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An Innovation-Based Strategy for a Sustainable Environment

*Nicholas A. Ashford**

Introduction

This article explores a role for government to provide a solution-focused, technology-based approach for addressing and setting priorities for environmental problems. It is argued that there is a need for a significant industrial transformation or displacement of those technologies and sectors that give rise to serious environmental problems, especially those that have remained stagnant for some period of time and that are ripe for change. Achieving sustainable production and consumption requires (1) a shift in policy focus from problems to solutions, (2) an appreciation of the differences between targeting technological innovation and diffusion as a policy goal, (3) the realization that the most desirable technological responses do not necessarily come from the regulated or polluting firms, (4) understanding that comprehensive technological changes are needed that co-optimize productivity, environmental quality, and worker health and safety, and (5) an appreciation of the fact that in order to change its technology, a firm must have the *willingness, opportunity,* and *capacity* to change.

Willingness, opportunity, and capacity are together the necessary and sufficient prerequisites for a firm undertaking technological change. The three affect each other, of course, but each is determined by more fundamental factors. Therefore, policy instruments need to be chosen and designed for their ability to change these more fundamental factors. *Willingness* is determined by both (1) *the firm's attitudes towards changes in production technology and products in general* and by (2) *its knowledge about what changes are possible*. Improving the latter involves aspects of capacity building, while changing the former may be more idiosyncratic to a particular manager or alternatively a function of organizational structures and reward systems. The syndrome "not in my term of office" describes the lack of enthusiasm of a particular manager to make changes whose benefit may accrue long after he has retired or moved on, and which may require expenditures in the short or near term.

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Opportunity involves both supply-side and demand-side factors. On the supply side, technological gaps can exist (1) between the technology used in a particular firm and the already-available technology that could be *adopted or adapted* (known as diffusion or incremental innovation, respectively), and (2) the technology used in a particular firm and technology that could be *developed* (i.e., major or radical innovation). On the demand side, four factors could push firms towards technological change -- whether diffusion, incremental innovation, or major innovation -- (1) regulatory requirements, (2) possible cost savings or additions to profits, (3) public demand for a less polluting and safer industry, and (4) worker demands and pressures arising from industrial relations concerns.

Capacity or capability can be enhanced by both (1) increases in knowledge or information about cleaner and inherently safer opportunities, partly through formal Technology Options Analyses (see later discussion), and partly through serendipitous transfer of knowledge from suppliers, customers, trade associations, unions, workers, and other firms, as well as reading about environmental and safety issues, and (2) improving the skill base of the firm through educating and training its operators, workers, and managers, on both a formal and informal basis. Capacity to change may also be influenced by the inherent innovativeness (or lack thereof) of the firm as determined by the maturity and technological rigidity of particular product or production lines. The heavy, basic industries, which are also sometimes the most polluting and unsafe industries, change with great difficulty, especially when it comes to core processes. Finally, it deserves emphasizing that it is not only technologies that are rigid and resistant to change. Personal and organizational flexibility is also important (Coriat 1995).

This article argues that government must provide the opportunity for technological transformation/sustainable development through the setting of clear standards and policy goals, while allowing flexible means for industry to achieve those goals. Care must be taken to avoid dominant technological regimes from capturing or unduly influencing government regulation. New entrants and new technology must also be given a chance to evolve to address environmental problems. Other demand-side policies (i.e., changes in public preferences for specific products, transportation systems, or services) are important in the long run for changing both government and private sector behavior. However, this article focuses on more direct intervention and competition for better environmental performance within the private sector.

Technological change is now generally regarded as essential in achieving the next major advances in sustainable development. The necessary technological changes include the substitution of materials used as inputs, process redesign, and final product reformulation. The substitution of products by services may also be needed. Initiatives focusing on technological change need to address multimedia pollution and to reflect fundamental shifts in the design of products and processes. Distinguished from end-of-pipe pollution control, those new initiatives are known as pollution prevention, source reduction, toxics use reduction, or cleaner technology (OECD 1987).[1]

Whichever term is used, this article argues that the key to success in achieving a sustainable environment is to influence managerial knowledge of and attitudes toward *both* technological change and environmental concerns. Encouraging technological changes for

[1] In-process recycling and equipment modification are sometimes also included in the category of new initiatives. The term *waste reduction* is also used, but it appears to be less precise and may not include air or water emissions. Pollution prevention has also been discussed as a preferred way for achieving sustainable development, giving rise to the term *sustainable technology* (Heaton, Repetto, and Sobin 1991).

production purposes and for environmental compliance purposes must be seen as interrelated, rather than as separate, activities (Ashford, Heaton, and Priest 1979; Kurz 1987; Rip and van den Belt 1988; Schot 1992). In order to bring about this integration, managers must encourage their engineers, scientists, and technologists to work on environmental and safety concerns so that those concerns are reflected in both design and operational criteria of a firm's technology. This may require a fundamental cultural shift in the firm. A related cultural shift in the regulatory agencies that influence how firms respond to environmental demands is also essential.

The above discussion addresses managerial factors that influence technological change. The technology of the firm, however, also influences managerial style and may limit the kind and extent of technological changes that are likely or possible. Thus, the design of governmental or corporate policies for encouraging a fundamental shift in production technologies must rest on an appreciation of the different kinds of technological change, as well as the dynamics of achieving those changes under a regulatory stimulus.

Technological change can involve both innovation and diffusion. *Technological innovation*[2] is both a significant determinant of economic growth and important for reducing health, safety, and environmental hazards. It may be major, involving radical shifts in technology, or incremental, involving adaptation of prior technologies. *Technological diffusion,* which is the widespread adoption of technology already developed, is fundamentally different from innovation. The term *technology transfer* is somewhat imprecise, sometimes referring to the diffusion of technology from government to industry or from one industry or country to another. If that transfer involves significant modifications of the originating technology, the transfer can be said to result in incremental or minor innovation. Finally, the term *technology forcing* is used to describe regulation and is similarly imprecise, usually meaning forcing industry to innovate, but sometimes meaning forcing industry to adopt technology already developed and used elsewhere, i.e., technological diffusion.

The Evolution of Environmental Regulation

The discovery of harmful effects of chemical substances (including human-made chemicals, such as vinyl chloride; human-released chemicals, such as lead; and natural substances, such as radon) on human health and ecosystems has given rise to a variety of legislative responses. There have been several lines or waves of regulation addressing different problems (see Figure 1). Two early waves developed more or less concurrently. The first addressed media-specific emissions and effluents that were by-products of industrial production, energy use, and transportation activities. The end-products or uses neither depended nor focused on bioactivity or biologically active compounds. The emission by-products were mostly combustion products yielding carbon monoxide, sulfur dioxide, nitrogen oxides, particulates, ozone, and lead. The effluents of concern and components of hazardous waste were heavy metals and other oxygen-depleting materials or substances.

[2] Technological innovation is the first commercially successful application of a new technical idea. By definition, it occurs in those institutions, primarily private profit-seeking firms, that compete in the marketplace. Innovation should be distinguished from *invention,* which is the development of a new technical idea, and from *diffusion,* which is the subsequent widespread adoption of an innovation by those who did not develop it. The distinction between innovation and diffusion is complicated by the fact that innovations can rarely be adopted by new users without modification. When modifications are extensive, the result may be a new innovation. Definitions used in this article draw on several years' work at the Center for Policy Alternatives at the Massachusetts Institute of Technology, beginning with a five-country study (CPA 1975).

The second line of regulation focused on products and substances that were themselves intended to be bioactive and therefore were expected to have biological or ecological side effects. These included pharmaceuticals, such as thalidomide, and chemicals used in agriculture and food production, such as pesticides (DDT) and food additives (Red Dye No. 3).

Later, it was realized that many products not intended to be bioactive were in fact harmful to human health, as was the case with vinyl chloride and asbestos, and to ecosystems, as was the case with PCBs (polychlorinated biphenyls). A third resulting wave of regulation focused on processes while remaining substance-specific. This wave included regulations on occupational exposure, chemical production and industrial use, and consumer products.

More recently, concerns have focused on emerging biotechnologies, spanning every conceivable

MEDIA
Air
Water
Waste
Clean-up liability

PRODUCTS
Drugs
Pesticides
Food additives

PRODUCT AND PROCESS
Consumer products
Worker health and safety
Toxic substances

DEVELOPING AND RECENT INITIATIVES
Biotechnology
Indoor air

Figure 1. Four stages in the regulation of toxics

area in which synthetic inorganic and organic chemicals have been used historically, from pesticides to the remediation of hazardous wastes. Endocrine disruption from certain organo-chlorines is also of increasing concern, where adverse biological effects can occur in the parts per billion or trillion range, 3-6 orders of magnitude lower than conventional pollution effects. There is now also a focus on the indoor air environment in both homes and non-industrial work places where consumer products and building materials and practices converge and result in unintended side effects, exacerbated in part from decreasing building ventilation in an effort to respond to energy concerns. These sources give rise to sick-building syndrome, building-related illness, and chemical sensitivity at levels of exposure much lower than illness associated with conventional toxic effects. Tight building structures have also exacerbated the problem of radon exposure. The current wave of regulation is confronting health and environmental effects that may require substance bans or very much more stringent levels of control than previously thought necessary. New technology may be needed.

Examining and understanding this legislative evolution in the context of industrial and commercial activities that have contributed to environmental, occupational, and consumer hazards are necessary if we are to devise a technology-based strategy for prioritizing our concerns.

A technology-based strategy, which includes an emphasis on pollution prevention and cleaner technology, should not be confused with technology-based standards, where technologies of control or production are specified. In contrast, a technology-based strategy is focused on expanding the technological options for reducing or eliminating the variety of risks associated with production technologies, industrial materials, and consumer technologies, rather than constraining industry to adopt a particular technological solution. Oddly enough, the practice of *technology assessment* -- characterizing the consequences of using or deploying a specific technology -- mostly is not an assessment of technical options for replacing a given technology, and for our purposes here it relates to the conduct of risk assessment. Later, I describe what I have termed Technology Options Analysis (TOA) as an essential basis for a technology-based, as opposed to a risk-based, approach to environmental problems.

Legislation in the United States (the Pollution Prevention Act) and in the European Union (the Integrated Pollution Prevention and Control Technology Directive) has been enacted to reflect the realization that a focus on pollution prevention and cleaner technology, rather than on the control of emissions and effluents and the treatment of waste, is required for achieving a sustainable environment.

In the remainder of this article, I discuss the limitations of the traditional practices of risk-based approaches, the usefulness of regulatory impact analysis to guide decision making, and current technology-based standards and pollution prevention approaches. Finally, I propose an innovation-driven technology-based strategy that argues that regulation can be used creatively to foster the needed technological changes.

Risk Assessment and Risk-Based Approaches to Priority Setting

Risk assessment was described in 1983 in the now near-legendary report by the National Academy of Sciences (NAS 1983) as comprising four steps: (1) hazard identification, (2) dose-response assessment, (3) exposure assessment, and (4) risk characterization. Risk assessment, of course, has been and continues to be an activity fraught with methodological difficulties and challenges. Its results reflect choices of data, models, and assumptions, and it is an activity where both values and science necessarily enter. This is especially the case where there is considerable uncertainty, notwithstanding assertions that risk assessment can be clearly separated from risk management. (See Ashford 1988 for a critique of this view; also see Hornstein 1992.)

Perceptual and Political Influences on Risk-Based Priority Setting

Different environmental and health and safety legislation incorporates concerns for risk, costs, technology, and equity in different ways. While it might be said that there are inconsistencies among regulatory areas or regimes because the cost-per-fatality reduced differs markedly (Sunstein 1990; Travis and others 1987), those differences could well be explained by differences in the risk posture (i.e., risk neutrality or risk aversion) of various regulatory authorities, the nature of the risk addressed (for instance, voluntary versus involuntary, chronic versus acute, mortality versus morbidity), the characteristics of the risk bearers (such as sensitive populations, children, workers), and different mandates in the legislation itself on balancing the costs and benefits of regulations. The regulatory systems are risk-driven; i.e., action is triggered by the discovery or assessment of risk. However, the differences among regulatory agencies are not, in fact, necessarily "irrational," unless rationality is tautologically defined as minimizing cost per unit of population risk as quantified via a "best estimate" (Shrader-Frechette 1991).

The exercise of priority setting becomes incredibly complicated depending on the context. It is one thing to prioritize options for controlling occupational carcinogens; it is another to prioritize efforts to reduce hazards with such diverse consequences as cancer, emphysema, acute poisoning and traumatic accidents, even within the same industry or context of exposure. Simply counting fatalities from each hazard does not fully capture the human impact of these hazards. While heroic assumptions have been made to value a life lost in economic terms, we scarcely know where to begin with the far more prevalent effects of morbidity, attended by great differences in pain and suffering, or with ecological effects resulting in the loss of a species. Even when we are comparing like hazards, such as fatal accidents, it is not clear that we should place equal emphasis on valuing opportunities for, say, reducing occupational risk versus highway deaths.

Even if we were to make no distinctions in the type of injury sustained, society has seen fit through legislation to regard, for example, exposure to carcinogens (and more recently to endocrine disrupters) through additives to the food supply as different from other consumer exposures. If the priority-setting discussion intends to revisit the wisdom of existing legislative directives, it will need to decide on the weighting criteria and principles involving issues of risk profiles, risk types, distribution of risks among risk-bearers and of costs among cost-bearers, the nature of the assumption of risk and many other factors. While the political agenda can be altered, it is not clear that a rational, inherently correct system based on risk can be identified. Moreover, even seemingly simpler challenges, such as that of prioritizing water effluents, also become unwieldy in the real world.

The problems are not simply political. Since regulation focuses on controlling or reducing particularized or specific hazards, political demands are translated into contests between affected publics and affected industries over a specific hazard and often within such specific regulatory regimes as food additives, occupational exposure, community contamination, or consumer products. The legislative structure and risk assessments on a specific hazard define the debate.

One cannot prioritize particularized political demands. Crisis driven demands (such as those arising from Love Canal or from Alar on apples) divert resources from a general plan in order to address them in a timely fashion. More general political demands (such as for worker safety and environmental protection) are juggled in the annual budgeting process. On the other hand, even where political demands did not drive or bombard an agency, attempts to act ahead of political demand -- for instance, by prioritizing chemicals to be tested, ranking chemicals for riskiness, and finally regulating them -- led to difficulties. During the first four years of the implementation in 1976 of the Toxic Substances Control Act (TSCA) under a willing administration, the U.S. Environmental Protection Agency (EPA) became hopelessly bogged down in its efforts to build a rational system. Prioritizing even the 100 chemicals in most common use was hardly begun after four years of effort. In order to understand this lack of success, it is necessary to examine priority setting in greater detail.

The Inherent Nonuniformity in Priority Setting

Priority setting for addressing and remedying environmental problems involves the articulation of an organizing principle for setting priorities and the establishment of a social/political/legal process for implementing the system. Even left to its own devices -- and free from political pressures -- responsible government faces challenges at several levels.

Given that different environmental problems are managed by different regulatory agencies or offices and fall under different legislative mandates, the first question of priority setting concerns the relative allocation of resources to different regulatory regimes; for example, controlling air emissions versus pesticide registration. In practice, this is influenced largely by the political process and is not based on some rational analytical scheme. However, even if this initial allocation does not seem to be rational, greater or fewer environmental benefits can be realized depending upon the extent to which each regulatory regime coordinates its activities with the others. For example, simultaneous, though separate, requirements for controlling cadmium in occupational environments, water effluents, and consumer products can be more cost-effective than uncoordinated efforts spread out in time. Part of this cost-effectiveness stems from the fact that those firms responsible for cadmium use and production have an opportunity to adopt a multimedia focus, where changes in the technology of production can have multiple payoffs for reducing risks. Being able to achieve multiple environmental payoffs through coordinating various regulatory efforts could alter an agency's internal priority scheme (discussed later) by placing a particular substance/problem higher on its list than the substance/problem would have been placed based on a single regulatory focus.

Even in the best of political times, such as when the U.S. Interagency Regulatory Liaison Group (IRLG) was formed to coordinate efforts, the attempt to coordinate regulatory efforts was not entirely successful. Within EPA, the more recent establishment of "multi-office clusters" to promote integrated cross-media problem solving on specific pollutants (such as lead) or on specific industries (such as petrochemicals) or efforts to address indoor air pollution may eventually be more successful, but fundamental problems remain. Later, this article explores an approach whereby the coordination of agency efforts focuses not on regulation of a single substance or class of substances, but on establishing a concerted effort to change an industrial process or production technology.

Given the political influence on the allocation of resources to different regulatory regimes, it is understandable that government would turn its attention to establishing priorities *within* each regime, rather than among them. The internal priority system for taking action could take on any of three forms:

- ranking problems by the number of persons at risk;
- ranking problems by expected (maximum individual) risk (for instance, a lifetime risk of cancer of one in 1,000 would rank higher than a risk of one in 10,000); and
- ranking regulatory interventions by their health-effectiveness, i.e., the amount of risk reduced per compliance dollar expended.

Generating these priority schemes would, of course, rely on risk assessments (and as mentioned earlier, a way of weighing different kinds of risks). The third option would need, additionally, estimates of compliance cost. All three options would also need to reflect a determination of how much residual risk would be “acceptable” or permissible under various legislative mandates. Finally, all three options would need to establish the means by which compliance would be achieved. Cost-effective means would be preferred, except where unjustifiable inequities exist as to either the beneficiaries of protection (citizens, workers, consumers) or those who bear the costs (small versus large firms, different industrial sectors, and so forth). For example, it has been suggested that the Occupational Safety and Health Administration (OSHA) abandon efforts to protect all workers from asbestos or noise exposure when it becomes too expensive. Equity concerns for differential treatment of workers in different plants prohibit this approach. On the other hand, the Clean Air Act permits differential treatment of new plants under its New Source Performance Standards.

All the complexities involved in priority setting within regulatory regimes reveal priority-setting schemes that take many factors into account: risk, efficiency of reducing risk, equity, technological and economic feasibility, and responsiveness to public demands and private concerns. All extant schemes are used to rank hazards, not industrial processes or industrial sectors, and only OSHA and the Consumer Product Safety Commission have promoted significant technological changes. [See Ashford and Heaton 1983 for examples, such as PVC (polyvinyl chloride) polymerization and substitutes for PCBs; see also OTA 1995]. While there have been constant calls for uniform approaches to risk assessment and uniform balancing of regulatory costs and benefits, the legal mandates and individual cultures of different regulatory regimes prevent the achievement of uniformity. Although uniformity might be a preferred goal of some analysts, differences between agency approaches should not be too quickly labeled as inconsistencies. The differences may be defensible. Demands for consistency that move all systems to a lower common denominator of environmental protection may simply be motivated by antiregulatory interests. Demands for tighter levels of protection to achieve consistency are made by different players from those who demand relaxing "overly restrictive" regulatory systems.

Given that priority setting for regulation involves an integration of benefits, cost, and equity concerns, the next section of this article delves into the possible decision rules for trade-offs that are made in deciding whether and how far to go in controlling a particular risk. Determining the appropriate level of control or regulation for a particular risk is a necessary first step in creating a priority-setting scheme for many risks. In other words, since priority setting depends on ranking the opportunities for risk reduction, a decision has to be made first as to how much of each risk type we would want to reduce. To facilitate this determination, an impact analysis of different amounts of regulation needs to be undertaken.

Impact Analysis of Proposed Regulations

Priority setting often begins by evaluating the impacts of a proposed regulation or regulatory options. These impacts include economic and health consequences for a variety of actors, as well as effects on the environment. Comparing these different kinds of impacts (i.e., incommensurables) and valuing their distributional consequences among actors and over time present special difficulties. These difficulties are beyond the familiar problems of discovering or observing a market-based value for reducing risk, or of discounting future streams of economic, health, and environmental effects. Consider the qualitatively different effects a regulation may have on a variety of actors.[3] Table 1 is an impact matrix that attempts to clarify the differences among the economic, health and safety, and environmental effects of regulations and to elucidate the relationships among actors. For each type of actor, this matrix illustrates the consequences of a particular decision, such as regulating a particular technology. The actors are divided into four groups: producers, workers, consumers, and "others," which might include residents of communities downwind from a polluter. The last group is distinguished from workers and consumers because its members are usually unconnected with producers, being in neither a contractual nor an employment relationship (as are workers), nor in a commercial relationship (as are consumers). Workers, consumers, and the others also have no relationship with each other, either contractual or commercial.

Net costs, $C_\$$, include items that have been accepted, noncontroversial dollar values such as profits, wages, and medical costs, as well as the often-contested estimates of the costs of

[3] This discussion is taken in part from Ashford and Ayers 1985. See also Ashford, Ayers, and Stone 1985; Ashford and Caldart 1991.

compliance. Risk assessment methodologies are used to provide estimates in the second and third columns of the matrix. Health and safety benefits, $B_{H/S}$, include items that can be quantified but that are difficult to monetize or to compare, such as incidence of disease and changes in longevity, morbidity, and probability of harm. Analytic efforts have traditionally concentrated on reduced fatalities. Far more important, in terms of total impact, may be reductions in nonfatal injuries and disease. Environmental benefits $B_{Environment}$ include nonmonetizable items, such as the benefits of preserving a species or the recreational value of fishing. The monetizable environmental costs, such as those reflected in loss of property value, are included in the net costs, $C_\$$.

TABLE 1
Impact Matrix of Environmental and Safety Regulation

Actors	Economic Effects	Health/Safety Effects	Environmental Effects
Producers	$C_\$$		
Workers	$C_\$$	B_{H/S^*}	
Consumers	$C_\$$	B_{H/S^*}	
Others**	$C_\$$	B_{H/S^*}	$B_{Environment}$

* $B_{H/S}$ refers to benefits of reducing hazards that impair health and safety
** Those with no employment or commercial relationship with producers

In filling in the matrix (i.e., in undertaking an impact analysis), the net of inquiry must be cast broadly enough to capture all important effects -- those important in magnitude and in distributional terms. As Shrader-Frechette (1991) points out, the risk of partial quantification in cost-benefit analysis is that the qualitative effects are recognized in principle but ignored in the calculations. For example, in the case of reducing the use of chlorofluorocarbons (CFCs), the costs and benefits conferred by possible substitutes must also be included. Economic costs (profits lost in CFC production) must be considered, but so must economic gains (profits increased in substitutes production). A similar duality is warranted in analyzing health effects, although while it is possible that unanticipated significant health, safety, and environmental consequences could arise from substitutes, it is becoming less likely given the close scrutiny received by new products or new uses of existing products before they enter the market.

The Costs of Compliance

It is especially important to look closely at economic effects associated with regulatory compliance. It is often assumed that, because the costs of complying with regulations can be easily monetized, they are reliable estimates of true costs. Unfortunately, there are many instances in which the costs are not only uncertain, but unreliable. Agencies depend to a large extent on industry data to derive estimates of compliance costs. The bias of those estimates has often been questioned. The regulatory agencies themselves often do not have access to the information that would enable them to develop the best estimates of the costs of compliance, i.e., information concerning alternative products and processes and resultant costs. In addition, compliance cost estimates often fail to take three crucial issues into account:

- Economies of scale inevitably arise in the demand-induced increase in the production of compliance technology or environmentally sounder technology.
- A regulated industrial segment is able to learn over time to comply in a more cost-effective manner -- what management scientists call the "learning curve."
- Technological innovation yields benefits to both the regulated firm[4] and to the public intended to be protected.

Indeed, some environmental, health, and safety regulation has been recognized as "technology forcing" by the courts and by analysts. The costs of compliance should not be based on static assumptions about the firm and its technology (Porter and van den Linden 1995). Otherwise, a large overestimation of regulatory costs can result.[5] Further, in the case of a displacement of a product or technology by a new entrant (or a new response by the old firm), a total impact assessment must include the new profits, jobs, and opportunities created by that displacement or shift.

In the last analysis, the costs and benefits of a regulation must be compared against what might have happened in the absence of that regulation. For example, if we were to estimate the benefits and costs of adopting a safety standard for a consumer product, we must ask whether the producer industry might not have made the product somewhat safer in the absence of regulation by responding to increasing product liability suits in the courts (see Ashford and Stone 1991). In this example, it would not be correct to attribute to regulation either all of the costs expended or all of the benefits conferred. The alternative scenario chosen by the evaluator can make the actual regulation look better or worse. Unless we have an alternative universe that we can define with reasonable certainty for analytical purposes, evaluations of the effects of a regulation are on very shaky ground. Often we are certain that a regulation will be promulgated later, even if it may not be imminent. In this case, what promulgating the regulation promptly represents are the marginal costs and benefits compared to a later enactment.

Cost-Benefit and Trade-Off Analyses Distinguished

Having faithfully uncovered all the direct effects of a proposed regulation and expressed them relative to likely alternative scenarios, the analyst can take two very different courses of action: complete a traditional cost-benefit analysis or undertake a trade-off analysis (Ashford and Ayers 1985). A traditional cost-benefit analysis confers monetary values to all impacts, sums the costs, and compares those costs to the sum of benefits, irrespective of the parties to whom the costs or

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[4] Ashford et al. (1979, 1983, and 1985) and Porter and van den Linden (1995) have independently argued that there are "ancillary benefits" or "innovation offsets" to compliance costs for the firm in terms of the benefits of correcting production inefficiencies resulting from pollution. These may be of great economic benefit to innovating firms by conferring first mover advantages. Also see remarks in the concluding section of this article.

[5] The minimal effects of the OSHA vinyl chloride standard on the private sector is a striking example of how different the actual economic impacts can be, compared to some ominous preregulation predictions of the economic demise of the industry (Ashford, Hattis, et al. 1980). In 1995, the U.S. Office of Technology Assessment published a review of many OSHA standards, with the general finding that post-compliance costs were actually one-third to one-fifth the costs of the pre-promulgation estimates as a result of unanticipated technological changes (OTA 1995).

the benefits accrue. Regulations whose net benefits are positive are justified in economic terms. More correctly, regulations are permitted to the extent that the marginal benefits exceed marginal costs; i.e., risk reductions should only go as far as "appropriate levels." (See Figure 3, which graphs economic efficiency as a criterion for regulation, and its related discussion later in this article).

In other words, traditional cost-benefit analysis reduces all effects to a common metric and, aside from possibly valuing distributional effects in the utility functions of the actors themselves (see Keeney and Winkler 1985), is indifferent to distributional effects.[6] This indifference calls into question the usefulness of traditional cost-benefit analysis and, further more, may make it the wrong paradigm entirely. For example, the net benefit calculations for regulations that have long-term, multigenerational consequences may be insensitive to the effects felt in future generations because future health or environmental benefits are discounted to small present values. What justification is there in essentially disregarding the distributional inequities among generations? Perhaps there is something wrong with the traditional cost-benefit paradigm or at least with its application to certain types of problems (Mishan 1982).

Instead, the decision maker could use a trade-off analysis, which does not cloud the differences between factors such as health, environment, and economic costs. This approach also does not cloud the distinction between those who benefit and those who suffer as a result of adopting a particular regulation. The analyst must utilize the impact matrix in Table 1 without collapsing (summing) the economic, health, and environmental effects into a single metric or summing the benefits or costs across different actors or generations.[7] The decision maker/analyst is forced to express any decision in terms of, for example, trading costs to consumers and producers now for a variety of benefits to citizens over the next three generations. (As has been discussed above, the possible benefits of substitute products and new firms entering the market in economic, health, and environmental terms must also be explicitly considered). This explicit trade-off reveals the preferences of the analyst, preferences in terms of both the magnitude of the effects and their distributional or equity consequences. Requiring the analyst to make these explicit trade-offs prevents what Tribe (1984) terms "the sin of abdicating responsibility for choice." In this sense, the monetization of benefits and costs does not ensure analyst accountability: it actually facilitates obfuscation of the trade-offs.

In traditional cost-benefit analysis, maldistributions are invisible and hence ignored. Moreover, trade-off analysis allows an explicit consideration of societal or individual risk averseness to worst-case probabilities, not "expected values." In contrast, in traditional cost-benefit analysis, while there is explicit valuation of health, safety, and environmental factors in monetary terms, what is missing is explicit valuation of what is traded off for what.

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[6] Note here, especially, the application of the Kaldor-Hicks criterion for a *potential* Pareto improvement, whereby those made worse off by a regulation could be compensated by those made better off and a net positive benefit might still remain. The actual transfer between winners and losers, which is a condition for a Pareto improvement, is not usually required by the regulatory agency or analyst (Mishan 1981).

[7] This does not mean that the analyst cannot collapse some elements of the trade-off matrix into a single metric. Frequently, such a procedure is desirable for both analytical and practical reasons. The difference is that this should not be required or automatically done. The assumptions underlying the procedure, which blur distributional or other effects when utilized, must be explicitly introduced, whereas in the case of cost-benefit analysis, summing *all* effects into a single monetary figure is imposed by the very nature of the cost-benefit paradigm. The construction of a benefit-to-cost ratio is only slightly more desirable than a net benefit calculation and suffers from most of the same deficiencies.

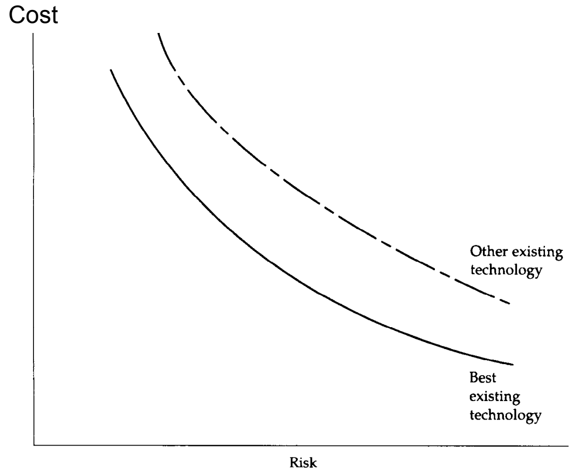

Figure 2. The efficient frontier for risk reduction compliance

It is also useful to compare an economic efficiency or cost-benefit approach to yet other alternatives. Consider the simplified case where the trade-offs involved are risks (to human health from an environmental carcinogen) versus costs (to the producer). In this case, referring to the impact matrix in Table 1, only two matrix elements predominate: producer costs and health/safety benefits to others. For different levels of environmental control, different benefits accrue. Figure 2 depicts the costs of risk reduction facing the producer as a function of different levels of risk. The curves represent the costs to reduce risks for a variety of different technological approaches open to the firm. At any given risk level, the point on the solid curve

represents the lowest cost approach using the best existing technology. This curve represents the *efficient frontier* for compliance with risk reduction regulation. As more and more risk reduction is required, the cost per unit of additional risk reduction increases to what economic analysts call "the point of diminishing returns," where enormous costs are incurred for small reductions in risk.

In Figure 3, we add to the curve representing the efficient frontier in Figure 2 a curve representing societal or worker demand for risk reduction as a function of risk. Where the two curves cross is the equilibrium point where the benefits of risk reduction equal the costs. [Note, strictly speaking, marginal cost and demand curves rather than total cost and demand curves should be used to determine the classical equilibrium point. However, the less stringent criterion that the benefits of regulations at least equal their costs is closer to political decision rules.] This is the "optimal" level of risk R_0 using economic efficiency criteria. Of course, public or worker demand must be expressed in monetary terms to use the efficiency criterion.

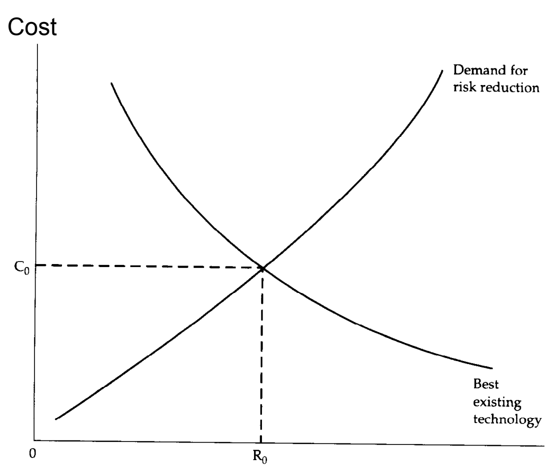

Figure 3. Equilibrium level of environmental risk as determined by costs of controls and perceived benefits

Alternatives to cost-benefit or efficiency criteria for choosing the appropriate level of risk reduction include:

- Reducing risk by imposing control options at the *limits of economic or existing technological feasibility*, i.e., the limits determined by rising cost curves as discussed. Maximum achievable control technology (MACT) in the Clean Air Act and OSHA standards are examples of this.
- Specifying *existing, easily accessible technologies* of control or production, usually "best available technology"(BAT) in the U.S context.
- Establishing a *strict health or environment-based standard* for a maximum acceptable risk, such as a lifetime excess cancer risk of one in one million, independent of cost considerations.

Requiring levels of risk reduction that represent more risk reduction than allowed by economic efficiency criteria usually can be justified on grounds of social justice or equity. However, economists are quick to point out that this uses scarce monetary resources inefficiently and can even give rise to negative effects.[8] As has been discussed earlier, different regulatory agencies impose different criteria for achieving risk reduction.

Regulatory regimes that establish acceptable levels of risk (the third approach), if stringent enough, may impose on industry the need to develop new technology or technological approaches giving rise to the label "technology-forcing regulation." Note that this is not technology-based standard setting, as the term is usually understood, represented in the first two approaches above. These two options only require the diffusion or adoption of technology already developed. However, all three options have the potential to shift the debate from risk to technology; for instance, which specific technology satisfies BAT or MACT requirements or whether industry can meet a strict, risk-based standard without developing new technology.

All the above discussion assumes that industry is already on the efficient frontier and is providing some level of risk reduction. If a particular firm is above the efficient frontier in Figure 2 (i.e., the firm finds itself on the dashed line and is not using the most cost-effective technology to comply with regulations), a technology-based regulatory focus may encourage it to change the particular technology it is using. It is here that the oft-heralded pollution prevention approach is relevant. For those firms not already using the best available technologies, costs of achieving compliance could be greater than for firms on the efficient frontier. However, firms that declined to devote expenditures in the past could in principle use the monies not spent in order to leapfrog to more cost-effective means of compliance especially by using pollution prevention options.

Technology-Based Standards and Pollution Prevention Distinguished: Does Either Go Far Enough?

For the purposes of discussion here, technology-based standards can be standards that either specify a particular control technology or material use or those that direct that control technology used be the best available or that which achieves the maximum pollution reduction achievable.

[8] See the inappropriate proposals for the use of risk-risk analysis by Keeney (1990) and resulting criticism of that approach (U.S. GAO 1992).

(As discussed below, using these standards is to be distinguished from a technology-based *strategy* for addressing environmental problems.) The success of a governmental program predicated on technology-based standards can be evaluated by the extent to which individual firms and sectors adopt the most efficient technology for the level of risk reduction they each are obligated to achieve,[9] and the extent to which the collective effort achieves the risk-reduction goal, reflecting both health and equity concerns.

In the last decade, we have witnessed four basic technological responses implemented by some firms: advances in control technology, input substitutes, changes in final products, and process redesign. (These last three types of technological response constitute the preferred hierarchy of what is called pollution prevention. They were developed slowly as limits were reached on the ability to make significant advances by controlling pollution at the "end of the pipe.") In other words, over time the efficient frontier depicted in Figure 2 has moved downward and to the left toward greater efficiency and more risk reduction. Furthermore, the mix of technologies becomes “richer” in pollution prevention options as traditional end-of-pipe approaches reach their limits of effectiveness. However, in the United States most firms over the period 1980-1992 did not move to the new frontier because enforcement of environmental laws had been lax. At the same time for those firms whose environmental performance was advancing, its productivity gains were also advancing due to technological changes. However, most firms were slow to change their technologies. Gradually at first, faced with numerous constraints -- increasing prohibition on landfills, off-site treatment costs, regulations on publicly owned treatment works, growth restrictions in nonattainment areas for air emissions, public scrutiny through community right-to-know laws, and environmental liability exposure -- firms began to embrace pollution prevention.

It has been said that all industry needs to change its technology is a wake-up call. But what changes can we expect? Here, the past predicts the future. Except for product-based firms that focus continuously on new product development, what has occurred largely is diffusion-driven pollution prevention -- adaptation of technology that exists elsewhere and is only new *to the firm* (See U.S. EPA 1991; INFORM 1985, 1992). A search by the regulated firm for better technologies to reduce pollution, considering only existing off-the-shelf technological options, does not require a cultural shift toward *developing* new technology -- i.e., toward innovation. The evidence shows that the bulk of pollution prevention efforts that move firms to the new efficient frontier have involved "picking the low-hanging fruit" -- i.e., using substitutes and technology already proven and used by a small number of firms, here or abroad. This tendency is useful in its own right, but eventually it is of limited benefit and unlikely to be long-lasting as more and more firms approach the efficient frontier. Of course, if some firms truly innovate, not all of them need to do so. The rest can simply adopt the new technologies developed by the technological leaders. What is important is to ensure that there is continuous leadership and innovation and that technology does not stagnate.

The much-heralded banning of CFCs, it should be remembered, did not bring about a new product. Rather, it allowed the substitution of an already-developed one with less ozone-depleting properties, but one that is an animal carcinogen (Zurer 1992). Had the Montreal Protocol been established with a longer time line for compliance, perhaps a different solution

[9] Note that in some regulatory regimes, different firms may be required to respond differently. For example, under the Clean Air Act, new sources have more restrictions than existing sources, and states can impose different emission requirements on various existing sources, reflecting differences in their situations.

would have been developed by new entrants rather than one promoted by the dominant existing firms from old options. In other words, competition could have been created to develop a new and safer substitute for CFCs, had the dominant firms not been able to capture the international regulatory regime. Without sufficient advance notice requiring new substitutes and specifying the unacceptability of all current substitutes, no firm or entrepreneur would be likely to develop new substitute products. It should also be realized that pollution prevention options chosen from existing technologies are likely to be similar to the status quo -- for example, the substitution of one organic solvent for another. Dramatic changes, such as the mechanical (pump) delivery system replacing CFC aerosol systems, are likely to require innovation.

Formulation of a "Win-Win" Technology-Based Strategy

The technology-forcing capability of regulation has been documented (Ashford and Heaton 1983), and theory has been developed on how to use regulation to encourage appropriate technological responses, be they new products, input substitution, or process re-design (Ashford, Ayers, and Stone 1985; Ashford et al. 1993). The challenge is how to use environmental regulation for win-win payoffs for *co-optimizing* growth, energy efficiency, environmental protection, worker safety, and consumer product safety. The idea is not fanciful, but it requires a shift from adopting technology new to the firm (diffusion) to developing new technology (innovation). Innovation can yield better performance for both environmental purposes and for productivity, but it is risky and requires that the firm be both capable and willing to innovate. Regulation, properly designed, can bring about a cultural shift in the firm or create opportunities for new entrants with better ideas.

Direct and Indirect Benefits of Regulation

It is significant that in its report *Preserving Our Future Today: Strategies and Framework* (U.S. EPA 1992), EPA moved from an approach that recommends choosing the options for risk reduction from existing technologies -- the Science Advisory Board's (SAB) report *Reducing Risk (U.S.* EPA 1990) -- to one recommending a greater reliance on economic incentives and innovation. In the later report, EPA states:

> Market forces are also part of a dynamic that produces innovations in technology and continued improvement in environmental protection will depend, in large part, on technological innovation. Economic incentives, for example, provide an important stimulus for creative pollution prevention and control. Innovative technologies include remedial methods, source reduction, treatment technologies, safer product substitutes, process controls and pollution controls. (U.S. EPA 1992)

What EPA as an agency has not addressed is *the strategic value of the combined interventions of regulation and economic incentives for directed innovation-driven pollution prevention.* However, the EPA National Advisory Council on Environmental Policy and Technology (NACEPT), in contrast to the SAB, has taken a technology-focused approach to environmental problems (NACEPT 1991, 1992, 1993). It is interesting to compare its work with that of the risk-focused SAB.

In devising a regulatory strategy, it must be realized that the benefits derived from direct regulation are only a part of the benefits that can be obtained from the regulatory process. Indirect, or leveraged, benefits are derived from the pressure of regulation to induce industry to deal preventively with unregulated hazards, to innovate, and to find ways to meet the public's need for a cleaner, healthier environment while maintaining industrial capacity. To put it another way, the positive side effects that accompany regulation need to be included in a complete assessment of the effectiveness of the agency's strategies. An example of leveraging is apparent in the observation that chemical companies are now routinely conducting short-term tests on new chemicals for possible carcinogenic activity, even though no general regulatory requirement exists. Specific regulations also induce leveraging. These indirect but by no means small effects are rarely included in any analysis.

Referring to the impact matrix in Table 1 discussed earlier, the leveraged effects rightly should be included in the assessment of the effects of regulation. They can be larger than direct effects. But further, an appreciation of the leveraging possibilities for regulation suggests an entirely new way to design strategies for approaching and prioritizing environmental problems. In developing this strategy, one must first understand how regulation can be used to influence the kinds of technological responses to meet environmental demands.

Regulation and Dynamic Efficiency

Several commentators and researchers have investigated the effects of regulation on technological change (Ashford 1993; Ashford, Ayers, and Stone 1985; Ashford and Heaton 1983; Hemmelskamp 1997; Irwin and Vergragt 1989; Kemp 1994 and 1997; Kurz 1987; Magat 1979; OECD 1985; Rothwell and Walsh 1979; Stewart 1981; Strasser 1997). Based on this work and experience gained from the history of industrial responses to regulation over the past twenty years, it is now possible to fashion regulatory strategies for eliciting the best possible technological response to achieve specific health, safety, or environmental goals. A regulatory strategy aimed at stimulating technology change to achieve a significant level of pollution prevention rejects the premise of balance: that regulation must achieve a *balance* or compromise between environmental integrity and industrial growth, or between job safety and competition in world markets.[10] Rather, such a strategy builds on the thesis that health, safety, and environmental goals can be co-optimized with economic growth through technological innovation (Ashford, Ayers, and Stone 1985).

The work of Burton Klein (1977) best describes the kind of industry and economic environment in which innovation flourishes. Klein's work concerns the concept of dynamic efficiency, as opposed to the static economic efficiency of the traditional economic theorists. In a state of *static efficiency,* resources are used most effectively within a fixed set of alternatives. *Dynamic efficiency,* in contrast, takes into account a constantly shifting set of alternatives, particularly in the technological realm. Thus, a dynamic economy, industry, or firm is flexible and can respond effectively to a constantly changing external environment.

Several conditions are critical to the achievement of dynamic efficiency. A dynamically efficient firm is open to technological development, has a relatively nonhierarchical structure, possesses a high level of internal and external communication, and shows a willingness to redefine organizational priorities as new opportunities emerge. Dynamically efficient industry groups are open to new entrants with superior technologies and encourage "rivalrous" behavior among industries already in the sector. In particular, dynamic efficiency flourishes in an environment that is conducive to entrepreneurial risk-taking and does not reward those who adhere to the technological status quo. Thus, Klein emphasizes structuring a macroeconomy that contains strong incentives for firms to change, adapt, and redefine the alternatives facing them. Regulation is one of several stimuli that can promote such a restructuring of a firm's market strategy.

While a new technology may be a more costly method of attaining *current* environmental standards, it could achieve *stricter* standards at less cost than adoption of existing technology. Figure 4 illustrates the difference, as explained below.

[10] Environmental, health, and safety regulation, as seen by economists, should correct market imperfections by internalizing the social costs of industrial production. Regulation results in a redistribution of the costs and benefits of industrial activity among manufacturers, employers, workers, consumers, and other citizens. Within the traditional economic paradigm, economically efficient solutions reflecting the proper balance between costs and benefits of given activities are the major concern.

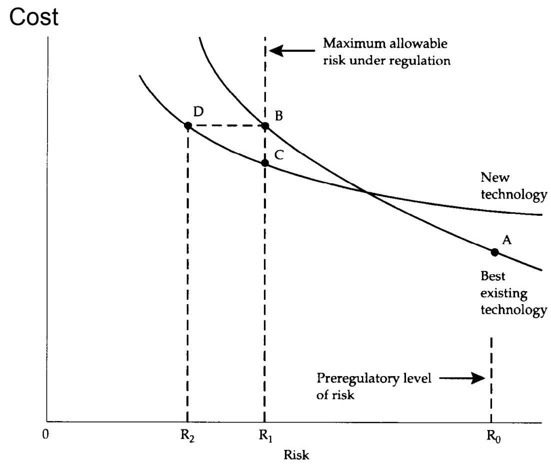

Figure 4. An innovative response to regulation

Suppose that either market demand or regulatory fiat determines that a reduction in risk from R_0 to R_l is desirable. Use of the most efficient existing technology would impose a cost represented by point B. Again, the "existing technology" curve represents the supply of lowest-cost technologies from among less-efficient existing technological options for achieving various levels of environmental risk. This curve is thus the present efficient frontier of existing pollution control and production technologies having different degrees of environmental risk. However, if it were possible to stimulate technological innovation, a new technology "supply curve" could arise, allowing the same degree of risk reduction at a lower cost represented by point C. Alternatively, a greater degree of health protection (R_2) could be offered if expenditures equal to costs represented by point B were applied instead to new technological solutions (point D). Note that co-optimization resulting in having your cake and eating it too can occur because a new *dynamic* efficiency is achieved.[11] Because end-of-pipe approaches have been used for a long time and improvements in pollution control have probably reached a plateau, it is argued that the new technology curve or frontier will be occupied predominantly by pollution prevention technologies (i.e., new products, inputs or production processes). Initiatives to bring firms into environmental compliance using new technologies are termed innovation-driven pollution prevention.

A Model for Regulation-Induced Technological Change

Prior work has developed models to explain the effects of regulation on technological change in the chemical, pharmaceutical, and automobile industries (Ashford and Heaton 1979, 1983;

[11] The firm could improve its efficiency in risk management by using better end-of-pipe control technology or by engaging in pollution prevention, which could be accomplished if the firm changed its inputs, reformulated its final products, or altered its process technology by adopting technology new to the firm. This would be characterized as diffusion-driven pollution prevention, and the changes, while beneficial, would probably be suboptimal because the firm would achieve static, but not dynamic, efficiency. If one were to add to Figure 4 the societal demand for risk reduction, the equilibrium point would occur at lower cost and risk than that in Figure 3.

Ashford, Heaton, and Priest 1979; Kurz 1987; Rip and van den Belt 1988). Figure 5 presents a modified model to assist in designing regulations and strategies for encouraging pollution prevention rather than sharply to trace the effects of regulation on innovation. The particulars of this model -- the nature of regulatory stimulus, the characteristics of the responding industrial sectors, and the resulting design of innovative technological and regulatory strategies -- are discussed below.

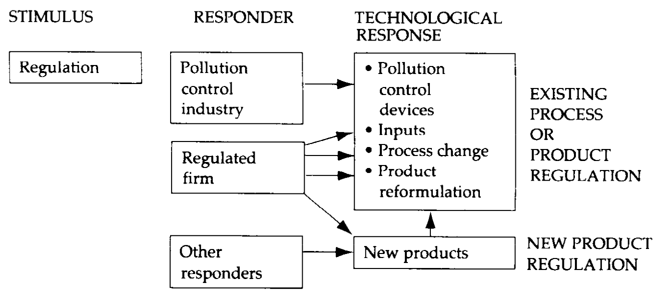

Figure 5. A model for regulation-induced technological change

The Regulatory Stimulus

Environmental, health, and safety regulations affecting the industry that uses or produces the regulated chemical include controls on air quality, water quality, solid and hazardous waste, pesticides, food additives, pharmaceuticals, toxic substances, workplace health and safety, and consumer product safety.[12] These regulations control different aspects of development or production; they change over time; and they are "technology-forcing" to different degrees.[13] Thus, designers of regulation should realize that the effects on technological innovation will differ among regulations that ensure the following conditions:

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[12] The statutes from which these regulatory systems derive their authority are as follows (listed as ordered in the text). Clean Air Act (CAA), 42 U.S.C. Sec. 7401-7642 (1990); Clean Water Act (CWA), 33 U.S.C. Sec. 1251-1376 (1982); Resource Conservation and Recovery Act (RCRA), 42 U.S.C. Sec. 6901-6987 (1982); Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), 7 U.S.C. 136 136y (1982); Federal Food, Drug, and Cosmetic Act (FDCA), 21 U.S.C. Sec. 301 392 (1982); Toxic Substances Control Act (TSCA), 15 U.S.C. Sec. 2601-2629 (1982); Occupational Safety and Health Act (OSHA), 29 U.S.C. Sec. 651-678 (1982); and Consumer Product Safety Act (CFSA), 15 U.S.C. Sec. 2051-2083 (1982).

[13] Technology-forcing here refers to the tendency of a regulation to force industry to develop new technology. Regulations may force development of new technology by different types of restrictions. For example, air and water pollution regulation focuses on "end-of-pipe" effluents. See, for example, CAA, Sec. 111, 112, 202, 42 U.S.C. Sec. 7411, 7412, 7521; CWA, Sec. 301, 33 U.S.C. Sec. 1311. OSHA, in contrast, regulates chemical exposures incident to the production process. See OSHA, Sec. 6, 29 U.S.C. Sec. 655. The FDCA, FIFRA, and TSCA impose a premarket approval process on new chemicals. See FDCA, Sec. 409, 505, 21 U.S.C. Sec. 348, 355; FIFRA, Sec. 3, 7 U.S.C. Sec. 136a; TSCA, Sec. 5, 15 U.S.C. Sec. 2604. The degree of technology-forcing ranges from pure "health based" mandates, such as those in the ambient air quality standards of the Clean Air Act, to a technology diffusion standard, such as "best available technology" under the Clean Water Act. CAA Sec. 109(b)(1), 42 U.S.C. Sec. 7409(b)(1); CWA, Sec. 301(b), 33 U.S.C. Sec. 1311(b). For a discussion of this issue and a comparison of statutes, see LaPierre 1977.

- Product safety must be demonstrated prior to marketing (pesticides, food additives, pharmaceuticals, and in some cases new chemicals). [14]
- The efficacy of products must be demonstrated prior to marketing (pharmaceuticals). [15]
- Product safety must be proved or product use must be controlled after marketing (for existing chemicals under the Toxic Substances Control Act, for worker protection, and for consumer products). [16]
- Production technology is controlled to reduce risks to workplace health and safety.[17]
- Emissions, effluents, or wastes are controlled in accordance with air, water, and hazardous waste regulation.[18]

Furthermore, the internal structure of regulations may alter the general climate for innovation. Elements of that structure include the form of the regulation (product versus process regulation), the mode (performance versus specification standards), the time for compliance, the uncertainty, the stringency of the requirements, and the existence of other economic incentives that complement the regulatory signal. The importance of these elements is discussed below; historical evidence is found in Ashford and Heaton 1983 and in Ashford, Ayers, and Stone 1985.

The distinction between regulation of products and regulation of processes suggests yet a further distinction.[19] New products differ from existing products, and production process components differ from unwanted byproducts or pollutants.[20] Regulations relying on detailed specification standards or on "best available technology" may discourage innovation while prompting rapid diffusion of state-of-the-art technology. Though a phased-in compliance schedule allows a timely industry response, it may prompt only incremental improvements in technology.

An industry's perception of the need to alter its technological course often precedes promulgation of a regulation. Most environmental regulations arise only after extended scrutiny of a potential problem by government, citizens, workers, and industry. Prior scrutiny often has greater effects on industry than formal rule making, because anticipation of regulation stimulates innovation (Ashford, Hattis, et al. 1979). For example, formal regulation of PCBs occurred years after the government expressed initial concern. Aware of this concern, the original manufacturer and other chemical companies began to search for substitutes prior to regulation.

[14] See FIFRA, Sec. 3, 7 U.S.C. Sec. 136a; FDCA, Sec. 409, 505, 21 U.S.C. Sec. 348, 355; TSCA, Sec. 5, 15 U.S.C. Sec. 2604.

[15] See FDCA, Sec. 505, 21 U.S.C. Sec. 355.

[16] See TSCA, Sec. 6, 15 U.S.C. Sec. 2605; OSHA, Sec. 6, 29 U.S.C. Sec. 655; CPSA, Sec. 7,15 U.S.C. Sec. 2056.

[17] See OSHA, Sec. 3(8), 6, 29 U.S.C. Sec. 652(8), 655.

[18] See generally CAA, 42 U.S.C. Sec. 7401-7642; CWA, 33 U.S.C. Sec. 1251 1376; RCRA, 42 U.S.C. Sec. 6901-6987.

[19] In practice, product and process regulations may be difficult to distinguish. If a process regulation is stringent enough, it effectively becomes a product ban. Product regulation generally gives rise to product substitution, and process regulation generally gives rise to process change (Ashford and Heaton 1979, 1983).

[20] Note, however, that component regulations normally specify elements of the production process designed to prevent undesirable by-products, while pollutant regulations specify unwanted by-products of production.

Similarly, most firms in the asbestos products industry substantially complied with OSHA asbestos regulation years before it was promulgated. This preregulation period can allow industry time to develop compliance technologies, process changes, or product substitutes while allowing leeway for it to adjust to ensure continued production or future commercial innovation.

The government's initial show of concern is often, however, an unreliable stimulus to technological change. Both technical uncertain ties and application of political pressures may cause uncertainty regarding future regulatory requirements. Nevertheless, some regulatory uncertainty is frequently beneficial. Although excessive regulatory uncertainty may cause industry inaction, too much certainty will stimulate only minimum compliance technology. Similarly, excessively frequent changes to regulatory requirements may frustrate technological development.

Regulatory stringency is the most important factor influencing technological innovation. A regulation is stringent either because compliance requires a *significant reduction* in exposure to toxic substances, because compliance using existing technology is *costly,* or because compliance is not possible with existing technology and hence requires a *significant technological change.* Legislative policy considerations dictate different degrees of stringency as well, since some statutes require that standards be based predominantly on environmental, health, and safety concerns; some on existing technological capability; and others on the technology within reach of a vigorous research and development effort.

In the early 1970s, most environmental, health, and safety regulations set standards at a level attainable by existing technology (LaPierre 1977). The regulations reflected both perceived limits to legislative authority and substantial industry influence over the drafting of standards. More recent regulations have tended toward greater stringency, but they still rely on existing technologies (but often those in minority or rare use).[21] (Examples are the technology-based standards for hazardous substances under Section 112 of the 1990 Clean Air Act Amendments requiring the use of MACT or the lowest achievable emission rate [LAER] under the new source regulation of Section 111). The effect of the agency's strategy on innovation is not confined to standard setting. Innovation waivers, which stimulate innovation by allowing noncompliance with existing regulation while encouraging the development of a new technology, are affected by enforcement strategies as well (Ashford, Ayers, and Stone 1985).[22] The degree to which the requirements of a regulation are strictly enforced may influence the willingness of an industrial sector to attempt to innovate. The implementing agency ultimately may strictly enforce environmental regulations against those firms receiving waivers or, alternatively, it may adopt a "fail-soft" strategy where a firm has made an imperfect but good faith attempt to comply (Ashford, Ayers, and Stone 1985). The latter strategy is an important element of the regulatory stimulus to innovate, as it decreases an innovator's risk of severe agency action in the event of failure.

[21] This statement is based mainly on a review of the literature on regulations under the CAA, CWA, OSHA, CPSA, RCRA, and TSCA promulgated in the period 1970-1985. For a more current commentary, see Strasser (1997).

[22] EPA has also initiated a pollution prevention element in enforcement negotiations for firms in violation of standards (i.e., the agency is encouraging state officials to press for the adoption of pollution prevention approaches by polluters in reaching settlements for violations of environmental laws and regulations). See Becker and Ashford 1995.

Characteristics of the Responding Industrial Sector

The industry responding to regulation may be the regulated industry (or its suppliers), the pollution control industry, or another industry (see Figure 5). Regulation of existing chemical products or processes might elicit installation of a pollution control device, input substitution, a manufacturing process change, or product reformulation. The regulated industry will likely develop new processes and change inputs, sometimes with the aid of its suppliers; the pollution control industry will develop new devices; and either the regulated industry or new entrants will develop reformulated or new products. Regulation of new chemicals (such as premarket screening) will, of course, affect the development of new products.

Past research on the innovation process in the absence of regulation has focused on the innovation dynamic in diverse industrial segments throughout the economy (see Abernathy and Utterback 1978; Ashford and Heaton 1983). The model of the innovation process on which that research focused refers to a “productive segment” (a single product line) in industry, defined by the nature of its technology. Automobile engine manufacture would be a "productive segment," as would vinyl chloride monomer production, but neither the automobile industry nor the vinyl chloride industry would be a "productive segment" since they both encompass too many diverse technologies. Over time, the nature and rate of innovation in the segment will change. Initially, the segment creates a market niche by selling a new product, superior in performance to the old technology it replaces. The new technology is typically unrefined, and product change occurs rapidly as technology improves.[23] Because of the rapid product change, the segment neglects process improvements in the early period. Later, however, as the product becomes better defined, more rapid process change occurs. In this middle period, the high rate of process change reflects the segment's need to compete on the basis of price rather than product performance. In the latter stages, both product and process change decline and the segment becomes static or rigid. At this point in its cycle, the segment may be vulnerable to invasion by new ideas or disruption by external forces that could cause a reversion to an earlier stage.

The Design of Strategies

Three implications of this innovation model relate directly to the design of strategies to promote innovation.

- First, the model suggests that innovation is predictable in a given industrial context.
- Second, it asserts that the characteristics of a particular technology determine the probable nature of future innovation within an industrial segment.
- Third, it describes a general process of industrial maturation that appears to be relatively uniform across different productive segments (see Ashford and Heaton 1983). This process is related to the eventual decrease in the ability of an industrial product line to innovate along either product or process-dimensions. This model does not, however, describe sources of innovation within the firm, nor does it elucidate the forces that may transform a mature segment into a more

[23] It is typical for the old technology to improve as well, although incrementally, when a new approach challenges its dominance.

innovative one. See Rip and van den Belt (1988), Schot (1992), and Kemp (1997) for insights into these dynamics.

The value of this theory of innovation is that it provides a rationale upon which the regulatory agency may fashion a regulation aimed at the industry most likely to achieve a regulatory goal and by which the private sector can develop a more appropriate response to environmental problems. Consistently, the theory relies on the assumption that *the regulatory designer can determine the extent of an industry's innovative rigidity (or flexibility)* and its likely response to regulatory stimuli with reference to objectively determinable criteria. The regulatory designer must make the following three determinations:

- What technological response is desirable?[24]
- Which industrial sector is most likely to diffuse or to develop the desired technology?
- What kinds of regulation and incentives will most likely elicit the desired response?

The first determination requires a technology options analysis, the second a knowledge of a variety of industrial segments, and the third an application of the model presented above.[25]

In sum, regulations must be designed explicitly with technological considerations in mind -- i.e., regulations should be fashioned to elicit the type of technological response desired. Again, both stringency and flexibility (through innovation waivers or enforcement practices) are important. Enforcement and permitting procedures must augment, not frustrate, the regulatory signals (see NACEPT 1991, 1992, 1993).

Regulatory design and implementation are largely in the hands of government, the exception being negotiated rule making or "voluntary" compliance efforts involving an industry-government effort.[26] Once the regulatory signals are crafted, the firm must be receptive to those signals that require change. As discussed at the beginning of this article, the key to successfully changing the firm is to influence both managerial *knowledge* and managerial *attitudes* affecting decision making that involves both technological change and environmental concerns.

Managerial knowledge, managerial attitudes, and the technological character of the firm are not actually independent factors, however, although policies can be devised to affect each directly. Managerial attitudes and responses obviously are influenced both by incentives and by the knowledge base and general practices and procedures (i.e., the culture) of the firm. Management's attitudes and responses to environmental problems may also be determined or constrained by the particular technology of the firm itself. There is a kind of "technological determinism" that influences not only what can be done, but also what will be done. For example, firms that have rigid production technologies (i.e., processes that are infrequently changed) are unlikely to have managers confident enough to embark on process changes. Certain technologies beget specific management styles -- if not particular managers per se. There is probably also a managerial selection in and out of the technology-based firm. For

[24] For example, should a regulation force a product or a process change (see Rest and Ashford 1988) and, further, should it promote diffusion of existing technology, simple adaptation, accelerated development of radical innovation already in progress, or radical innovation?

[25] Ashford and Stone (1985) review and develop methodologies for assessing past and future dynamic regulatory impacts involving technological change.

[26] For a detailed examination of negotiated agreements in both the environmental and worker health and safety areas, see Caldart and Ashford (1999).

example, if changing or reformulating the final product requires a process using a different scale of production, the firm may not have managers experienced at operating at smaller (or larger) scales.

Relevant to managerial attitudes and decision processes, Karmali (1990) reviewed three different theoretical approaches useful in understanding what influences managerial attitudes that affect the willingness (or even the ability) of the technology-based firm to undergo change.

Technological determinism is based on the principle that technological developments have their own dynamics and constraints that determine the direction of change even when stimulated by external forces.[27] Economic *determinism* considers the market and economic competition to be the main driving forces behind technological innovation. Essentially, this approach treats technology as a black box. Unlike the first two approaches, *social constructivism* attempts to move away from such unidirectional models and suggests that different social groups, such as the users of the technology and those potentially affected by it or its impacts, are able to exert influence on those who develop the technology. Any technological change is thus seen as the product of a dynamic interaction, rather than one deriving force from inside or outside the firm. Social constructivism can thus be viewed as a means of bridging the gap between the organizational internalists and externalists (Cramer et al. 1989; Cramer et al. 1990; Karmali 1990; Kemp 1994 and 1997; OECD 1989; Rip and van den Belt 1988; Rennings 1998; Schot 1992).

All these factors may well influence managerial attitudes and hence decision making toward environmental demands. But further, policy instruments that *per se* affect technology, economic incentives, and social relationships can be used to influence the firm toward a more socially optimal technological response to environmental problems.

Decisions, of course, are also affected by the knowledge base of the firm. This can be improved by requiring the firm to identify technological options for source reduction and to conduct through-put analysis, i.e., a materials accounting survey (Hearne and Aucott 1992; NAS 1990). The regulatory agency can also provide or promote technical assistance to firms, demonstration projects, continuing education of engineers and materials scientists, and the use of appropriate engineering consulting services (Ashford, Cozakos, et al. 1988).

Priority Setting Using a Technology-Based Strategy

Described above is the design of technology-based strategies that promote technological changes, whether via diffusion or innovation. Next, one might ask how to devise a priority-setting scheme using a technology-based strategy for addressing the many environmental problems facing an agency. Such a scheme is outlined below. First, the issue of information needs to be addressed. In risk-based approaches, much effort might be devoted to performing animal studies (costing upwards from S2,000,000 each), exposure studies, epidemiological studies, and risk estimates. In a technology-based approach, what is required first is a technology options analysis.

[27] While much has been written on the influence of the organization of the firm (Karmali 1990; Kurz 1987; U.S. OTA 1986; Schot 1992), it is the author's contention that the technology of the firm can determine corporate structure and attitudes as much as the other way around.

The Technology Options Analysis

In order to facilitate pollution prevention or the shift to cleaner technologies, options for technological change must be articulated and evaluated according to multivariate criteria, including economic, environmental and health/safety factors. The matrix developed to facilitate trade-off analysis (see Table 1) can be used to document the aspects of the different technology options and, further, it can be used to compare improvements that each option might offer over existing technological solutions. The identification of these options and their comparison against the technology in use is what constitutes Technology Options Analysis (TOA). Hornstein (1992) points out, in contrast, that "it is against the range of possible solutions that the economist analyzes the efficiency of existing risk levels" and that "to fashion government programs based on a comparison of existing preferences can artificially dampen the decision makers' actual preference for changes were government only creative enough to develop alternative solutions to problems" (Hornstein 1992).

At first blush, it might appear that TOA is nothing more than a collection of multivariate impact assessments for existing industrial technology and alternative options. However, it is possible to bypass extensive cost, environmental, health and safety, and other analyses or modeling by performing *comparative analyses* of these factors (such as comparative technological performance and relative risk and ecological assessment). Comparative analyses are much easier to do than analyses requiring absolute quantification of variables, are likely to be less sensitive to initial assumptions than, for example, cost-benefit analysis, and will enable easier identification of win-win options. Thus, while encompassing a greater number of technological options than simple technology assessment (TA), the actual analysis would be easier and probably more believable.

TOAs can identify technologies used in a majority of firms that might be *diffused* into greater use, or technologies that might be *transferred* from one industrial sector to another. In addition, opportunities for technology development (i.e., innovation) can be identified. Government might merely require the firms or industries to undertake a TOA.[28] On the other hand, government might either "force" or assist in the adoption or development of new technologies. If government takes on the role of merely assessing (through TA) new technologies that industry itself decided to put forward, it may miss the opportunity to encourage superior technological options. Only by requiring or undertaking TOAs itself is government likely to facilitate major technological change. Both industry and government have to be sufficiently technologically literate to ensure that the TOAs are sophisticated and comprehensive.

Encouraging technological change may have payoffs, not only with regard to environmental goals, but also to energy, workplace safety, and other such goals. Because many different options might be under taken, the payoffs are somewhat open-ended. Hence, looking to prioritize different problem areas cannot be the same kind of exercise as a risk-assessment-based approach. A fraction of the amount of money devoted to a single animal study could instead yield some rather sophisticated knowledge concerning what kinds of technology options exist or are likely in the future. Expert technical talent in engineering design and product development can no doubt produce valuable information and identify fruitful areas for investment in technology development.

[28] For development of the argument that government should require technology options analysis in the context of chemical process safety, see Ashford, Gobbell, et al. 1993 and Ashford 1997.

Innovation-Driven versus Diffusion-Driven Strategies

Problem areas for encouraging technological change, by their nature, turn out not to be substance-focused, but rather industrial-process focused, so that by a single technological change, one might address not only multimedia concerns for many chemicals associated with the process, but also consumer and worker safety. One kind of prioritization that can proceed is *the identification of areas in which innovation, as opposed to diffusion, might be preferred.* Table 2 lists some of the characteristics of the polluting technology, the replacing technology, and the hazards addressed that favor an innovation -- or a diffusion-driven approach.

Table 2. Conditions favoring innovation-driven and diffusion-driven strategies

Innovation	Diffusion
Large residual risks even after diffusion and/or high costs of diffusion	Distance from the efficient frontier (opportunities for significant and adequate risk reduction)
Innovative history/innovative potential or opportunity for new entrant	Noninnovative history; "essential" industry/product line
Multimedia response desired	Single-medium response adequate
Multihazard industry	Single-hazard problem
Flexible management culture	Rigid management culture

Knowing just how far firms/industries are from the efficient frontier could provide an organizing principle for diffusion-driven strategies. If risk can be reduced to a socially acceptable level using existing technologies, priorities can be established based on achieving maximum risk reduction per compliance dollar expended, but tempered by favoring regulations with multimedia payoffs (inducing worker and consumer safety), advancing opportunities for changing the culture of the firm, and encouraging other technological responses. Examples of areas where diffusion-driven, technology-based strategies might be considered are: encouraging substitutes for permanent-press resins containing formaldehyde, using nonchemical degreasing technologies in replacing chlorinated solvents, and phasing out fertilizers containing cadmium.

Innovation-driven strategies are by their nature even more open-ended than diffusion-driven approaches, more commercially risky, and more capable of yielding greater and broader payoffs, such as multimedia control of many substances and productivity gains. The discussion above has attempted to persuade the less heroic that innovation is largely predictable and can be directed readily, even if the exact outcome is not known.

Setting Priorities

Since innovation-driven approaches are likely to produce win-win strategies, rather than win-lose outcomes, criteria for choosing "which problem to attack first" take on a different character. They might include the presence of large risks left unaddressed by existing approaches, high costs of achieving risk reduction using even the best existing technologies, a history of or potential for innovation in the industrial segment responsible for the risks, and the enthusiasm and capability of the industrial sector or firm most likely to undertake the technological change involving product or process innovation. *Risk based approaches, in contrast, would never consider the third and fourth of these criteria, and would tend to regard the second as indicating a low-priority risk (because of the expense of control using existing technology) rather than a high-priority innovative effort.*

Areas ripe for change stimulated by an innovation-driven technology-based approach include some pesticide uses, chlorinated hydrocarbon uses, formaldehyde-containing industrial and consumer products, and endocrine disrupting chemicals. Innovative technology need not depend on chemical approaches. For example, we might also place a high priority on ultrasonic cleaning technology or on the substitution of electric vehicles for cars powered by the internal combustion engine.

It may not be important to prioritize problems according to payoffs in the narrow sense, but rather to choose to attack problems with the broadest possible applicability (i.e., transfer potential or likely subsequent diffusion of the approach), leveraging potential, and demonstration potential to contribute to both industry and agency cultural shifts. An innovation-driven pollution prevention policy, unlike a diffusion-driven one, is likely to produce some specific successes and failures (with more of the former preferable). For that reason, a portfolio approach to evaluating the outcome of that strategy applied to many targets is the appropriate approach. In order to get significant technological changes, some failures in attempts have to be tolerated. For those, "fail-soft" strategies need to be devised.

Risks of Innovation

Innovation is risky, but large returns on investment can be realized only with some risk taking. For some regulated firms that have lost their innovative capabilities, these risks are too large to take. Encouraging new entrants and competitors will not be welcomed by firms whose technology or products are likely to be displaced or replaced. But *innovation is more predictable and capable of being directed than invention or serendipitous discovery.* Unfortunately, in the case of highly polluting technologies, the existing markets are dominated by powerful and mature firms that block changes necessary for advancement. The firms or divisions not yet established, which would come up with better ideas, have no political representation. (One possible exception may be biotechnology firms using approaches that offer dramatically different ways to increase agricultural yield, control pests, produce pharmaceuticals, and remediate waste, as these are new and flexible emerging technologies). It is an innovation-driven technology-based strategy, rather than a diffusion of existing technologies, that represents the future private and public interest.

Final Commentary

Two different approaches are evident in addressing environmental problems and in setting environmental priorities. The first asks the question: how do we identify and rank the risks or opportunities for reducing risks to health and environment? The second asks: how do we identify and exploit the opportunities for changing the basic technologies of production, agriculture, and transportation that cause damage to environment and health? But further, do we want to effectuate a transformation of the existing polluting or problem industrial sectors are do we want to stimulate more radical innovation that might result in technology displacement?

Considerations of risks, costs, and equity are relevant to all these questions. Historically, the U.S. EPA and most economists, scientists, and risk analysts have dedicated their efforts to exploring rational approaches to answering the first question. They also implicitly assume a static technological world in pleading for a rational use of scarce resources and in assuming that the conditions dictate a zero-sum game. On the other hand, activists and those interested in an industrial transformation focus on the second question and argue for application of political will and creative energy in changing the ways we do business in the industrial state. The first effort promotes rationalism within a static world; the second is arational -- not irrational -- and promotes transformation of the industrial state as an art form. Interestingly, it is the first approach that is criticized as being too technocratic, but it is the second that argues for technological change.

In my view, an industrial transformation is essential in which the affected publics have major voices and that approaches to cutting up what is viewed as a shrinking pie, using dubious tools of risk and cost analysis, are regressive and now out of date.

In a January 1994 report, EPA reveals a clear evolution of its thinking from a preoccupation with risk to a concern for fundamental technological change. In the introduction to the report, EPA states:

> Technology innovation is indispensable to achieving our national and international environmental goals. Available technologies are inadequate to solve many present and emerging environmental problems or, in some cases, too costly to bear widespread adoption. Innovative technologies offer the promise that the demand for continuing economic growth can be reconciled with the imperative of strong environmental protection. In launching this Technology Innovation Strategy, the Environmental Protection Agency aims to inaugurate an era of unprecedented technological ingenuity in the service of environmental protection and public health...This strategy signals EPA's commitment to making needed changes and reinventing the way it does its business so that the United States will have the best technological solutions needed to protect the environment. (U.S. EPA 1994)

Unfortunately, this article of faith has not been followed up with action, and neither the U.S. nor Europe has come to grips with just how radical technological innovation should be encouraged, especially if it means the displacement of dominant technologies and even firms.

The Dutch 'Polder Model' boasts of success in stimulating environmentally superior technological solutions by involving the polluting firms with other stakeholders in a "covenant" to engage in continuous improvement of environmental performance. (See Gouldson and Murphy 1998). The 'Dutch Covenant' can be much more than a voluntary agreement between industry and government. There is participation by environmentalists, as well, and milestones and oversight with legal power to back up the agreements. Some success at incremental or modest innovation is apparent. Still, if Factor 10 (or greater) is what is desired in pollution or material/energy use reduction, cooperation with existing firms could limit success -- especially if the targets, as well as the means and schedule for reaching the targets, are negotiated between government and those firms.

This article has reviewed the U.S.-based research into the effects of government regulation in the United States. In a number of MIT studies beginning in 1979, it was found that regulation could stimulate significant *fundamental changes in product and process technology* which benefited the industrial innovator, provided the regulations were stringent and focused. This empirical work was conducted fifteen years earlier than the emergence of the much weaker Porter Hypothesis which argued that firms on the cutting edge of developing and implementing pollution reduction would benefit economically through "innovation offsets" by being firstmovers to comply with regulation. Perhaps paradoxically, in Europe where regulation was arguably less stringent and fomulated with industry consensus, regulation was not found to stimulate much significant innovation (Kemp 1997). Analysis of the U.S. situation since the earlier MIT studies reinforces the strategic usefulness of properly designed and implemented regulation complemented by economic incentives (Strasser 1997).

An important Dutch researcher whose views are informed mainly by European environmental regulation (Kemp 1994 and 1997) fails to see that regulation can be an important tool -- maybe the most important tool -- both to stimulate radical and environmentally superior technology and to yield economic benefits to innovating firms. In contrast, a comparison of the Dutch and UK regulatory systems (Gouldson and Murphy 1998) concludes that stringent regulation, without yielding to the pressure of the regulated firms common in the UK system, is essential to bring about significant technological changes. Kemp argues that for a technology regime to shift – i.e., to transform -- there has to be a unique/new niche which a firm can carve out for itself through the process of "strategic niche management" (Kemp 1994). What he apparently fails to see is that regulation can indeed create that niche -- and possibly not for the regulated firm alone. New entrants can be the responders, and it may be that technological innovation by new entrants is what is needed for sustainable development.

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