The Effects of Health and Environmental Regulation on Technological Change in the Chemical Industry: Theory and Evidence

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This paper presents the final results of a research effort which investigated the effects of environmental/safety regulation on technological change in the U.S. chemical industry. (1) The term environmental/safety regulation is used to include the legislation, regulations, and other related actions which attempt to control environmental pollution, protect worker health and safety, or ensure the safety of consumer products. Technological changes arising from regulation encompass both the immediate modifications in manufactured products or industrial processes which may be necessary in order to comply with regulation and the more indirect, or ancillary, effects regulation can have on technological change for non-regulatory, "main business" purposes. The major emphasis in this work is on technological change for compliance purposes.

We distinguish technological change from innovation. Innovation means new product or process technology actually brought by a firm into first commercial use. The term technological change has a broader scope and includes "non-innovative" changes such as the adoption of an existing technology.

The study's focus was on the regulations and chemical technologies pertaining to:

- lead
- mercury
- polychlorinated biphenyls (PCB's)
- vinyl chloride.

These are typical of substances that are in wide use and which are highly regulated. The choice was made to have a diversity of regulations and industrial contexts in our sample and to keep the study within manageable proportions.

The study involved both the construction of a model of the effects of regulation on compliance technology and the testing of certain relationships, suggested by the model, concerning the characteristics of the regulation, the nature of the technology employed by the regulated/responding firms, and the ultimate

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technological response. Data about these relationships were obtained from two series of interviews with firms subjected to the principal regulations on lead, mercury, PCB's, and vinyl chloride.

Other Work on the Regulation-Technological Change Relationship. A 1975 literature survey of the chemical and allied products industries concluded:

> Unfortunately, almost no work has appeared in the literature which has attempted to measure or even to model in a rigorous way the impacts of environmental regulation on technological innovation. (2)

Since that time, some important work has been concluded. In early 1979, as part of the Domestic Policy Review on Industrial Innovation undertaken by the U.S. Department of Commerce, the MIT Center for Policy Alternatives (CPA) undertook a systematic structuring of the effects of environmental/ safety regulation on innovation, citing support for different effects from the existing work. (3)

Although there are some broad, general studies and others specific to particular industries, within the chemical industry the most extensive literature concerns pharmaceutical innovation. Several researchers have argued that regulation has unduly slowed the introduction of new drugs in the U.S. and has resulted in a net health disbenefit to consumers. (4,5,6) However, a recent analysis of the literature presented at the 1977 HEW Panel on New Drug Regulation (the Dorsen Panel) has concluded that the available data are not sufficient to support such an assertion. (7)

Several new analyses have recently been offered concerning the general effects of regulation on innovation in chemicals. All stress the idea that the regulatory framework now applicable to the chemical industry has created a fundamental change in the business environment which will have important long-term impacts on the nature of innovation. Many of these impacts will be felt through the level and nature of R&D support. One study based on industry interviews has found a decline in real R&D spending in general but a large increase in R&D devoted to environmental control. (8) Others see the regulations as having a very uneven impact across the industry, providing some firms with a lucrative market opportunity and penalizing others. (9) Another study (10), based on unstructured chemical industry interviews and concerned mostly with the R&D effects, found considerable innovation in control technology arising from the research devoted to environmental amelioration but a general "dampening influence" on other new product and process development in large chemical companies. Changes in corporate organizational structure are consistently cited in all the studies.

Taken as a whole, the existing studies are useful in providing some general insights into the nature of the impacts regulation can have upon technological change and in sometimes providing documentation of those impacts in specific industries. However, they can only be characterized as a beginning exploration of the regulation-technological change relationship. A fundamental failing which pervades most of the studies is that they do not pose or rest upon any articulated model of the relationship between regulation and innovation. Many of the studies are broad, general overviews. On the other hand, the few industry studies which exist have only limited generalizability. What results from this lack of conceptual framework is that the previous work lacks both precision and subtlety. The regulatory stimulus is typically considered as a single, uniform event or signal; in reality, different regulations are vastly different in purpose and form and therefore can be expected to have significantly different effects. Similarly, innovation tends to be treated as a simple phenomenon. Little attempt is made to distinguish between innovation for compliance purposes and innovation for general corporate purposes. Lastly, the studies are rarely rigorously constructed to yield valid statistical results. Rather, they are typically surveys of a general nature which try to make a beginning exploration in an ill-defined research area.

A General View of the Regulation-Technological Change Relationship. It is essential to distinguish between two separate effects of regulation on technological change -- the technological changes necessary for compliance purposes and the other, ancillary changes in technology which may also result. This distinction highlights an important premise of this research -- that it is unwise to attempt to draw general conclusions about the regulation-technological change relationship. Too much depends on the characteristics of individual cases -- in particular, the form of the regulation, the kind of industry, and the peculiar character of the firm affected. Thus, one of the few certainties in this area is that there are no simple, general answers. Most of the answers lie in particular cases.

When one considers the technology developed for compliance purposes, it is clear that regulation encourages technological change. Indeed, this is almost a tautology since regulation is intended to ameliorate the adverse consequences of technology by changing technology itself. Certainly, the existence of a vigorous pollution control industry attests to the fact that the regulations have an important expansive effect. In these instances regulation creates a new market opportunity, which can be met very profitably by some firms. In some cases, the regulated firm markets the compliance technology.

On the other hand, regulation, imposes a direct constraint upon technological change. Certain regulatory systems are intended to discourage some innovations in the sense that the regulators must refuse to allow the introduction of certain unsafe products. Moreover, all regulation forecloses or discourages certain technical options and therefore constrains to some degree the innovation process.

Another regulatory constraint to innovation, but one which is indirect, may occur as a result of the cost of environmental control. To the extent that the costs of environmental control divert resources away from other corporate activities, like R&D, and to the extent that innovation is directly related to the level of these resources, regulation is likely to penalize innovative activity.

Regulation may also indirectly stimulate innovation. Often, firms respond creatively to crises, and to the extent that regulation poses crisis conditions it may foster innovative responses. This appears to be the case particularly in older, non-innovative firms which, prior to regulation, felt no need to innovate.

A last kind of effect may result from a basic change in the nature of the business environment created by the "new regulation". This is a systemic effect which will significantly affect the skill mix of chemical firms, their R&D processes, and their general business strategy. These effects in turn have important, though still largely unpredictable, effects on the nature (as well as the outcome) of the innovation process in the chemical industry.

A Conceptual Model of Regulation-Induced Technological Responses

In its simplest terms, our model of the regulation-technological change relationship consists of three basic elements:

- the regulatory stimulus
- the responding industrial unit
- the technological response

Regulation may impinge on a regulated firm and, as a result, a response of some kind is elicited. A responding industrial unit to that regulation may not be the regulated firm. It might be a supplier; it might be a new entrant to the field. It is important to identify the unit that sees a market signal or a constraint and responds in some measure. Depending on the kind of regulation and the characteristics of the responding unit or the regulated unit, different responses can result.

The Regulatory Stimulus. The term regulation brings to mind a governmental edict, such as a piece of legislation, an agency rule, or a guideline. Similarly, the concept of a regulatory stimulus to technological change suggests that such change occurs as a result of a regulation. After completing this research, we have concluded that both of these commonly held conceptions are too simple.

In the environmental/safety context, "regulation" should be given a broad meaning. It should include all forces (both governmental and non-governmental) that are related to the governmental effort to ameliorate environmental or safety problems. The reason for adopting this broad definition of regulation is that any narrower concept (e.g. one limited to legislation and Federal agency rules) is not realistic and would impute more causality to a single government action than is in fact the case. In short, the regulatory process is complex, and should be viewed as such.

There are many "regulatory" stimuli faced by the firm. Some regulations appear to pose little, if any, stimulus because they are based upon industry consensus and thus simply ratify into law the existing practice of the majority of firms. Similarly, to the extent that regulations are based upon concepts like "feasibility" or "best available technology", they may be rooted closely to the technological <u>status quo</u> as it exists in at least some firms. Accordingly, regulation often stimulates change in only part of the industry. Moreover, the regulatory stimulus is often not responsible for (i.e., does not require) all of the technological changes which occur. Indeed, regulation often gives firms the opportunity to make needed modernizations. Although these changes would not have occurred but for the regulatory stimulus, it is not proper to relate them to that stimulus alone. Not only is the regulatory stimulus complex, but it also interacts in a complex way with other economic, technological and social stimuli.

A first important aspect of the regulatory stimulus is what part of the technology the regulation focuses on. There are three principal <u>classes of regulation</u> important for the regulation-technological change relationship:

- product regulation -- focusing on product characteristics
- pollutant regulation -- focusing on unwanted side products from production processes
- component regulation -- focusing on individual elements of the production process

A second important aspect of the regulatory stimulus is its purpose or kind. Obviously, it is to be expected that occupational safety and health regulation, for example, will produce different kinds of changes from water pollution control or pesticide regulation. Similarly, it is important to distinguish among differing operational mechanisms or <u>modes</u> of regulation, such as performance vs. specification standards, or tax incentives vs. mandatory standards.

Other characteristics of regulation appear to have an important influence on the nature of technological changes. The stringency of regulation, measured by its cost or by the degree of change it requires, is obviously a major determinant of the kinds of changes which result. Similarly, when there are a multiplicity of regulatory stimuli rather than a single event, the resulting change may be greater, other things being equal.

Characteristics of the regulatory process may also be important in determining the resulting technological changes. For example, close participation of industrial representatives with government officials in drafting standards often appears to result in regulating at a level which is clearly feasible with existing technology, thus requiring little change. The length of time within which the regulatory scenario takes place also is important in allowing for appropriate responses, as is time-phasing of the regulation. Contrastingly, too much uncertainty is often seen as inhibiting the most efficient compliance efforts. Also, it is clear that most regulations tend to change over time and that the form of their changing requirements is closely linked to the evolution of compliance technology.

The Responding Unit or Units. The person who has the legal duty to comply with regulation is called the legally bound party. However, the legally bound party may not be the responder to regulation because the legal obligation does not always provide the most important stimulus to respond. For example, there may be joint responses to regulation by more than one firm or industry.

A productive unit is the smallest production element employing a particular technology that could conceivably stand alone as an individual firm. It may be a firm or only part of a firm. For example, a single PVC polymerization plant (or part of a larger plant) would constitute a productive unit.

The group of firms or units within firms that employ a particular technology can be termed a productive segment. For example, all the firms that polymerize vinyl chloride would constitute a productive segment.

The productive segment whose technology is the target of a regulation is called the regulated segment. This concept includes productive segments not legally bound to comply but which are nevertheless so commonly and closely related economically to the legally bound segment that they can legitimately be included within the regulated segment. (For example, the lead-in-gasoline regulations technically apply primarily to marketers of gasoline; however, the lead additive manufacturers are so closely linked that both would be considered regulated segments.) Non-regulated segments are defined as productive segments not within the regulated segment that is responding to the regulation.

Regulation may be seen as imposing requirements on technologies used in industry. We have attempted in this research to categorize these technologies. The most important aspect of a technology for this categorization is the concept of technological rigidity. This is defined as a continuum that has at one extreme evolving (fluid) product lines and uncoordinated production technologies, and at the other extreme, mature, commodity-like products and highly integrated, cost-effective production technologies. Productive segments may be placed along the continuum of rigidity according to a set of objective criteria which describe their technology.

To simplify the analysis, we have separated the continuum of rigidity into three distinct stages: fluid , segmented and rigid segments. The concept of rigidity used in this work is related to, but not identical with, that of Abernathy and Utterback. (11,12) They visualize an evolutionary process whereby product and process technology develop together from an initial stage in which the product is poorly defined and rapidly changing and the process is uncoordinated and based on general purpose equipment, through an intermediate stage in which the product begins to standardize and portions of the process are automated and optimized, to a final stage in which the product is a highly standardized commodity and the process is automated, integrated and large scale. Utterback and Abernathy's work suggests that the likely future pattern of change can be predicted based on the recent past. If units respond to regulation in the same way that other technological changes are undertaken, then this work would suggest that the particular kind of compliance response might be determined by the technological rigidity of the responding segment.

The Technological Response. In analysis of regulation-induced technological change, we distinguish between (1) responses which are primarily for compliance purposes ("compliance responses"), and (2) responses which primarily affect the development of technology for "main business" purposes ("ancillary responses"). The compliance response consists of those technical modifications to a firm's products or processes that are necessary for it to comply with a regulatory mandate. They also include non-hardware changes, such as changes in R&D, that are related to the development of compliance technology, as well as unsuccessful technological changes.

The important characteristics of the compliance response chosen for investigation in this study were:

- whether the response is principally a product or process change
- the "stage of development" of the response
- the "novelty" of the response
- the "comprehensiveness" of the response

The "ancillary" responses are the technological changes that occur in firms as a result of regulation that are not required for compliance with regulatory requirements. They are the developments that would not have occurred in the absence of regulation. They include the development of innovations within a company's "main business." There are two basic kinds of ancillary responses. One we have called "product- or process-specific" because it includes new or existing industrial products or processes directly traceable to a compliance response; the other we have termed "systemic," because it results from changes in the corporate structure or environment within which innovation occurs.

Relationships Within the Model. As discussed above, the concept of a productive segment is fundamentally a characterization of a technology. A basic postulate of this research is that the characteristics of a productive segment's technology are important determinants of its technological response to regulation, along with the characteristics of the regulatory stimulus.

The model constructed during the course of this research, relating the regulatory stimulus, the regulated/responding unit, and the technological response, is presented in Figure 1. In the figure, the elements of the model that are connected with solid lines are those which were the main focus of the research. The elements connected by dashed lines are those about which less information was collected. Hypotheses were developed concerning those elements connected only with solid lines. Figure 2 is a schematic of the specific relationships which were investigated.

The hypotheses tested in this research were as follows:

- Responses to regulation from the regulated segment will be predominantly product or process in a proportion corresponding to the expected pattern of innovation in the segment in the absence of regulation.
- All responses to regulation (whether or not from the regulated segment) will be predominantly product or process in a proportion corresponding to the expected pattern of innovation in the regulated segment in the absence of regulation.
- A large proportion of responses to regulation will arise from inside the regulated segment and inside the legally bound firm.
- A greater percentage of product responses than process responses will arise from outside the regulated segment.
- A much greater percentage of product responses than process responses will arise from outside the legally bound segment.
- Most responses to regulation are in a late stage of development and require only moderate development.
- Product responses will tend to be in somewhat earlier stages of development than process responses.
- Almost all responses will be in the "least novel" cate-

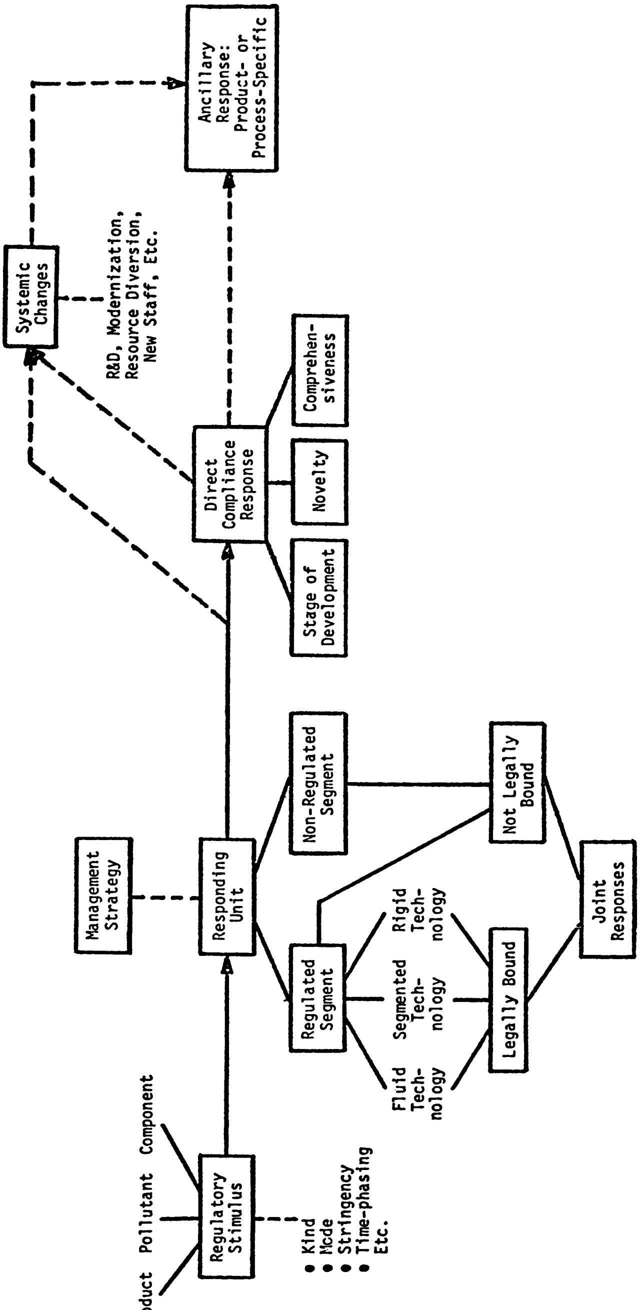

Figure 1. Conceptual model of the regulation–technological change relationship

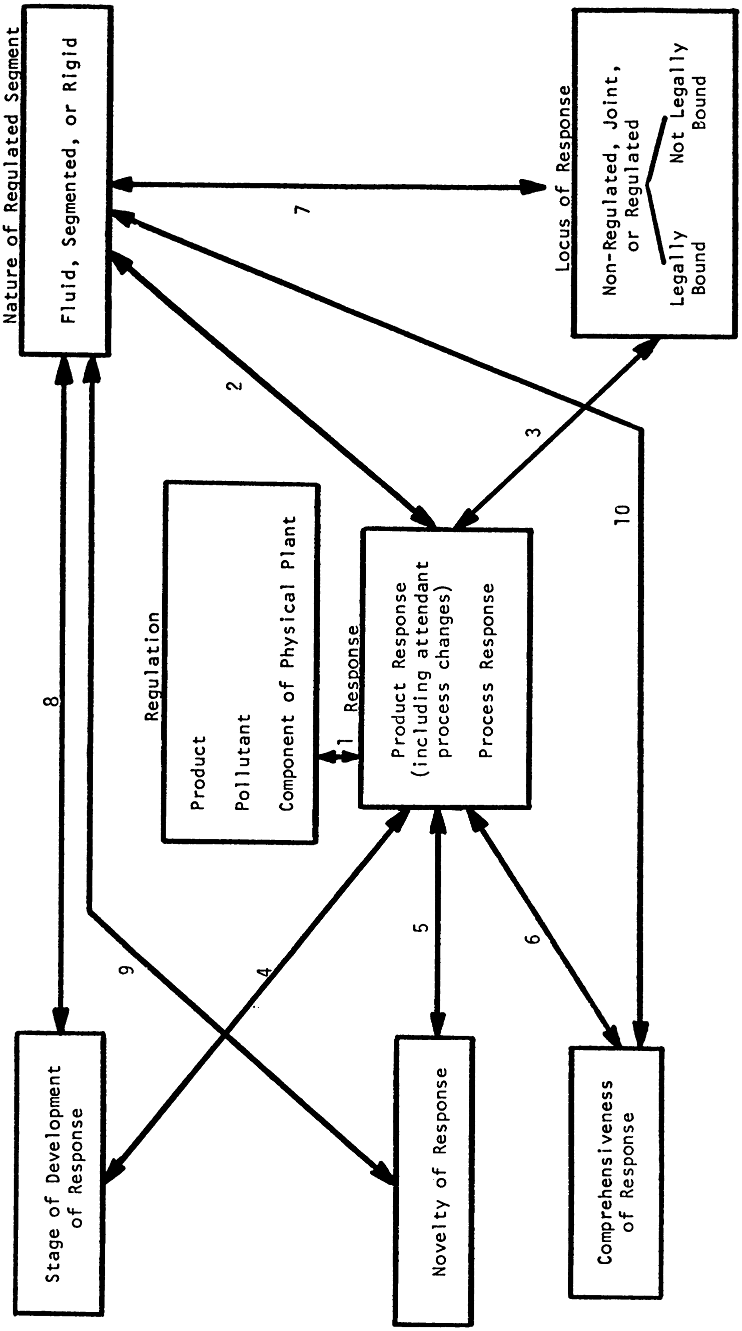

Figure 2. Schematic of relationships investigated

gory, with occasional moderately novel responses and very few novel responses.

- Novelty will be equally as likely for product and process responses.
- In fluid segments, the response to regulation is more likely to come from an earlier stage of development than in rigid segments.
- The responses to regulation will be less novel, the more rigid the segment.
- Responses will tend to be more comprehensive, the more rigid the segment.

Description of Empirical Procedures

The research was divided into three phases:

- Phase I: An initial taxonomic exercise in which basic concepts of the regulation-technological change relationship were developed from first principles and existing literature
- Phase II: Pilot in-depth in-person interviews with a small number of leading companies believed to have made important technological responses to regulations on four extensively regulated chemical hazards
- Phase III: Focused telephone interviews with randomly-selected companies in the same industries studied during Phase II.

The Phase I survey of the diverse legislative mandates applicable to the chemical and allied products industry revealed that almost all of the individual environmental/safety regulations are substance-specific. Accordingly, we organized the study around a series of candidate hazard regulations which would provide case studies of how the productive segments concerned with the selected hazards responded technologically to regulation.

A search of the regulations promulgated in each of the major legislative areas yielded a large list of chemicals which had been the subject of at least some governmental action. This list was reduced in several stages to a final group of four hazards -- lead, mercury, PCB's, and vinyl chloride -- which were (1) subject to a diversity of regulatory actions of different kinds and modes which significantly restricted production or methods of use, (2) used in a number of different productive segments within the chemical industry, and (3) economically important in a number of uses.

In Phase II, the goal of our interviews was to develop hypotheses about the factors important in shaping technological responses to regulation and about the characteristics of the actual responses. To facilitate this task, the sample of firms for the pilot interviews was deliberately enriched with firms that were known to have made relatively innovative technical responses to the regulation(s) in question and by firms that were relatively easy to study because they were receptive to interviews and located in convenient geographic areas. The sample of firms was drawn from 12 productive segments where the four subject hazards were principally in use.

Interviews were conducted with 10 firms. (Because some firms spanned more than one productive segment, we were able to gain information about all twelve productive segments.) Interviews of about two hours' duration were conducted by two members of the study team with one to four people from the firm. The discussions were informal and flexible in order to allow the interviewees ample latitude to enlighten us about the aspects of the regulations covered, the industry, and the technical responses which they considered particularly significant. In all cases, the interviewees performed one (or both) of the following functions in the firm:

(i) management of the details of the compliance response (i.e., the product or process change needed for compliance)

(ii) management of the overall firm response to regulation, including contact with the agencies, securing clearance for expenditures from corporate management, providing directions to the technical group, etc.

Phase III contained the major part of our empirical work. Its goal was to ascertain whether or not the hypotheses developed from the Phase II interviews and our model of the regulation-technological change relationship would be reinforced or altered by information derived from a more representative sampling of companies within productive segments. To construct the interview sample, we first arranged ten of the original twelve productive segments that had been directly subject to regulatory action in a matrix according to: (i) the characteristics of the segment's technology (i.e., rigidity/fluidity) and (ii) the primary type of regulation (i.e., product/pollutant), affecting the segment.

Next, lists of companies in each productive segment were compiled, and up to 16 companies per productive segment were randomly selected and arranged in a priority order for interviews. These ordered lists were then used to call companies; roughly equal numbers of usable interviews were obtained in each cell of the matrix. This procedure resulted in a sample that was stratified according to the two major foci of our investigation (i.e., technology and regulatory characteristics).

Forty Phase III interviews were conducted by telephone. The Phase III interviews were much shorter and more focused than those in Phase II, generally lasting less than thirty minutes. In addition they proceeded according to a rather specific questionnaire. In some cases it was possible to combine information from Phase II and Phase III interviews for analytical purposes.

The survey instrument consisted of a set of ten questions which resulted in ten specific replies out of 33 possible replies in an interview. For example, one question which was used to determine the nature of the productive segment of the respondents resulted in one of three replies -- fluid, segmented, or rigid. In Phase II and III of the project there were 50 interviews and these interviews provided 121 sets of ten replies. Each set of replies is focused on a firm's response to regulation. A response was a particular set of actions directed toward meeting the requirements of the regulation. On the average, firms exhibited three responses to regulation and industrial segments exhibited twelve responses. The analysis presented here describes interrelationships among variables related to the 33 possible replies -- drawn from appropriately aggregated responses of the industrial segments. The nature of the data collected led to a number of complexities for analysis. The interested reader is referred to the final report of the project for a detailed discussion. (1)

Summary of Major Findings and Conclusions

The conceptual framework developed for this research was valuable as a structuring device and seems to be an accurate description of compliance behavior. We feel that the model articulates most of the important aspects of the regulation-technological change relationship on an individual firm level and should serve as a basis for further empirical research.

The Regulatory Stimulus. The regulatory stimulus is a very complex, time-dependent and variable signal. Regulation is not a simple, single point-in-time phenomenon that elicits an industrial response. Various "regulatory" signals -- research findings, advance notice of rule-making, informal agency-industry contacts, etc. -- all influence firm behavior. Moreover, regulatory demands often change substantially over time, particularly as compliance technology changes. The way regulatory signals are perceived by the firm is also very important. These perceptions may sometimes differ quite substantially from those in the agencies and may even be incorrect as to the regulatory requirements.

Informal "regulatory" stimuli are as important, or more so, than formalized rulemaking. Informal stimuli include publicity, government scrutiny, non-regulatory legal mechanisms like tort and contract law, and customer (or supplier) pressure. These additional forces tend to multiply the effect of regulation, and sometimes even preclude the need for regulation. The example of PCB's best illustrates this point. Only government "scrutiny" had occurred by 1970 when Monsanto, the sole U.S. producer, began restricting production. Fear of tort suits and adverse publicity were major motivators for action by PCB users long before the passage of the Toxic Substances Control Act in 1976, which phased-in a ban on PCB production.

In part because of the extra-regulatory forces at work, it is clear that compliance with regulatory goals may sometimes substantially pre-date actual promulgation of a rule. In such cases, the actual regulation serves the function of ratifying action that has already occurred and provides a model for similar requirements which might be mandated in the future. Forces other than regulation are thus the major stimuli for technological change in these instances.

We have also seen consistently that agencies use substantial industry input in drafting regulations. This input results from industry participation in the formalized rule-making process as well as through informal contacts with agency personnel. Industry input appears to be dominated by the large firms (and trade associations) which employ a variety of full-time specialists to handle regulatory affairs. The agencies often adopt the suggestions offered in comment on their rules. For example, the CPSC's final rule on lead-in-paint was modified substantially (principally as to the breadth of its application) on the basis of hearing comments.

For the four hazardous materials surveyed, the actual standards which finally emerged from the regulatory process appear in most instances to be based largely on considerations of technological feasibility or best available technology. It was rare to observe a standard set to require technology not already in use by at least some firms, although we did observe this in one important instance. (The OSHA vinyl chloride regulations apparently required a series of innovative process modifications for virtually all firms in the VC polymerization industry.) This is not to say, however, that a standard cannot successfully bring about changes in technology. The change may either be the development of an entirely new product or process -- or the diffusion of a given technology throughout an industrial segment. More recent regulatory initiatives, relying on stringent health-based criteria, may well require technological responses which go beyond current capability.

There is, as expected, a very strong correlation between the type of regulation and the nature of the technological response. Thus, "product" regulation generally leads to a product response, and "pollutant" and "component" regulations generally lead to process responses. In a few cases, however, product regulation was seen to elicit primarily a process change. For example, the petroleum refiners' principal response to regulatory limits on the lead content in gasoline has been to increase catalytic reforming, a process change.

We suspect that other characteristics of the regulatory stimulus not investigated here in detail or systematically are also important for technological change. They include the stringency of the regulatory demands, the time period allowed for the compliance response to develop, the mode of regulation (e.g. performance vs. specification standards), and the presence or absence of several regulatory demands in combination.

The Responding Units. We conclude that the characteristics of the technology in productive segments/units are major factors determining the nature of the technological response to regulation. The technology in use before regulation tends to dominate the compliance response to regulation. Variations among individual firms were found, but overall, responses were fairly predictable across a productive segment.

Other more specific findings supported this basic conclusion. First, we found that the kinds of technical changes that firms within a productive segment made in order to comply with a given regulation were highly uniform. This uniformity cannot be attributed to regulatory signals which required a single compliance technology because most of the regulations investigated were performance standards. Rather, the response uniformity within productive segments suggests that the character of the existing technology does indeed dominate the response.

Second, we found that the proportion of product and process responses to regulation closely resembles the expected balance of product/process innovations occurring in the segment in the absence of regulation. Thus, we saw that fluid industries tended to respond to regulation with product modifications, and rigid segments tended to have more process responses than product changes. Segmented industries, in contrast, exhibited both product and process changes and a greater overall amount of change than fluid or rigid segments. These responses are highly consistent with the usual pattern of innovation in the absence of regulation.

Perhaps the most interesting result concerns the relationship between the novelty of the response and the rigidity of the segment. Regulation of rigid segments often elicited responses as novel as those in fluid segments. For example, highly innovative responses were attempted, but unsuccessfully, to deal with the lead-in-gas regulations. These included the development of an entirely new fuel, "gasohol," and efforts by the lead alkyl manufacturers to develop new automobile engine designs capable of using leaded gas. On the other hand, the response to lead-in-paint regulations by paint manufacturers (a fluid industry) was simply to utilize existing substitutes. This finding lends some support to the idea that regulation can change the overall character of innovation in rigid industries. Creative responses to regulation may occur especially when the regulation precipitates "crisis" conditions for the industry.

Regulatory requirements are typically made applicable to a specific industry or industries. Nevertheless, the response to regulation need not arise from the regulated segment or the legally-bound firm. Although we have found that a large preponderance of responses will arise from inside the regulated segment, the responses from outside the regulated segment are also significant. Several very important, innovative responses were seen to have arisen from new entrants to the industry, whose entry was made possible by regulation. For example, successful PCB substitutes arose from large oil and chemical companies, transformer/capacitor manufacturers, and foreign corporations -- none of whom had been in the PCB manufacturing business.

When responses do arise from outside of the regulated segment or the legally-bound firm, they still require some kind of adaptation or modification by the firm undertaking compliance. Thus, responses from outside the regulated segment or firm are typically joint efforts.

Although there are examples of both product and process responses arising outside of the regulated segment, a greater percentage of process responses arose from outside efforts than for product responses. There appears to be some tendency for rigid firms that are legally bound to look elsewhere for the compliance solution, and some tendency for fluid firms that are legally bound to develop their own compliance solution. There are several important examples of the suppliers to regulated firms actually providing the technical solution to their customer's regulatory compliance problem. In one such case, the worker exposure and emissions problems of PVC fabricators were essentially solved by the PVC polymerizers, their suppliers. The polymerizers' production of "clean resins" largely eliminated the potential for emission of vinyl chloride monomer during fabrication.

The Characteristics of Compliance Responses. Most technological responses to regulation are in a late stage of development and require only moderate development in order to achieve compliance. This means that when the response to regulation was begun there was, in most cases, an existing technology which could be adapted to the regulatory purpose without the need for major research/development work. (For example, in the mercury chloralkali industry there were two principal production processes in use, one of which was a significant mercury polluter. Regulations on mercury have prompted a diffusion of the second process.) Thus, one might say that most responses were drawn from technology already "on the shelf".

Comparing product and process responses, it was found that product responses tended to be in somewhat earlier stages of development.

It appears equally likely that rigid and fluid segment responses will require substantial development, although we expected that the responses of fluid segments would be drawn from an earlier stage of development than the responses of rigid segments. After reconsideration of the original expectations, this finding appears to be consistent with the theory that regulation has the effect of disrupting established modes of operation in rigid segments, and thereby elicits creative responses.

We found that almost all responses to regulation fell into the "least novel" category. This finding is consistent with the earlier finding that responses tended to be drawn from a late stage of development. It was also found that product and process responses were approximately equally novel (or non-novel).

Tests of the relationship between novelty and technological rigidity provided especially interesting results. The most novel responses seem to come from segmented firms, although we had expected that responses would be most novel in fluid segments. Moreover, it appears clear that rigid firms do not have less novel responses than fluid firms. Again, this finding supports the idea that rigid firms are prompted to develop creative solutions to severe regulatory problems. (Perhaps the principal example of segmented firm innovation comes from the vinyl chloride polymerizers, who modified their process in several important ways in responding to OSHA and EPA regulations. This response, especially the unique combination of responses, was perceived as remarkable by many in the industry, which had feared that the regulatory demands could not be met.)

No general relationship appears evident between comprehensiveness and product versus process change. It was found, however, that responses tended to be more comprehensive in more fluid segments. This finding appears consistent with the idea that fluid technologies, being relatively undefined (as opposed to rigid segments) are able to make a greater degree of change with more ease.

Qualitatively, the data show only a very few examples of radically new technologies arising in response to regulation. These few arose outside of the regulated segment and were in most cases, ultimately unsuccessful. (As mentioned above, "gasohol" has not succeeded nor have automotive design changes like "lead traps," etc.) However, successful responses did in some instances show a creative adaptation of existing techniques. For example, the development of MMT, a manganese-based fuel additive that now has been in commercial use for several years (although it recently was denied continued use by EPA) built creatively upon the research which had taken place several decades ago.

Most responses were developed over a relatively short time period. This perception is consistent with the finding that most responses were relatively non-novel and drawn from a rather late stage of development.

Systemic Changes. Although this study did not attempt to measure systemic changes in any rigorous way, we nevertheless were impressed by the assertion of many interviewees that the character of their business had changed as a result of environmental regulation.

An important phenomenon reported in several instances is the ability of new entrants to capitalize upon opportunities created by regulatory demands. This may occur, for example, when products are banned or when an existing process technology is severely restricted. (For example, mercury has long been the most important biocide for paint uses. The regulations on this use have elicited several new non-mercurial products, sometimes from companies not previously in the industry.) New entrants may thus be competitively advantaged by the opportunity to comply with regulations.

Systemic changes were investigated quantitatively via questions about environmental affairs groups in the firms. About 65% of interviewed firms had such groups. Although the primary purpose of environmental affairs units appears to be to aid the direct compliance effort, their new capabilities may have important long-term implications for the pattern of innovation in the primary lines of business.

Most of the environmental affairs groups had as their primary purpose a liaison function between the regulators and their company. They participated regularly in the regulatory process, often indicating to the regulatory agencies the technical limits of existing compliance capability. Inside the firm, the environmental affairs unit often functioned in a manner very similar to a regulatory agency. Specifically, environmental review procedures were often established, with the environmental affairs unit able to "pass" on the acceptability of various products or processes, particularly in their early stages of development. Thus, these groups are likely to be an important force for the production of safer products and process technologies.

Environmental affairs units appear to be more common in larger corporations. They are typically located in the central corporate headquarters rather than in production facilities. They may be staffed with young environmental scientists rather than engineers. As such, it appears they often do not play a major role in the development of new compliance technology or in the engineering aspects of compliance. These latter functions are more typically within the realm of the plant-level engineers or R&D personnel.

Another widely reported phenomenon was a change in the skill-mix in firms in order to give them the new capabilities and expertise to comply with regulation. One change, widely reported, is the improvement in analytical chemistry capability. This was made necessary by regulation but, of course, aids companies generally in establishing better the properties of their products and finding new uses for them. The effect of interjecting new technical skills into regulated firms is difficult to assess. To the extent that these new personnel are concentrated in environmental affairs units, their impact on abatement technologies is likely to be no different from that discussed above. However, we are also left with the impression that new skills and a new environmental awareness are being absorbed by engineers and that this may have a profound impact both on abatement technology and other innovations. Many interviewees at the plant level indicated that their jobs were very different since environmental regulation. Some said this begrudgingly, but others said they now found the work more "challenging and exciting."

Ancillary Changes. "Ancillary responses" to regulation are technological changes that occur as a result of regulation but which are not necessary in order to bring those firms into compliance with regulatory requirements.

Ancillary changes were investigated by a simple direct question to the interviewees. Approximately 20% stated that there had been ancillary innovations resulting from regulation. These innovations benefitted the company in areas not related to compliance. Ancillary responses included: development of a new catalyst for petroleum refining; initial development of a new chlorine manufacturing process; increased yields of PVC resin; better process monitoring techniques for PVC polymerization; and new paint formulations.

More work needs to be done in the investigation of ancillary responses. However, we do feel that their existence is beyond doubt. One of the problems in investigating ancillary responses arises from the fact that they are very diffuse and indirect and not likely to be appreciated fully by any single individual in the firm. Indeed this fact was cited often by interviewees in response to our questions.

Other Conclusions. Although no systematic attempt was made to assess the level of compliance with regulatory requirements, the interviewers were left with a very strong feeling that firms are substantially in compliance with regulatory mandates for lead, mercury, PCB's and vinyl chloride. By this, we do not mean that companies are simply on a legally sanctioned compliance schedule; but rather, that they have reached or surpassed the goals of the regulation in question. Thus, regulation did not, in any instance we investigated, present an insurmountable technical problem.

At least for the four hazards investigated, the level of controversy concerning regulatory demands appears to have abated considerably, and industry has accepted the necessity of compliance.

Within the 50 firms interviewed, the interviewees were remarkably candid, open and willing to discuss in detail the effects of regulation on the technology in use in their companies. Only a very small number of companies refused to be interviewed.

The vast majority felt that the research topic was worthwhile and thus were glad to contribute to our effort.

The encouraging attitude of the firms interviewed suggests that further empirical work to investigate the systemic and ancillary responses to regulation may be worthwhile.

Implications for Regulatory Policy

The model of the relationship between regulation and technological change developed in this research appears to be successful in analyzing past responses of the chemical industry to environmental and health regulation. Moreover, this conceptual framework may be useful both in the design of future regulations and in planning corporate strategy for responding to these requirements.

In the past, the chemical industry has been resilient in its response to significant regulatory efforts. It has reached or surpassed the technological requirements of regulation. In part, this is because the previous standards imposed appear to have been based on present technological feasibility or best available technology. But, in addition, the industry has been able to accelerate the development of new process technology which was needed for compliance. There is strong evidence that regulation can change the overall character of product and process innovation in the industry, providing the regulations are stringent enough and of the right kind.

The industry might well be viewed as being in a transition period between a past history of little emphasis on environmental and health concern and a future pattern of much greater activity. This is evidenced by increasing managerial attention to these issues via both the formal establishment of environmental affairs units and shifting emphasis in the nature of chemical product design and production. Direct regulation of specific hazards must be seen within the context of a more general need to restructure the nature of chemical production technology over the next decade or more, if real improvements in environmental quality and public health are to be made. The newer regulatory efforts, especially those concerned with workplace hazards, consumer products, and new activities by EPA under the Toxic Substances Control Act, may be particularly important for innovation both in compliance technology and in process or product redesign. This is to be contrasted with past efforts at air and water quality control which focused on single pollutants as emissions or effluents at the end of the production process.

In order to succeed in achieving a more general shift in the nature of chemical production, regulations must be designed to elicit the best possible technological response from the industry. Regulation must be "technology forcing". The past pattern of basing standards on existing technology must be altered. In addition, the overall stimulus for change must be strong enough to effect a shift in the general management approach to all possible hazards associated with production. The adoption of generic regulations or regulation of classes of chemicals would provide a stronger impetus for change than a substance-by-substance approach.

Our model of the regulation-technological change response implies that care must be taken in deciding whether to regulate the product or the process in a specific case. The technological response may be different. OSHA, CPSC, and EPA under their respective legislative mandates can bring about radically different responses to a particular hazard. For example, a product safety regulation controlling the permissible concentration of benzene in industrial solvents is much more likely to change the nature and production technology of those solvents than regulating workplace exposure. In addition, worker protection might more assuredly be achieved. This example illustrates the importance of selecting an appropriate regulatory strategy. This can be accomplished most effectively by coordination among the agencies, for example, through the recently-formed Interagency Regulatory Liaison Group.

In the past, one of the impediments to the design of "technology forcing" regulations has been the fact that the agencies have relied on the regulated industries as the source of their information about the potential for technological change. Accordingly, compliance has been largely the adoption of "off the shelf" technology and has resulted in less protection of health and the environment than might have actually been possible. Our research suggests that important changes in technology can be encouraged by regulation. This will be the case especially if, in the future, both the agencies and the industry develop an appreciation for the complexities of the regulation-technological change relationship. The regulatory agencies should be aware of the fact that it is possible to design regulations to stimulate the development of new technologies whose performance exceeds the expectations of both industry and government. This work is intended to help develop that awareness.

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