THE EFFECTS OF ENVIRONMENTAL REGULATION ON INNOVATION*†

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INTRODUCTION

In this day of increasing public concern with high inflation rates, low productivity gains, and a growing maze of environmental, health, and safety regulation, policymakers are beginning to examine the effects of this "social" regulation on technological advance. The Executive Branch has completed its Domestic Policy Review on Industrial Innovation and Congress, through its Office of Technology Assessment, is pursuing a similar study of the effect of regulation on technology. These studies confirm the conclusion of an earlier National Science Foundation sponsored literature search on the same subject that

> . . . our knowledge of the effects of regulation on technological innovation is indeed limited. We discovered no theoretical treatments and the empirical literature is limited to a few studies of the impact on pharmaceutical innovation of the 1962 Kefauver-Harris Amendments to the Food, Drug, and Cosmetic Act.[1]

Hypotheses about the effects of various forms of social regulation on technological advance are loosely stated, rarely derived from any analytical models of the firm's research and development (R&D) decision process, and seldom supported by empirical evidence. William M. Capron concludes that the effects of traditional industry–management regulation on innovation also apply to social regulation:

> . . . a priori expectations cannot easily be tested against the record because (1) regulation is only one of many factors that account for the actual course of technological change in these industries; (2) the industries themselves differ in significant respects; and (3) the actual record of technological change in any

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[1] C. HILL, A STATE OF THE ART REVIEW OF THE EFFECTS OF REGULATION ON TECHNOLOGICAL INNOVATION IN THE CHEMICAL AND ALLIED PRODUCTS INDUSTRIES 'CAPI Project' 2 (Center for Dev. Technology, Washington Univ., Feb. 1975).

> industry does not, in and of itself, indicate what changes could or would have taken place without regulation.[2]

This paper will focus on one subset of the problems described above, namely, how do the various types of environmental regulation which are proposed in the literature and employed in practice affect the rate and kinds (often called direction or bias) of innovation produced by firms, where by innovation we shall include both the invention of new technology and its first commercial use (only the latter activity is sometimes referred to as innovation).[3] Although the full impact of technological advance will not occur until it has moved through the diffusion stage, we will have less to say about this latter stage.

Many economists recognize that the effects of environmental regulation on technological advance may well be more important than the static efficiency effects. For example, Allen V. Kneese and Charles L. Schultze argue that, "[O]ver the long haul, perhaps the most important single criterion on which to judge environmental policies is the extent to which they spur new technology toward the efficient conservation of environmental quality."[4] Given the importance of the problem, the literature contains surprisingly few analytical models. A recent paper by this author[5] on the effects of effluent standards and charges on innovation will serve as the basis for many of the hypotheses proposed in this paper. Earlier works consist of V. Kerry Smith's model demonstrating that an effluent charge may alter the path of innovations chosen by a firm,[6] Richard O. Zerbe's graphical model of the effects of effluent charges, subsidies, and standards on innovation,[7] and Adam Gifford, Jr.'s model of the effect of effluent charges on growth.[8] In addition, Roger A. McCain has recently verified one of the conclusions in the author's earlier paper.[9]

Section II of this paper explains the qualifications and assumptions which limit the focus of this effort, while Section III describes the five types of environmental regulation to be modelled and provides examples of each type. Sections IV through VIII model each of the five types of environmental regu-

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[2] Capron, *Introduction* to TECHNOLOGICAL CHANGE IN REGULATED INDUSTRIES 3 (W. Capron ed., Brookings Inst. 1971).

[3] *See* J. SCHUMPETER, THE THEORY OF ECONOMIC DEVELOPMENT 65–74 (1934).

[4] A. KNEESE AND C. SCHULTZE, POLLUTION, PRICES AND PUBLIC POLICY 82 (Brookings Inst. 1975).

[5] Magat, *Pollution Control and Technological Advance: A Dynamic Model of the Firm*, 5 J. ENVIR. ECON. MANAGEMENT 1 (1978) [hereinafter cited as Magat].

[6] Smith, *The Implications of Common Property Resources for Technical Change*, 3 EUR. ECON. REV. 469–79 (1972).

[7] Zerbe, *Theoretical Efficiency in Pollution Control*, 8 W. ECON. J. 364–76 (1970).

[8] Gifford, *Pollution, Technology, and Economic Growth*, 40 S. ECON. J. 210–15 (1973).

[9] McCain, *Endogenous Bias in Technical Progress and Environmental Policy*, 68 AM. ECON. REV. 538–46 (1978).

lation and generate hypotheses about their effects on innovation. The five types of regulation are: effluent charges, non-technology-based effluent standards, marketable permits, technology-based effluent standards, and subsidies for abatement capital. Finally, Section IX summarizes the major findings.

I

QUALIFICATIONS AND ASSUMPTIONS

Besides environmental regulation, there are many other factors which influence the rate and direction of technological advance chosen by a firm. In making comparisons of the effects of the five types of regulation on innovation, we will assume that the levels of these other factors remain constant. Where we suspect the comparison between different environmental regulations would be affected by the level of other factors, we will qualify our conclusions. The effects of these other factors on innovation provides an even longer list of hypotheses about technological advance, many of which are contained in Roger G. Noll's summary article.[10] The other factors include: the extent of market competition; the opportunities available for technological progress; wage and rental rates; product prices; the extent to which inventions are supplied by non-profit institutions, such as the government; the appropriability of new ideas; the expectations of each firm concerning the likelihood of innovation in the industry; and uncertainty due to the lack of enforcement of and changes in environmental regulations.

Uncertainty, we assume, can arise from three sources: uncertainty due to the stochastic nature of the R&D process, uncertainty due to lack of perfect enforcement of regulations,[11] and uncertainty due to changes in future values of the regulatory parameters (e.g., taxes and standards). We assume either that firms face no uncertainty from these three sources or that their decisions are based on the expected values of the outcomes from R&D spending, of enforcement, and of future regulatory parameters, and that uncertainty does not affect their decisions. This represents a strong assumption and one area in which the results of this paper could be studied further.

Some authors have objected strenuously to the induced innovation model which we employ precisely because it does not *describe* how any *particular* firm deals with uncertainty inherent in the R&D process. This represents a legitimate criticism of the induced innovation model for predicting the innovation-producing behavior of individual firms, but the criticism is not applicable to

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[10] R. Noll, Government Policy and Technological Innovation: Where Do We Stand and Where Do We Go? (unpublished paper, Cal. Inst. of Technology Social Science Working Paper No. 86 May 1975).

[11] To assume perfect enforcement of any environmental regulation is indeed an heroic assumption, as Paul B. Downing and James Kimball have so vividly explained in Enforcing Administrative Rules (unpublished paper, Nat'l. Bureau of Economic Research, Proceedings of Conference on Public Regulation of December 15, 1977).

use of the model for making public policy recommendations that apply to numerous firms. As long as the model predicts the behavior of firms, *on average*, it is useful for public policy purposes, even if it does not describe accurately the behavior of any particular firm. For example, the Nelson–Winter model of evolutionary behavior is more descriptively accurate, but suggests *average* behavior that is not very different from that predicted by the induced innovation model. Hans Binswanger[12] suggests this conclusion by extracting the following quote from Nelson and Winter concerning their evolutionary model that is consistent with a major prediction from induced innovation literature:

> . . . a higher wage rate nudges firms to move in a capital intensive direction compared with that in which they would have gone. Also, the effect of a higher wage rate is to make all technologies less profitable (assuming, as in our model, a constant cost of capital) but the cost increase is proportionately greatest for those that involve a low capital-labour ratio.[13]

In addition, we assume that no single firm can influence either the type of environmental regulation imposed upon it or the levels of the regulatory parameters. If a firm can negotiate the level of its environmental regulation (e.g., the stringency of a standard), then these parameters can no longer be assumed to be fixed and our analysis would have to be significantly altered. This assumption is most reasonable in cases involving large numbers of polluting firms. For our analysis the assumption becomes crucial to our definition of an effluent charge which is "equivalent" to a given effluent discharge standard. Since most effluent charge schemes proposed for air or water pollution problems have *not* been firm-specific, the equivalency we define will be between a given total effluent discharge standard for all polluting firms in a region and a charge which induces all firms to meet that total discharge limit. Thus, no single firm's decisions affect significantly this equivalence. We usually will not consider the effects of each type of regulation on ancillary industries (i.e., pollution control equipment and toxicological testing), although these do constitute important questions.

II

TYPES OF ENVIRONMENTAL REGULATION

In Ronald Coase's delightful and now familiar article, *The Problem of Social Cost*,[14] he argues that the inefficiency created by externalities can be eliminated if private negotiations between all concerned parties can be arranged. One must always respond to this attack on the need for any form of govern-

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[12] Binswanger, *Induced Technical Change: Evolution of Thought*, in BINSWANGER, RUTTAN, ET AL., INDUCED INNOVATION 13, 29–32 (1978).

[13] Nelson and Winter, *Neoclassical vs. Evolutionary Theories of Economic Growth: Critique and Prospectus*, 84 ECON. J. 886, 900 (1974).

[14] Coase, *The Problem of Social Cost*, 3 J. LAW ECON. 1–44 (1960).

ment regulation when writing about environmental regulation. We will adopt the assumption that information and transactions costs make private negotiations between polluters and pollution victims an infeasible solution to the environmental problems with which we are concerned (e.g., urban air pollution, river pollution, and lake pollution).

Given the diversity of regulatory approaches available to attack environmental problems, it is unreasonable to assume that they all affect firms' technological development decisions in the same manner. Although it is unreasonable to ask whether "regulation" affects innovation, it is reasonable to ask what the differences are in the effects of various *types* of environmental regulation on a firm's rate of technological advance and the mix of improvement between pollution abatement technology and output production technology. From a public policy perspective, this last set of comparisons is important because each kind of pollution usually employs only one type of regulation.

We will consider five types of environmental regulation that directly affect the production decisions of firms. One approach is to impose effluent charges, often called fees or taxes, on polluting firms.[15] Although favored by many economists, the only use of this approach in air and water policy occurs in waste surcharges required of industrial water polluters discharging into municipal sewer systems under the 1972 Water Pollution Control Act Amendments (WPCAA).[16] A second approach is to use non-technology-based effluent standards to reduce effluent discharges, standards determined by trading off costs and benefits, by cost-effectiveness analysis, or by some other criteria not solely based on technological feasibility.[17] Compliance could be achieved either by fines or by compliance fees. The air pollution effluent standards, set by states to comply with the ambient air quality standards mandated by the 1970 Clean Air Act (CAA),[18] are one example. A third approach, also based on providing economic incentives, is to create a market for pollution permits.[19] The EPA's offset policy for air polluters in non-attainment areas represents one such example.[20] Under this policy, firms which desire to start or expand production in a region not meeting the national ambient air quality standards are allowed to pay other firms in the region to make offsetting pollution reductions. A fourth approach is to impose technology-based effluent standards on polluting firms, standards with levels determined solely by the

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[15] *See* A. KNEESE AND B. BOWER, MANAGING WATER QUALITY: ECONOMICS, TECHNOLOGY, INSTITUTIONS 141-42 (Resources for the Future, Inc. 1968) [hereinafter cited as KNEESE AND BOWER].

[16] Federal Water Pollution Control Act Amendments of 1972, Pub. L. No. 92-500, 86 Stat. 816, 144-77 (1972).

[17] *See* KNEESE AND BOWER, *supra* note 15, at 135-38.

[18] Clean Air Act Amendments of 1970, Pub. L. No. 91-604, 84 Stat. 1676, 1679-83 (1970).

[19] J. DALES, POLLUTION, PROPERTY AND PRICES 93-100 (1968) [hereinafter cited as DALES].

[20] Clean Air Act Amendments of 1977, Pub. L. No. 95-95, 91 Stat. 685, 715, 717-19 (1977).

limits of current or available technology.[21] Again, compliance could be achieved by fines or by compliance fees. Examples include the "best practicable technology" (BPT) and "best available technology" (BAT) industrial water pollution standards[22] and new source performance standards for industrial air pollution.[23] The fifth approach involves providing subsidies for firms and municipalities to use abatement capital.[24] Tax-exempt financing for industrial pollution abatement,[25] rapid amortization of pollution control equipment,[26] and the 75 percent federal subsidies of municipal waste treatment plant capital expenditures (under WPCAA) represent examples of this approach.

We will not study environmental regulations which restrict the composition, use, and characteristics of the final product, such as a ban on the use of phosphates in detergents, pesticide use restrictions, and automobile emission standards.

III

EFFLUENT CHARGES AND TECHNOLOGICAL CHANGE

In this and the four subsequent Sections we will present two types of results about the effects on innovation of the five types of environmental regulation. Results called theorems are derived logically from models of firm behavior under the particular regulatory regime. Results called propositions come from careful reasoning about the effects of regulation, but they are not supported by an explicit model of firm behavior.

A. The Model[27]

In order to focus on the problem of technological change, we employ a simple model of production in which a firm employs one variable input (at rate L), to produce its output (at rate y), and a pollutant (at discharge rate x). This represents a simplification of most firms' production processes, since they typically employ a variety of inputs while producing multiple outputs and more than one pollutant. Nonetheless, we are interested in the effects of

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[21] A. Freeman, Technology-Based Effluent Standards: The U.S. Case (unpublished paper on file with the Environment and Indus. Div. of the Organization for Economic Cooperation and Dev. 1976).

[22] Federal Water Pollution Control Act Amendments of 1972, *supra* note 16.

[23] Clean Air Act Amendments of 1970, *supra* note 18.

[24] *See* Renshaw, *Should the Federal Government Subsidize Industrial Pollution Control Investments?* 1 J. ENVT'L. ECON. MANAGEMENT 84–88 (1974).

[25] Revenue and Expenditure Control Act of 1968, Pub. L. No. 90–364, 82 Stat. 251, 267 (1968).

[26] 26 U.S.C. § 169 (1976).

[27] For a more detailed explanation of the model, *see* Magat, *supra* note 5, at 3–7. For a discussion of Kamien and Schwartz's model of factor-augmenting technological change, *see Induced Factor Augmenting Technical Progress from a Microeconomic Viewpoint*, 37 ECONOMETRICA 668-84 (1969) [hereinafter cited as Kamien and Schwartz].

regulation on pollution abatement technology innovation and output technology innovation and we can safely suppress the firm's choice among various factors of production, outputs, and pollutants. Technical change occurs through product augmentation, where Ay and Bx represent the effective output rate and the effective effluent discharge rate. The augmentation parameters, A and B, are positive scalars respectively measuring the levels of the output production and effluent abatement components of the technology. This joint production relation is summarized by the production function, $L = g(Ay,Bx)$. We assume that employing more of the input, L, either raises the output rate, y, lowers the pollution rate, x, or some combination of these two effects. Note that improvements in output production technology are represented by a *decrease* in A, whereas improvements in the effluent abatement technology are represented by an *increase* in B. Appendix A provides a more detailed description of the production function.

We see technological advance occurring through expenditures, M, by a firm that produces a combination of output technology innovation and effluent abatement technology innovation. The parameter, β, measures the allocation of effective R&D effort between the two types of technological advance. We assume that for a *given* expenditure, M, on R&D, the tradeoff between output technology innovation, $\dot{A}/A$, and abatement technology innovation, $\dot{B}/B$, occurs along a smooth innovation-possibilities frontier, such as the one given in Figure 1.[28] Increases in R&D spending, M, shift out the frontier. We shall call M the rate of technological advance, while β measures the bias or direction of technical change. Appendix A provides a more detailed description of the model of technological advance.

Again, as with the model of production, this technological advance model is a simplification of the manner in which technological change actually occurs. We addressed this issue in Section I, but a further explanation is needed. Individual advances tend to be awkward, incorporating discrete changes in both the output production and effluent abatement technologies. In the aggregate, or on-average, environmental regulations do bias R&D effort towards abatement technology innovation and they do affect the rate of R&D spending in a systematic manner. It is not necessary that the model be *descriptively* accurate for any *particular* firm, as long as, *on-average*, firms behave according to the model. There is good evidence to support the predictive accuracy of the induced innovation model.[29]

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[28] $\dot{A}$ and $\dot{B}$ stand for the derivatives of A and B with respect to time, so that $\dot{A}/A$ and $\dot{B}/B$ measure the proportional time rates of change of the output production and effluent abatement technologies, respectively.

[29] Binswanger, *supra* note 12.

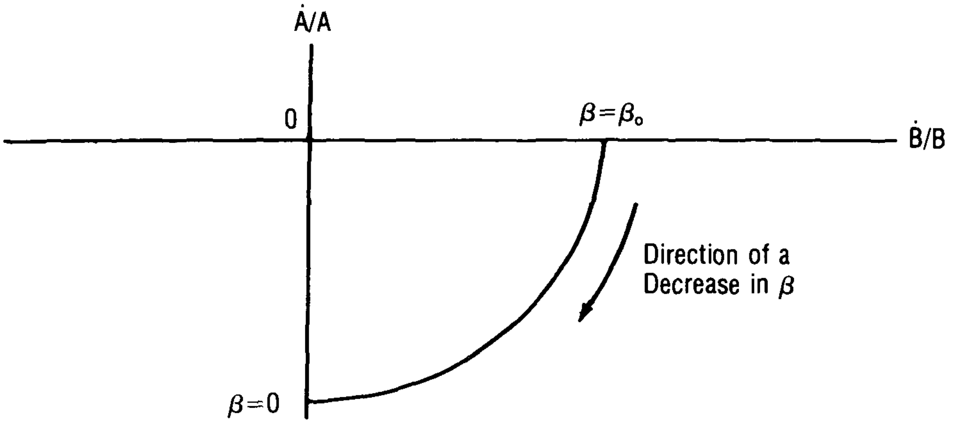

FIG. 1. Innovation-Possibilities Frontier

The proofs of the theorems which follow require the use of these models of production and technological advance; however, the details of the models are not necessary to an understanding of the theorems themselves and their implications.

B. The Results

Let us first consider how imposing an effluent charge, τ, on each unit of pollution discharged by the firm would affect the bias in its technical advance. Assume that the firm's output can be sold at the competitive price p.

Theorem 1: An effluent charge causes the firm to bias its technological advance towards abatement technology innovation.[30]

Appendix B contains the proof of the theorem. The proof is based on the observation that without an effluent charge, a firm seeks to maximize the rate of output technology growth, $\dot{A}/A$. In Figure 1 this direction of technical advance is represented by the point $\beta=0$, where the innovation-possibilities frontier crosses the $\dot{A}/A$ axis. Generally, maximization of the rate of output technology growth could occur in either the southeast or southwest quadrants. In these cases the maximum occurs in technology which is becoming either less or more polluting, respectively. When faced with a positive effluent charge, the firm possesses an incentive to reduce its total effluent charge bill. One

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[30] To be more exact, we must qualify *all* of our theorems to indicate that they hold under the assumptions of the model of the firm in Section III A and under the additional assumption that the firm selects its rates of output and effluent discharge and its rate and bias in technical advance to maximize the rate of increase of net profits.

way is to develop a less-polluting technology, so it moves from the flat point on its innovation-possibilities frontier to a positively-sloping point where its abatement technology is advancing more rapidly. Thus, imposing an effluent charge induces the firm to shift some of its effective R&D effort from output technology improvement to effluent abatement technology improvement.

Theorem 2: An effluent charge can cause the firm either to reduce or increase its R&D expenditure rate.

If the effect of the reduced output rate and the bias away from output technology improvement outweigh the effect of a positive charge, then the R&D expenditure rate M would decline. Otherwise it would increase. The exact effect depends upon the specific characteristics of a firm's production function and the shape of its innovation-possibilities frontier (see the proof in Appendix C). We cannot conclude that, in general, effluent charges lower a firm's expenditure on R&D.

Theorem 3: If without an effluent charge a firm devotes no R&D effort to abatement technology improvement, then an effluent charge will induce it to invest in abatement technology innovation.

Appendix D provides the proof of Theorem 3, which follows from Theorems 1 and 2. Note that if a firm's innovation-possibilities curve flattens out inside the southeast quadrant (i.e., the rate of *output* technology innovation is maximized by devoting some R&D effort to abatement technology innovation), then some positive amount of abatement technology innovation would occur without an effluent charge. From Theorem 2 the R&D rate could conceivably decrease after imposing an effluent charge. If this reduction in the R&D rate is significant enough, it could outweigh the effect of directing more of the firm's R&D effort towards abatement technology innovation. Thus, it is possible, although highly unlikely, that imposing an effluent charge could reduce a firm's rate of abatement technology innovation.

Theorem 4: Imposing an effluent charge is likely to reduce a firm's rate of output technology innovation, but it need not have this effect.

Appendix E contains the proof. The unlikely event of an increase in output technology innovation could occur only if the effluent charge induced the firm to spend so much more on R&D that at this higher expenditure level the now smaller share directed toward output technology improvement was larger than the original effort devoted to output technology innovation. We have confirmed the usual working hypothesis that an effluent charge is likely to reduce a firm's output productivity growth rate. Precisely because firms tend to trade-off output technology advance for more abatement technology advance, many policy-makers are concerned about implementing effluent charges in particular and environmental regulations in general.

IV

NON–TECHNOLOGY–BASED EFFLUENT STANDARDS AND TECHNOLOGICAL CHANGE

As an alternative to the effluent charge approach, the government can set an effluent discharge standard, $\bar{x}$. A firm then seeks to maximize its profits (the difference between total revenue and the cost of the variable input) subject to the constraint that its effluent discharge rate not exceed the standard. From equations (10a), (10b), (30a) and (30b) of Magat, we recognize that with an effluent charge equal to the Lagrange multiplier for the constrained problem, the first-order conditions for the solution to this problem under a standard are equivalent to those conditions which characterize the profit-maximizing output and effluent discharge decisions under an effluent charge. By setting the level of the effluent charge equal to the corresponding Lagrange multiplier, *the same* production decisions can be induced.[31] Moreover, the rate and direction of technical advance selected under an effluent standard will be *exactly those* chosen under an equivalent effluent charge, implying that the effects of imposing an effluent standard on a previously unregulated firm will be the same effects described under Theorems 1 through 4 for the equivalent effluent charge. In summary,

Theorem 5: An effluent standard induces the firm to bias its technological advance towards abatement technology innovation, while the firm's R&D expenditure rate may either decrease or increase. If, without an effluent standard, the firm devotes no R&D effort to abatement technology improvement, then an effluent standard will cause it to invest in abatement technology innovation. Imposing an effluent standard is likely to reduce a firm's rate of output technology innovation, but it need not have this effect for all firms.[32]

Having compared the firm's rate and direction of technical advance under an effluent standard with that under no regulation, let us examine in detail

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[31] This assumes, of course, that the second–order conditions for profit maximization are satisfied. Some authors have criticized the effluent charge approach because the externalities themselves can create non–convexities which might lead a firm to non–optimal output level and effluent decisions. Certainly to the extent that this problem leads to static inefficiency through the use of the charges policy, it would also make much less clear the equivalence between charges and standards described in this section. *See* Starrett, *Fundamental Nonconvexities in the Theory of Externalities*, 4 J. ECON. THEORY 180–99 (1972).

[32] Having discovered that imposing an effluent standard induces the firm to shift its direction of technical change towards more abatement technology innovation, a natural further question is whether lowering the level of the standard (i.e., increasing its stringency) causes the bias to shift towards even more abatement technology innovation. In one special but important case, the answer is surprisingly no. When substitution of labor between output production and effluent abatement is difficult (formally, when the elasticity of transformation defined in Magat, *supra* note 5, at 6–7, is less than one) and when the elasticity of the returns to scale function, ϕ is constant, then no matter what the level of the standard the bias, β, converges to the same steady-state value. For a proof of this result *see id.* at 19, Theorem 8.

the comparison between the rate and direction of technical advance under an effluent standard and under an effluent charge.

With perfect information about the marginal costs of abatement, an effluent charge can usually be found which induces the same level of abatement as any given standard. However, over time technological advance causes the marginal abatement cost function to shift so that the effluent charge would have to change in order to induce the same level of abatement. In practice it would be extremely difficult for a regulator to maintain this equivalence of effluent charges and standards over time, for the regulator would have to announce a time–varying schedule of effluent charges that anticipates the effect of abatement technology advance on the firm's marginal abatement cost function. In a world in which administrative costs and lack of information make determining even the correct *initial* level of the charge a difficult task, it would be highly unlikely to find regulators willing or able to announce a time–varying schedule of effluent charges which are equivalent to a fixed effluent standard.[33]

A more workable alternative is to set an effluent charge at a level which is initially equivalent to the standard, but thereafter the rates of effluent discharge, output, abatement technology advance and output technology advance would diverge. Another alternative is to adjust periodically the level of the charge to induce the firm to stay "close" to meeting the level of the fixed effluent standard. The analysis summarized in Table I of Magat[34] indicates that, in general, we cannot determine which temporally constant policy will yield the greatest increases in abatement and output technology advance.

In the special case in which only abatement technology advances (and not output technology), Richard O. Zerbe has shown that a *fixed charge* provides a greater incentive for abatement technology advance than a *fixed standard*.[35] Let us consider his argument based on his Figure 1, reproduced as our Figure 2. In Zerbe's example the firm originally possesses the marginal cost of abatement curve MC_1 and faces the effluent standard qx, or the equivalent effluent charge T_1. After a technological advance, the marginal abatement cost curve drops to MC_2 (to simplify the example he assumes no output technology improvement). The cost-saving incentive from innovation, given the standard, is acdb, while the cost-saving incentive under the charge is acdb, *plus* ced, *assuming* that the charge remains fixed at T_1.

It might be realistic to assume that the level of the charge would not adjust in the short run, but after the abatement technology advance charge T_1 can no longer be considered equivalent to the standard qx, for under the charge

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[33] For a discussion of an iterative approach to setting charges *see* Baumol, *On Taxation and the Control of Externalities*, 62 AM. ECON. REV. 307–22 (1972).

[34] Magat, *supra* note 5, at 21.

[35] Zerbe, *supra* note 7, at 371–75.

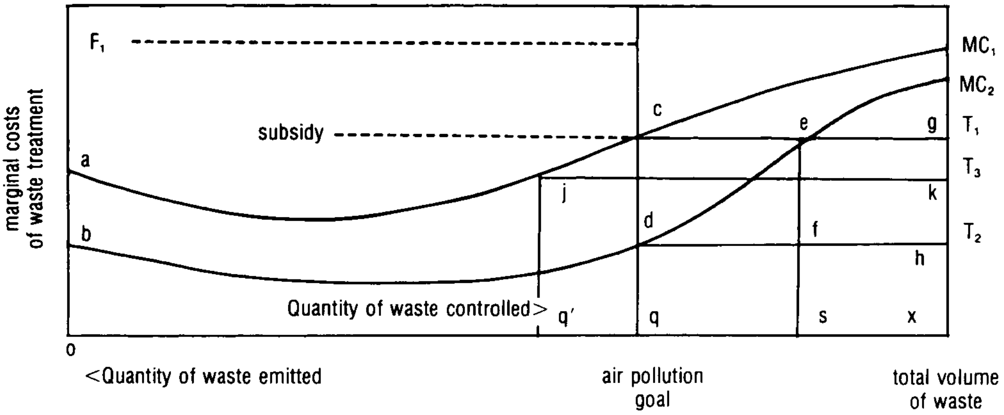

FIG. 2. The equivalence between emission charges and standards.

T_1 less waste (sx) is discharged by the firm. Even though Zerbe's example demonstrates that the *fixed* charge T_1 creates a stronger incentive to innovate than the *fixed* standard qx, to claim that the two regulatory policies are equivalent remains troublesome.

We believe that the only reasonable definition of "equivalent" effluent charge and standard policies requires that the charge induce the *same* level of effluent discharge as the standard over the *entire* period of analysis.

We will now analyze a model which does compare the rates of abatement and output technology advance for two policies which meet the above definition of equivalency. We do not claim that the model accurately describes all situations under which two equivalent policies can be applied; however, it does demonstrate how simple the model must be before *any* comparison can be made of equivalent policies.

Specifically, let us consider the case of an urban air pollution problem in which many firms discharge pollution. In this large-numbers case it is reasonable to assume that adjustments in the charge (necessitated by abatement technology advances by all firms) would not result directly from the actions of any *single* firm, or at least that no one firm would expect any significant adjustment in the charge to all firms because of its abatement technology advance. In practice the regulator would have to announce in advance a time-varying schedule of charges based on his expectation of how all firms would react to the charge through investing in abatement technology improvement.

In the context of Zerbe's example, abatement technology advance causes the equivalent charge to fall to T_2 (see Figure 2) and the firm will enjoy the tax reduction cghd automatically. As long as the firm does not recognize that its abatement technology innovation *causes* the effluent charge reduction (i.e., there are many polluters), it calculates a cost-reduction from innovation of acdb, exactly the same incentive provided by the equivalent standard.

A more general example would allow for output technology innovation, in which case output rises and total wastes would rise for most firms.[36] This would extend the right boundary of Figure 2 and under a temporally-constant effluent standard the quantity of waste controlled would move to the right of oq, implying that the new equivalent charge would be above T_2. Theorem 7 of Magat indicates that for most firms the equivalent tax would actually *increase* above T_1. As long as the firm does not recognize that it causes this change in the charge level, the incentive to innovate under the two policies is equal.

In the context of the model of Section A the same result holds due to equivalence of the first-order conditions for the two problems.[37] We will record this result as a theorem.

Theorem 6: Under the Section A model and the assumption that firms do not expect their technological advance to cause an adjustment in the level of the effluent charge, the identical rate and direction of technical advance are induced by an effluent standard as are induced by the equivalent effluent charge.

As long as an effluent charge is set at a level that induces an effluent discharge level which exactly meets a standard, the two policies will have the same effect on a firm's R&D investment decisions. By comparing first-order conditions for a firm operating under the two regulatory policies, the proper equivalence between effluent standards and effluent charges is clear. The result that the two equivalent policies yield the same rate and direction of technical advance follows easily. However, most economists have missed the implications of this equivalence for technological advance, or they have been considering the case of a small number of polluters or two policies which are not equivalent dynamically. It is fair to say that their working hypothesis is that effluent charges produce a stronger incentive for abatement technology advance than do effluent standards.

Theorems 5 and 6 imply that the likely reduction in the firm's rate of output technology innovation under an effluent standard will be equivalent to that under the comparable effluent charge.

Before leaving the subject of the incentives to innovate under an effluent standard, it is useful to consider the effect of different enforcement mechanisms. We have been assuming implicitly that the firm is either shut down if it discharges pollution at a rate greater than the standard or that it faces an infinite fine for violating the standard. The 1977 Amendments to the Clean Air Act mandate the use of compliance fees after mid-1979, so we will consider

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[36] *See* Theorems 1, 2, and 3 in Magat, *supra* note 5, at 9–11.

[37] *See* Section IV, paragraph one.

how this enforcement policy would affect the conclusions of this Section. Examination of Figure 2 again shows that as long as the compliance fee (per unit of effluent, F_1) exceeds the level of the charge equivalent to the standard (T_1), the firm will discharge only qx units of waste. The cost-saving incentive from innovation is acdb, as under the effluent standard policy (with perfect enforcement) and under the equivalent effluent charge policy.

V

MARKETABLE PERMITS AND TECHNOLOGICAL CHANGE

The EPA's recent offset policy for limiting air pollution in cities which have failed to meet national ambient air quality standards has renewed interest in the marketable permits policy first popularized by John H. Dales in 1968.[38] A public agency would provide a market for the exchange of air pollution permits and police the actions of polluters to insure that they were not using more than their purchased share of permits. As part of its duties in operating the market, the agency would: determine how many permits to sell, sell the initial offering of permits, and then act as a central exchange for the transfer of permits.

From the firm's point of view, the price that it must pay for air permits is equivalent to paying an effluent charge on its effluent discharge, so the imposition of an air permits market would affect the firm's innovation decisions in the same way as imposing a charge at the level of the market clearing price. Formally,

Theorem 7: Imposing a pollution permits market on the area in which a firm operated would cause it to bias its technical advance towards abatement technology innovation, while its R&D expenditure rate may either decrease or increase. If, without a pollution permits market, the firm devotes no R&D effort to abatement technology improvement, then the pollution permits market will cause it to invest in abatement technology innovation. Imposing the pollution permits market is likely to reduce the firm's rate of output technology innovation, but it need not have this effect for all firms.

VI

TECHNOLOGY-BASED EFFLUENT STANDARDS AND TECHNOLOGICAL CHANGE

A. Abatement Technology Innovation

The reliance upon technology-based effluent standards to protect water quality was the most significant aspect of the 1972 Water Pollution Control

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[38] DALES, *supra* note 19.

Act Amendments. By 1977 all industrial, point-source polluters were to meet the so-called "best practicable control technology currently available" (BPT) standards, which were to be based upon engineering analysis of the available control technologies. By 1983 they must comply with standards based on the "best available technology economically achievable" (BAT). EPA also set technology-based standards for new sources of both water and air pollution, so this regulatory approach has become a central part of the agency's control strategy.

Most technology-based effluent standards are written into discharge permits as the levels of effluent discharge *consistent* with the specified technology. Legally a firm may adopt another technology and still avoid a fine if the alternative technology meets the effluent standards. However, in practice a firm is much less likely to be fined if it fails to meet the standards but adopts the specified technology than if it fails to meet the standard and has adopted what it considers to be a less-polluting technology. For practical purposes, standards, such as the BPT standards, require the *use* of a specified technology, and they discourage innovation directed at less-polluting production and treatment processes.[39] Technology-based standards also discourage abatement technology innovation by a polluting firm because the innovation will cause the regulator to mandate its early use in all the firm's plants (including old ones) requiring the firm to incur more costs sooner than it would otherwise. To the extent that regulators, such as EPA, often change their standards between those initially proposed and those finally promulgated, a polluting firm faces an incentive to slow down the invention and adoption of new abatement technology because it may not meet the final regulations.

We can think of only one way in which technology-based effluent standards encourage abatement technology innovation by either polluting or non-polluting firms. To the extent that a regulatory agency mandates the wide-spread adoption of a new technology developed by a firm, the agency creates a widely-expanded market for that firm's innovation. However, given the inherent difficulty in appropriating the benefits from new abatement technology[40] and the lag between the discovery of a new abatement technology and its final promulgation into regulations by a regulatory agency, such as EPA, it is highly unlikely that this incentive to innovate could dominate the other disincentives for abatement technology innovation.

Paul B. Downing and Gordon Brady have documented the difficulties which Dana and Echlin, two manufacturers of NO_x automobile retrofit de-

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[39] A. Myrick Freeman III describes this practice and quotes a conclusion of the National Commission on Water Quality Staff Report stating that in many cases the abatement [technology] which is *actually* being installed is equivalent to the suggested *technologies*, rather than being designed to meet the *limitations* per se. *See* Freeman, *Air and Water Pollution Policy*, in CURRENT ISSUES IN U.S. ENVIRONMENTAL POLICY 56 (P. Portnoy ed., 1978).

[40] *See* Noll, *supra* note 10, at 5–9.

vices, faced in attempting to meet a market demand for approved retrofit devices created by the California Air Resources Board (CARB).[41] In 1971 CARB was empowered to accredit NO_x retrofit devices and to require certificates of compliance at the initial automobile registration and at the ownership transfer. Dana and Echlin had received CARB approval to market their retrofit devices in the state program, but by 1974 the program had still not been implemented, so they joined a Clean Air Constituency suit against CARB.[42] Dana claimed a loss of $9 million in the development and warehousing of its NO_x device, and Echlin claimed a $4.7 million loss. While only one example, this case illustrates the problems which a firm may encounter in attempting to appropriate the benefits from a new technology developed for approval by an environmental regulatory agency. In summary,

Conjecture 1: Unless the benefits from the use of new abatement technologies can be appropriated by their owners and unless regulatory agencies quickly revise their regulations based on the new abatement technologies, non-technology-based effluent standards create a stronger incentive for abatement technology innovation than do technology-based effluent standards.

Even if technology-based effluent standards induce less *innovation* than do non–technology–based standards, they are likely to cause faster *diffusion* throughout a given industry of those innovations which are produced. This introduces an important trade-off between faster diffusion of new or existing innovations and a reduced pool of innovations which will be available for diffusion throughout the industry in the future. The choice between technology- and non–technology–based effluent standards rests on identifying the relative strenghts of these two effects in reducing the cost of achieving cleaner air or cleaner water.

B. Production Technology Innovation

Relative to non–technology–based standards, technology–based standards discourage output technology innovation because the range of possible new output technologies is limited by the requirement that they be consistent with the mandated abatement technology. In addition, the effluent standards may mandate part of the output technology.

Conjecture 2: Non–technology–based effluent standards create a stronger incentive for output technology innovation than do technology–based effluent standards.

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[41] Downing and Brady, *Implementing the Clean Air Act: A Case Study of Oxidant Control in Los Angeles*, 18 NAT. RES. J. 237, 274 (1978).

[42] Clean Air Constituency v. California State Air Resources Board, 523 P.2d 617, 114 Cal. Rptr. 577 (1974).

Thus we have argued that technology-based effluent standards are inferior to non-technology-based standards (which, under the assumptions of Theorem 6, are equivalent to effluent charges and marketable permits) in inducing both abatement technology and output technology innovation.

VII

SUBSIDIES FOR ABATEMENT CAPITAL AND TECHNOLOGICAL CHANGE

The effect of granting a subsidy for abatement capital installed by a firm can be studied by suitable reinterpretation of the output variable in the Kamien and Schwartz model of factor-augmenting technological progress. Rather than considering their output variable y to represent the firm's principal product, we let it stand for the level of pollution abatement or treatment. To simplify the analysis, we will not consider the trade-off between output production and effluent abatement that was possible with the formal model employed in the previous Sections. The two inputs, capital K and labor L, then are the quantities of inputs which are devoted to pollution abatement. As in the Kamien and Schwartz model, r and w stand for the unit costs of capital and labor, respectively.

An abatement capital subsidy lowers the unit cost of capital r, which initially causes the direction of technical change to shift towards relatively more labor augmentation and relatively less capital augmentation.[43] However, over time the capital-labor ratio rises to adjust the reduction in the cost of capital and at the new equilibrium the direction of technical change has moved back to its original direction.[44] Only in the short run does a capital subsidy bias the direction of technical advance towards relatively more labor augmentation; in the long run it has no effect. Unfortunately, we cannot determine whether the capital subsidy always causes an increase or a decrease in the rate of R&D spending; therefore, it is impossible to determine how the absolute amount of capital and labor augmentation change due to the capital subsidy. In summary,

Theorem 8: An abatement capital subsidy causes an initial rise in the relative rate of labor versus capital augmentation; however, in the long run the direction of technical advance is unaffected.[45] The effect of these subsidies on the rate of abatement technology advance is indeterminate.

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[43] This result follows from Kamien and Schwartz's equation (36), since initially K/L is fixed. *See* Kamien and Schwartz, *supra* note 27, at 676.

[44] This result follows from Theorem 5. The equilibrium value for the direction of technical change is independent of the capital cost. This equilibrium is stable only for an elasticity of substitution less than one, which is not an unreasonable assumption. *See* Kamien and Schwartz, *supra* note 27, at 677.

[45] These results are based on the assumptions underlying the Kamien and Schwartz model.

between non-technology-based standards, charges, and marketable permits, then in the case of a large number of polluters the model presented in this paper indicates that all three types of environmental regulation provide exactly the same incentive for both abatement technology and output technology innovation. If standard, charge, and marketable permit levels are all constrained to be constant over time (in which case they are *not* dynamically equivalent), then their effects on innovation differ, but, in general, the differences are too complex to conclude that one policy stimulates more abatement innovation than another.

Each of the three types of regulation induces a firm to bias its technological advance towards abatement technology innovation. The regulations can cause a firm to spend either more or less on R&D, depending upon its production technology and innovation possibilites. If, without any environmental regulation, a firm devotes no R&D effort to abatement improvement, then imposing either of the three regulations will increase the rate of abatement technology innovation. However, if a firm did invest in improving its abatement technology without regulation, then the three types of regulation could decrease (but most likely would increase) the rate of abatement technology innovation. Similarly, the three regulatory approaches will most likely decrease a firm's rate of output technology innovation, although the effect could be positive.

A fifth type of environmental regulation, abatement capital subsidies, was studied to determine whether it would bias technological advance towards relatively more abatement labor augmentation and less abatement capital augmentation. Initially the subsidy does bias innovation towards labor augmentation. However, over time the firm completely adjusts by raising its ratio of capital to labor, while the equilibrium direction of technical change settles back to its original level. In the long run, abatement capital subsidies do not induce a bias towards relatively more labor augmentation.

These conclusions, even if supported by empirical evidence, do not imply that society should be indifferent to non-technology-based effluent standards, effluent charges, and pollution rights markets. There are several other criteria, such as enforceability and administrative ease, on which the choice of environmental policy could be based. In addition, practical considerations may require that society choose between policies which are not equivalent over time. However, the results do indicate that all three policies induce firms to shift their R&D efforts towards more abatement technology innovation. On the basis of this single criterion no one policy is more effective than the other two.

APPENDIX A: THE MODEL OF PRODUCTION AND TECHNOLOGICAL CHANGE

In order to facilitate the separation of the effects of returns to scale from substitution between output production and effluent reduction, we represent the production function, g(Ay,Bx), as the composite function

(1) $L = \phi(F(Ay,Bx))$.

The composite function $\phi(F)$ is homothetic, since the function ϕ is assumed to be an increasing function of the linear homogeneous function f. Formally,

(2) $\phi' > 0, \phi'' > 0, \phi(0) = 0,$

so that the marginal product of labor in output production is positive and decreases with increased output levels, whereas the marginal product of labor in effluent abatement is also positive, but increases with the effluent discharge rate.

Technological progress occurs through expenditures on R&D that produce changes in the technology coefficients, A and B. Formally,

(4a) $\dot{A}/A = g(\beta)h(M),$
(4b) $\dot{B}/B = \beta h(M),$
where
(5a) $h(M) \geq 0,\ h'(M) > 0,\ h''(M) < 0,\ h'(0) = \infty,\ h(0) = 0,$
(5b) $\beta \geq 0,\ g(\beta) \leq 0,\ g'(\beta) > 0 \text{ for } \beta > 0,\ g''(\beta) > 0,$
(5c) $g'(0) = 0,\ g'(\beta_0) = \infty,$
and β_0 satisfies $g(\beta_0) = 0$.

The curve is analogous to the production-possibilities curve for two conventional outputs which is found in most intermediate microeconomics texts. It was first suggested by Kennedy in the context of a *factor* augmentation model.[48] For convenience we assume (5c) that the innovation-possibilities curve becomes horizontal at the $\dot{A}/A$ axis and vertical at the $\dot{B}/B$ axis, although the rate of output technology advance ($\dot{A}/A$) could be maximized by advances which either improve or worsen the abatement technology (i.e., the curve could become horizontal in either the southeast or southwest quadrants of Figure 1).

Under the assumptions of (5a) an increase in R&D spending, M, shifts out the entire innovation-possibilities curve, although we do assume decreasing returns to scale in R&D investment, M. The last assumption, that h(0) = 0, means the firm receives no exogenous technological advance, such as from the government. This restriction could be relaxed with little effect on the re-

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[48] Kennedy, *Induced Bias in Innovation and the Theory of Distribution*, 74 ECON. J. 541–47 (1964).

sults of the paper. Also, we refer to M as R&D spending in-house, but it could be thought of as expenditures on new technology from other firms, although we admit that the market for innovations does not function as smoothly as most other markets because of the public goods nature of innovations.

APPENDIX B: PROOF OF THEOREM 1

Equation (20a) in Magat requires that the optimal bias, β, satisfy

$$g'(\beta) = \frac{\tau x}{py}, \qquad (6)$$

where y and x are the profit-maximizing output and effluent rates. When $\tau = 0$ then $g'(\beta) = 0$. Under assumption (5c) $(\dot{B}/B) = 0$ and $|\dot{A}/A|$ reaches its maximum value for a given value of M. It is possible that, unlike the example drawn in Figure 1, the innovation-possibilities frontier flattens out inside the southeast quadrant; in which case abatement technology could be improving even without an effluent charge. However, the point is that without a charge all the R&D effort is devoted to maximizing the rate of output technology improvement $\dot{A}/A$. By imposing a charge the slope of $g'(\beta)$ must be positive (unless the pollution rate fell to zero, which Magat shows to be unlikely), so β must increase.

APPENDIX C: PROOF OF THEOREM 2

Equation (20b) in Magat requires that the optimal rate M of R&D expenditures satisfy

$$\frac{r}{h'(M)} = \beta\tau x - g(\beta)py, \qquad (7)$$

where r is the firm's discount rate. Without an effluent charge, $r/h'(m) = -g(\beta)py$. Since under an effluent charge Theorem 1 proved that $-g(\beta)$ is smaller and it can be shown that output is reduced, the second term is reduced. However, the first term increased from zero to a positive number, thus we cannot say whether imposing an effluent charge reduces or increases R&D spending.

APPENDIX D: PROOF OF THEOREM 3

From (4b) the proportional rate of increase in abatement technology, $\dot{B}/B$, equals the product of the bias in technical advance, β, and the effective R&D effort, h(M). If the firm directs no R&D effort to abatement technology improvement, then $\beta = 0$, and $\dot{B}/B = 0$. From Theorem 1 the bias increases (β becomes positive), so B/B must increase.

APPENDIX E: PROOF OF THEOREM 4

From (4a) $\dot{A}/A = g(\beta)h(M)$, Theorem 1 proves that imposing an effluent charge lowers the absolute value of $g(\beta)$, but Theorem 2 indicates that R&D spending could either decrease or increase, so it is possible for the effluent charge to spur output technology innovation.