Industrial Response to the Banning of CFCs: Mapping the Paths of Technical Change*

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Policymakers assume risks when they attempt to mandate environmental changes in industry practice that go beyond existing technical capabilities. In the case of the international regulation of chlorofluorocarbons (CFCs), the electronics and automobile industries responded successfully by making a transition to CFC-free alternatives. Nevertheless, the nature and timing of responses differed significantly between the two industries. Large multinational electronics firms considered the global restrictions a challenge, and moved swiftly to develop alternatives to CFC-based chemicals. Their counterparts in the automobile industry, however, delayed in making a commitment to air conditioning systems which run on CFC substitutes. The differences between the two industries can only be explained by a complex mix of technical, organizational, and institutional factors. In light of these cases, we suggest that policymakers need to consider regulatory approaches that are more tailored to particular industries.

During the past decade, industry has increasingly recognized that product and process improvements can often simultaneously enhance environmental performance, while improving quality and lowering costs. Nevertheless, companies often overlook opportunities for innovation without the mandates imposed by government and regulation remains the primary method of inducing environmentally related technical changes in industry.

A small body of literature examines the influence of environmental regulation on technological innovation from a sociological and organizational perspective (Ashford, 1993; Ashford, Ayers, & Stone, 1985; Ashford & Heaton, 1983; Kemp & Soete, 1992; Rothwell, 1981; Schot, 1992). One common thread in this literature is that regulations often induce environmental innovation. Often times, however, these regulations fail to fulfill their potential. They force innovation at high cost, mandate the adoption of end-of-pipe technologies, or stifle innovation altogether. The never-ending challenge for policymakers is to develop regulations that lead to environmental improvements, but develop them in a way that minimizes the burdens on industry. Past research on government policies designed to support innovation suggests that if policymakers are to foster innovation, it is essential that they understand the factors driving the process. As important, they must understand how these factors vary across different firms and industries (Ashford, 1993; Nelson & Langois, 1983; Utterback, 1974).

In this paper, we look at the response of two user industries, electronics and automobiles, to the restriction of, and ensuing global ban on, chlorofluorocarbons (CFCs) in the late 1980s. Both industries ultimately responded successfully to the global ban by developing alternative technologies to CFCs. However, large multinational firms within the two industries differed in the nature and timing of their response to the phase-out of CFCs. Large electronic firms considered the global restrictions as a challenge, and moved swiftly to develop alternatives to CFC-based chemicals. Many of the large automotive companies, however, delayed in making a commitment to air conditioning systems that ran on CFC substitutes, despite the fact that delays could potentially cause a large and costly retrofit problem for the industry.

We believe that the different responses between the two industries, as well as among certain firms, cannot simply be explained by existing models of firm response to environmental regulation. It was a complex interaction of technological, organizational and institutional factors that influenced firms' willingness to innovate and respond "proactively" to technology-forcing regulations. The case of CFCs is thus of both theoretical and practical interest in identifying factors that shape industry's response to technology-forcing regulation. The information for this study was collected through interviews with representatives from these industries in 1992 and 1993, as well as extensive research of secondary source material as part of the Massachusetts Institute of Technology Norwegian Chlorine Study (Technology Business and Environment Program, 1993).

LITERATURE REVIEW

The Determinants of Technological Change

Although a significant amount of research has been conducted to understand the relationships between scientific discovery, innovation, markets and other institutions external to the firm, much remains to be discovered about the nature of technological progress. There is a growing body of literature on the processes and institutions involved with technological advance (Tushman & Nelson, 1990). Several theorists have proposed that technological change is far more complex than traditional “market-pull” or “technology-push” models suggest. Instead, they argue, technology moves along an evolutionary path, the direction of which is determined by a number of technical, organizational and contextual factors (Dosi, 1982; Nelson & Winter, 1982; Rosenberg, 1969; van den Belt & Rip, 1987).

Empirical work supports the notion, for example, that organizational factors are a critical influence on the nature of technological change. Technology is related to the efforts, knowledge and skills of individuals in the organization, as well as the structure of the organization as a whole (Dosi, 1982; Nelson & Winter, 1982). As described by Dosi (1982, 152), firms operate within an existing technological paradigm, which is a "pattern of solutions to selected technological problems, based on selected principles derived from natural sciences and on selected material technologies." This paradigm encompasses certain cognitive and organizational limits by encouraging the development of certain skills and behavioral routines over others. Once a technological paradigm has been selected, these limits exclude alternative technological possibilities and technological progress moves down a specific path or trajectory. Over time, organizational routines and capabilities evolve to operate under the current paradigm, and movement along a given path builds momentum, directing problem solving activity and technology development in a certain direction.

Beyond the organization's boundary, change is motivated not only by exogenous needs expressed through market signals, as suggested in the traditional "market-pull" model, but also by a whole host of institutional and political factors (Nelson & Winter, 1977). The influence of the operating context on the path varies. External forces can challenge organizations to focus on new technological innovation paths or operate under new technological paradigms. Alternatively social structures, procedures, relationships and norms can support existing technological paradigms, encouraging technological change down the existing path (Tushman & Rosenkopf, 1992). Tushman and Rosenkopf (1992) propose that the significance of these factors in determining the path of technological change varies with the complexity of the system at hand; the more complex the system, the more relevant institutional and political factors will be in determining the path of development.

Theoretical and empirical work has attempted to establish when these various factors exert the greatest influence on the process of technical change. For the most part, this work finds that the determinants of technological change vary in importance along with the phases of technology development throughout the product life cycle (Anderson & Tushman, 1990; Tushman & Anderson, 1986; Tushman & Rosenkopf, 1992). Tushman and Rosenkopf (1992) suggest that social and organizational factors have the most effect during periods of experimentation, when keen competition exists between old and new technological regimes. Once a dominant design has been established, technological change proceeds incrementally. At this stage, social, political and organizational factors are less influential and technological change is driven more by the "logic" internal to the technology (Tushman & Rosenkopf, 1992).

It is clearly difficult to separate the influence of myriad of factors on the process of technological innovation (Bijker, Hughes, & Pinch, 1987). As Hughes (1988) points out, technology, organizations, and social context can all be part of one "seamless web". Organizational characteristics, such as the management structure, depend on the characteristics of the technological artifacts, while technologies are shaped by the organization in which they are used (Thomas, 1994; Orlikowski, 1992). Similarly, both technological and organizational systems can be closely related or even mirror the institutional context in which they operate (DiMaggio & Powell, 1991; Hughes, 1987).

The Impact of Regulation on Technical Change

Environmental regulations are powerful institutional factors motivating technological change. A prominent analytical model of this process is offered by Ashford (1993) and Ashford and Heaton (1983). The model elucidates how various types of environmental regulation lead firms to modify the development and production of technology, and are technology-forcing to different degrees. The firms or industry assume a critical role in the model when they respond to the regulatory stimuli. Ashford and Heaton (1983) hypothesize that industry's response to regulatory stimuli is primarily shaped by the location of the regulated technology within its overall life cycle. Specifically, they rely on the Abernathy and Utterback (1978) framework which suggests that: (1) innovation is predictable in any given industrial context, (2) the characteristics of the particular technology are the main determinant of the nature of technological change and (3) the process of innovation is relatively uniform across widely different productive segments (Ashford & Heaton, 1983).

Ashford and Heaton's model, though useful, has certain limitations. First, empirical evidence supports the notion that not all technologies follow a predictable life cycle (Henderson, 1994). Second, although Ashford (1993) and Ashford and Heaton (1983) recognize that the technological innovation processes is far more complex than the Abernathy and Utterback (1978) model suggests, they have not attempted to incorporate other factors into the model. Factors such as organizational and industry culture, market dynamics, regulatory history, history of technological innovation and even individual actions are overlooked even though they are critical in understanding the response to regulation at the industry and firm level.

In the next section we will illustrate the varying impact of regulation on technical innovation by looking at the responses of two user industries, the automobile and electronics industry, to the phase-out of CFCs called for in the Montreal Protocol. This case is particularly interesting because the Montreal Protocol is the first example of a global accord that calls for the total phase-out of a group of chemicals. Both the automobile and the electronics industry were faced at the time of the Protocol with major technical challenges, as alternative products and processes did not appear to be immediately available. Their responses to these constraints differed markedly.

THE BANNING OF CFCs

CFCs are chemical compounds derived from simple hydrocarbons with halogen atoms substituted for hydrogen. They have been used in industry increasingly since the 1930s in a growing number of applications. By the late 1970s and early 1980s, CFCs were widely used in a number of sectors. The principal substances used were CFCs 11 and 12, with growing use of HCFC-22. These two together account for 73% of the world ozone depleting potential.

In 1987, the Montreal Protocol called for a 50% cut in CFC production by the year 2000. In the year following the signing of the Montreal Protocol, a series of events led the United States (US) and some of the European governments to renew their calls for a total CFC phase-out (Maxwell & Weiner, 1993a). Two scientific reports contributed significantly to the hardening of public opinion against CFCs and the generation of sufficient political will required to negotiate more stringent controls. Only two weeks after the Protocol's signing, the first results became available from the US led Antarctic Airborne Ozone Experiment (AAOE). The results demonstrated definitively the link between chlorine and the hole (Science, 1987). The second key report was that of the NASA/WMO Ozone Trends Panel. Published in March 1988, it revealed unexpectedly large ozone depletions at middle/high northern latitudes during winter (Watson, Prather, & Kurylo, 1988). Within ten days of the study's release, DuPont announced its plans to curtail production of CFCs, and to speed the transition to alternative chemicals, underlining the technical feasibility of a shift within the decade (DuPont Corporate News External Affairs, 1988). In August 1988, ICI announced its intention to join DuPont in an orderly phase-out of existing CFCs and in a rapid commercialization of substitutes. In June 1990 the London Revisions to the Protocol were signed, establishing a timetable leading to total phase-out of CFC production by the year 2000.

All countries which use or produce CFCs in significant quantities have ratified or accepted the Protocol, including China, India and the Russian Federation (United Nations Environment Programme, 1992). The Protocol was amended in 1990 and in November of 1992. The principal limits are that production and consumption of CFCs 11, 12, 113, 114 and 115 and halons are subject to specific limits based on 1986 levels, which gradually decrease until no production or use is permitted by 1 January 2000. Consumption and production of other fully halogenated CFCs are frozen at 80% of 1989 levels from January 1993, declining until they are fully phased out by January 2000. Several countries have instituted stricter provisions than the Protocol, particularly in response to new scientific evidence. In addition, the United States established an excise tax that increases rapidly over time on ozone depleting substances manufactured or imported for use in the United States (United States Environmental Protection Agency, 1991).

Because the Montreal Protocol and its implementing legislation in the signatory countries places bans on the production of CFCs, there are no restrictions on the quantities individual user companies may use. In principle, companies could continue to use fully halogenated CFCs well past the phase-out date. Despite this, many users are attempting to reduce or eliminate their use of all ozone destroying chemicals as rapidly and substantially as possible, in some cases going well beyond the regulatory requirements. Much of this activity is in anticipation to the rapid reduction of available CFCs as the phase-out is implemented by the producer industries. Pressure for change increased when several of the world's major producers voluntarily moved their phase-out schedules up beyond the Protocol and more progressive national deadlines (Maxwell & Weiner, 1993b; Oye Maxwell, 1994).

Electronics Industry

At the time the Montreal Protocol was under negotiation, the electronics industry was one of the most vociferous opponents of mandatory bans. They countered the environmentalists with claims that there were no alternatives available and that the costs involved with phasing out CFCs would jeopardize an extremely important and growing industry. For example, the American Electronics Association gave evidence to the US

House of Representatives in March 1987, saying "The electronics industry has a keen interest both in the continued availability of this indispensable solvent and in its safe use....While near-term alternatives to other CFCs appear increasingly likely, the industry is troubled that no suitable alternatives to CFC-113 appear likely in the near future.....The issue has profound and troubling implications for the US high-tech industry's international competitiveness and for international trade (United States House of Representatives, 1987)."

Yet in the following year, 1988, one of the world's major electronicsmanufacturers announced its commitment not only to drastic reductions in CFC consumption, well in excess of requirements, but also to a total phase-out in the near future. This commitment took place *prior* to a complete ban on CFCs was even negotiated. Many of the other major electronics companies followed shortly afterwards. In the forthcoming sections, we will discuss the major uses of CFCs by the electronics industry and discuss technical paths chosen by actors in this industry.

<u>Overview of Electronics Industry.</u> The principal regulated ozone depleting substances used by the electronics industry are CFC-113 and, to a lesser extent, methyl chloroform and carbon tetrachloride. CFC-113 is one of the principal fully-halogenated CFCs, with an ozone depletion potential of 0.8 (with CFC-11 as a base of 1) and accounts for some 23% of all CFCs produced in 1990 (United States Environmental Protection Agency, 1991). Prior to the Protocol, the electronics industry made up almost half of the global use of the substance (Electronic Engineering Association, 1987).

The electronics industry uses CFC-113 principally to remove flux from printed circuit boards (PCBs), printed wiring assemblies (PWAs) and other electronic assemblies. The industry also cleans other equipment such as disk drives, although this makes up only a small proportion of all cleaning operations in the industry. Assemblies are cleaned either by CFC-113 spray, immersion in liquid, or immersion in vapor. In general, the need for cleaning increases with the level of reliability required. Many simple consumer electronics have never been cleaned.

A number of options for reducing CFC use have emerged in response to the Montreal Protocol. These can be summarized in four general categories; conservation and recovery, hydrocarbons, aqueous cleaning, and no clean technology:

(1) Conservation and Recovery. CFC solvents were cheap prior to international controls on production (estimates vary, but typical prices for CFC-113 were around $1.60/lb, excluding any excise taxes (United States Environmental Protection Agency, 1988)) and made up a very small part of the overall manufacturing costs of electronic equipment. They are also non-toxic and were thought to have no environmental effects. This means in the past they tended to be used wastefully, and that substantial reductions can be made through simple housekeeping methods. The United States Environmental Protection Agency (1990) reports that many companies have reduced losses by up to 70-85% through conservation and recovery programs. These reductions allow companies to easily match the reductions in the production schedules laid out in the Montreal Protocol and even in some of the most strict national legislation.

(2) Hydrocarbons. Companies have marketed several hydrocarbons for semi-aqueous cleaning,[1] but the most common are terpenes, chemicals which occur naturally in most essential oils and in the oleoresins of plants. They were first developed for rosin flux removal from printed circuit boards in 1983 by AT&T and Petroferm. AT&T has shown that they can be used to clean surface mounted circuit boards, which is essential if they are to be a long term alternative to CFC's. Since they are not a drop-in replacement for CFC-113; companies using this method have to make substantial equipment modifications.

The advantages of terpene solutions stem from their workability in close spaces, and at room temperatures, as well as their being non-corrosive. Certain potential problems

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[1] DuPont, for example, markets a non-terpene semi-aqueous hydrocarbon blend called "Axarel 38."

or questions, however, are associated with terpene use. The effects of occupational exposure to these substances are currently unclear.[2] Terpenes also have environmental drawbacks. One problem concerns the waste produced by using them in semi-aqueous cleaning. The second concern is that terpenes are volatile organic compounds (VOCs), molecules that evaporate at their use temperature and lead to a photochemical reaction causing atmospheric oxygen to be converted into tropospheric ozone under favorable climatic conditions. Mists and vapors therefore need to be controlled so as not to contribute to the formation of photochemical smog. Equipment also must be available to control for the odor and flammability of these compounds.

(3) Aqueous Cleaning. Aqueous cleaning is the longest-established alternative to halogenated solvents for the electronics industry, and many companies have used this method to some extent for years. Aqueous cleaning can be used with both the conventional rosin fluxes and with water-soluble fluxes, on surface mount as well as through-hole assemblies.

The technique basically involves placing assemblies in an industrial washing machine, where they are sprayed with pure water or with a water-based mixture. When the industry began to look for alternatives to ozone depleting substances, water cleaning was thought to be greatly inferior to CFC-113 as it has a higher surface tension, which would make it difficult to get water into small gaps in the boards, and even harder to get out again. In practice, many companies have found that water can clean small gaps in both surface mount and through-hole assemblies, particularly with the help of new nozzles and high pressure/high volume sprays.

The advantages of this type of cleaning come from its occupational safety benefits

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2 The US Halogenated Solvents Industry Alliance (HSIA) has classified them as of “high toxicity”, yet Petroferm, the manufacturers of one of the leading brands, says BioAct EC7R can be used without harm to workers. United Nations Environment Programme (1989) and the United States Environmental Protection Agency (1991) report that there has not yet been sufficient toxicity testing to resolve the issue.

and its process flexibility. Design, formulation and concentration can all be adjusted for cleaning different assemblies with different types of contaminant. This method, however, is not without its disadvantages. In process terms there are problems because the equipment takes up more space on the factory floor and because this technique requires more careful engineering and control than cleaning with CFC-solvent. In environmental terms, the first problem comes from water itself being a scarce resource in many parts of the world, and the high purity water required often being very expensive. The need to dry assemblies makes energy consumption higher using this method than using CFCs. This process also generates contaminated wash water, which has to be treated before discharge to sewer. Recycling of the waste water therefore makes economic and environmental sense. Closed loop and zero discharge systems would make aqueous cleaning an ideal alternative from technical, economic and environmental perspectives. Yet these systems are in general not fully developed. Zero-discharge systems are available for some, but not all, water-soluble flux applications and are under development for rosin and organic acid fluxes.

(4) No-Clean Techniques. An option increasingly being chosen by companies committed to early phase-out dates is not to clean the boards at all. The idea of leaving solder on assemblies is not new. Many manufacturers of "low performance" electronic goods have never removed solder residues. On the whole, industry has tended to clean equipment which has to be very reliable, or in which corrosive fluxes are used. Managers of plants producing high performance products who are now changing their processes over to no-clean technology say that the option was "in the literature", but that there was no incentive to investigate its applicability for their process (Hartbauer, 1992). New fluxes coming onto the market are starting to change this. Typical fluxes contain 15-35% solids, whereas the new types of flux contain as little as 1% solids, which leave minimal residue and therefore will have very little effect on product reliability.

This technique has the obvious advantage of eliminating one stage in the manufacturing process. This simplification not only reduces cleaning costs, but also increases efficiency as companies can test the reliability of the assemblies ("bed of nails testing") immediately after wave soldering, rather than having to wait until after cleaning and drying. This technique, however, may not be appropriate for certain applications, particularly those with magnetic components such as disk drives (Technology Business and Environment Program, 1993). There is also some concern that, as assembly technologies become finer and more compact, cleaning will become necessary (Dulmage, 1992).

The principal obstacle to wholesale adoption of no-clean, however, is not technical, but organizational. Traditional product testing methods use cleanliness of the surfaces as a measure of reliability. Boards that have been soldered using this method obviously compare badly in this respect with those that have been cleaned, even if there is no demonstrable difference in reliability. This method of reliability testing is currently being changed. At the same time as a need for a change in standards arises, companies need to change their customers' perceptions. Northern Telecom cited customer resistance as the principal obstacle to adopting no-clean technology (Technology Business and Environment Program, 1993). This resistance has diminished substantially, however, as customers have begun to use equipment where the boards have not been cleaned and have seen that performance is not impaired.

<u>Industry Responses.</u> The first company to commit to a total CFC phase-out was Northern Telecom, which announced in 1988 its decision to phase-out all ozone depleting substances by December 1991. The company committed to all newly acquired sites being CFC free within 15 months of purchase. To reach this goal, the company has implemented a number of technical options. It considers, however, that no-clean fluxes are the best alternative for 80-90% of its through-hole technology boards. It estimates that this program will save $50 million over the next 8 years. Northern Telecom was one of the initiators of the Industry Cooperative for Ozone Layer Protection (ICOLP), a group

comprised of nine companies and the US Environmental Protection Agency. ICOLP is an industry-run information exchange system through which companies can exchange technical information and ideas. It also aims to aid the transfer of technology to assist the phase-out of CFC use in the electronics industry in developing countries.

AT&T reduced CFC-113 consumption to 50% of 1989 levels by 1991 (1988 consumption was 3 million lbs) and committed in 1989 to a phase-out by 1994 (Chittock, 1991). As with most other electronics firms, these reductions only apply to CFCs used in manufacturing, and do not include those used in refrigeration or air conditioning. AT&T announced that by 1994 it would stop accepting products from suppliers who use CFCs. By 1991 the company had stopped accepting foam packaging from outside sources that had been made with CFCs. AT&T has chosen terpenes on the whole, but is increasingly investigating no-clean. Results from terpenes have been good, and AT&T has shown them to be the cheapest of the alternatives for their needs.

In 1989, IBM published a commitment to eliminate CFCs altogether in its manufacturing process by 1993 (use in 1988 was 11.3 million lbs). By the end of 1991, 20 of the 40 plants that had been using CFCs had stopped entirely, and emissions company-wide had reduced by 83% since 1987 (Technology Business and Environment Program, 1993). For the most part, IBM uses aqueous cleaning as an alternative to CFCs, with saponifiers and air dryers. IBM is currently reviewing the cost implications of changing over to no-clean technology, and estimates that the savings in operating costs, through avoiding buying solvent, at least outweigh the costs of investing in new capital equipment.

Digital Equipment Corporation began its phase-out program in 1988, and had reduced consumption and use by more than 90% by 1992. The company has chosen aqueous cleaning for most applications. It has worked with an equipment supplier to develop a new nozzle, patented technology that it has made available, free of charge through ICOLP. This is the first technology that offers adequate performance with aqueous solutions cleaning surface mount boards.

Summary. The response of the electronics industry was marked by two characteristics. First, despite protests to the contrary, within a year of the signing of the Montreal Protocol in 1987, in which only a 50% reduction by the year 2000 was called for, the electronics industry was announcing a rapid phase-out of CFCs. Lead by Northern Telecom and AT&T, the industry recognized that the Protocol in 1987 was just the first step to an eventual ban. As stated by one industry representative, at that point, "the writing was on the wall." Second, technological choices of the various companies within the industry varied, as there was a number of technical options available for companies. The factors that lead to this approach will be discussed in comparison to those in the automobile industry later in the paper.

The Automotive Industry

In response to the Montreal Protocol in the late 1980s, automobile manufacturers began investigating alternatives to CFCs for use in automobile air conditioners. Like the electronics industry, the feeling at the time was that no options existed and that the new technology just could not be developed. As one industry manager commented, "When we first started discussing the options for CFC-free air conditioners, I thought 'this is impossible.'" A number of chemical options, including blends such as CFC-12/DME, CFC-500, and HCFC-142b/22 were explored. While these mixtures appeared attractive for short-term reductions in CFC-12, each one presented technical obstacles to implementation and had non-ideal environmental and health performance characteristics.

Two chemicals emerged as the most feasible alternatives to CFC-12. One was HCFC-22, a chemical which has only 5% of the ozone-depletion potential of CFC-12. The other was HFC-134a, a lesser known chemical with zero ozone depleting potential. Spurred by legislation in Sweden that banned the use of CFCs by 1995, Swedish manufacturers Volvo and Saab spent a significant amount of time investigating HCFC-22 in automobile air conditioning systems (Keebler, 1989). When it seemed that HCFC-22 would emerge as the chosen substitute, some companies took the initiative to propose new alternative technologies using the coolant. Ultimately, however, auto manufacturers were reluctant to undertake the extensive and costly engineering changes that were needed for HCFC-22. Because of HCFC-22's ozone depleting potential, many feared future regulatory controls on the substance (Keebler, 1989).

The automobile industry eventually turned its attention to HFC-134a for use as the alternative coolant. The most attractive feature of HFC-134a was that it had zero ozone depleting potential (ODP), compared to ODP of 1.0 for CFC-12 (Montreal Protocol 1989 Refrigeration Air Conditioning and Heat Pumps Technical Options Committee, 1989). While there was some fear of regulatory controls on HFC-134a due to its global warming potential, industry officials felt that ozone depletion was a more tangible and immediate threat, and there were no other alternatives at that time with zero ODP. Data revealing that HFC-134a had a global warming potential approximately one tenth that of CFC-12 further reduced these concerns (Bateman, 1992).

The most immediate concern with HFC-134a was the uncertainty surrounding its availability. In 1988, however, two large chemical manufacturers, DuPont and ICI, began to accelerate their commercialization schedules to meet the needs of the auto industry, and HFC-134a became the best alternative to meet the pressing CFC reduction schedule.

Once it had been established that HFC-134a could be supplied in adequate quantities, automobile manufacturers and their suppliers began working more aggressively on redesigning the air conditioning system to run on this substitute. Unlike the electronics industry, very little of this technology had been researched at any great depth prior to the Protocol. Using HFC-134a required a redesign of the entire air conditioning system. Selection of a lubricant compatible with HFC-134a presented the industry with one of the most problematic challenges in the development of the new air conditioning system. In addition, differences in the chemical properties required that systems operating with HFC-134a have new seals, hoses, fans, and more powerful compressors in order to reach the same level of cooling performance as CFC-12 (Yamanda, Yasuhisa, & Arakawa, 1992).

Unlike other industries affected by the CFC ban, the replacement of CFC-12 in automobile air conditioning units presented the automobile industry with technical problems that reached much further than design changes in the unit itself. Many of these problems stemmed from the fact that the new units, in order to reach the same level of performance as their predecessors, usually needed larger and heavier components. For most manufacturers this meant an entire redesign of the front end of the automobile, which is usually extremely tight for space, in order to maintain the same shape. In addition, since reducing vehicle weight is one of the main considerations when increasing automobile fuel efficiency, the weight of the new units, which were as much as two pounds heavier than the old units, was also of primary concern. In an industry where efforts are made to reduce vehicle weight by less that an ounce, introduction of the heavier air conditioning units meant reducing the weight of the vehicle through material substitutions. Further complicating the issue, each change in vehicle design required a subsequent alteration in production facilities. These changes, although a familiar occurrence in automobile assembly plants, nonetheless presented costly obstacles to change.

Companies had varied success in designing air conditioning systems which were small and light enough to reduce the impact on total vehicle design. For the most part, the first wave of new air conditioners were both heavier and larger. One exception in this regard was a system already being looked into by Nissan for efficiency reasons, in which a unique parallel condenser allowed them to design a unit which was the same size as their old air conditioning unit, reducing the impact on total vehicle redesign (Technology Business and Environment Program, 1993). Air conditioners based on this and other designs started to emerge from the industry and its suppliers, making new air conditioners both smaller and lighter than their CFC based counterparts. For the most part, most companies are now utilizing similar technologies in their new CFC free air conditioners.

Companies started to introduce CFC air conditioners in 1991, three years after the Montreal Protocol was passed. Within the industry, some companies have been slower than others to phase-out CFC based air conditioners from their products. Early movers in this transition were Volvo, Saab and Mercedes, with Mercedes producing the first vehicle with the new coolant. Most other producers started the transition in 1992. Possibly more importantly, the length of the transition time varied among companies. While some European and Japanese manufacturers planned to be completely phased out by production year 1993, many producers, such as Toyota, Volkswagen, and Chrysler targeted 1994 as their phase-out deadline. American producers GM and Ford initially set their phase-out deadline to be 1995. In light of the new US deadline and impending CFC shortages, several producers, including Chrysler, Toyota, and Ford, have moved up their phase-out schedules by one year. The Environmental Protection Agency now estimates that approximately 90% of all new motor vehicles will have CFC free air conditioners by 1994 (Nirk, 1993). A complete phase-out is expected by 1995 (Cavenaugh, 1993).

Servicing of Old Vehicles: A Costly Problem. Aside from the expense of designing the new air conditioning systems, the cost of new units are not significantly higher than the ones built to run on CFC-12 (Wald, 1993). Instead, the primary costs of the phase-out to automobile consumers stem from the servicing of air conditioning systems that run on CFC-12. For automobiles under warranty, these costs will likely be borne by automobile companies. The source of these costs are twofold. First, the price of CFC-12 is rapidly rising due to its high demand and lowering supply; CFC-12 has already been sold for as much as $20 a pound in areas such as California and Arizona (Keebler, 1993). In the United States, a $3.35/pound excise tax added in 1993 contributes to this number (McMurray, 1992). Second, as the supply of CFCs becomes scarce, the industry and consumers will face significant costs for retrofitting obsolete air conditioners.

The problem arises from the fact that approximately 80% of the CFCs used as automobile air conditioner coolant is consumed in the service of old systems (Montreal Protocol 1991 Refrigeration Air Conditioning and Heat Pumps Technical Options Committee, 1991). UNEP has estimated that, assuming a full global implementation of an alternative coolant in 1995, the demand for CFC-12 will peak in 1994 due to the servicing of old vehicles. In 2005, however, a large number of vehicles will still require CFC-12 for service (Montreal Protocol 1991 Refrigeration Air Conditioning and Heat Pumps Technical Options Committee, 1991).

Recycling of CFC-12 had been identified as the primary method of sustaining the CFC-12 supply for the servicing of existing A/C systems. Although recycling CFCs is not mandated by the Montreal Protocol, several countries have recognized the benefits of sustaining the existing supply of CFCs and are regulating CFC recycling (Montreal Protocol 1991 Refrigeration Air Conditioning and Heat Pumps Technical Options Committee, 1991). Initial recycling efforts by the automobile industry and suppliers were pushed by this type of regulation. The costs of recycling equipment are substantial. Depending on the level of sophistication, a service station may pay from $1500 to $5000 to acquire one of these machines. Costs are recovered by some service shops by charging a service fee for a CFC refill. Due to the skyrocketing costs of CFCs from taxes and a diminishing supply, the manufacturers of recovery/recycle and recovery-only equipment have contended that most of the machines will pay for themselves in a month (Gardner & Baker, 1992). This type of overwhelming financial incentive is pushing rapid adoption of CFC recycling.

Although recycling will help meet the demand for CFC-12, it can not be relied upon to supply all future CFC-12 needs. Spot shortages have already occurred in the United States as the production of CFC-12 is being phased out; larger shortages are predicted for future years. Because of the CFC shortage, the Mobile Air Conditioning Society has estimated that as many as 100 million vehicles will need to have their air conditioners serviced without the use of CFC-12 (Keebler, 1992). Two options are being explored to address this problem. One is the development of a "drop-in" substitute for CFC-12, which would eliminate the obsolescence of the old air conditioning units. This option has met with significant resistance by many in the automotive industry because of the ability of these drop-ins to contaminate the supply of the other coolants. The fear is that mechanics, not knowing a substitute refrigerant has been used, will suck the refrigerant into their recycling machines and contaminate the supply of existing coolants, destroying air conditioners that run on these coolants (Laugesen & Spencer, 1992).

In the absence of a "drop-in" substitute, automobile owners will have to purchase retrofit technology to enable their air conditioners to run on HFC-134a. Retrofitting is a major concern to the automobile industry because the number of vehicles requiring this technology is great and the associated costs to them are high. The estimated costs of retrofitting technology, for those vehicles that have retrofit kits available, varies between $200-1000 for each vehicle. The costs largely depend on the level of technology of the existing vehicles. Newer vehicles, such as 1992 or 1993 models, will be less expensive to convert since the air conditioners were designed with technology such as less permeable seals and barrier hoses that could withstand the demands of R-134a. Older cars will be at the higher end of the price range since more components will need to be changed.

The Environmental Protection Agency has estimated that because of the retrofit problem, pushing the deadline up from 2000 to 1997 for the CFC phase-out cost the automobile industry approximately $2.8 billion. These costs were even higher when the deadline was pushed up to 1995. The magnitude of the retrofit problem forced the EPA to ask DuPont to extend its production of CFC-12 to service the millions of air conditioners in existing vehicles. As stated by one consultant, "EPA looks like 'the bad guy. They're begging DuPont to make it [CFC-12].'" (Kirschner, 1994)

Summary. In making the transition to systems that can run on the new coolant material, the automotive industry moved relatively slowly as compared to the electronics industry.

Companies started phasing out old technologies in 1992, and a complete phase-out won't be achieved until 1995. In comparison to the electronics industry, there were higher costs associated with technology development. To reduce these costs, many firms undertook a slower pace of change. The need for retrofit technologies for automotive air conditioners, however, made these delays a costly option as well. The retrofit problem could cost the automotive industries and ultimately consumers several billion dollars. While most firms have utilized similar technologies to replace CFC based air conditioners, they have implemented different schedules for the phase-in of new air conditioning units in their automobiles. In the next section we will analyze the response of the automobile industry, in comparison to the electronics industry, and discuss the factors that have contributed to the responses of each industry, as well as firms within these industries.

DISCUSSION

Overall, the Montreal Protocol and its subsequent amendments represent a successful example of technology-forcing regulation. Despite initial industry resistance, the transition from CFCs has been achieved with great success in almost every case. Once faced with inevitable controls on CFCs, the electronics industry found ways of reducing consumption, and either developed new alternatives or adapted other cleaning methods they had already been using. In the automobile industry, where the alternatives seemed less attractive, companies modified existing technologies and are coming up with even higher-performance CFC-free products.

Both industries eventually shifted to CFC alternatives. In neither industry did the phase-out of CFCs require radical breakthroughs in technology. Technology-forcing regulations induced both industries to re-examine their existing technical options and make improvements. In both industries, the costs of making a transition to alternatives were not prohibitive. For automobile companies, new technologies initially represented only a small added cost to the total cost of the vehicle. Many firms in the electronics industry even saved money by shifting to alternatives.

Yet, the two industries differed in the rate and nature of their responses to the technology-forcing regulation. Technical differences help to explain some but not all of the differences in the responses of the two industries. For the electronics industry, most of the technologies existed, even if only in the research stage. For the automobile industry, the technical challenge was perhaps more complex and depended on the availability of HFC-134a. In addition, as part of an inherently complex product, the replacement of CFC-12 in automobile air conditioning units presented the industry with technical problems beyond design changes in the unit itself.

Existing models of technical innovation would predict the significance of these and other technological characteristics as they exist along the product life cycle, for understanding the path of technical change (Tushman & Rosenkopf, 1992; Ashford & Heaton, 1983). For the most part, however, these models do not account for the tight coupling among technological, organizational, and institutional factors that occurred in this case. First, long standing organizational routines within each industry played a role. The electronics industry is characterized by innovation, short product cycles, frequent process changes, and short product lead times. Firms respond quickly to technical and market changes and their organizations are designed to facilitate continuous innovation. Because they were already exploring new technological options, many companies chose the technical solution that they had been using before the environmental concerns arose. Existing technologies created cognitive frameworks and behavioral routines that supported the pursuit of certain technical options in firms. Digital Equipment Corporation, for example, has been using an aqueous system for cleaning since 1974, and has now developed a new aqueous technology to cope with the problems associated with cleaning surface mount boards.

Second, there were also influences of corporate environmental strategy. The use of ozone depleting substances challenged the electronics industry in the late eighties and managers saw the advantages of moving ahead of regulations. Despite uncertainties resulting from varied and shifting national phase-out schedules, many of the electronics firms felt that it was more effective to take voluntary action than be constrained by a future regulation over which they might exert little control. Many of the firms in the automobile industry perceived similar regulatory stimuli from a different vantage point. As late as 1992, GM, Chrysler and Ford showed surprise at the Bush administration's announcement regarding a new phase-out timetable in the United States (Wald, 1993). Even after the Bush announcement, American automobile companies hesitated. They still held the view that allowances would be made for the servicing of old vehicles. More specifically, they believed that an extension would be made for CFC production for use in automobile air conditioners as an "essential" use of the substance. In 1992, these companies still requested more specific guidelines on how to proceed with the phase-out (Technology Business and Environment Program, 1993).

This response of the automobile industry emerged from a long history of treating environmental regulations as a constraint rather than an opportunity for innovation; the automobile industry found it difficult to modify their underlying approach to environmental regulation. Following Roberts and Bluhm's (1981) work on electric utilities, rather than being "positively responsive," companies within the industry seemed to engage in "optimistic self deception." Firms institute unique strategies with respect to environmental regulations; these strategies are strongly influenced by the organizational history and past experiences of its managers.[3]

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3 Looking at the industry responses to recycling legislation emerging in Europe and more recently in the United States, while the automobile industry is attempting to undertake a strategy of "positive responsiveness," they are struggling to do so with the same organizational structures and cultures. As a result, one can see similar patterns of response beginning to emerge in the electronics and automobile industry in the area of product take-back and recycling (MIT Conference, The Greening of Durable Products: What's the Best Route?, March 22-23, 1993; MIT Conference, The Greening of Durable Products:

Related to overall environmental strategy, implementation of CFC alternatives in the two industries was also shaped by the level of management support and resources. This factor is especially important for environmental initiatives, which often do not yield high rates of return on investment. Some of the faster moving companies in the automobile industry sought to eliminate CFCs as part of their corporate commitment to improving environmental performance, and resources were allocated to allow design teams to meet stringent internal CFC deadlines. In several automobile companies, however, although senior environmental managers decided to move early, their efforts were often hindered by a lack of internal support. Other environmental issues were considered far more pressing. This was particularly problematic since CFC dependent products and processes were not regulated directly and no strict deadlines existed for the phase-out by user industries. Environmental managers in these automobile companies indicated that they had encountered resistance from top management when they sought to devote the large amounts of resources that would be needed to phase-out CFCs at a rapid pace. It was only when the potential for a costly retrofit problem became evident that a rapid phase-out schedule was endorsed by these companies. Even then, environmental mangers struggled to convince top management to address this critical issue.[4]

In the electronics industry, reasons, such as image, cost, the availability of CFC 11 and 12 and concern for the environment, were cited as reasons for a more rapid transition to alternatives than that mandated by regulation. In the electronics industry, senior management in a number of companies committed early to a phase-out date. This commitment gave plant managers an incentive to implement changes and to innovate on their own.

In addition to these organizational factors, institutional factors help to explain the differences observed among firms within each the two industries. Regional differences in

Improving Coordination in the World of Recycling, October 3-4, 1994)

4 U.S. industry executive, Interview with Author, 5 May, 1993.

policy development and the general climate towards environmental issues influenced the implementation schedules of various companies. European automobile companies were encouraged to move swiftly by the aggressive Swedish and German CFC deadlines that were set earlier then those established in the Montreal Protocol and its amendments.[5] The United States, on the other hand, waited until 1992 to change its phase-out date to 1995. As discussed above, this no doubt had a profound impact on the responses within the industry, as all three American companies based their initial schedules on the 2000 phase-out date established in the 1990 London amendments and the 1990 Clean Air Act Amendments.

The major theoretical implication of the cases outlined in this paper is that differences between the two industries can not be explained by models dependent on placing a technology within its overall life cycle. Instead, we found that industry responses to regulatory stimuli were shaped by complex interactions among a number of technical, as well as organizational and institutional forces. Managers in the two industries perceived the ozone depletion problem differently and reacted accordingly. Senior management in the electronics industry recognized the salience of the issue, and framed the issue as another technological problem demanding a solution. Environmental managers in the automobile industry saw the regulations as a constraint. They also had difficulty obtaining the attention and support of senior management for more rapid changes. In addition, institutional factors help to explain the different implementation paths taken by individual firms within the two industries.

<u>Implications for Researchers</u>

1) This experience highlights the challenge for researchers is gaining a deeper

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5 Currently, in Europe where concern over global warming is more pronounced, some German refrigerator manufacturers are indicating that they will be going directly to propane based refrigerants, and skip the "middle step" of HFC-134a (Air Conditioning Heating & Refrigeration News, 1993).

understanding of the interaction between regulation as a stimulus for change with the cognitive, organizational and institutional factors influencing firms response to technology-forcing regulation. More research is needed to understand which organizational and institutional factors are important, how they interact, and under what circumstances they are salient. From their work on electric utilities, Roberts and Bluhm (1981) hypothesize that if a regulatory agency provokes a crisis situation in a firm, organizations can become "rigid." This rigidity encourages the firm to rely on established routines that act as a barrier to learning. This and other hypotheses about organizational and institutional factors need to be explored more systematically across firms and industries.

As discussed earlier, Tushman and Rosenkopf (1992) suggest that organizational and social factors have the most influence during periods of experimentation. This case builds upon this hypothesis further by suggesting that social factors such as regulation are more likely to be responded to progressively by industries or firms characterized by an "experimental" culture. Further work in this area is clearly needed to suggest when various factors may be more significant then others for the process of technical change.

2) Yet another issue underlying the different responses to regulatory stimuli in the automobile and electronic industries is the importance of attention allocation. As seen in this case, while regulations are designed to force organizational attention to be devoted to environmental innovation, they do so with varying degrees of success. Understanding how top managers focus attention on the numerous and competing issues facing their organizations and then subsequently manage attention allocation within the rest of the organization is a critical area for future research (Ocasio, 1995). An understanding of attention allocation within firms can lead to more useful guidelines for effective environmental management within firms.

<u>Recommendations for Policymakers</u>

To ensure environmentally responsible innovation, policymakers need a more in-depth understanding of the industry and firms being affected by regulation. Similar to other broad based policies, such as tax, anti-trust and patent policies, environmental policies such as chemical bans will influence firms and technology development within these firms in very different ways (Nelson & Langois, 1983). Several key policy issues emerge from the above discussion.

1) This paper illustrates that regulations can act as powerful stimuli to technical innovation, but in this case firms faced the additional impetus to respond from market-based regulatory policies. The U.S. excise tax on CFCs forced firms to internalize the cost of CFCs to the environment, and gave environmental managers an argument for action that aligned with other industry objectives. Thus, the case suggests that technology-forcing regulations are likely to work more effectively when combined with financial incentives.

2) Industry's response to the banning of CFCs demonstrates the lack of fit than can occur between regulatory policy and industrial product cycles, a problem of particular salience when regulations apply to several industries which vary in their technical capabilities and planning cycles. When government officials establish regulations that are inconsistent with product life cycles, they run the risk of raising the cost of compliance to industry and stifling needed innovations. One approach to this issue is to devise regulatory approaches targeted to particular firms and industries. This approach can help to reduce costs and enhance flexibility in achieving environmental goals. EPA's 33/50 program, which negotiated agreements with particular firms, and the Industry Cooperative Ozone Layer Protection (ICOLP) are recent examples of quasi-regulatory programs targeted to specific firms and industries.

ISSUES FOR THE 21ST CENTURY

Our research suggests that technology-forcing regulations can be effective when they do not require major technical breakthroughs and when the cost is modest. In cases requiring large technical advances and significant capital costs, they are likely to meet with stiff resistance. Yet the organizational characteristics of the industry being regulated are important influences on the process of innovation. So too are the industry's or firm's regulatory history and standard operating procedures toward environmental regulation. Industry's response to the next wave of environmental regulation is likely to be shaped by the character of industrial innovation, as well as the key organizational characteristics of particular firms and industries.

Footnotes

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