde{d}$ will be used to denote this solution value).

A natural first question is 'when will the optimal implementation lag be non-zero?' (i.e. when will the regulator wish to drag his feet at all?) Given convexity of social welfare in d a necessary and sufficient condition for $\tilde{d} > 0$ is that the following be satisfied:

$$[6]\quad G_d(0).\Gamma(r_1^*(0),r_2^*(0)) + \sum_{i=1,2}\left\{\left[\Gamma_{r_i}(r_1^*(0),r_2^*(0)).G(0) - 1\right].\frac{dr_i^*(0)}{dd}\right\} > 0$$

The expression on the left-hand side here is the total derivative of social welfare (as defined in Equation [5]) with respect to changes in d, evaluated in the vicinity of $d=0$. The interpretation to be given to the various components of the expression will be outlined shortly. If this condition is satisfied then $\tilde{d}$, the optimal regulatory lag, will be implicitly defined by the first-order condition associated with the regulator's problem:

$$[7]\quad G_d(\tilde{d}).\Gamma(r_1^*(\tilde{d}),r_2^*(\tilde{d})) + \sum_{i=1,2}\left\{\left[\Gamma_{r_i}(r_1^*(\tilde{d}),r_2^*(\tilde{d})).G(\tilde{d}) - 1\right].\frac{dr_i^*(\tilde{d})}{dd}\right\} = 0$$

Lengthening the implementation lag impacts upon social welfare in two distinct of ways. First, it leads to a negative *static efficiency effect* (which is captured by first term in Equation [7] and is strictly negative). For any given probability of development of the advanced technology (i.e. for given values of r_1 and r_2) immediate updating is optimal and delaying such updating imposes an expected loss in static welfare. Manipulating d, however, also allows the regulator to influence the R&D decisions of the two players and hence affect the probability of technological advance. Second, then, changes in d generate a *dynamic efficiency effect* by inducing changes in equilibrium patterns of R&D spending. $(\Gamma_{r_i}.G - 1)$ is the social marginal value of increases in research expenditure by player i, whilst (dr_i^*/dd) is the change in the equilibrium level of that expenditure generated by a marginal lengthening of the implementation lag. Summing the former, weighted by the latter, across all players gives the marginal social dynamic return derived from increases in d.

Optimality requires that the regulator lengthen the lag up until that point at which the marginal social dynamic return from so doing equals the marginal social static cost. This point, $\tilde{d}$, is implicitly defined by Equation [7]. The static deadweight loss from postponement of ratchetting, G_d, equals the difference between the foregone flow of environmental amenity (the rectangular area(1345)) and the saving in (net) compliance costs (the area(2345)) - i.e., the three-sided area(125). The shape (as well as the position) of the marginal compliance cost curve affects, then, the static loss term. Since the static efficiency effect of any increase in d is always welfare-reducing, a necessary but not sufficient condition for a longer lag to be desirable is that the dynamic efficiency effect is positive.

It should be noted that $(\Gamma_{r_i}.G - 1)$ being positive implies that r_i is below its socially optimal level. This is necessarily the case for $i=2$, and given that (dr_2^*/dd) is negative (at least given the assumptions made) this implies that the dynamic impact of any increase in d through r_2 is necessarily welfare-reducing. As such this reinforces the static effect and allows us to conclude that any increase in d that is welfare-improving will be so *despite* its implications for the R&D behaviour of engineering firms outside the polluting industry, rather than *because* of them.

The potentially welfare-improving component of the dynamic effect comes through induced changes in the equilibrium R&D activities of the polluting firm itself. The sign of

$(\Gamma_{r_1}.G - 1)$ is ambiguous - r_1^* may be above or below its socially optimal level - but the sign of *(dr_1^*/dd)* is also ambiguous (and may or may not be coincident). It is clear that a necessary but not sufficient condition for a lengthening of the implementation lag to be (overall) welfare-enhancing is that these two be of coincident sign such that the longer lag is pushing r_1 'in the right direction' (i.e. towards its socially optimal level). The most usual story would, of course, be that both $(\Gamma_{r_1}.G - 1)$ and *(dr_1^*/dd)* are positive - the polluting firm is initially doing less R&D than is socially optimal because the regulatory ratchetting sequesters part of the surplus generated by innovation in the form of higher environmental standards, and leaving a longer lag between innovation and ratchetting reduces the extent of this sequestering and so encourages it to do more - and this probably remains the most likely scenario here. Modelling the strategic aspects of the R&D decisions of the players yields, however, the interesting possibility that a longer lag could be welfare-enhancing for precisely the opposite set of reasons. $(\Gamma_{r_1}.G - 1)$ and *(dr_1^*/dd)* could both be negative implying that the polluting firm does *more* R&D than is socially optimal (to reduce the risk of having to pay large rents to the external) and that longer lags (by reducing the propensity of the external to do R&D) could induce a *reduction* in it.

DISCUSSION, EXTENSION AND CONCLUSIONS

In a variety of contexts EPA' s are required to apply cost-benefit/cost-efficiency criteria in determining regulatory standards. They often appear, however, to be 'sluggish' in ratchetting standards in response to the emergence of technological advance and are accused, by environmental groups and others, either of incompetence or of having been 'captured' by the polluting industry that they were supposed to be policing (Kalt and Zupan (1984), Heyes (1995), Yaeger (1991)).

The analysis presented suggests that an efficiency interpretation can be given to 'inertia' in the implementation process. Though the 'inertia' could come in a number of guises, for the purposes of the analytics we have proxied it by a simple scalar implementation lag. Implementation lags here play a role somewhat analogous to that played by a 'patent' in the conventional R&D literature, and in a number of ways our derivation of the optimal implementation lag parallels existing approaches to the derivation of optimal patent length. Given the emergence of a new production technology static optimality requires that everyone be given immediate access to its use (or, in the case of a new product, everyone have the immediate right to compete in its production and distribution). In general, however, patents, giving legal (if temporary) monopoly rights of exploitation, are conferred upon the innovator. This gives the innovator a chance to extract monopolistic rents from his work and is granted because it is recognised that otherwise there would be insufficient incentive for firms to expend effort developing new processes and products in the first place. The longer the patent the greater the dynamic incentives but the greater the associated loss in static welfare and the aim of existing models of optimal patent length is to assess the point at which the two effects are equated at the margin. In the context of pollution-control technologies the ability of an agent to extract surplus from the successful development of a new (or his improvement of an existing) one also depends critically upon the way in which regulatory requirements are updated through time. In setting the implementation lag the regulator must trade off the marginal loss in static efficiency with any dynamic efficiency improvement.

The model here is complicated further by the fact that there are two would-be developers - the polluting firm itself and a specialist firm outside the industry - whose objective functions are quite different. From the point of view of an external developer the rental that can be extracted is greater after standards have been ratchetted than it is before, such that his efforts are encouraged by the prospect of prompter ratchetting. To the regulated firm, on the other hand, upon whom the costs of compliance themselves are incident, rapid updating is a disincentive to R&D effort.

The other obvious analogy is with the emerging literature on the optimal length of regulatory lags (frequency of regulatory reviews) in the context of price cap regulation. More frequent recalibration of the price cap allows the regulator to extract more of the surplus generated by cost-reducing innovations by the regulated firm, but reduces tthe incentive for the firm to pusue such innovations (see Armstrong et al (1994) for an excellent theoretical treatment). Again, however, it is generally assumed in these models that the only potential source of technical advance is the regulated industry itself and, as such, strategic interaction analogous to the type modelled here is assumed away (see Armstrong et al (1994) or Clemenz (1991) for examples).

Though the model captures the essentials of the problem it necessarily constitutes a highly stylized and simplified picture of the real world. There are a number of ways in which it could usefully be extended:

[1] Market Structure Effects: It would be interesting to characterize the implications for optimal regulatory practice of varying market structure within the polluting industry and/or outside. As the polluting industry became fragmented the R&D efforts of any individual firm in it would come to be motivated both by internal compliance cost considerations and by the prospect of extracting rental payments by supplying know-how to other firms in the industry. (See

Dosi (1988), Tirole (1991) and the citations there in for an overview of the literature on relationship between market structure and R&D).

[2] Imperfect Appropriability: The assumption that in the event that the external entrepreneur was the sole successful developer of the advanced compliance-technology he would be able to act as a perfectly discriminating monopoly supplier of his know-how, could be relaxed. It is more realistic that, for a variety of reasons, he would only be able to appropriate some fraction of that increase in aggregate producer surplus that his innovation generated such that, other things being equal, his incentive to engage in R&D will be blunted. Understanding and modelling the market for pollution-control hardware and know-how adequately is a vital prerequisite for improving the specification of the R&D game further. (See Levin (1986), Mansfield et al (1981) for a general review of the issues determining the appropriability of rents from innovation, Kemp et al (1992) for specific application to pollution-control technologies).

[3] Qualitatively Distinct R&D Projects: The players have been assumed to be engaged in exactly parallel R&D (i.e., resulting (if successful) in the development of exactly substitutable technologies). In reality R&D output can vary qualitatively and the agents could reasonably be expected to select R&D projects strategically. The external entrepreneur would, for example, be likely to seek to develop a device that could be cost-efficiently used *in addition to* any device - to favour building compatibility (both with existing technologies and technologies that might emerge later) into compliance technologies - such as to reduce the risk of commercial redundancy. The polluting firm might attempt to parallel the direction of any external R&D projects in order to make such external R&D less attractive. Manipulating implementation lags could be expected to effect not just how much R&D is done but its qualitative characteristics. (See Baumgardner (1991) for some discussion of the interface between regulation and the qualitative characteristics of corporate research portfolios in the context of the pharmaceuticals industry).

[4] Differences in Technical Ability: Adopting a common R&D production function for the two agents in the model simplified notation but had no significant impact on our analysis. It could be expected that the research productivities of the different developers could differ and this could be incorporated in the model. It is not clear, in general, where R&D would be more productive since (i) the external engineering company might be expected to have specialist expertise and experience in managing R&D - which will not (except in very unusual cases) be the polluter's core activity - but at the same time (ii) the polluting company may have 'inside' information about the polluting process and/or the specifications of the polluting plant making 'seeing' a likely solution easier (see Georg et al (1992) for some case study consideration of this ambiguity in the pollution-control technology context). This may, in reality, tie in to number [3] as the different parties may be good at different types of development (see Georg et al (1992: 548) and Nolte (1982)). In particular there is evidence that external entrepreneurs are generally better at the design of engineering-intensive, 'pipe-end' devices, the polluting firm at the design of more radical changes in production techniques (towards what is sometimes called 'inherent' or 'embodied' cleanliness) and better 'housekeeping' techniques (the organizational aspects of optimizing existing plant from an environmental perspective).

[5] Discriminatory Lags: We have assumed that the same implementation lag follows the development of a new technology regardless of the identity of the innovator. The model could straightforwardly be extended by allowing the regulator to set discriminatory lags. The trade-offs involved will remain the same, though the analysis will be significantly complicated. The motivation for having only a single lag here was our view that the most likely mechanism by which implementation lags would be established and committed to by the regulatory agency would be through institutional/procedural design, and in that case it is likely that there would be legal and other barriers constraining discrimination by source.

[6] More Sophisticated Strategic Action by Private Sector: There may, for example, be scope for collusion between the two players in setting their respective R&D levels. Another interesting possibility is that the regulated firm might have an incentive to misreveal *ex post* - to claim failure of its own research programme in the event that its own R&D programme was scientifically successful, but its external competitor's was not. It is also plausible to suppose that the private agents might have private information regarding the cost conditions (either the functional form $p(r)$ and/or $c(s|t)$) in the industry such that any comprehensive treatment of the regulatory problem would require these asymmetries of information be incorporated properly into the model.

Overall the issues raised are, we believe, interesting and important ones. The scope for the development of clean technologies in many industrial contexts is great and a key consideration in the assessment of any regulatory regime is likely to be the dynamic incentives that it generates since it is the R&D of today which provides the basis for higher environmental standards tomorrow. How EPA' s can exploit such discretion as their political masters grant them to best manipulate incentives for the development of new pollution-control technologies, or inherently 'greener' production technologies is an important thing to study. Refinement of the model here remains for future work.

ENDNOTES

1 I am grateful to Robert Cairns, Ngo van Long, Dennis Snower, David Begg, David Blake, Sandeep Kapur and seminar participants at Birkbeck and Royal Holloway Colleges, University of London for constructive comments on earlier drafts. Errors and omissions are mine alone.

2 Because it is the state of technology which determines the stringency of the regulatory standard this approach to standard-setting is often referred to as being 'technology-based' (see, for example, Harrington and Krupnick (1981: 540))

3 Bigham (1992) supports this view. In some cases marginal benefit will be given a greater than unit weight to reflect a presumption in favour of environmental- over producer-surplus at the margin (Pearce and Brisson (1993)).

4 In an international context the International Commission on Radiological Protection stipulates that national standards for radiological pollution should be such as to be 'as low as reasonably achievable' (ALARA), where what is reasonable is determined by cost-benefit considerations (- as one industry-expert puts it the ALARA requirement '... resolves the issue of how safe is safe enough by saying that a practice is being performed at a level of risk which is sufficiently low if and only if the benefit from further reduction in that risk is outweighed by the incremental cost' (Webb (1986: 3)). The ALARA/BATNEEC criterion has also been adopted by the 1987 International Conference on the Protection of the North Sea in the context of the control of marine pollution, and is used by the Convention on the Long Range Transport of Air Pollution for the determination of target loads in the context of acid rain regulation (see Pearce and Brisson (1993), ApSimon and Warren (1992)).

5 Georg et al (1992), for example, spell this out in the case of the Danish Environmental Protection Act, 1986: '(F)irms are not required to use specific technologies but rather to comply with tightening standards. Clean technology innovations contribute to the ongoing reassesment of just what constitutes reasonable increases in regulatory demands' Georg *et al* (1992: 547). In

the USA '. . . the Federal Water Pollution Control Act Amendments (1972) required the EPA to establish effluent limitations specifying, for each industrial category, the pollution abatement achievable by the best available technology economically achievable. Industrial dischargers were required to meet the standards . . . but were not required to adopt the technologies suggested by EPA guidelines' (Harrington and Krupnick (1981: 540)).

6 In many cases, in fact, this sloth is institutionalized - embodied in the procedures and norms of agency practice - and it is these institutional manifestations which come under fire. Notice that the term 'foot-dragging' may mean different things to different people. We use it specifically to refer to the unwillingness of EPA's to immediately incorporate new technologies into regulatory requirements.

7 Cadot and Sinclair-Desagne (1994) also assume that the regulatory action to be taken is exogenously determined. They differ in assuming that whilst the EPA cannot commit to the timing of implementation in a deterministic sense it is able to commit to a mixed strategy describing the probability of transition from the unregulated to the regulated state in any given period. The usual criticism of mixed strategies applies here.

8 'Very little attention has been given to the fact that other firms - not just the polluters - may have an incentive to innovate in pollution control. Existing analysis neglects other important sources of innovation. This is not to say that polluting firms are not innovative, but merely to stress the fact that they are not the sole innovators' Georg et al (1992: 534). Harrington and Krupnick (1981) make the same point.

9 Kemp *et al* (1992) provide interesting case study evidence of the significance of these strategic considerations in a variety of contexts (including, for example, the development of 'membrane technology' for cleaning the effluent of the metal-plating plants).

10 For ease of notation the production period is normalized to be of unit length.

11 There are two reasons why letting the regulator move first and with commitment makes sense

here: (i) In most contexts the primary channel by which the regulator exercises discretion over the speed of implementation is through the design of institutions and procedures. It is not a case of deciding on a case-by-case basis how long a lag to leave, but rather an issue of electing how much inertia to build into the apparatus of regulatory implementation (such that *d* can be seen as embodied). The frequency and speed of regulatory reviews, the complexity and length of verification procedures, the length of technological assessment and demonstration periods, the rules and conventions adopted in compliance-scheduling and so on, are all examples of things which can sensibly be categorized as institutional- or procedural-design variables, discretion over which is typically delegated to the executive agency. (ii) The game here can be seen as a single stage-game in a repeated regulatory relationship. Under repetition commitment by the regulator to non-zero implementation lags is likely to be feasible through the development of reputation. (For a good textbook treatment of the theory of reputation in repeated games see Tirole (1989)).

12 The assumption of perfect appropriability is, of course, a strong one and is intended as an abstraction rather than to be realistic. Levin (1986), Kemp *et al* (1992) outline the principle market and other considerations which will determine the division of rents from innovative activity.

13 This can be shown to amount to a restriction that $(C_{HL}-C_{HH})$ - the rental that the external supplier can extract after ratchetting - be not too great.

Appendix [1]: Implicit differentiation of Equation [2] implies that

[A.1.1] $$\left[\frac{\delta r_1^*}{\delta r_2}\right] = -\left[\frac{1}{F_{r_1 r_1}(r_1^*, r_2, d)}\right].\left[-p_r(r_1).p_r(r_2).(1-d).(C_{HL}-C_{LL})\right]$$

which can be seen to be positive (note that $F_{r_1 r_1}(r_1^*, r_2, d)$ is positive by the associated second-order condition and that $C_{HL}>C_{LL}$).

Appendix [2]: Implicit differentiation of Equation [4] implies that

[A.2.1] $$\left[\frac{\delta r_2^*}{\delta r_1}\right] = -\left[\frac{1}{R_{r_2 r_2}(r_2^*, r_1, d)}\right].\left\{-p_r(r_2).p_r(r_1).\left[d\,(C_{LL}-C_{LH}) + (1-d).(C_{HL}-C_{HH})\right]\right\}$$

which can be seen to be negative (note that $R_{r_2 r_2}(r_2^*, r_1, d)$ is negative by the associated second-order condition and that $C_{LL}>C_{LH}$, $C_{HL}>C_{HH}$).

Appendix [3]: For any particular value of r_1, r_2^* (the privately optimal level of r_2) and r_2^{SO} (the socially optimal level) are implicitly defined, respectively, by Equation [4] in the text and

[A.3.1] $$p_r(r_2^{SO}).(1-p(r_1)).\Upsilon - 1 = 0$$

where $\Upsilon = d.(C_{LL}-C_{LH}) + (1-d).(C_{LL}-C_{HH}+b.(s_H-s_L))$.

It can be seen from Figure [1] that $b.(s_H-s_L) > C_{HL}-C_{LL}$ ($b.(s_H-s_L)$ is the area(1345) whilst $(C_{HL}-C_{LL})$ is the area(1346) which is strictly bigger). This means that Υ is greater than Z. Since $p(r)$ is concavely increasing in r this implies that, for given r_1, $r_2^{SO} > r_2^*$.

For given r_2, r_1^* (the privately optimal level of r_1) and r_1^{SO} (the socially optimal level) are implicitly defined by (respectively) Equation [2] in the text and

[A.3.2] $p_r(r_1^{SO}).(1 - p(r_2)).\Phi - 1 = 0$

where $\Phi = d.(C_{LL} - C_{LH}) - (1 - d).(C_{HH} - C_{LL} - b.(s_H - s_L))$. Since $p(r)$ is concavely increasing in its argument, for any given value of r_2, $r_1^{SO} > r_1^*$ if and only if

[A.3.3] $(1 - p(r_2)).\Phi > - \Psi$

or, more explicitly, if and only if

[A.3.4] $\frac{(1 - p(r_2))}{p(r_2)}.(1 - d).b.(s_H - s_L) >$

$$(1 - d).(C_{HL} - C_{LL}) + (C_{HL} - C_{HH}) + d.(C_{HH} - C_{LH})$$

The condition is satisfied when $p(r_2)=0$, but violated when $p(r_2)=1$. Given that the right-hand side is invariant to r_2, the left-hand side continuous and monotonically decreasing in it, we can conclude that $r_1^{SO} > r_1^*$ when and only when r_2 is sufficiently small (near to zero).

Appendix [4]: Equation [2] in the text implicitly defines r_1^*. Further differentiation of it yields the following (all evaluated in the vicinity of equilibrium):

[A.4.1] $F_{r_1 r_1} = p_{rr}(r_1).\Psi > 0$

[A.4.2] $F_{r_1r_2} = p_r(r_1).p_r(r_2).(1 - d).(C_{LL} - C_{HL}) < 0$

[A.4.3] $F_{r_1d} = p_r(r_1).\left[(C_{LH} - C_{HH}) - p(r_2).(C_{LL} - C_{HL})\right] > or < 0$

The sign of the expression in [A.4.3] is ambiguous. It can be seen from Figure [2] that $(C_{LL}-C_{HL})<(C_{LH}-C_{HH})<0$ ($(C_{LL}-C_{HL})$ is minus the area(1346), $(C_{LH}-C_{HH})$ is minus the area(2345)). Thus F_{r_1d} will be positive (negative) when and only when r_2 is sufficiently large (small).

Equation [4] in the text implicitly defines r_2^*. Further differentiation of it yields the following (all, again, evaluated in the vicinity of equilibrium):

[A.4.4] $R_{r_2r_2} = (1 - p(r_1)).p_{rr}(r_2).Z < 0$

[A.4.5] $R_{r_2r_1} = - p_r(r_1).p_r(r_2).Z < 0$

[A.4.6] $R_{r_2d} = (1 - p(r_1)).p_r(r_2).\left[(C_{LL} - C_{HL}) - (C_{LH} - C_{HH})\right] < 0$

Proposition [2] concerns the partial derivatives of r_1 and r_2 with respect to marginal changes in d. Application of the implicit function theorem implies: $(\delta r_1^*/\delta d) = - (F_{r_1d}/F_{r_1r_1})$ and $(\delta r_2^*/\delta d) = - (R_{r_2d}/R_{r_2r_2})$. The latter is unambiguously negative. The sign of the former is the opposite of the sign of F_{r_1d} and hence is positive (negative) when and only when r_2 is sufficiently small (large).

Proposition [3] is about the equilibrium impact of a marginal increase in d. Application of

Cramer's rule to the system of Equations [2] and [4] yields the following:

$$[A.4.7] \quad \frac{dr_1^*}{dd} = \frac{1}{|\Delta|}.\left\{- F_{r_1 d}.R_{r_2 r_2} + R_{r_2 d}.F_{r_1 r_2}\right\}$$

$$[A.4.8] \quad \frac{dr_2^*}{dd} = \frac{1}{|\Delta|}.\left\{- F_{r_1 r_1}.R_{r_2 d} + R_{r_2 r_1}.F_{r_1 d}\right\}$$

where $|\Delta| = F_{r_1 r_1}.R_{r_2 r_2} - F_{r_1 r_2}.R_{r_2 r_1} < 0$. Given the assumption made in the text (that equilibrium is to the left of the 'fulcrum' in Figure [3] - i.e. that $F_{r_1 d}$ is negative in the vicinity of equilibrium) the expression in [A.4.8] is unambiguously negative, whilst that in [A.4.7] is of ambiguous sign (the source of this ambiguity is outlined in the text).

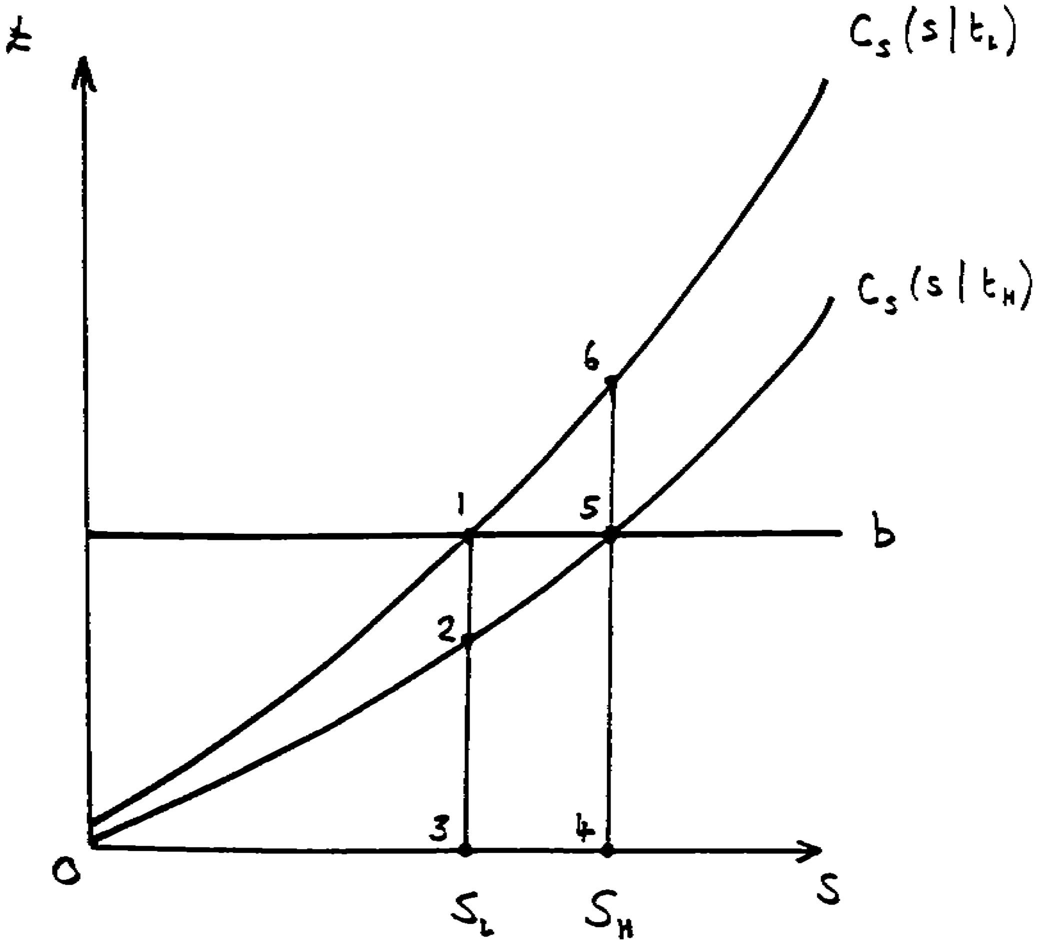

Figure [1]: Determination of cost-benefit compatible standards

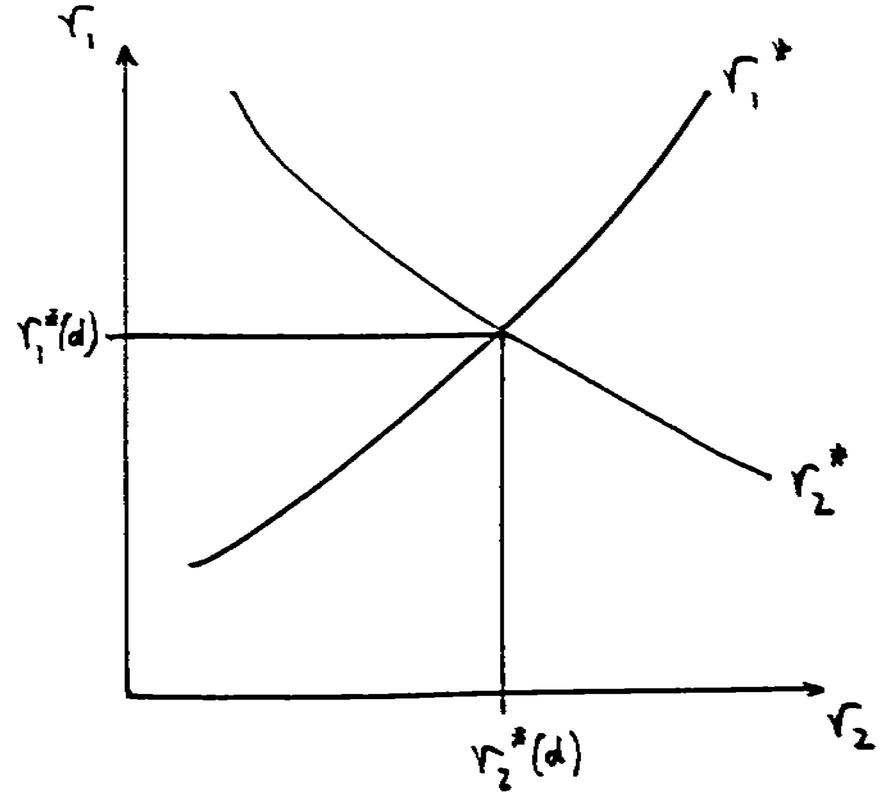

Figure [2]: The reaction functions and Nash equilibrium in R&D game

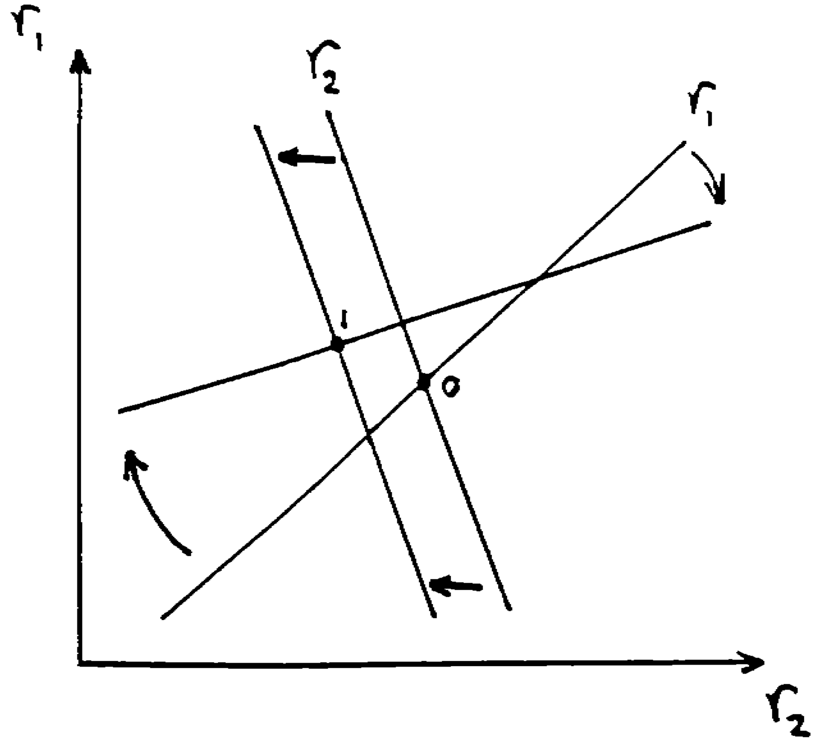

Figure [3]: Impact of increase in *d* on equilibrium in the R&D game

Bibliography

ApSimon, H. M. and R. F. Warren (1992), 'Using Critical Loads to Determine Relative Prices in an Emissions Trading Scheme', report prepared for UNECE, Imperial College, London.

Armstrong, M., S. Cowan and J. Vickers (1994), *Regulatory Reform: Economic Analysis and the British Experience*, MIT Press, Cambridge MA.

Armstrong, M., R. Rees and J. S. Vickers (1991), 'Optimal Regulatory Lag Under Price Cap Regulation', mimeo, Institute of Economics and Statistics, Oxford.

Baumgardner, J. R. (1991), 'The Interaction Between Forms of Insurance Contract and Types of Technical Change in Medical Care', *Rand Journal of Economics* (22), 36-53.

Bigham, A. (1992), '"Excessive" in BATNEEC', *Integrated Environmental Management* 7: 4-7.

Cadot, O. and B. Sinclair-Desagne (1994) 'Environmental Regulation, Industrial Policy and Technical Change', Nota di Lavoro 20.94, Fondazione Eni Enrico Mattei, Milan.

Carraro, C. and G. Topa (1992) 'Taxation and Environmental Innovation' in Environmental Papers, Fondazione Eni Enrico Mattei, Milan.

Clemenz, G. (1991), 'Optimal Price Cap Regulation', *Journal of Industrial Economics* (39), 391-408.

Dosi, G. (1988), 'Sources, Procedures and Microeconomic Effects of Innovation', *Journal of Economic Literature*, 1120-71.

Downing, P. B. and L. J. White (1986), 'Innovation in Pollution Control', *Journal of Environmental Economics and Managment* 13, 18-29.

Georg, S., I. Ropke and U. Jorgensen (1992), 'Clean Technology - Innovation and Environmental Regulation', *Environmental and Resource Economics* 2: 533-50.

Harrington, W. and A. J. Krupnick (1981), 'Stationary Source Pollution Policy and Choices for Reform', *Natural Resources Journal* 21:539-64.

Heyes, A. G. (1995), 'Environmental Penalties and Environmental Protection' forthcoming *Journal of Public Economics*.

Kalt, J. P. and M. A. Zupan (1984), 'Capture and Ideology in the Economics of Politics', *American Economic Review* 74(3), 279-300.

Kemp, R., X. Olsthoorn, F. Oosterhuis and H. Verbruggen (1992), 'Supply and Demand Factors of Cleaner Technologies: Some Empirical Evidence', *Environmental and Resource Economics* 2: 615-34.

Laffont, J. J. and J. Tirole (1994), 'A Note on Environmental Innovation', Nota di Lavoro 42.94, Fondazione Eni Enrico Mattei, Milan.

Lester, R. (1990), 'Regulatory Institutions and Reform', mimeo, Harvard University.

Levin, R. C. (1986), 'A New Look at the Patent System', *American Economic Review*, May, 199-202.

Magat, W. A. (1979), 'Pollution Control and Technological Advance: A Dynamic Model of the Firm, *Journal of Environmental Economics and Management* 5, 1-25.

Malik, A. S. (1991), 'Permanent versus Interim Regulations', *Journal of Environmental Economics and Management* 21, 127-39.

Mansfield, E., M. Schwartz and S. Wagner (1981), 'Imitation Costs and Patents: An Empirical Study', *Economic Journal*, pp. 907-18.

Mendelsohn, R. (1984), 'Endogenous Technical Change and Environmental Regulation', *Journal of Environmental Economics and Management* 11: 202-07.

Milliman, S. R. and R. Prince (1989), 'Firm Incentives to Promote Technological Changein Pollution Control', *Journal of Environmental Economics and Managment* 17(3), 247-265.

Mintz, J. A. (1988), 'Agencies, Congress and Regulatory Enforcement: A Review of the EPA's Hazardous Waste Enforcement Effort 1970-1987', *Environmental Law* (18), 683-759.

Moro, A. (1993), 'A Survey on R&D and Technological Innovation: Firm's Behaviour, Regulation and Pollution Control', Nota di Lavoro 73.93, Fondazione Eni Enrico Mattei, Milan.

Nolte, R. F. (1982), 'Innovation and Environmental Protection' in A. A. Ullmann (ed) *Umweilpolitik in Wandel*, Campus Verlag, pp. 77-95.

Orr, L. (1976), 'Incentives for Innovation as the Basis of Effluent Charges Strategy', *American Economic Review* 56: 441-47.

Pearce, D. and I. Brisson (1993),'BATNEEC: The Economics of Technology-based Environmental Standards with a UK Case Illustration', *Oxford Review of Economic Policy* 9(4): 24-40.

Shapiro, M. (1990), 'Toxic Substances Policy' in Paul R. Portney (ed.) *Public Policies for Environmental Protection*, Rsources for the Future, Washington DC.

Tirole, J. (1989), 'The Theory of Industrial Organisation', MIT Press, Cambridge MA.

Webb, G. A. M. (1986), 'The Development of ALARA - Philosophy and Practice' in J. R. Lakey and J. Lewins (eds) *ALARA: Principles, Practice and Consequences*, Adam Hilger, Bristol.

Yaeger, P. E. (1991), 'The Limits of the Law: Public Regulation of Private Pollution', Cambridge University Press, New York, NY.

Yao, D. A. (1988), 'Strategic Responses to Automobile Emissions Control: A Game Theoretic Analysis', *Journal of Environmental Economics and Management* 15, 419-38.

OXFORD INSTITUTE FOR ENERGY STUDIES
57 WOODSTOCK ROAD, OXFORD OX2 6FA ENGLAND
TELEPHONE (01865) 311377
FAX (01865) 310527
E-mail: publications@oxfordenergy.org
http://www.oxfordenergy.org