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TITLE: The Influence of Government Actions on Innovative Activities in the Development of Environmental Technologies to Control Sulfur Dioxide Emissions from Stationary Sources

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Carnegie Mellon University

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A Dissertation Submitted to the Carnegie Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Engineering and Public Policy

By

Margaret R. Taylor

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Chapter 1 Introduction

Motivation and Definitions

In the management field of strategy, it is understood that the structural conditions of many industries are strongly determined by government policies. Michael Porter's seminal book, *Competitive Strategy*, lays out several ways in which government affects the forces driving industry competition. Government actions, including regulation and subsidies, can form a barrier to entry or even exit in an industry. Similar actions can strongly affect the relative positions of an industry's suppliers and buyers (government can also *be* a supplier or a buyer itself). Finally, government actions can affect the positions of substitutes vis-à-vis existing firms, as well as rivalry among existing competitors (Porter, 1980).

Less well-developed in the management and economics literatures, however, is the concept that a diverse set of government actions is similarly influential in the decisions of organizations both to engage in and to manage innovative activities. One reason for this is that it is difficult to parse out the role of government from among the numerous factors driving innovation. By studying innovation in an area in which government clearly plays a strong role, however, it should be possible to gain insights into the relationship between government actions, private innovative activities, and ultimately, the technologies that result from innovation. These insights could lead to a better understanding of the inducement mechanisms for innovation inherent in government actions, ranging from regulations to taxes to subsidies to public innovative activities, in a number of industries in which government plays a more subtle role. With this enhanced understanding, it should be possible for better policies to be designed to promote innovation for social and economic goals ranging from industrial competitiveness to environmentally sustainable growth.

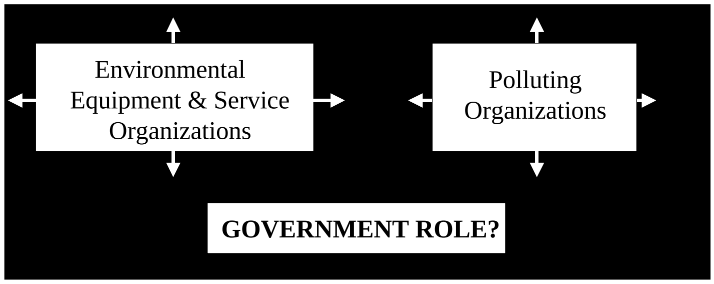
In light of these eventual policy goals, this dissertation studies the interaction between government actions and innovative activities in a technology area in which government is well known to play an important role: environmental control technology. As referred to in this dissertation, environmental control technology is equivalent to end-of-pipe technology, or the subset of environmental technology that reduces emissions of pollutants after they have been formed (see U.S. Environmental Protection Agency, 1997). There are two main reasons why government has a strong role in promoting innovation in environmental control technology. First, environmental technological innovation has been considered by academics to be central to meeting environmental goals since at least the mid-1970s (see Kneese and Schultze, 1975; Magat, 1978; Orr, 1976). In recent years, the appeal of promoting environmental technological innovation has increased as concerns about global climate change mitigation and the maintenance of economic growth have grown. Examples of environmental policy instruments with technological goals incorporated into their design include: "best available control technology" standards in command and control regulation that provide first mover advantages and lock-in possibilities to innovators; market-based instruments that encourage the development of lower cost environmental technology options; and subsidies that attempt to support an appropriate level of expenditure on environmental control technology research, development, and demonstration. The second reason for a strong government presence in fostering innovation in environmental control technology stems from the fact that a clean environment is a public good that typically provides weak market incentives for private investment and development.

There are, of course, very important private actors involved in innovation in an environmental control technology, and two are particularly central: polluting organizations and organizations that manufacture, sell, and service environmental control equipment. Although polluting organizations conduct a broad range of innovative activities to meet environmental control obligations and occasionally produce environmental control equipment for their own use, the more typical situation is that these organizations purchase environmental control technology from outside suppliers (see Kemp 1997, p. 40). These outside suppliers conduct important innovative activities both to maintain their in-service technologies and to develop new generations of their technologies. There are two important parallels between the innovative activities conducted by both polluting organizations and environmental equipment suppliers. First, both organizations, to a greater and lesser extent, often have more important lines of business than environmental control; innovative activities in these technologies are therefore not always the highest research and development (R&D) budget priority for these organizations. Second, neither organization typically conducts innovative activities in a vacuum; both learn from each other, as well as from other sources of innovation in environmental control technology such as government, universities, and non-profit research and development organizations.

Because of this interconnectedness of sources of innovation in environmental control technology, innovation in this area must be depicted and investigated as revolving around a complex of organizations. Figure 1.1 represents the "black box" of an "industrial-environmental innovation complex," defined by the relationships among organizations involved with innovation in an environmental control technology. The arrows surrounding the two central private actors in this figure represent organizational connections, primarily to the other sources of innovation discussed above.

FIGURE 1.1

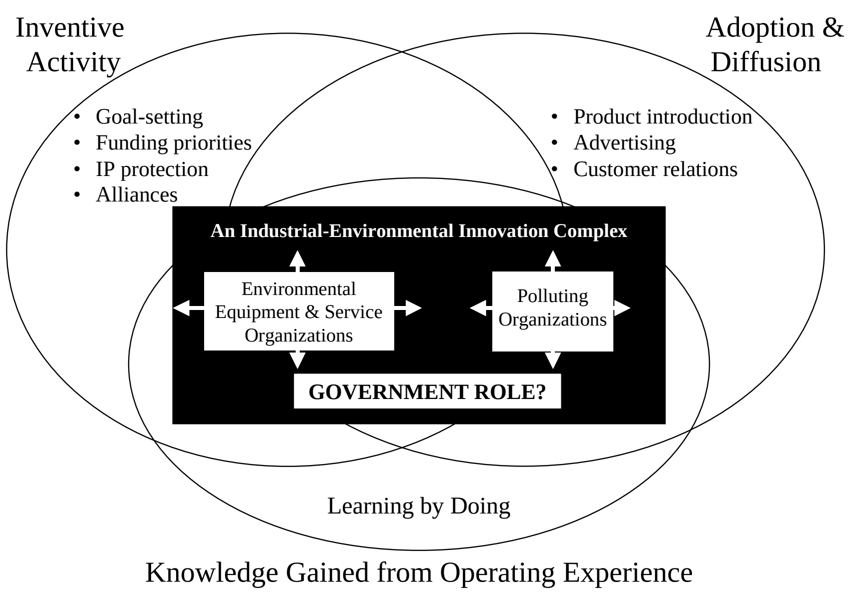
An Industrial-Environmental Innovation Complex



Inside this black box, overlapping innovative activities occur, while outside this black box, innovative outcomes can be observed in the technologies that result from these activities. Figure 1.2 illustrates the combined innovative activities of invention, adoption and diffusion, and learning by doing that take place within an industrial-environmental innovation complex, and provides sample business choices that are related to these activities.

FIGURE 1.2

Sample Innovative Activities within an Industrial-Environmental Innovation Complex



The depiction of innovative activities in this figure is partially based on definitions in Rogers (1995), Rosenberg (1994), and Schumpeter (1942). In keeping with definitions begun in

Schumpeter (1942), “invention” or “inventive activity” here refers to the development of a new technical idea. As stated in Clarke and Riba (1998), “an invention is an idea, sketch, or model for a new device, process or system. It might be patented or not, it might lead to innovation or not.” “Innovation,” or “adoption” here, in Schumpeter’s rubric refers to the first commercial implementation of a new invention into the marketplace. “Diffusion” refers to the widespread use of a commercial innovation and is often studied by researchers as a communication process through which future users become persuaded to adopt new technologies, in part due to information from previous users (Rogers, 1995). Finally, post-adoption innovative activities that result from knowledge gained from operating experience, such as “learning by using,” “learning by doing,” and “reinvention,” are referred to here as “learning by doing.” Learning by doing refers to technological improvements that occur as a result of a user’s modifications of the operations of an adopted innovation in order to correct difficulties or take advantage of opportunities observed during operation. Studies have shown that a considerable amount of innovative activity can be traced to operating personnel or to the contact of other researchers with operating personnel (for a discussion, see Cohen and Levin, 1989).

Previous Research

Previous research on the effects of government actions on innovative activities in environmental technology can be found in two literatures.[1] The first, the mainstream innovation literature, is rather large and generally traces its origins to Schumpeter (1942). It is this literature, which often consists of aggregate, multi-industry empirical economic studies (although sociological studies and some focused case studies are also included) that is the basis for the

[1] In both literatures, the broader set of technologies encompassed by “environmental technology” is generally addressed, rather than the more limited “environmental control technologies.”

definitions of innovative activities used in this dissertation (for a review, see Stoneman, 1995). This literature is generally centered on technologies for which market forces have been the primary drivers. Environmental technology, however, was considered in this literature at least as early as a 1969 article by Rosenberg that sought historical examples of the "forces which provide inducements to technical change … what Hirschman has called 'inducement mechanisms' [reference to Hirschman (1958) in Rosenberg (1969, pg. 1)]." One of the inducement mechanisms Rosenberg found was a constraint-imposing environmental legislation that a 1948 article showed improved the competitive advantage of the Swedish sulphate producers that were able to meet it.

Although influential economists and others have dealt with environmental technological innovation in more recent years, their work is typically considered part of a second literature, the environmental technology literature. This literature, while considerably smaller than the mainstream innovation literature, is diverse, encompassing theoretical economic studies, a few large empirical economic studies, and a number of case studies scattered among various disciplines [for a useful review and critique of much of this literature, see Kemp (1997)]. In this literature, the observation made by Rosenberg, among others, that competitive advantage sometimes accrues to firms able to meet environmental constraints has been popularized in the last ten years by debate on the "Porter Hypothesis." This hypothesis emerged from an influential page-long essay by the strategy expert Michael E. Porter in 1991 in which he argues that tough environmental standards that stress pollution prevention, do not constrain technology choice, and are sensitive to costs can spur innovation and thereby enhance industrial competitive advantage (Porter, 1991).

Underlying this idea is the concern that environmental standards only spur innovation if the details of these standards are properly specified; this concern has been a long-standing theme in the environmental technology literature. Since at least the early 1970s, a major thrust of the theoretical economic studies in this literature has been for economists to consider the possibility that "market-based" environmental approaches such as taxes, subsidies, and permits would induce technical innovation more effectively than traditional "command-and-control" regulation. In a review of these theoretical economic studies by Jaffe and Stavins (1995, S-45), the authors found that while most supported the idea that market-based approaches *should* be most effective in inducing innovation, they had inconsistent and inconclusive results about specific approaches. In addition, the authors state that other theoretical research has found that "which policy instruments are most effective in encouraging innovation and diffusion depends upon specific elements of instrument design and/or characteristics of affected firms." (Jaffe and Stavins, 1995, S-45)

The idea that specifics matter to the understanding of the influence of environmental government actions on innovation is especially well articulated in Kemp (1997). He effectively argues that many environmental technology studies ignore four central features of environmental technology innovation.[2] These features are: the innovative role of outside suppliers; the control efficiencies of specific technologies; the implementation issues that affect firm behavior (such as the amount of advance notice given about pending regulation and the speed with which the policy instrument requires firms to act to meet a stated environmental goal); and the complicated relationship between regulators and industry. Two studies that empirically consider the effects of regulatory stringency as a driver of environmental technological innovation, to contradictory

[2] In addition, he argues that many environmental technology studies are seriously limited by tendencies to ignore the political economy effects of policy instruments

results, provide useful examples of the importance of being sensitive to these features. Jaffe and Palmer (1997), for example, found that there is no statistical correlation between pollution abatement expenditures and patenting activity.[3] These authors conduct their analysis as if regulated firms perform all of the R&D measured by patents, although the important innovative role of other organizations has been demonstrated repeatedly (Ashford, Ayers, and Stone, 1985; Dupuy, 1997; Heaton, 1990; Kemp, 1997; Lanjouw and Mody, 1996). Lanjouw and Mody (1996), in contrast, found that pollution abatement expenditures and patent activity parallel each other across environmental media with roughly a two-year lag. These authors assume for measurement purposes that "all environmentally responsive innovation in a field responds to events in a broadly similar fashion." (Lanjouw and Mody, 1996, p. 557) This is despite the fact that specific technologies in an environmental problem area, which often exhibit a variety of control efficiencies, may react differently to different environmental standards. The results of both studies are therefore somewhat in doubt because of their reliance on aggregate data sources that mask the complexities of environmental technological innovation.

Case studies of environmental technological innovation necessarily pay more attention to the specifics of government actions and environmental technologies than do theoretical and some empirical economic studies. What they gain in accuracy, however, they are typically considered to lose in generalizability. One instance in which case studies can have a generalizable impact is when a relatively large number of such studies show similar findings. Such a grouping of case studies has been analyzed and synthesized in an article by Ashford, Ayers, and Stone (1985) that Kemp (1997) states is the most "comprehensive review" of the technology effects of specific environmental policies. In this article, the authors review (although not in complete detail) ten cases of regulation between 1970 and 1985 and their effects on the innovation and diffusion of

[3] Pollution abatement expenditures are the authors' somewhat questionable proxy for regulatory severity.

technologies by private firms. For each case, basic information is provided about the regulated substance and technology, the regulating authority, regulatory characteristics, and the industrial response, including the authors' categorizations of the type and degree of technological innovation. Appendix A contains a table summarizing these cases that was adapted from Ashford, Ayers, and Stone (1985) and Kemp (1997).

Three particularly interesting findings emerge from these cases. First, Ashford et. al. find that "a relatively high degree of [regulatory] stringency appears to be a necessary condition" for inducing higher degrees of innovative activities (Ashford, Ayers, and Stone, 1985, note 36 at 429).[4] Second, Ashford et. al. find that while "excessive regulatory uncertainty may cause industry inaction, too much certainty will stimulate only minimum compliance technology" (Ashford, Ayers, and Stone, 1985 pg. 426).[5] Third, Ashford et. al. find that in some of the cases they studied in which government scrutiny was clear well before regulations were imposed, "anticipation of regulation stimulates innovation" (Ashford, Ayers, and Stone, 1985 pg. 426).[6] Other studies of environmental technological innovation, such as the innovation survey of firms in the United Kingdom by Green, McMeekin, and Irwin (1994) and the diffusion study of the Ontario organic chemical industry by Dupuy (1997), support these findings.

This discussion has focused on findings in the environmental technology literature about innovative responses to characteristics of environmental regulation as well as to "market-based" mechanisms such as taxes, subsidies, and permits. Other government actions that influence

[4] The authors define a regulation as stringent for at least one of three reasons: it requires significant reduction in exposure, it requires costly compliance using existing technology, or it requires significant technological change (Ashford, Ayers, and Stone, 1985).
[5] Examples of some of these regulatory uncertainties can be found in Organization for Economic Cooperation and Development, Environment Committee (1985).
[6] Although the Ashford et. al. examples focused on innovation by polluting organizations, it is likely that anticipation of regulation is a driver of innovation by environmental equipment and service organizations as well. This is because regulation can guarantee a demand for these organizations' products; demand has been shown in the mainstream innovation literature to be an important spur for innovation (see Mowery and Rosenberg, 1982).

environmental technological innovation include innovation waivers, public innovative activities, and efforts by the public to promote technology transfer. The environmental technology literature has basically overlooked the importance of public innovative activities and technology transfer mechanisms in promoting environmental technological innovation, although it has considered past experiences with innovation waivers in the U.S. In theory, innovation waivers – incentive devices built into environmental regulation that generally extend regulatory deadlines and exempt polluting organizations from penalties in return for efforts by firms to develop innovative technologies to meet environmental standards – are very attractive to polluting organizations and regulatory agencies. In practice, innovation waivers proved to be ineffective because of ambiguous requirements, short deadlines, and institutional and administrative difficulties (see discussions in Ashford, Ayers, and Stone, 1985, pp. 443-62, and Kemp, 1997).

Approach and Organization of this Dissertation

This dissertation seeks to contribute to the environmental technology literature by concentrating on an extended case study of innovative responses to multiple government actions centered on the abatement of a single pollutant. This approach has several virtues. First, it learns from the criticisms of aggregate studies by allowing the specifics of policy instruments, environmental technology features, and affected organizations within the industrial-environmental innovation complex to contribute to the resulting insights. Second, it limits the variety of environmental technology features, such as those articulated in Kemp (1997), which could undermine insights into innovative responses since it considers a single set of technologies over time. Third, it allows for the consideration of the effects of many government actions – ranging from command and control regulation, to market-based approaches, to public innovative activities and technology transfer mechanisms – on environmental technological innovation.

This is important because it is the universe of government actions, rather than any single government action, which really affects corporate strategy and resulting innovative activities.

An additional contribution of this dissertation is that it conducts this extended innovation study through the integration of several established and repeatable quantitative as well as qualitative research methods. This is important for two reasons. First, this methodological approach provides a more realistic understanding of innovative processes than any single method would be able to provide (for a useful review of methodological issues in the study of technological innovation, see Cohen and Levin, 1989; Schmoch and Schnoring, 1994). Second, the fact that these methods are well established and repeatable increases the likelihood that the insights of this dissertation will be able to be synthesized with those of similarly conducted future case studies. These insights could then have a more generalized impact on policy discussions related to innovation, particularly in the environmental area.

The case study examined by this dissertation is the set of technologies that control sulfur dioxide (SO_2) emissions from electric power plants. This is a particularly useful case to investigate because the history of both the government actions pertinent to these technologies and innovative activities in these technologies is well documented and long-standing. In addition, the international availability and relevance to other environmental problems of the polluting and controlling technologies involved in this case make the case a useful basis for future comparison with other environmental control technologies.[7] The political, institutional, and industrial history of these technologies is explored in Chapter Two.

The specific methodologies used in this dissertation, which include analyses of U.S. patents, SO_2 control technology conference proceedings, learning curves, and interviews of

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[7] Electric power plant emissions are implicated in such environmental problems as global climate change and smog formation, while SO_2 control technologies are seen as the basis of other power plant end-of-pipe solutions.

influential experts, are depicted in Figures 1.3 and 1.4. Figure 1.3 illustrates the methodologies used to delve into the innovative activities of invention, adoption, diffusion, and learning by doing that occur within the black box of the SO_2 industrial-environmental innovation complex. These innovative activities are explored in Chapters Three, Four, and Five. Figure 1.4, on the other hand, illustrates the methodologies used to understand the outcomes of these activities, as observed in technological improvements realized over time. These outcomes are primarily addressed in Chapter Two, although they are contextually important to the entire dissertation. The various insights of Chapters Two through Five are synthesized in Chapter Six.

FIGURE 1.3

Methodologies Used in this Dissertation: Innovative Activities

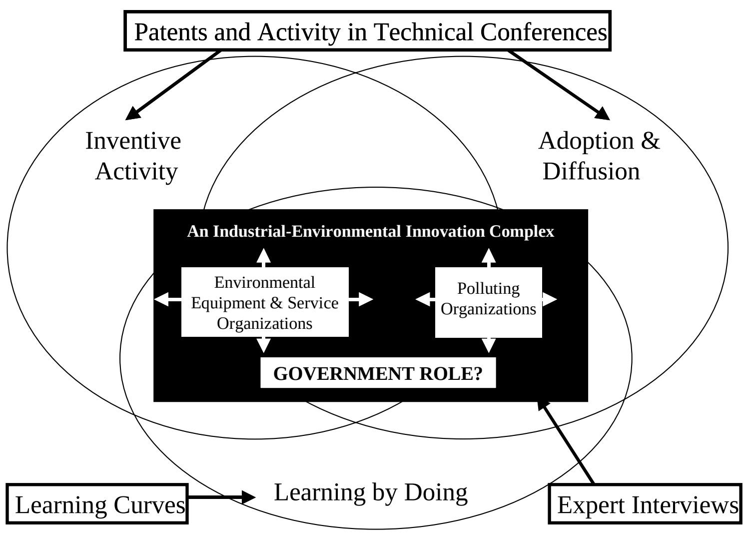
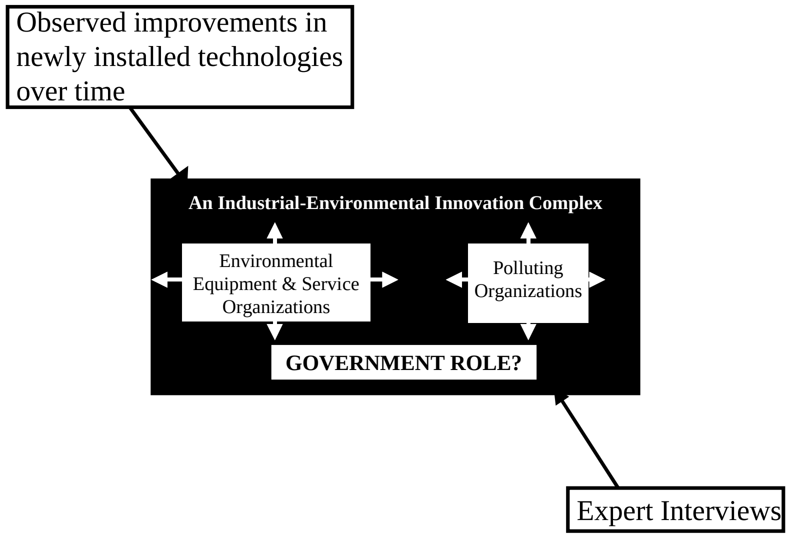


FIGURE 1.4

Research Approach of this Dissertation: Innovative Outcomes



Note on Expert Interview Method

Most of the research methods depicted in these figures lend insight into only one or two overlapping innovative activities or to innovative outcomes, and are thus described in detail in the appropriate sections of Chapters Two through Five. The research method of expert interviews, however, speaks broadly to both innovative activities and outcomes and will briefly be discussed here. Expert interviews were sought for two main reasons. First, they were sought in order to ground the other research methods in the organizational context and constraints of the industrial-environmental innovation complex. Second, they were sought in order to gain insight into the validity of some of the data sources used in the other research methods. For example, they provided insight into the importance of patents to the protection of SO_2 control technologies.

In order to gain the most useful insights out of the interview process, a relatively large, yet logistically reasonable set of experts had to be identified, contacted, and interviewed. There were two main selection factors behind the choice of experts to be interviewed. First, the expert would have to have been significantly active in research in the SO_2 industrial-environmental innovation complex for a long enough period of time to have historical perspective on innovation in these technologies and on government actions that were important to their development. Second, since the SO_2 industrial-environmental innovation complex encompasses multiple sources of innovation, the experts interviewed would have to represent a number of different organizational affiliations. In answer to the first selection criteria, experts were identified primarily through the frequency with which they presented papers at a technical conference held on SO_2 control technologies for over three decades.[8] In answer to the second selection criteria, the experts interviewed represented a variety of organizational affiliations in the SO_2 industrial-environmental innovation complex, including the U.S. government, EPRI, utilities, architect and engineering firms, vendor firms, and universities. Table 1.1 describes the affiliations of the twelve experts interviewed for this dissertation, as well as assigns labels to each of these experts for use in identifying their statements throughout this dissertation.

TABLE 1.1

Characteristics of Experts Interviewed, with Dissertation Identification Labels

Expert Affiliations	Label
Architect and Engineering Firm	A
Utility	B
Environmental Equipment Vendor	C
Utility, Architect & Engineering Firm	D
Consulting Firm, Environmental Equipment Vendor	E
Contract Non-Profit Research & Development Organization	F
Utility	G
University, Government Agency	H
Consulting Firm, Contract Non-Profit Research & Development Organization	I
University	J
Government Agency	K
Consulting Firm	L

[8] For a fuller explanation of the method for interviewee selection, see Appendix B.

The interviews conducted for this dissertation follow the methodological tradition of innovation counts and surveys in the mainstream innovation literature (for reviews, see Archibugi, 1988; Archibugi and Pianta, 1996; Cohen and Levin, 1989; Hansen, 1992; Smith, 1992a; Smith, 1992b). One of the prominent uses of such innovation surveys is to understand what technical experts consider to be significant innovations in a technology area. In this dissertation, experts were asked not only their perceptions of the significant technological and organizational developments in the evolution of SO_2 control technologies, but also their perceptions of significant government actions affecting the SO_2 industrial-environmental innovation complex (the interview protocol is included in Appendix C). In addition, experts were asked targeted questions about some of the data sources analyzed in this dissertation, as well as questions about the role of operating experience in the evolution of SO_2 control technology. The results of these questions are discussed in Chapters Three, Four, and Five, as are expert opinions about the causes of patent trends developed in Chapter Three. More general insights derived from the expert interviews inform the entire dissertation.

Chapter 2 The Innovative Context of SO_2 Control Technologies

Sulfur dioxide (SO_2) is primarily emitted to the atmosphere through the burning of sulfur-containing materials, of which fossil fuels such as coal and oil are the most important examples. SO_2 is, therefore, the byproduct of many long-standing economically productive processes. Table 2.1 demonstrates that, although the importance of selected sources of SO_2 emissions in the United States has changed over time, coal-fired electric power plants have been the primary source of these emissions since 1960.

TABLE 2.1

U.S. Sulfur Dioxide Emissions Estimates, 1940-1998 (Thousand Short Tons)

Activity \ Year	1940	1950	1960	1970	1975	1980	1985	1990	1995	1998
Fuel Combustion										
Electric Utilities	2,427	4,515	9,263	17,398	18,268	17,469	16,272	15,909	12,080	13,217
Coal	2,276	4,056	8,883	15,799	16,756	16,073	15,630	15,220	11,603	12,426
Oil	151	459	380	1,598	1,511	1,395	612	639	413	730
Gas	NA	NA	NA	1	1	1	1	1	9	2
Industrial Processes	6,060	5,725	3,864	4,568	3,310	2,951	3,169	3,550	3,357	2,895
Coal	5,188	4,423	2,703	3,129	1,870	1,527	1,818	1,914	1,728	1,485
Oil	554	972	922	1,229	1,139	1,065	862	927	912	773
Gas	145	180	189	140	263	299	397	543	548	558
Other	3,642	3,964	2,319	1,490	1,082	971	579	831	793	609
Industrial Processes										
Chemical & Allied Manufacturing	215	427	447	591	367	280	456	297	286	299
Metals Processing	3,309	3,747	3,986	4,775	2,849	1,842	1,042	726	530	444
Copper	2,292	2,369	2,772	3,507	1,946	1,080	655	323	177	NA
Petroleum & Related Industries	224	340	676	881	727	734	505	430	369	345
Other	334	596	671	846	740	918	425	399	403	370
Transportation										
On-Road Vehicles	3	103	114	411	503	521	522	542	304	326
Non-Road Engines/ Vehicles	3,190	2,392	321	83	99	175	208	934	1,008	1,084
TOTAL ALL SOURCES	19,952	22,357	22,227	31,161	28,011	25,905	23,229	23,678	19,189	19,647

Sources: Adapted from U.S. Environmental Protection Agency,
Office of Air Quality Planning & Standards (1997); (1998); and (1999)

Public concern about SO_2 pertains to its negative effects both on human health and on ecosystem well being, although both types of effect have not always been recognized. Its human health effect is as a local eye, nose, and throat irritant, which in the extreme has contributed to such deadly air pollution incidents as the killer smogs that occurred in Donora, Pennsylvania, in 1948 and London, United Kingdom, in 1952 (Snyder, 1994; Cooper and Alley, 1994).[9] In addition, in recent years it has been implicated in increased mortality due to its role as a fine particle. Its ecosystem effect is as a major contributor (with nitrogen oxides) to acid deposition (acid rain), the regional air pollution phenomenon related to the acidification of lakes and streams, plant damage, and reduced forest growth.

Environmental technology strategies pertinent to SO_2 emissions take one of three approaches: (1) alternative power generation technologies such as fluidized bed combustion and synthetic fuels; (2) pre-combustion reduction of sulfur in the burning of lower-sulfur fuels, either naturally as in the case of switching to low-sulfur coal, or technologically through the removal of sulfur from existing coals; and (3) removal of SO_2 from the post-combustion gas stream.[10] Only the latter two of these strategies, pre-combustion and post-combustion removal, involve a technological response relevant to the standard coal-fired power generation processes generally in use over the last thirty years.[11] Pre-combustion control technologies primarily involve physical removal processes such as crushing and grinding to remove inorganic sulfur in the form of pyrite from coal. More advanced chemical and biological pre-combustion technologies exist

[9] These incidents resulted from simultaneous high concentrations of SO_2 and particulates.

[10] Sub-bituminous and lignite coals, found primarily in easily surface-mined deposits in the western U.S., are typically lower in both heat and sulfur content. Bituminous and anthracite coals, found primarily in deposits that are deep-pit mined in the eastern U.S., are typically higher in heat and sulfur content (Laitos and Tomain, 1992, p. 450).

[11] Tall gas stacks that disperse SO_2 from local areas were once promoted by the electric power industry as an effective method of controlling SO_2 emissions from existing generation processes. These are no longer relevant because of regional concerns about SO_2 and acid rain.

that can also remove some of the organic sulfur from coal for a greater overall SO_2 emission reduction, but these processes are costly and exist only in non-commercial stages. None of these pre-combustion technologies, however, removes as much SO_2 as post-combustion control technologies.

These technologies, which are installed on roughly 90 gigawatts (or about one-third) of U.S. electrical capacity, can be grouped under such names as "flue gas desulfurization" (FGD) systems or "scrubbing" technologies. FGD systems involve contacting a post-combustion gas stream with a base reagent in order to remove SO_2. These systems can be categorized as wet, dry, or other, following an article by Jozewicz et. al. in 1999. Wet FGD processes include wet throwaway and gypsum by-product processes involving reagents like limestone, lime, dolomitic lime, sodium carbonate, and seawater. Dry FGD technologies include the throwaway processes of spray drying, sorbent injection into the furnace, boiler, or downstream duct, and circulating fludized bed. Other FGD processes include regenerable processes with reagents such as sodium sulfite (Wellman-Lord) and magnesium oxide, as well as combined sulfur oxide/nitrogen oxide technologies. The two most dominant wet and dry systems will be described here.

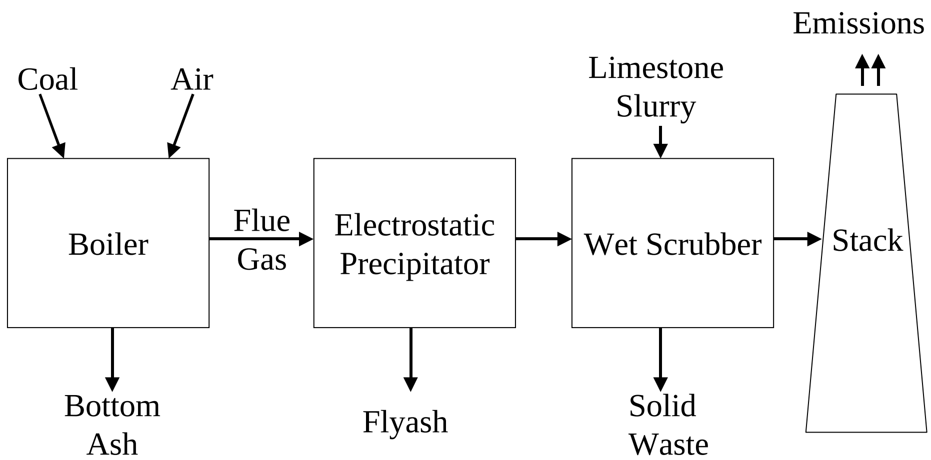
The dominant wet FGD systems use limestone as the scrubbing reagent and today achieve reliable, 95%+ SO_2 removal efficiencies.[12] Figure 2.1 shows a simple schematic of a wet limestone FGD system. In the wet scrubber in this figure, limestone slurry is typically contacted with flue gas in a gas absorber where SO_2 is absorbed, neutralized, and partially oxidized to calcium sulfite and calcium sulfate.[13] Equation 2.1 displays the overall stoichiometry of the limestone SO_2 absorption process.

[12] Wet limestone scrubbing is dominant in the worldwide utility FGD market in part because limestone is inexpensive and widely available

[13] Absorber devices include packed towers, plate or tray columns, venturi scrubbers, and spray chambers (Barbour et. al. 1995).

FIGURE 2.1

Schematic of a Typical Wet Limestone FGD System



EQUATION 2.1

Stoichiometry of the Limestone SO_2 Absorption Process

$$CaCO_3\ (s) + 2SO_2 + H_2O \rightarrow Ca^{+2} + 2HSO_3^{-} + CO_2\ (g)$$

$$CaCO_3\ (s) + 2HSO_3^{-} + Ca^{+2} \rightarrow 2CaSO_3 + CO_2 + H_2O$$

Source: (Cooper and Alley, 1994, p. 454)

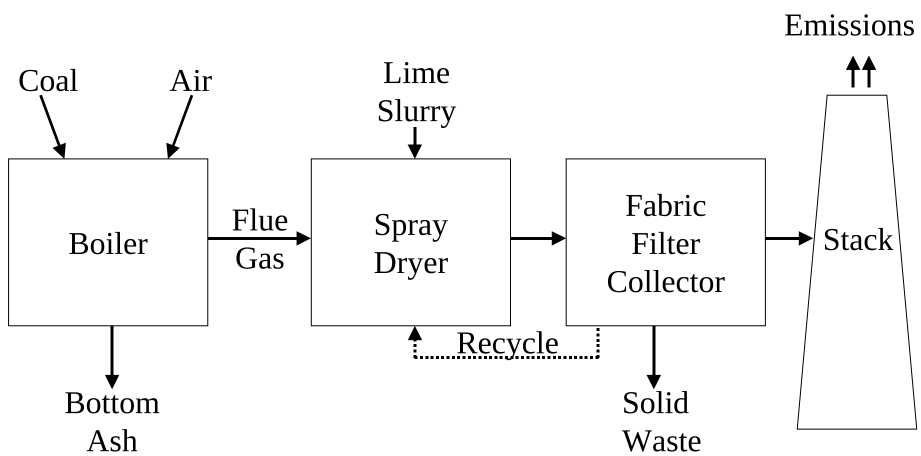
Thorough contact between the gas and the sorbent is essential to the success of the mass transfer operation of absorption. Absorber towers have different flow designs to accomplish this: countercurrent, crosscurrent, and cocurrent. In the most commonly installed countercurrent designs, the waste gas stream enters at the bottom of the column and exits at the top while the sorbent stream does the opposite. One of the main advantages of these designs is that they provide the highest theoretical removal efficiency because gas with the lowest pollutant concentration contacts liquid with the lowest pollutant concentration. In addition, they usually require lower liquid-to-gas ratios than cocurrent designs, in which both the waste gas and the sorbent enter the column at the top of the tower and exit at the bottom (Barbour et. al., 1995). In general, greater liquid-to-gas ratios mean higher SO_2 absorption efficiency, but also higher operating costs because of higher energy needs due to high pressure drops and pumping needs. This is important to consider since the power consumption of a limestone FGD unit is typically large, on the order of 3 to 6% of the power generated by the plant for older FGD systems and 2 to 3% for newer ones (Cooper and Alley, 1994, p. 467). In a crosscurrent tower, the waste gas flows horizontally across the column while the sorbent flows vertically down the column. The advantage of these designs is that they generally have lower pressure drops and require lower liquid-to-gas ratios than the other two designs, while the disadvantage of these designs is that they offer less contact time for absorption (Barbour et. al., 1995).

It is very important to optimize the process chemistry of wet limestone FGD systems; failure to do so can result in scaling and plugging of system internals based on the precipitation of calcium sulfite and sulfate inside the scrubber, as well as corrosion of internals due to the high acidity of the SO_2 removal environment. Since scale typically forms via natural oxidation when the slurry oxidation level ranges between 15 and 95 percent, scaling and plugging issues have largely been resolved in state-of-the-art scrubbers by either increasing the oxygen content of limestone slurry above this range (forced oxidation) or decreasing the oxygen content below this range (inhibited oxidation, accomplished with slurry additives like emulsified sulfur or sodium thiosulfate) (Srivastava, Singer, and Jozewicz, 2000, p. 4). Corrosion has been dealt with through the use of new construction materials such as alloys, clad carbon steel, and fiberglass. An additional concern with wet limestone scrubbing has always been waste disposal, since early vintage scrubber wastes required expensive disposal options such as the construction of large sludge ponds with liners or significant landfilling. Even modern inhibited oxidation processes require landfilling of byproduct calcium sulfite. In limestone forced oxidation processes with nearly complete oxidation of over 99%, however, saleable gypsum byproducts are produced that can be useful in such industries as wallboard manufacture and cement production (Jozewicz et. al. 1999; Cooper and Alley, 1994, p. 454-65). These limestone forced oxidation systems are "the preferred process for wet FGD technology worldwide" (Jozewicz et. al. 1999).

The dominant dry FGD systems are lime spray drying processes, which typically achieve lower removal efficiencies at lower costs and for smaller capacities than wet systems. Figure 2.2 shows a simple schematic of a lime spray dryer FGD system. In lime spray dryers, a lime slurry is sprayed into the tower and SO_2 is absorbed to form calcium sulfite and sulfate. The water evaporates and the dry solids are collected in a fabric filter collector with fly ash. Equation 2.2 displays the overall stoichiometry of scrubbing SO_2 with a lime reagent, which is much more reactive than a limestone reagent (and is similarly more expensive). As in the case of limestone scrubbing, the dilute concentration of SO_2 in flue gas is an issue for dry scrubbing since contact between the gas and the base reagent is essential for SO_2 removal. This is more difficult in dry systems, although ultrafine grinding of reagents has contributed to the resolution of this difficulty (Cooper and Alley, 1994, pp. 457-8).

FIGURE 2.2

Schematic of a Typical Dry FGD System



EQUATION 2.2

Stoichiometry of the Lime SO_2 Absorption Process

$$CaO + H_2O = CaOH_2$$

$$SO_2 + H_2O = H_2SO_3$$

$$H_2SO_3 + Ca(OH)_2 = CaSO_3 * 2H_2O$$

$$CaSO_3 + 2H_2O + 1/2O_2 = CaSO_4 * 2H_2O$$

Source: (Cooper and Alley, 1994, p. 455)

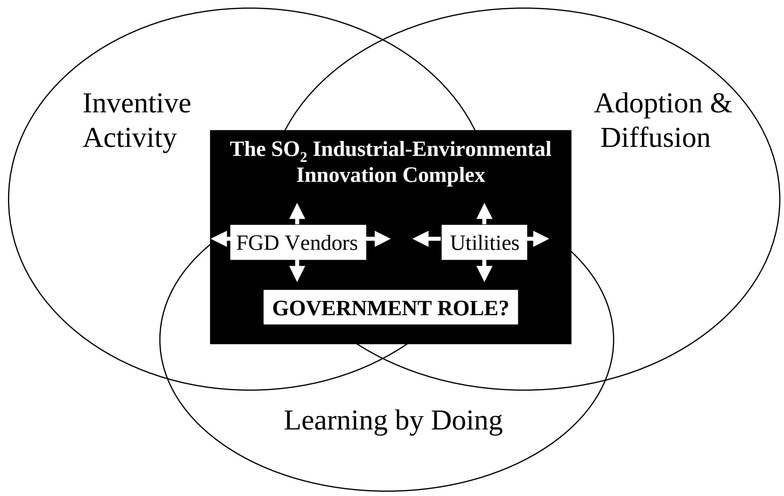
The various post-combustion FGD processes described here provide the central technology set for the SO_2 industrial-environmental innovation complex defined in Chapter One.[14] As a result, the vendors of these systems – wet FGD processes in particular – are the primary environmental equipment and service organizations discussed in this dissertation. The primary polluting organizations discussed are, as previously indicated, the utility companies that

[14] Pre-combustion technologies as well as monitoring and instrumentation technologies help to round out this technology set.

operate coal-fired electric power plants. Figure 2.3 represents the SO_2 industrial-environmental innovation complex as a black box, inside which actors such as FGD vendors, utilities, and government affect the combined innovative activities of invention, adoption and diffusion, and learning by doing.

FIGURE 2.3

Innovative Activities in the SO_2 Industrial-Environmental Innovation Complex



To the first order, government is vital to this complex because it has worked to define, through such actions as legislation, executive orders, and lawsuits, the need to control SO_2 emissions that abatement technologies seek to meet. Some of these government actions, however, have been used not only to define the rationale for and level of SO_2 emissions reductions needed, but have also defined, in various ways, the manner in which emissions reductions should be achieved by polluting organizations. For example, over the past fifty years, SO_2 legislation and its sometimes-accompanying regulation, has: proposed financial incentives for installing abatement equipment; set the stringency of emissions control that technological solutions must meet; defined the flexibility and time constraints that SO_2 polluting organizations have to address abatement requirements; and defined through their scope the market size of equipment suppliers. In addition, government has funded research, training, and technical assistance programs including demonstration projects, grants to vendors, and technology transfer opportunities that directly affected the operation and design of equipment used to control SO_2 emissions.

Government actions, therefore, have had a considerable influence on the SO_2 industrial-environmental innovation complex and its resulting technologies. The remainder of this chapter describes some of the government actions that have influenced the development of SO_2 control technologies since before 1970. It also details some of the actions of other components of the SO_2 industrial-environmental innovation complex over time. In addition, it sketches the chronology of technological changes in SO_2 control throughout the text and in a special section at the end of the chapter that helps to quantify the innovative outcomes observed outside the black box of the SO_2 industrial-environmental innovation complex.

In order to maintain the narrative clarity of over three decades of evolving political, institutional, industrial, and technological developments regarding SO_2 control technologies, the majority of this chapter is broken down into chronological sections. These are oriented around the passage of three major national environmental legislative events involving SO_2 emissions from stationary sources: the Clean Air Act Amendments of 1970, 1977, and 1990. These amendments are landmarks in the evolution of government SO_2 control actions because each establishes a different national regulatory strategy and corresponding technological options for the SO_2 industrial-environmental innovation complex.

Before 1970

Government Actions Before 1970

The role of government in air pollution control evolved from the local level to the federal level during the three decades preceding the passage of the 1970 Clean Air Act Amendments. The first major impetus for the shift in this role is generally considered to be the December 1948 smog incident in Donora, Pennsylvania, during which twenty people died and over 6,000 became ill (see Snyder, 1994; Bailey, 1998, p. 89). In 1949, representatives of the Donora and Pittsburgh areas introduced the first two air pollution control bills in Congress, although no action was taken on them. These two bills called for greater research into the health effects of pollution, and similar bills over the next few years also called for health research as well as possible methods of preventing pollution, including tax relief for the purchase by companies of pollution abatement equipment (see Bailey, 1998).

The similarity of the Donora incident to other incidents in urban areas in America over the preceding fifty years, however, "did little to shake the prevailing belief that air pollution was a periodic, local problem that could be addressed by local governments" (Bailey, 1998, p. 91). More important in changing this perception were the recurrent automobile-driven smog of Los Angeles and the efforts of a number of members of California's congressional delegations to bring air pollution under federal control. As a result of failed legislative efforts and a successful lobbying effort of President Eisenhower led by Senator Thomas H. Kuchel of California, the nation's first major national air pollution legislation was drafted as an amendment to the 1948 Water Pollution Control Act. When it was signed in 1955, the resulting Air Pollution Control Act provided for five million dollar annual authorizations for five years under the rubric that the federal government should protect the right of states and local governments to control air pollution while supporting and aiding research and devising and developing abatement methods (Bailey, 1998, pp. 95-6). The Air Pollution Control Act, which was extended in 1959 and 1962, provided for federal surveys of specific local problems upon request and for the publication of reports by the Surgeon General. The authorized five million dollars was to be spent on demonstration projects, grants-in-aid to state and local government air pollution control agencies, and for research by the Public Health Service (PHS).

Congress followed this initiative by passing the Clean Air Act in 1963. The research of the Air Pollution Control Act had provided evidence to Congress of the extent of the air pollution problem and "the inadequacy of state control arrangements" (Bailey, 1998, p. 104). Beyond research results, public concern about air pollution had been growing for some time. The London smog disaster in 1952, in which almost 700 people died, had received a large amount of publicity. This incident combined with broad public concern about fallout from the atmospheric testing of nuclear weapons to heighten public awareness about air pollution. Then in 1962, the publicity received by the publication of Rachel Carson's book *Silent Spring* appeared to provide a catalyst to transform this concern into civic action. Associations representing local politicians began to lobby for an enhanced federal role in response to growing constituent concern, and the Kennedy and then Johnson administrations supported such an enhanced role. When signed on December 17, 1963, the Clean Air Act authorized $95 million for fiscal years 1964-67 to expand the traditional federal role in conducting research and offering financial assistance to the states. But for the first time it also empowered the federal government, through the Secretary of the Department of Health, Education, and Welfare, to take legal action against interstate polluters.

During the remainder of the 1960s both public and congressional interest in air pollution control grew. For example, the results of periodic public opinion polls by the Opinion Research

Corporation demonstrate that a rapidly increasing percent of respondents agreed that air pollution was a "very or somewhat serious problem." Although only 28% agreed with this statement in 1965, this percentage increased to 48% in 1966, 55% in 1968, and eventually 69% in 1970 (see Bailey, 1998, pp. 125, 140; Erskine, 1972). By 1970, pollution was considered the second most important problem facing the nation (Jones, 1973).[15] Major air legislation passed in 1965 (the Motor Vehicle Air Pollution Control Act) and in 1967 (the Air Quality Act), while minor reauthorizations passed in 1966 (the Clean Air Act) and 1969 (the Air Quality Act). In 1966, the first action to provide tax relief for investments in air pollution control equipment passed after the defeat of forty-four previous tax incentive bills introduced between 1949 and 1965 (Bailey, 1998, p. 126).[16]

The 1967 Air Quality Act was the first national environmental legislation in which lobbying at cross-purposes emerged between the coal industry and the utility industry on the issues of abatement equipment and federal air pollution standards for stationary sources. The coal industry was particularly interested in "federal pre-emption of state authority and greater research into abatement technologies" because of strict air pollution efforts outside of the federal legislative sphere (Bailey, 1998, pp. 128-9). The New York City Council in 1965 had severely restricted the use of high sulfur coal, including an outright ban for domestic heating appliances. Four northeastern states in December 1966 had announced plans to combat air pollution that threatened the coal industry. And in March 1967, the Secretary of the Department of Health, Education, and Welfare published a report that recommended reducing the reliance on high sulfur coal because citizens in virtually all major American cities were exposed to unhealthy

[15] This perception was enhanced by the January 1969 Santa Barbara oil spill and the inflaming of Cleveland's Cuyahoga River in the summer of 1969 (Bailey, 1998, p. 140).
[16] Air pollution control equipment was exempted from the suspension of the tax investment credit in new and used machinery provided in the Revenue Act 1962.

levels of SO_2. The coal lobby's influence helped incorporate into the Air Quality Act, as signed by President Johnson on November 21, 1967, $125 million (down from the Senate's proposed $375 million) for research into methods of reducing the pollution caused by fuel combustion. The 1967 Air Quality Act also directed the states to set ambient air quality standards; if the states did not do so in fifteen months after passage, the act called for federal intervention. But although various drafts of the Air Quality Act incorporated federal emissions standards, the bill as finally passed did not (Bailey, 1998, p. 135).

In the period before 1970, therefore, there were three major government legislative actions on air pollution that were particularly relevant for the control of SO_2 from stationary sources: the 1955 Air Pollution Control Act, the 1963 Clean Air Act, and the 1967 Air Quality Act. In all three of these measures, Congress provided research funding, with provision of a federal role in demonstration programs included as early as 1955. Federal financial assistance to state and local governments for the control of air pollution was also an aspect of all three of these measures. Finally, these three measures evince a growing federal enforcement role in air pollution, from authority over interstate polluters in 1963 to all states without ambient air quality standards by February 1969. Congress and the President would expand the federal role even further in the 1970s.

Other Actions by the Industrial-Environmental Innovation Complex Before 1970

The earliest FGD device used by an electric power plant was installed in 1926 at the Battersea Power Station in London, England. The alkaline water from the Thames River provided most of the reagent for the device as well as the ultimate destination of the scrubber effluent. Other early scrubbers using lime as the reagent were installed in the United Kingdom in 1935 and 1937, but they were shut down early in World War II due to the concern that their "vapor plumes provided possible aerial guidance to enemy aircraft" (see McIlvaine, 1990).

Lime/limestone scrubbing did not reemerge until the 1950s. In the United States, the Tennessee Valley Authority (TVA) conducted small-scale and limited pilot-plant studies. Large-scale FGD operations, however, first occurred abroad. In 1964, a scrubber installation began operating at an iron ore sintering plant in Russia, and in 1966, a lime scrubber began operating at a large sulfuric acid plant in Japan (McIlvaine, 1990).

The first major plant work in the United States appears to have been that of Universal Oil Products (UOP) at a Wisconsin utility installation beginning in 1965. In 1966, Combustion Engineering, in conjunction with National Dust Collector Riley Environeering, tested a system involving boiler injection of limestone, followed by scrubbing, in a pilot unit at a Detroit Edison power plant. The first commercial installations of this process in boilers larger than 100 MW occurred in St. Louis, Missouri, and Lawrence, Kansas, in 1968. The pilot installation of this process demonstrated SO_2 removal of 98 percent at a stoichiometric limestone-to-SO_2 ratio of 1.1 to 1. Unfortunately, the installations demonstrated a number of problems, including pluggage, and the design was then changed so that limestone was no longer introduced directly into the boiler but rather into slurry recycle tanks. This change improved the reliability of the system, although it resulted in lower SO_2 removal efficiencies (McIlvaine, 1990).

The U.S. FGD equipment and services industry, therefore, had its start in the years before 1970, although significant growth did not occur in this industry until after 1970. By the late 1960s, however, there was enough interest in the operating experience problems of FGD technology that the first SO_2 Control Symposium was held in 1969. This conference continued to convene regularly and became a major agent of knowledge transfer in the SO_2 industrial-environmental innovation complex.

1970-1976

Government Actions 1970-76

The debate about what level of government should have jurisdiction over air pollution continued into the 1970s. Many favored the primacy of state and local governments based on the idea that they best understood local air conditions and industry sources. Others favored a strong role for the federal government because of its large resources and ability to set uniform industry standards that would keep the competitive playing field level. The 1970 amendments to the Clean Air Act, in fact, incorporated both of these positions.

The 1970 Clean Air Act Amendments (1970 CAA) were signed on December 31, 1970, almost a year after President Nixon submitted proposals with some of its basic provisions. The 1970 CAA divided the nation's sources of SO_2 emissions into two categories – existing and new – and directed the newly created Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) for criteria air pollutants, including SO_2.[17] These pollutants, so-called because the NAAQS were established based on health criteria, were to be subject to primary standards, which protected human health, and secondary standards, which addressed such environmental welfare concerns as structures, crops, animals, and fabrics (Cooper and Alley, 1994, p. 3; Findley and Farber, 1992, pp. 100-1). Primary NAAQS were expressly prohibited from taking into consideration economic or technical feasibility.[18] For SO_2,

[17] Presidential Reorganization Order #3 created this agency in July 1970 by combining fifteen existing units of the federal executive branch, particularly from the National Air Pollution Control Administration in the Department of Health, Education, and Welfare (Ackerman and Hassler, 1981 p. 133; Zimmerman et. al., 1980, p. 3-2).
[18] This was affirmed in Union Electric Co. v. EPA (1976) (Laitos and Tomain, 1992, p. 157).

the NAAQS were set at values of 0.14 parts per million (ppm) averaged over one day, and 0.03 ppm averaged over a year.

Within nine months of the promulgation of an NAAQS, each state had to submit to the EPA a State Implementation Plan (SIP) setting out how the state would achieve and maintain the NAAQS for existing sources.[19] According to the 1970 CAA Section 110 (a) (1-2), a SIP was required to provide for the attainment of primary NAAQS within three years of the plan's approval. Secondary standards were to be achieved within "a reasonable time." Once the EPA Administrator approved a SIP, it became enforceable as both state and federal law, with penalties up to $25,000 per day and up to one year in prison for each SIP provision violation (Bryner, 1995, p.101; Findley and Farber, 1992, p. 103). Under the SIPs, SO_2 emissions from existing sources that contributed to violations of primary NAAQSs were to be eliminated by 1975-77. Thus, the SIPs became an important regulatory force for reducing SO_2 emissions from existing power plants and other sources.

The 1970 CAA also spoke to new sources when it directed the EPA to set nationally unified performance standards for major categories of stationary sources including fossil-fuel-fired steam electric generators. Section 111 of the 1970 CAA stated that the EPA Administrator was to set these performance standards in a manner that would take advantage of the "best system of emission reduction which (taking into account the costs of achieving such reduction), the Administrator determines has been adequately demonstrated (Ackerman and Hassler, 1981, p. 11)." In December 1971, the EPA fulfilled this mission by setting New Source Performance Standards (NSPS) for SO_2 emissions from new and modified steam generators with a heat input greater than 250 million British Thermal Units (MBTU) per hour. The NSPS for SO_2 set a

[19] The EPA promulgated NAAQS on the first five criteria air pollutants in April 1971 (Bailey, 1998, p. 167).

maximum allowable emission rate of 1.2 pounds of SO_2 per MBTU of heat input. This standard was based on the EPA Administrator's finding that the ability of scrubbers to eliminate at least 70 percent of a coal burner's SO_2 had been adequately demonstrated. This would allow the NSPS to be met with the use of scrubbers, based on the combustion of the high sulfur eastern coals typically in use at the time (the sulfur content of these coals was about 4 pounds of SO_2 per MBTU heat input, so a 70% reduction would allow the emission of 30% of the SO_2 per MBTU combusted, or 1.2 pounds per MBTU).[20] Alternatively, plants could burn low-sulfur coals (of about 0.7% sulfur or less) and still achieve the NSPS emission level. Such low-sulfur coals were generally available only in the western U.S., however, which was remote from most coal-fired power plants at the time.

In addition to the 1970 CAA and its associated NSPS for SO_2 from stationary sources, two other legislative developments of note occurred in 1970-76 that had implications for SO_2 control.[21] First, in response to the Arab oil embargo of October 1973 and the resulting U.S. energy crisis, President Nixon signed the Energy Supply and Environmental Coordination Act (ESECA) in June 1974 in order to promote the use of domestic coal versus foreign oil.[22] The ESECA emerged from a lengthy legislative process in which the philosophy of the 1970 CAA came under attack. As passed, it reauthorized the 1970 CAA for another year while allowing suspensions of final clean air standards until January 1, 1979, provided that primary NAAQS would not be violated (Bailey, 1998, p. 182). The second important legislative development arose from some of the court challenges to the 1970 CAA and the EPA that were undertaken at

[20] See description of 37 Fed. Reg. 5767-71 (1972), published after Kennecott Copper Co. v. EPA, 462 F. 2d 846 (D.C. Cir. 1972) required more specific explanations of the reasoning underlying the EPA's ambient air regulations (Ackerman and Hassler, 1981, p. 19, 139).
[21] Also of interest was the introduction of a bill in 1971 to tax SO_2 emissions (Bailey, 1998, p. 171).
[22] In the mid-1970s, oil-fired generation represented 16-17 % of U.S. generation (Energy Information Administration, 2000b, p. 215).

cross-purposes by environmentalist and industrial lobbying groups during the 1970-76 period. In one of these cases, Fri v. Sierra Club 412 US 541 (1973), the Supreme Court agreed with environmentalists that the EPA could not approve SIPS that permitted the degradation of areas of air that were cleaner than the 1970 CAA minimum standards. In response to this decision, in 1974 the EPA issued “prevention of significant deterioration” (PSD) regulations that divided all clean air areas of the country into three categories based on their levels of industrial development. Pristine parks and wilderness areas were to be allowed almost no change in existing air quality, while areas in the other two categories would be permitted industrial development ranging from moderate to the maximum possible without violating national air quality standards.

Multiple options were available to utilities to attain compliance with federal SO_2 legislation and regulation in the 1970-76 time period, but EPA officials particularly promoted scrubbing in part due to perceived difficulties with alternative options. One alternative to scrubbing, switching to low-sulfur western coal, was considered unfeasible due to its heat and ash characteristics, high transport costs, and perceived unavailability compared to more abundant higher sulfur coals. This availability concern was especially important since the United States was trying to increase its fossil fuel independence during the energy crisis, and reliance on a limited supply fuel would not advance this goal. Other alternatives to scrubbing, such as chemical coal cleaning, fluidized bed combustion (FBC), solvent refined coal, and low-BTU gasification, were researched during this period but not considered to be even potentially competitive until the early 1980s. In addition, between 1973 and 1976 EPA officials removed their support for tall stacks and other supplemental control systems that primarily dispersed SO_2 for local health concerns as new findings on sulfate transport emerged (Gage, 1976; Quarles Jr.

et. al., 1974; Train, 1976). The only exception to EPA's generally negative stance toward scrubbing alternatives lay in technologies such as physical coal cleaning and the blending of low- and high-sulfur coals, which were considered sufficient control methods for plants facing modest reductions.

In support of its position favoring FGD technology, the EPA engaged in multiple research, development, demonstration, and technology facilitation activities during this time period, six of which are noted here. First, starting in 1967 and lasting throughout the 1970-76 period, the EPA and its predecessors began funding the Tennessee Valley Authority (TVA) Office of Agricultural and Chemical Development to prepare cost estimates of various FGD processes. These estimates required the TVA to be very familiar with the state of technology development over the years (McGlamery et. al., 1976). It is important to note that TVA was a good choice for these estimates. TVA held the unique position among utilities of being not only the nation's largest electric utility system but also a quasi-governmental agency with good working relationships with government (Durant, 1985, pp. 8, 36-7).[23] Eighty percent of TVA's generation came from a number of high-sulfur coal burning steam plants first constructed in the late 1940s, so it had a strong interest in SO_2 control strategies (see McCraw, 1976; Durant, 1985). Finally, TVA had significant expertise in air quality protection (although not to the same extent as water quality). TVA had pioneered electrostatic precipitators for controlling particulate emissions in the 1950s, its expertise in modeling the effects of wind currents on pollution

[23] TVA was established in the 1930s under Franklin Delano Roosevelt's New Deal in order to provide low-cost power that would fuel the economic development of the depressed Tennessee Valley. It was under federal oversight through the congressional appropriations process, yet it had private organizational direction through a three-member board.

transport was world-renowned, it had installed an early, experimental FGD system in the 1960s, and it had also developed a system-wide intermittent SO_2 control strategy in the 1960s.[24]

In addition to this technology evaluation activity with TVA, the EPA supported five other research, development, demonstration, and technology facilitation activities in the 1970-76 period. First, the EPA established the influential Shawnee test facility in April 1972, in cooperation with TVA and the engineering firm Bechtel. Equipped with three 10 MW boilers, this facility provided invaluable operating data on scrubbing, beginning with lime/limestone systems (Quarles Jr. et. al., 1974). Second, in 1973 the EPA began its financial commitment to the SO_2 Control Symposium, a technical conference that continues today. Third, in March 1974 the EPA contracted with PEDCo-Environmental Consultants, Inc. to evaluate the status of FGD technology in the U.S. on a bimonthly basis (Devitt, Isaacs, and Laseke, 1976). These FGD evaluations continued into the late 1980s. Fourth, the EPA engaged in cooperative research and demonstration activities with utility/vendor teams and in 1975 signed a Memorandum of Understanding with the recently formed Electric Power Research Institute (EPRI, founded in 1973) to "facilitate sharing of technical information and cooperation of R&D projects (Gage, 1976)." Finally, the Federal Nonnuclear Energy Research and Development Act, passed in December 1974, provided the legislative authorization for the EPA's energy/environmental control technology program, which was to be particularly important in conducting SO_2 control research in the late 1970s (Zimmerman et. al., 1980).

Government actions in the 1970-76 period centered around the 1970 CAA, which spawned litigation, legislation, and research. Both the 1970 CAA and the 1971 NSPS were flexible regarding the viable technological alternatives for attainment for both existing and new

[24] This plan included increasing stack height to dilute emissions, periodic shutdowns when SO_2 levels were high, and burning low-sulfur or cleaned coal when health hazards existed.

sources of SO_2, and a number of technological strategies were pursued during this time. The stringency of the NSPS and the limited availability of coal emitting less than 1.2 pounds of SO_2 per MBTU, however, provided a particularly strong incentive for the development of FGD technology. The tight deadline for attainment of primary SO_2 emissions standards – May 31, 1975 – also provided a profit incentive for FGD vendors to expand their commercial capabilities.

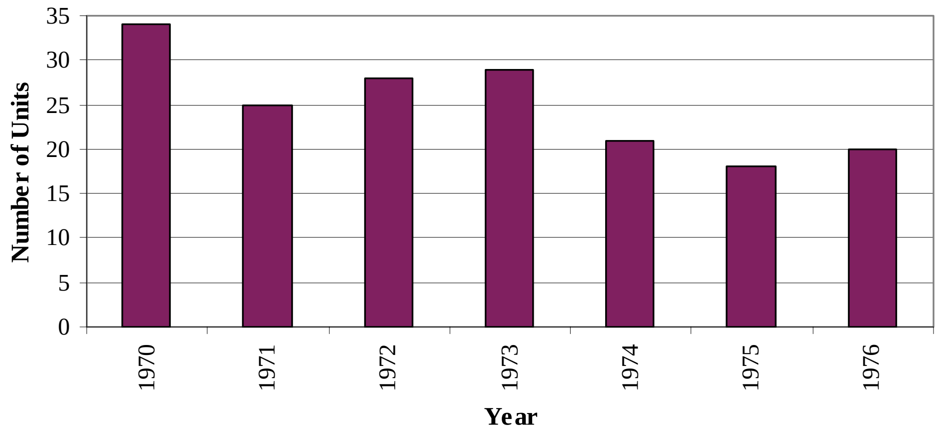
Other Actions by the Industrial-Environmental Innovation Complex 1970-76

By the time of the promulgation of the SO_2 NSPS in 1971, only three commercial scrubber units were operating on power plants in the United States. The oldest of these would be discontinued later that year (Ackerman and Hassler, 1981). The next five years, however, saw the total number of commercial scrubber units grow by a factor of ten.

In order to understand the market forces operating on the SO_2 industrial-environmental innovation complex, it is important to keep in mind the 1970 CAA division of sources into the categories of "existing" and "new and modified." In general, "new" FGD units accompany the construction of new coal-fired utility boilers, while "retrofit" FGD units are constructed on existing boilers. Figure 2.4 shows the number of new utility-operated coal-fired steam turbine units brought online between 1970 and 1976. This is the market background for new FGD units, particularly after the 1971 NSPS. Figure 2.5 shows the total number of commercial FGD units brought online between 1973 and 1976, broken down into the realized categories of new and retrofit construction. By comparing the two datasets underlying these figures, it appears that 10% of the new coal-fired boilers brought online between 1973 and 1976 had new FGD units. Retrofit FGD technology accounted for 72% of total FGD unit installation between 1973 and 1976 and was thus the driver of the utility FGD market. This is despite the construction of significant numbers of new coal-fired boilers after the 1971 NSPS and despite the fact that retrofit technology was generally 25-30% more expensive than new technology during the 1970-76 period (Ackerman and Hassler, 1981, p. 135).

FIGURE 2.4

Number of New Utility-Operated Coal-Fired Steam Turbine Units in 1970-76

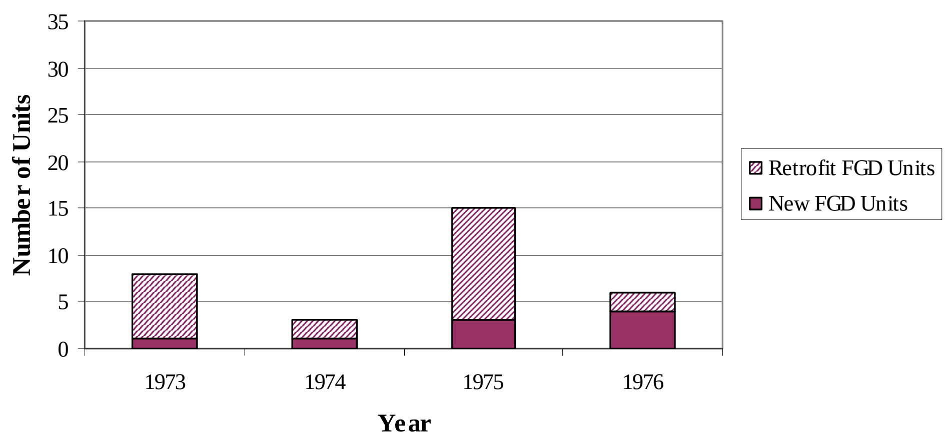


Source: Adapted from Energy Information Administration (1996)

Notes: The year of commercial operation is the year that control of the unit was turned over to the dispatcher. Includes all units active since 1970.

FIGURE 2.5

U.S. Scrubber Market, 1973-76



Source: Adapted from Soud (1994)

The predominant type of FGD technology in 1970-76 was wet lime/limestone, but some utilities during this period had begun to investigate less expensive spray dryers. In addition, a few commercial regenerable processes were installed in the early 1970s (Devitt, Isaacs, and Laseke, 1976; McIlvaine, 1990). According to a 1976 overview of FGD technology by PEDCo-Environmental Consultants, Inc., SO_2 removal efficiencies ranged from 40 to 90% during the 1970 to 1976 period. FGD technology had been installed during this period on units varying both in size – from 30MW to 800MW – and in the sulfur content of coals consumed.[25] The PEDCo-Environmental Consultants, Inc. overview also noted that

> (1) More systems are being installed to meet state standards that are more stringent than NSPS levels. (2) More systems are being installed on low sulfur coal vs. high sulfur coal applications. (Devitt, Isaacs, and Laseke, 1976, p. 18).

The number of scrubber vendors increased greatly during the 1970-76 period and throughout the 1970s. In 1971, only one scrubber vendor was in the utility FGD market. In 1972, two firms were in the market. A year later, seven vendors (Peabody International, Combustion Equipment Associates, Chemico, Research-Cottrell, Combustion Engineers, Davy Powergas, and UOP) "stated that they are now prepared to offer full scale commercial systems (Quarles Jr. et. al., 1974, p. 32)." In 1974, there were ten such vendors, in 1977 there were thirteen such firms, and in 1978 there were fourteen scrubber vendors in the FGD market. By the end of the 1970s, sixteen U.S. firms supplied FGD systems to utilities, as did the U.S. government agencies of TVA and the Department of Interior's Bureau of Mines. The foreign firms Chiyoda International, Davy Powergas, and Mitsubishi International Heavy Industries Ltd., also served the U.S. utility FGD market by the end of the 1970s.

Table 2.2 lists the sixteen U.S. scrubber vendors and shows relevant acquisition information for these firms. They are listed in order of their year of entry into the domestic

[25]Coals with 0.4-1.0% sulfur were considered "low" and 6.0% sulfur were considered "high" in these years. Perceptions of low and high sulfur coals varied over time with overall sulfur percentages dropping for both types of coal. Coals with 2.6% sulfur are now considered high sulfur.

utility FGD market. The major line of business of most of these firms was not air pollution control. In fact, air pollution control activities were major lines of business of only American Air Filter (before its acquisition by Allis-Chalmers), Combustion Equipment Associates, Peabody International, and Research-Cottrell. Only Research-Cottrell realized more than 50% of its total sales revenues from air pollution control equipment (Zimmerman et. al., 1980, pp. 4-10).

TABLE 2.2

U.S. Firms Entering Domestic Utility FGD Market in the 1970s

Firm Name (1980 Parent Corporation in Parentheses)	Year of Entry into Domestic Utility FGD Market	Year of Purchase by Parent Corporation
Combustion Engineering	1971	NA
Buell (Envirotech)	1972	1972
American Air Filter (Allis-Chalmers)	1974	1978
Babcock & Wilcox (J. Ray McDermott)	1974	1978
Combustion Equipment Associates	1974	NA
Peabody International	1974	NA
Research-Cottrell	1974	NA
Riley Stoker (Riley Co.)	1974	1971
UOP (Signal Companies, Inc.)	1974	1969
United Engineers (Raytheon Co.)	1974	1978
Chemico (Envirotech)	1976	1976
FMC Corporation	1977	NA
Pullman Kellogg (Pullman, Inc.)	1977	1944
Wheelabrator - Frye	1977	NA
Western Precipitation (Joy Manufacturing)	1978	NA
Rockwell International	1979	NA

Source: Adapted from Zimmerman et. al. (1980)

As indicated by the acquisition information in Table 2.2, a number of large diversified corporations entered the utility FGD market during the 1970s in what was “perceived to be a booming market (Zimmerman et. al., 1980, pp. 4-8).” Unfortunately, as Table 2.3 indicates, this market exhibits relatively low profitability as compared to the S&P 400, although data show that profitability was gradually increasing in the industry in the 1976-78 period. Gross profitability was highest for Joy Manufacturing and also rather high for Wheelabrator, two early leaders in the dry FGD systems that found quick popularity in low-sulfur coal applications (McIlvaine, 1990; Zimmerman et. al., 1980, pp. 4-22). In addition, the FMC Corporation demonstrated consistently good performance. The volatility of the FGD equipment and services industry, indicated in the large number of acquisitions in this period, ultimately caused Riley, American Air Filter, and Combustion Equipment Associates to drop out of the business (McIlvaine, 1990).

TABLE 2.3

Profitability Ratios of the Utility FGD Industry as Compared to Standard & Poor's 400 Industrials, 1976-78

Firm Name	Gross Profitability[a] (% of Revenues)			Net Profitability[b] (% of Revenues)		
	1976	**1977**	**1978**	**1976**	**1977**	**1978**
Combustion Engineering	7.7	7.9	8.8	3.0	3.3	3.4
Buell, Chemico (Envirotech)[c]	7.1	6.3	3.6	3.8	3.1	1.2
American Air Filter (Allis-Chalmers)[c]	9.9	10.4	11.3	3.5	3.6	4.3
Babcock & Wilcox (J. Ray McDermott)[c]	NA	NA	9.3	NA	NA	3.0
Combustion Equipment Associates	14.4	12.6	Loss	7.0	8.0	Loss
Peabody International	9.3	9.3	10.1	3.9	4.0	4.3
Research-Cottrell	6.6	7.9	7.5	2.7	3.4	3.7
Riley Stoker (Riley Co.)[c]	6.0	4.6	4.9	2.3	2.9	3.1
United Engineers (Raytheon Co.)[c]	7.9	8.6	9.1	3.5	4.0	4.6
UOP (Signal Companies, Inc.)[c]	9.2	9.5	9.4	2.5	3.3	3.3
FMC Corporation	12.4	12.4	10.9	5.3	5.5	4.8
Pullman Kellogg (Pullman, Inc.)[c]	2.2	2.6	4.0	1.5	1.6	2.5
Wheelabrator - Frye	9.1	10.4	10.5	4.6	4.7	5.1
Western Precipitation (Joy Manufacturing)[c]	17.4	16.0	14.3	7.5	7.1	5.5
Rockwell International	6.9	7.1	9.0	2.3	2.5	3.7
S&P 400 Industrials	14.4	14.2	NA	5.3	5.1	NA

Source: Adapted from Zimmerman et. al. (1980, 4-24,5)

a Gross profitability, as percentages of revenues, is defined as revenues less operating costs but before depreciation, interest, and taxes.

b Net profitability, as percentage of revenues, is defined as revenue less operating costs, depreciation, interest, and taxes but before extraordinary items.

c Parent corporation in parentheses.

The large number of subsidiary firms in the FGD market and the small number of firms with air pollution control as the major line of business makes economic analysis difficult, especially for R&D expenditures. Nevertheless, Table 2.4 provides a snapshot of R&D budgets for the four companies whose major line of business was air pollution control in order to indicate the approximate level of R&D being conducted by scrubber vendors in the late 1970s.[26]

TABLE 2.4

1976-79 R&D Expenditures by Utility FGD Suppliers with Major Business Area of Air Pollution Control Equipment

	1976	**1977**	**1978**	**1979**
American Air Filter	2,801	3,547	Acquired	Acquired
Combustion Equipment Associates	800	993	1,002	1,246
Peabody International	1,700	2,100	2,400	2,700
Research-Cottrell	3,772	3,225	4,168	3,638

Source: Adapted from Zimmerman et. al. (1980, p. 4-28)

Notes: Units in thousands of (assumed) 1980 Dollars. For American Air Filter and Research-Cottrell, customer-sponsored research, development, and demonstration projects were undertaken.

Analysts believed at the time that these R&D expenditures were not as large as they would be in a strictly market-driven industry. A National Research Council Study on R&D in the EPA published in 1977 explained this view:

> The current set of legislative mandates to EPA … does not take full advantage of self-interest by instituting incentives for private parties to perform research, especially on pollution control technology…. Some legislation may even have the effect of discouraging private research initiative. As a consequence, the government is forced to conduct research that might be more efficiently performed in the private sector. … The validity of research conducted by EPA to support its decision-making will always be suspect merely because the agency is … in the adversary process of regulation and standard setting (Zimmerman et. al., 1980 3-19, 3-20).

[26] This business line is typically dominated by particulate control equipment.

The R&D being conducted by various actors in the SO_2 industrial-environmental innovation complex in the 1970-76 period focused in large part on the reliability problems experienced by scrubber users. Table 2.5 summarizes the major reliability problems of scrubbers operating during this period, as detailed in an important EPA hearing on power plant compliance with SO_2 air pollution regulations.

TABLE 2.5
Observed Technical Problems in Early Scrubbers

Problem	Comm. Ed. Will County	Mitsui Chemico Plant	EPA Shawnee	K.C. P&L LaCygne	Louisville G&L Paddy's Run
Chemical Scaling	Minor	No	No	Minor	No
Demister Pluggage	Yes	No	No	Yes	No
Wet/Dry Pluggage	No	No	No	No	No
Erosion/ Corrosion	Yes	No	Minor	Yes	No
Reheater Problems	Yes	No	No	Yes	No
Mechanical Problems (Fans, pumps, dryers, etc.)	Yes	No	No	Yes	Minor
Start-up Date	Feb. 1972	Mar. 1972	Apr. 1972	Feb. 1973	Apr. 1973
Process	Limestone	Lime	Limestone & Lime	Limestone	Limestone
Oil or coal	Coal	Coal	Coal	Coal	Coal
Size, MW	156	156	3*10 MW	840	70

Source: Testimony at hearing on power plant compliance with SO_2 regulations conducted between October 18, 1973 and November 2, 1973 by the EPA (Quarles Jr. et. al., 1974, p. 35)

In addition to these problems, sludge disposal was widely recognized by diverse SO_2 industrial-environmental innovation complex actors at this hearing as a significant problem with potential implications for the environment (Quarles Jr. et. al., 1974, p. 51).

According to PEDCo-Environmental Consultants, Inc., by 1976, performance of units had improved to the point that the average operability of scrubber units ranged "from about 80-95% depending upon the system and the averaging period (Devitt, Isaacs, and Laseke, 1976, p.24)."[27] Other technological improvements by 1976 were in increased limestone utilization and sludge oxidation for more effective waste disposal. The TVA reported in 1976 on some of the lime and limestone technological developments that had recently occurred.[28] These changes included sludge fixation; a growing tendency for utilities to increase scrubber redundancy and sparing as insurance for reliability problems; the use of spray towers in place of mobile-bed scrubbing devices; and measures to promote increased operating reliability (McGlamery et. al., 1976, p. 88).

Besides these changes in scrubber design, EPRI, which had started its own R&D program for FGD in 1974, called on the utility industry in 1976 to institute some changes in scrubber operations. To maximize reliability, EPRI stated that "utilities must assume responsibility to make the scrubber system work." According to EPRI, assuming responsibility meant having a qualified staff of "chemists as well as mechanical and chemical engineers," not depending on process guarantees and fixed-cost contracts, and giving "the scrubber operating and maintenance priority equal to all other power station systems (Nannen and Yeager, 1976, p. 112)."

In summary, the 1970-76 period was one of great activity in the SO_2 industrial-environmental innovation complex. As the SO_2 control market grew rapidly, many firms either entered the utility FGD market or acquired existing entrants. Although FGD vendors as well as utilities – particularly through EPRI – initiated R&D efforts during this time period, the EPA's legislative mandate was recognized by contemporaneous observers to have provided only a limited incentive or even a disincentive for private rather than public R&D. The technological successes of both types of R&D helped to improve reliability, limestone utilization, and waste

[27] Operability, or the hours the FGD system was operated divided by boiler operating hours in the period, was the most commonly reported variable representing scrubber reliability due to data availability.
[28] There had not been as many noteworthy developments in regenerable processes.

disposal in the 1970-76 period, although a considerable amount of progress in FGD technology was still to occur.

1977-1989

Government Actions 1977-89

The 1977-89 period was characterized by competing goals and needs that affected government actions relevant to the SO_2 industrial-environmental innovation complex. Competition between national environmental, energy, and economic priorities on the one hand, and competition between regional economic goals and interests on the other, particularly defined the legislative climate and associated implementation regulations and research budgets during this period.

The 1977 Clean Air Act Amendments (1977 CAA), with their associated New Source Performance Standards (1979 NSPS), were products of conflict between the environmental, coal industry, and utility industry lobbies, and uncertainties within the EPA itself. Enacted August 8, 1977 after a two-and-a-half year legislative process, the 1977 CAA benefited both these lobbies in different ways. The 1977 CAA benefited environmentalists interested in SO_2 emissions reduction by (1) codifying Prevention of Significant Deterioration review, (2) requiring continuous emission controls in light of emerging concerns about the long-range transport of sulfates, and (3) extending EPA's regulatory domain to include industrial boilers below 250 MBTU (Bailey, 1998, p. 190; Train, 1976, p. 5). The amendments benefited polluting organizations by (1) extending deadlines for industrial polluters, states, and cities with particularly acute air pollution problems to achieve emissions reductions and (2) granting new source building rights in non-attainment areas for NAAQS as long as “best available control technology” (BACT) was installed.[29]

The 1977 CAA also satisfied an unlikely alliance between environmentalists and the coal industry. In its Section 111 it directed the EPA to implement, within one year, a new NSPS for SO_2 emissions based on a percentage reduction from levels that sources would emit in the absence of control technology (Findley and Farber, 1992, p. 105). This percentage reduction provision was intended to promote the universal use of scrubbing technology (Ackerman and Hassler, 1981, p. 37). Environmentalists were interested in scrubbers to cut new plant emissions below 1.2 pounds per MBTU, while the coal lobby wanted the 1.2 level maintained but the SO_2 reductions to come from control technology so that high sulfur coal could supply the new power plant market. Despite the scrubber promotion of section 111, a subsection (h) kept the legislation from being absolutely “technology-based” since “the subsection denies the administrator the authority to require a particular ‘design, equipment, work practice, or operational standard (Ackerman and Hassler, 1981, p. 51).’”

Although section 111 directed the EPA to implement a new NSPS for SO_2 emissions by August 1978, intra- and inter-agency conflict stymied the development of the final NSPS until June 1979. At issue was how stringent the percentage standard would be and what it would mean for FGD technology. In late fall 1977, EPA’s Office of Air, Noise, and Radiation (OANR) circulated a recommendation for a “full scrubbing” regulation. Besides requiring all coal burning plants to meet both the old 1.2 pound per MBTU limit, the OANR regulation would require the removal of 90% of the SO_2 released by coal combustion, which was the highest removal efficiency state-of-the-art FGD could achieve at the time (hence the term “full

[29] EPA Administrator Russell Train had announced on May 30, 1975 that thirty-four of the nation’s 247 air quality control regions would be unsuccessful in meeting primary NAAQS for SO_2 emissions (Bailey, 1998, p. 184).

scrubbing") (Ackerman and Hassler, 1981, p. 80). At about the same time, the EPA's Office of Air Quality, Planning, and Standards (OAQPS) began working on a computer model to compare the OANR plan versus a "partial scrubbing" alternative in which some scrubbers would be allowed to scrub at percentages lower than 90% in order to reduce operating and maintenance costs (Ackerman and Hassler, 1981, p. 82). The Department of Energy (DOE), which had been established in October 1977 to take responsibility for coordinating a comprehensive national energy plan, strongly supported the OAQPS partial scrubbing option as better for the nation's energy independence.[30]

The EPA was slow to resolve the full versus partial scrubbing options. In July 1978, it became clear that the EPA would not meet the statutory deadline on the SO_2 NSPS. At this time, the Sierra Club obtained a court order to ensure that the EPA decision was made by June 1979. On September 19, 1978 the first EPA proposal on the NSPS – based on the OANR plan, but leaving the full versus partial scrubbing issue unresolved – was published in the Federal Register (Ackerman and Hassler, 1981, pp. 85-7). By January 1979, opinion within the OAQPS centered on reducing the emissions ceiling from 1.2 pounds per MBTU to 0.55 pounds per MBTU. This ceiling is the equivalent of requiring an 86.25% emission reduction for high sulfur coals of 4 pounds per MBTU, since it would allow the emission of 13.75% of the SO_2 per MBTU combusted, or 0.55 pounds per MBTU. The 0.55 ceiling would force the use of some type of control technology, since no coal could achieve this goal alone without technological assistance. This ceiling would force technology at greater advantage to environmental interests and, since partial scrubbing was cheaper than full scrubbing, at lower costs to utilities and other polluters

[30] The Department of Energy Organization Act brought together into a cabinet level department such federal government energy-related organizations the Energy Research and Development Administration, the Federal Energy Administration, and the Federal Power Commission (Zimmerman et. al., 1980, p. 3-23).

than the OANR plan (Ackerman and Hassler, 1981, pp. 89-90). Eastern coal interests, however, objected to the 0.55 ceiling. The National Coal Association presented an estimate that a 0.55 limit, assuming scrubber removal efficiencies of 85%, would preclude the burning of 75-100% of the coal produced in Ohio, Illinois, Indiana, northern West Virginia, and western Kentucky (although the organization had transparently excluded major eastern zones of low sulfur coal) (Ackerman and Hassler, 1981, p. 99). Congressional concern based on this presentation was impossible for the EPA Administrator to ignore in April and May 1979, especially since the Senate Majority Leader was Robert Byrd of coal-producing West Virginia.

The ultimate solution to the NSPS for SO_2 lay in dry scrubber technology. Research indicated that dry scrubbers could operate more cheaply than conventional wet scrubber technology at removal efficiencies of 70% or less. In April 1979, the EPA began modeling runs based on cost estimates of the dry scrubber, and in June 1979, the EPA finally issued the new NSPS for SO_2, which set a "wet-scrubbing/dry-scrubbing sliding scale" of 1.2 pounds per MBTU with a 90% reduction, or 0.6 pounds per MBTU with a 70% reduction (Alm and Curham, 1984, p. 108). Under this sliding scale, models showed costs to be far lower than the full scrubbing option of OANR, with SO_2 emissions almost as low as in the 0.55 ceiling OAQPS plan (Ackerman and Hassler, 1981, p. 101). This regulation was challenged in court on the basis that it did not meet the statutory command to require in all situations "the best technological system of continuous emissions control." But the regulation was upheld, and subsequently made the practice of fuel switching to lower sulfur coals insufficient to obtain compliance with the NSPS.

Concern about fuel switching, from eastern high-sulfur coal to western low-sulfur coal, and from oil and natural gas to coal and synthetic fuels, was at the heart of not only much of the conflict related to the 1977 CAA, but also of competing interests between the EPA and the DOE. Two major energy acts, the National Energy Act of 1978 and the Energy Security Act of 1980, demonstrate the changing perception of optimal fuel choices in support of the national goal of reducing dependence on foreign oil. The five pieces of legislation that composed the earlier bill promoted the use of U.S. coal, as had the earlier Energy Supply and Environmental Coordination Act. The several pieces of legislation that comprised the later bill, however, attempted to turn "energy policy away from conventional resources and toward the development and promotion of synthetic oil and gas derived from coal, oil shale, and tar sands (Laitos and Tomain, 1992, p. 425)." In addition, the Energy Security Act of 1980 also promoted renewable resources and conservation.

Whereas the EPA's involvement in air pollution research, development, and demonstration (RD&D) stemmed primarily from its role in the CAA, the DOE's involvement in air pollution RD&D began to grow in the late 1970s due to its promotion of environmentally acceptable coal use either through direct combustion or in synthetic fuels creation. Although in 1979, the EPA was still the "principal federal participant in the [RD&D] of air pollution control technologies;" by 1985 that role had shifted to the DOE (Zimmerman et. al., 1980, p. 3-3). One of the first indicators of that shift was the transfer in fiscal year 1979 of much of the FGD component of the EPA's Energy/Environmental Control Technology program to the DOE Fossil Energy Research Program (FERP) Advanced Environmental Control Technology program (Zimmerman et. al., 1980, pp. 3-7, 3-33).[31] Table 2.6 and Table 2.7 show the changing RD&D budget situation for the EPA, DOE, and other entities involved in research on SO_2 abatement from stationary sources in 1977 to 1985.

[31] In 1979, the EPA Energy/Environmental Control Technology program was planned, reviewed, and implemented cooperatively between EPA and DOE.

TABLE 2.6

1977-81 Federal Government Budgets and Expenditures for Air Pollution Control RD&D

	1977	1978		1979		1980		1981
	Actual	Bdgtd	Actual	Bdgtd	Actual	Bdgtd	Actual	Est.
EPA Air Pollution Control								
Ind. Processes: Air Quality	6,586	500	5,691	5,000	3,989	4,050		4,099
Energy/Env. Control Tech.								
Fuel Proc., Prep., & Adv. Combustion	18,700	18,150	21,360	11,167	12,598	12,822		18,537
Flue Gas SO_x Control	4,940	3,200	11,604	2,099	3,054	1,889		3,514
NO_x Control	9,740	10,100	21,275	14,850	13,879	13,815		12,484
Flue Gas Particulate Control	3,550	3,900	14,183	9,889	9,392	8,000		8,040
Total	43,516	40,350	74,113	43,005	42,912	40,576		46,674
EPA Energy								
Coal Cleaning	4,500	4,360	8,110	1,469	1,325	1,213		
Fluidized Bed Combustion (FBC)	5,930	6,000	5,040	3,309	4,354	4,925		
Adv. Oil Processing	2,660	1,200	1,950	755	428	-		
Syn. Fuels	5,610	6,590	6,260	5,634	6,491	6,487		
Biomass Conversion	-	-	-	-	-	147		
Total	18,700	18,150	21,360	11,167	12,598	12,822		18,537
DOE Env. Engineering								
Coal	4,100	4,900		4,735		4,743		5,826
Nuclear	4,000	6,500		5,950		3,895		5,055
Oil Shale	200	800		773		819		1,431
Petrol. & Gas	2,400	3,300		3,287		7,897		8,407
Solar, Etc.	800	1,300		1,432		1,406		1,491
Total	11,500	16,800		16,177		18,760		22,210
DOE FERP: Coal Prep.			5,020	2,371			12,650	11,000
DOE FERP: Adv. Env. Cont. Tech.								
Flue Gas Cleanup								
Adv. FGD					600		8,300	9,000
Combined FG Cleanup					1,300		5,700	6,000
Wet Limestone FGD					800		6,050	6,000
Subtotal					2,700		20,050	21,000
Gas Stream Cleanup								
Fuel Cell Cleanup					-		1,400	3,000
Process Mod.					1,000		2,000	2,000
Turbine Cleanup					1,400		7,000	8,000
Subtotal					2,400		10,400	13,000
Tech. Support					1,900		7,000	8,000
Cap. Equip.					-		800	500
Total					7,000		38,250	42,500
DOE FERP: Combst. Sys. Program								
Atmospheric FBC			24,500		23,600		25,900	22,800
Pressurized FBC			15,229		14,234		15,000	21,400
Adv. Combst. Tech.			13,036		7,342		4,950	2,000
Alt. Fuel Utilization			1,915		9,400		2,500	22,000
Combst. Sys. Demo. Plants			11,000		-		2,500	-
Cap. Equip.			465		573		-	300
Total			66,145		52,149		50,850	68,500

Source: Adapted from Zimmerman et. al. (1980, p. 3-9)

Notes: Units are in thousands of (assumed) 1980 dollars. In 1981, only estimated figures are available for this budgetary breakdown due to limitations in the source data.

TABLE 2.7

1981-85 Expenditures for Air Pollution Control R&D, 1981-85

	DOE	EPRI	EPA	TVA	GRI	Assoc-iations	States	Private Cofndg
Fuel & Feedstock Prod. Tech.		229,220						
Coal Prep.	36,739			3,994			3,974	13,798
Coal Mixtures/Alt. Fuels	27,242					730	24	9,742
Liquefaction	302,108						8,899	470,233
Surface Gasification	223,069				40,500	112	2,879	212,972
Underground Gasification	35,633				4,400	768		5,042
Power & Energy Producing Technologies		239,625						
AFBC	21,059			82,610		1,354	4,093	46,312
PFBC	69,260							15,861
Fuel Cells	179,308			178	63,300	652		65,465
Magnetohydrodynamics	177,961							6,913
Heat Engines	67,469					343		8,383
Environmental Pollution Reduction Technologies								
Flue Gas Cleanup	50,477		19,000	24,824		19,737	2,376	21,542
Gas Stream Cleanup	45,832		40,300			303	9,938	913
Advanced Combustors	7,723			200		499	1,187	6,998
Cross-Cutting R&D								
Coal Waste Management	19,134			1,884	1,700		532	14,629
Adv. Research & Tech. Development	213,744				4,900	603	5,115	82,057
Subtotals								
Clean Coal R&D	798,583	239,625	59,300	113,512	42,200	2,078	25,003	358,063
Other Coal	578,175	229,220		178	72,600	2,023	14,014	622,797
Total	1,476,753	468,845	59,300	113,690	114,300	25,101	39,017	980,860

Source: Adapted from U.S. Department of Energy, Office of Fossil Energy (1987, p. 39)

Notes: Units are in thousands of (assumed) 1987 dollars. "Other coal" includes liquefaction, underground gasification, fuel cells, and elements of advanced research and technology development. GRI stands for the Gas Research Institute.

EPA's R&D focus shifted from wet FGD improvements in the mid-1980s to low-cost dry technologies such as the spray dryer, lime/limestone injection with multistage burners, advanced calcium silicate injection, and electrostatic precipitator sulfur oxides removal. The main impetus for this work was the "anticipation of a major U.S. acid rain retrofit program being considered by Congress (U.S. Environmental Protection Agency, 1995, p. 4)." The DOE, in the meantime, continued to sponsor some wet FGD work. In December 1985, the DOE added to its existing coal-based environmental research efforts a major new program called the Clean Coal Technology Demonstration Program (CCT).

This $2.5 billion program was enacted largely through the efforts of Senator Robert Byrd of West Virginia in order to keep coal research alive after the demise of the Synfuels Corporation. The program, which is expected to run until 2004, partnered DOE research with that of various industries to demonstrate advanced "clean" coal technologies at a scale large enough for the market to judge their commercial potential. Industries provided over 50 percent of the cost of the CCT demonstrations and also played a major role in project definition and in ensuring eventual commercialization. The program has been implemented through a series of project selections in response to nationwide competitive solicitations known as Program Opportunity Notices (PON) with different levels of government funding and objectives (U.S. Department of Energy, Assistant Secretary for Fossil Energy, 1996, p. 2-1). Table 2.8 provides a snapshot of the status of the CCT program selection process as of December 31, 1995.[32] As was the case with earlier funding by the DOE of air pollution control R&D, the CCT projects have not been limited in their focus to SO_2 emissions reductions alone.

TABLE 2.8

CCT Project Selection Process Summary

Solicitation	PON Issued	Proposals Submitted	Projects Selected	Projects in CCT Program by 12/31/95
CCT-I	February 17, 1986	51	17	8
CCT-II	February 22, 1988	55	16	11
CCT-III	May 1, 1989	48	13	13
CCT-IV	January 17, 1991	33	9	6
CCT-V	July 6, 1992	24	5	5
	TOTAL:	**211**	**60**	**43**

Source: (U.S. Department of Energy, Assistant Secretary for Fossil Energy, 1996, p. 2-1)

[32] 57% of the projects had completed operations by the end of fiscal year 1998 (U.S. Department of Energy, Assistant Secretary for Fossil Energy, 1999).

One of the reasons for the shift in air pollution R&D preeminence from the EPA to the DOE was the success of President Ronald Reagan's deregulation agenda in cutting EPA's operating budget by more than one-third between 1981 and 1983, with resulting personnel losses of 20% (Vig and Kraft, 1990, p. 38). The EPA budget never returned to the pre-1980 level throughout the 1980s. The DOE, meanwhile, did not suffer as much during this period even though President Reagan had pledged to abolish the DOE and the Solar Energy Research Institute, as well as to dismantle the United States Synthetic Fuels Corporation established under the Energy Security Act of 1980 (Laitos and Tomain, 1992, pp. 426-7).

The conflict between President Reagan's anti-government supporters and pro-environment legislators was also a contributing factor to the dearth of legislation passed in the 1980s to regulate SO_2 emissions, although conflicting environmental, industry, and coal interests were still the greatest barriers to government action. Acid rain had become the prominent concern about SO_2 emissions by 1980, prompting the passage of the Acid Precipitation Act of 1980 which established the U.S. National Acid Precipitation Assessment Program (NAPAP). The NAPAP program ultimately spent $500 million by the time it published in 1990 "the definitive scientific and technical synthesis" on acid precipitation (Irving, 1990). Other than the establishment of NAPAP, however, Congress was unable to pass any legislation on acid rain throughout the 1980s despite high-level lobbying by the Canadian government.

This stalemate did not reflect a lack of effort in Congress, particularly by congressional representatives of northeastern states, which suffered more from acid rain than other parts of the country. In 1982 and 1984 the Senate reported legislation out of committee that would mandate SO_2 emissions reductions to curb acid rain (Bailey, 1998, pp. 218, 220). In 1986 the House reported a bill out of subcommittee that would provide for a "phased reduction in the emissions that caused acid rain and sought to reduce the financial burden on the Midwest by imposing a national tax on electricity (Bailey, 1998, p. 221-2)." And in 1987, the Senate reported out of committee an overhaul of the CAA that would tighten acid rain precursor controls (Bailey, 1998, p. 226). With this bill, as with the others, conflict between U.S. regional economic interests pertaining to the coal and utility industries precluded further legislative action, as attempts to balance these competing interests were unsuccessful. This is evidenced in the case of the 1987 bill, when a proposal was circulated to have the federal government subsidize the capital cost of installing scrubbers. This proposal was included to allay the fears of senators from high-sulfur coal producing and consuming regions about the economic impact of SO_2 controls. Senators from western states opposed this proposal, claiming that utilities in their states burned low-sulfur coal and "had already installed scrubbers at their own expense (Bailey, 1998, p. 226)."

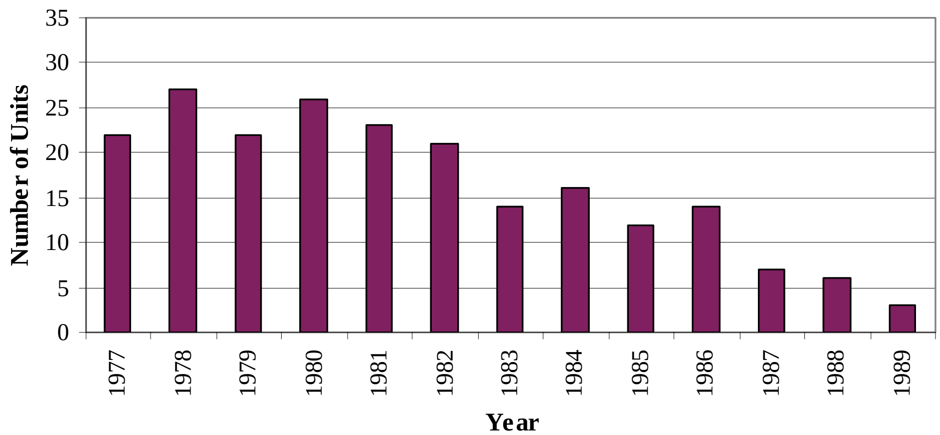
By the end of the 1977-89 period, leadership transitions in the Senate and the Executive branch of government helped to alter the balance between these competing interests. In addition, the long period of study of acid rain and several attempts at producing acid rain legislation set the stage for the passage of the 1990 Clean Air Act Amendments, in which the control of acid rain was finally dealt with legislatively.

Other Actions by the Industrial-Environmental Innovation Complex 1977-89

The U.S. market for FGD grew between 1977 and 1983, then declined between 1983 and 1989. Figure 2.6 shows the general decline in the number of new utility-operated coal-fired steam turbine units brought online between 1977 and 1989. This is the market background for new FGD units, particularly after the 1979 NSPS. Figure 2.7 shows the total number of commercial FGD units brought online between 1977 and 1989, broken down into the realized categories of new and retrofit construction. Note that new FGD units associated generally with new power plant construction dominated the FGD market in the 1977-1989 period, with 69% of all FGD units installed in 1977-89 (in contrast to the 28% of all units in the 1973-76 time period). The market dominance of new FGD units is important to understand in light of the overall decline in new coal-fired unit construction in the utility industry throughout the 1980s. By comparing the two datasets underlying these figures, it appears that 60% of the new coal-fired boilers brought online in these years had new FGD units.[33]

FIGURE 2.6

Number of New Utility-Operated Coal-Fired Steam Turbine Units in 1977-89



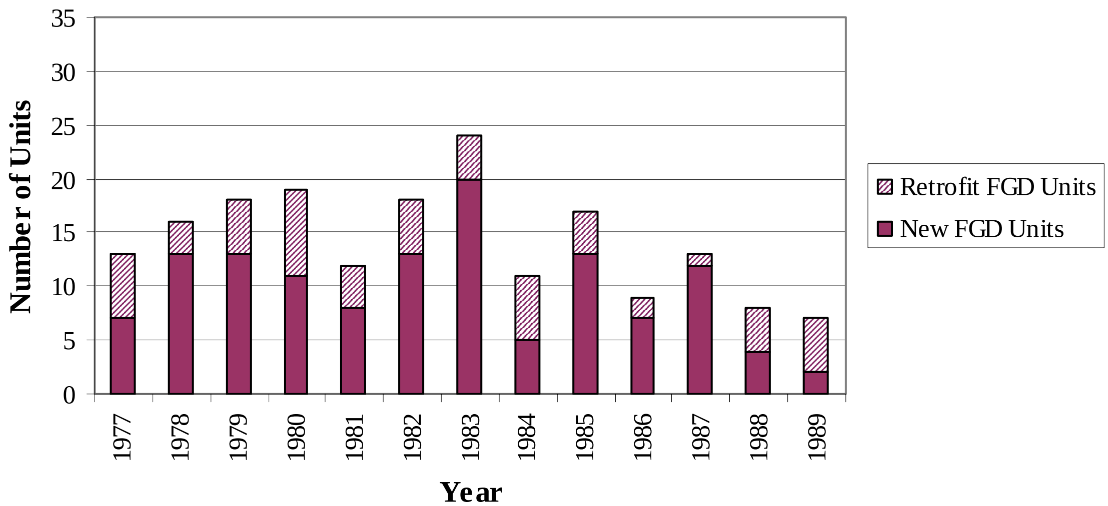
Source: Adapted from Energy Information Administration (1996)

Notes: The year of commercial operation is the year that control of the unit was turned over to the dispatcher. Includes all units active since 1977.

[33] There are three years in this time period in which the number of new FGD units listed exceeds the number of new coal-fired units listed. This may be due to errors in the data or to a definitional issue in which some "new" FGD units actually accompany substantially modified coal-fired utility boilers that are not included in the new utility boiler dataset.

FIGURE 2.7

U.S. Scrubber Market, 1977-89



Source: Adapted from Soud (1994)

For U.S. scrubber vendors, the decline of the total domestic FGD market after 1983 was partially compensated for by a sudden growth in the European FGD market. In 1983 Germany adopted a stringent program to control acid rain that resulted in 35,000 MWe of FGD systems being installed in four years, 33% of which were licensed from U.S. companies. Other European countries started following Germany's lead in the second half of the 1980s (McIlvaine, 1990).

FGD equipment and service organizations experienced some change in the 1977-89 period, as befits a period of changing demand. Table 2.9, however, shows that the top five FGD vendors, in terms of U.S. market share, did not change much during the period. Note that the FGD market remained highly concentrated. A number of acquisitions also happened during this period, as had occurred in the late 1970s. Particularly noteworthy are the acquisition of Combustion Engineering by ABB Environmental Systems (which also purchased the patents of

Rockwell International) and the acquisition of Envirotech by General Electric Environmental Services (GEESI) (McIlvaine, 1990).

TABLE 2.9

Top Five FGD Vendors in the U.S. in 1980 and 1989

Five Leading FGD Vendors (1980)	Market Share of U.S. Operating MW (1980)	Five Leading FGD Vendors (1989)	Market Share of U.S. Operating MW (1989)
Envirotech=GEESI	23.2%	Combustion Engineering=ABB E.S.	25.2%
Combustion Engineering=ABB E.S.	16.3%	Envirotech=GEESI	14.3%
Research-Cottrell	14.3%	Babcock & Wilcox	13.6%
Combustion Equipment Associates	9.7%	Wheelabrator	9.3%
Babcock & Wilcox	9.3%	Research-Cottrell	7.9%
Total Market Share	72.8%	Total Market Share	70.4%

Source: 1980 data from Zimmerman et. al. (1980); 1989 data from Soud (1994)

Recall from Table 2.7 that a number of non-governmental actors engaged in air pollution control R&D in the early 1980s, including the Gas Research Institute (GRI), EPRI, associations, utilities, and scrubber vendors. One of these research activities was of particular importance: the 1987 founding of the EPRI High Sulfur Test Center, located at New York State Electric and Gas's Kintigh Station. This facility was equipped with wet scrubbers at the bench scale, the mini-pilot scale, and the pilot scale, as well as with a spray dryer at the pilot scale and facilities for dry duct injection testing. It has generated considerable data on the operating characteristics of FGD systems treating combustion gases from coal of greater than 2% sulfur (Row, 1994, pp. 301-2). Table 2.10 lists the perceptions of various R&D actors in wet and dry FGD technology of the stimuli, methods, and impediments pertinent to their R&D activities in 1980. It serves as an important reference for the consideration of this dissertation's central topic, the influence of government actions on technological change in SO_2 control technologies.

TABLE 2.10

1980 Perceptions of Stimuli, Methods, and Impediments involved in Technology Development Efforts

	User (Utilities, EPRI)	**Vendor**	**Government (EPA, DOE)**
Wet Limestone FGD			
Stimuli	• CAA (SIP, NSPS) • Compliance cost reductions • Presence of EPRI • Regulatory impact of acid rain problem	• Market opportunity/profit motive • CAA (NSPS, SIP) • Cost-effectiveness of technology	• Necessity of demonstrating technology which could achieve standards • Probability of technical success • Cost-effectiveness of technology
R&D Methods	• In-house R&D • Cooperative participation in pilot and full-scale demonstrations • Litigation to change regulations	• In-house R&D • Government contracts	• Interagency R&D and operation of pilot and full-scale demonstrations • Cooperative participation with users-vendors on pilot and full scale demos
Impediments	• Funding • Lack of corporate support of R&D • Legal constraints • Rate determination • Regulatory uncertainty	• Funding • Legal constraints (antitrust laws, patent policies) • Regulatory uncertainty	• Uncertainty – intra-agency roles • Lack of government-industry cooperation re: best sites for demos
Dry FGD Systems			
Stimuli	• Complexity/unreliability of existing technology • CAA (NSPS) • EPA enforcement intentions • Lack of government R&D	• Market opportunity/ profit motive • Cost-effectiveness of technology • Relative maturity of technology • CAA (NSPS) • Solicitation from utilities • EPA enforcement intentions • Patent policies	• Enhancement of air quality • Acid rain problem
R&D Methods	• In-house R&D • Cooperative participation in pilot and full-scale demos with vendors and government • Litigation to change regulations	• In-house R&D • Cooperative participation in pilot and full-scale demos with utilities and government • Government contracts	• Intra- and inter-governmental R&D on operation of pilot-scale demonstration • Cooperative participation with users/ vendors on pilot-scale demos
Impediments	• Funding • Legal constraints (antitrust laws) • Uncertainty – government-industry roles • Inadequate lead time	• Funding • Utility industry inertia • Nonapplicability of technology to high-sulfur coal • Unresolved technical questions • Legal constraints (antitrust laws) • Uncertainty – governmental R&D	• Funding • Reluctance of vendors to participate in demos • Unresolved technical questions • Uncertainty – inter-governmental roles • Political constraints

Source: (Zimmerman et. al., 1980, pp. 2-2, 2-3)

Notes: Stimuli include those factors that encourage or facilitate R&D. Methods are the means by which the institutional actor is involved in the R&D process. Impediments discourage or present barriers to R&D.

The technological changes that occurred in the 1977-89 period increased state-of-the-art wet FGD removal efficiencies to 95% and dramatically increased scrubber reliability. A study of 111 FGD installations in 1986-88 showed that FGD systems contributed 1% or less to the total unavailability factor in 70% of the installations, regardless of retrofit status or bypass capability (Rittenhouse, 1992, p. 23). Chief among the technological changes behind these improvements was the development of a better understanding of scrubber process chemistry, which led to the development of the limestone forced oxidation and inhibited oxidation processes. Other technical developments in this time period included: the development of chemical additives to increase the performance of the scrubber sorbent; the improvement of scrubber construction materials; and the reduction of limestone particle size to improve gas-liquid contact. The development of chemical additives was of particular importance. The addition of organic acids, such as dibasic and adipic acid, to the scrubber sorbent can improve SO_2 removal efficiencies, reduce the required liquid-to-gas ratio, reduce scaling, improve sorbent utilization, and improve waste-handling characteristics (Irving, 1990, p. 25-138). By the end of the 1977-89 period, organic acids had only been added to existing scrubber facilities in the U.S., although in Germany they had already begun to be used in new scrubber design.

By the end of the 1977-89 period, a considerable amount of experience had been gained in constructing and operating FGD units. A better understanding of process chemistry developed in this time period, which dramatically improved scrubber reliability and increased removal efficiencies to 95%. While the scrubber itself changed in these years, the major firms selling these scrubbers did not change considerably. The main FGD equipment and services firms remained the same between 1977 and 1989, although the U.S. market fluctuated and foreign markets became more important to the industry.

1990-99

Government Actions 1990-99

Government actions on SO_2 emissions control in the 1990-99 period focused almost entirely on the provisions of the 1990 Clean Air Act Amendments (1990 CAA) pertaining to acid rain control. Although the 1990 CAA's establishment of a new permitting system for stationary sources in Title V was of interest to the SO_2 industrial-environmental innovation complex, the Title IV program for Acid Deposition Control was of particular interest because it legislated a national cap on SO_2 emissions. The emissions trading system implemented to meet this cap was instituted in two phases, with several intermediary deadlines and exceptions built into the law. This trading system provided new flexibility for utilities to comply with SO_2 reduction requirements for existing sources, including switching to lower sulfur fuels and trading emission allowances.

The 1990 CAA had precursors in both the 1987 draft bill to reform the CAA (as mentioned previously) and in the presidential campaign of 1988. In August 1988, presidential candidate George Bush promised to "cut millions of tons of SO_2 by 2000 (Bailey, 1998, p. 229)." On June 12, 1989, President Bush's proposals to reform the CAA were released. One of the three main goals of the proposal was to combat acid rain; to do so, Bush called for a system of tradable permits to control SO_2 emissions, which would be reduced by 10 million tons by 2000. These proposals progressed through Congress, with some political compromises and the shortening of deadlines in the administration's proposal by one year, until the 1990 CAA was enacted into law on November 15, 1990.

As passed, the 1990 CAA acid rain provisions in Title IV establish an SO_2 allowance emissions "cap and trade" program for existing and new units (see Environmental Law Institute, 1994). Under this program, U.S. SO_2 emission levels will be capped permanently in 2010 at about half of industry-wide 1980 emission levels, or 8.95 million annual tons (U.S. Environmental Protection Agency, Office of Air and Radiation, Acid Rain Division, 2000). This emissions cap will be accomplished gradually through phases in which first, a subset of existing plants reduce their emissions, and then the industry overall meets a cap that is less stringent than the ultimate cap. In Phase I of the program, which lasted between January 1, 1995 and December 31, 1999, the subset of plants targeted for emissions reductions included 261 utility units specifically required to participate ("Table A Units").[34] These units were to be limited to an aggregate rate of 2.5 lb/MBTU (note the relative laxity of this standard when compared to the NSPS emissions ceiling of 1.2 lb/MBTU). Phase I also included 125 utility units that elected to participate as part of multi-unit compliance plans, as well as ten other units that opted into the program.[35] In 1999, the emissions target established by the program for the 398 participating units was 6.99 million tons (U.S. Environmental Protection Agency, Office of Air and Radiation, Acid Rain Division, 2000). In Phase II of the program, which takes place between 2000 and 2009, the nationwide cap for all utilities with a capacity greater than 25 megawatts (over 2100 total units), will be 9.48 million tons (or an aggregate of 1.2 lb/MBTU). It is currently estimated that an additional 500 new units will be built in the next two years that will be subject to Phase II

[34] The Table A generating units required to participate were from 110 plants in twenty-one eastern and midwestern states, and included all units with a capacity of at least 100 MWe and a 1985 SO_2 emission rate greater than 2.5 lb/MBTU. Table A units represented 17% of U.S. generating capacity in 1990. Two of the Table A generators have two boilers, so the number of Table A units is sometimes listed as 263 rather than 261 (Zipper and Gilroy, 1998, p. 830; Schmalensee et. al., 1998).

[35] Table A units could reassign their emission reduction requirements to "substitute" non-Table A units if both were controlled by the same owner or operator. Table A units that reduced their generation requirements (and therefore emissions) could transfer their generation to a "compensating" non-Table A unit that had not had substantial emissions reductions since 1985 and was either in the Table A unit's dispatch system or in contractual agreement with the Table A unit. In addition, a voluntary opt-in program allowed non-affected industrial and small utility units to participate in Phase I (Schmalensee et. al., 1998; Zipper and Gilroy, 1998).

of the program (U.S. Environmental Protection Agency, Office of Air and Radiation, Acid Rain Division, 2000).

The allowance program that implements these emissions caps involves the distribution and gradual reduction of tradable facility "allowances," where one allowance is worth the right to emit one ton of SO_2. Allowances are given to facility operators by the EPA Administrator, based on several provisions of Title IV, and are then transferable and bankable by these operators.[36] An annual allowance auction and direct sales held by the EPA beginning in 1993 (direct sales were eliminated in 1997) provide formal opportunities for allowance transfers, although transfers can occur outside these events. No matter how many allowances a facility accrues, however, it is not allowed to violate federal or state limits for the protection of human health under Title I of the CAA. At the end of every year, the EPA "reconciles" the annual emissions of each unit (as measured through continuous emission monitors) with the allowances held by the unit. A 30-day grace period at the end of the year provides utilities with an opportunity to purchase additional allowances if necessary in order to avoid fines (Environmental Law Institute, 1994; Zipper and Gilroy, 1998).

Phase I Table A units provide an example of how the allowance system works. These units were allocated allowances by multiplying 2.5 lb/MBTU by the average annual heat input for each unit in 1985-7 (considered the "baseline," and excluding outage periods greater than four months).[37] In any given year, the total allowable emissions level for SO_2 is the number of

[36] Additional allowances were given to: (1) Illinois, Indiana, and Ohio to compensate for additional costs associated with their high SO_2 emissions (Bryner, 1995, p. 166); (2) "compliance" utilities for demand-side management or renewable energy use (Zipper and Gilroy, 1998); (3) utility systems that reduced coal use by at least 20% between 1980-5 and that rely on coal for less than 50% of total electricity; (4) "clean" states to boost economic growth (Bryner, 1995); and (5) "control units," which demonstrated that they had cut emissions by 90% by 1997 using "qualifying technology," and "transfer units" which reassigned their emissions to control units (U.S. Environmental Protection Agency, Office of Air and Radiation, Acid Rain Division, 1999).

[37] Units without an operating history in these years were to have their baselines set by the EPA Administrator (Molburg, 1993).

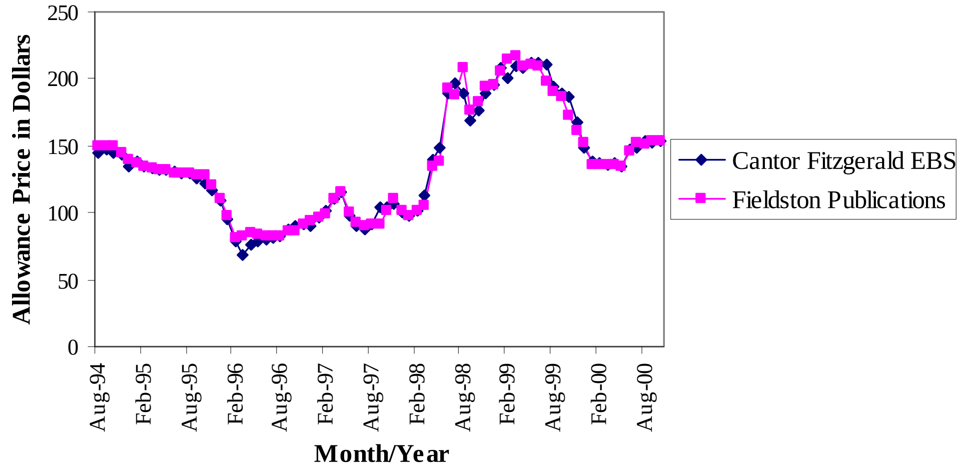
allocated allowances plus any allowances banked from the previous year. Thus, the total allowable emissions level for SO_2 in 1999 was the 6.99 million 1999 allowances granted to the Table A and participating non-Table A units, plus an additional 9.63 million allowances banked from 1998.

On the basis of emissions reductions and compliance costs, the completed Phase I of Title IV has been considered a general success.[38] In 1995, SO_2 emissions reductions were almost 40% below their required level and emissions levels were lower than allocation levels in each of the years of Phase I. Initial estimates for allowance prices ranged between $400 and $1000/ton, but, as Figure 2.8 demonstrates, prices have been considerably lower than estimates (U.S. Environmental Protection Agency, Office of Air and Radiation, Acid Rain Division, 2000). It is not yet clear whether Phase II of Title IV will be equally successful.

[38]There have been challenges to the flexibility of Title IV, however. The ongoing coal industry concern about the competition of low sulfur coal with scrubbed high sulfur coal prompted attempts by at least five states – Kentucky, Illinois, Indiana, Ohio, and Pennsylvania – to protect high sulfur coal interests (Ellerman and Montero, 1998, p. 37). In addition, the concern that national allowance trading would not suitably improve the regional acid rain transport and chemistry patterns that adversely impact New York prompted the state to pass a bill preventing “clean” New York utilities from trading allowances with “dirty” utilities upwind (Hernandez, 2000).

FIGURE 2.8

Monthly Average Price of Sulfur Dioxide Allowances Under Title IV, 1993-2000



Source: Monthly price report of Cantor Fitzgerald Environmental Brokerage and a market survey conducted by Fieldston Publications (U.S. Environmental Protection Agency, 2000)

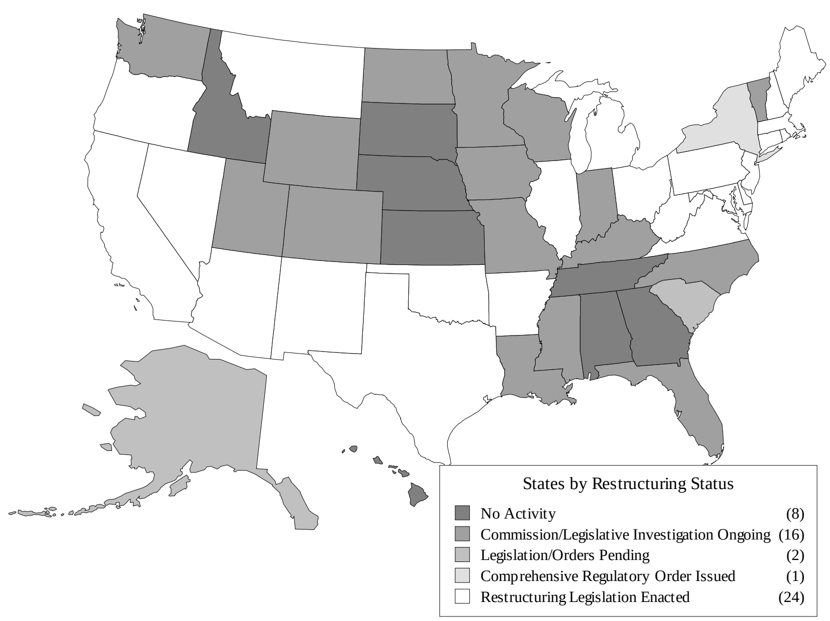
In addition to the 1990 CAA, polluting organizations in the SO_2 industrial-environmental innovation complex were affected profoundly by one other set of government actions in the 1990s: actions related to utility restructuring, or deregulation. The utility industry is currently transitioning from a vertically integrated and regulated monopoly to a competitive market in which retail customers choose electricity suppliers. Although this change originated with the Public Utility Regulatory Policies Act (PURPA) of 1978, when utilities were required to interconnect with and buy power from nonutilities meeting certain criteria at the utilities' avoided cost, most of the government actions behind this change have occurred in the 1990s. In 1992, the Energy Policy Act (EPACT) opened access to transmission networks and exempted certain nonutilities from the Public Utility Holding Company Act of 1935 (PUHCA).[39] In 1996,

[39] PUHCA had required vast interstate holding companies to divest until each became a single utility system serving a bounded geographic area, while limiting their business only to those activities considered appropriate to the operation of an integrated utility.

the Federal Energy Regulatory Commission issued Order 888, which facilitated nonutilities' transmission access, and Order 889, which required utilities to share electronic information about available transmission capacity. With national government actions thus clearing the way for nonutilities to participate in wholesale electric power sales, state legislators were able to put into practice a common belief held by governmental and non-governmental actors: that electricity generation would be more cost-effective in a competitive market. Figure 2.9 shows the current status of state electric industry restructuring activity in the U.S. Note that transmission and distribution will remain regulated and noncompetitive (Energy Information Administration, 2000a).

FIGURE 2.9

Status of State Electric Industry Restructuring Activity as of December 2000



Source: Energy Information Administration (2000c)

Other Actions by the Industrial-Environmental Innovation Complex 1990-99

Several early uncertainties associated with the implementation of Phase I of the 1990 CAA affected the FGD market strongly in the 1990-99 period. Allowance prices were the central uncertainty, as they were at the root of utility compliance choices between fuel switching and FGD installation in order to meet the relatively modest Phase I emissions cap.[40] Program deadlines enhanced this uncertainty, as Phase I utilities had to submit compliance plans to the EPA by February 15, 1993, before EPA's rules were proposed and before the first allowance auction was held in the spring of 1993 (Burtraw, 1996, p. 82). In EPRI workshops held in 1992, 60% of utility respondents called "uncertainties" their greatest concern about the 1990 CAA (Rittenhouse, 1992, p. 21). With these polluting organization abatement uncertainties, environmental equipment and service organizations had a much more difficult time anticipating the future size of the utility FGD market in the U.S. Initial and widespread Phase I predictions, based in part on the unrealistically high Phase I allowance price predictions, had scrubber vendors anticipating "35-40 scrubber contracts between 1995 and 1999," and expressing concern about "the capacity of FGD manufacturers in the United States to meet the demand (Burtraw, 1996, p. 90; Munton, 1998, p. 28)."

The ultimate market for utility FGD, however, was considerably smaller than anticipated. Table 2.11 displays the range of Phase I compliance options chosen by affected units by 1995. FGD unit installations were chosen by only 10% of Table A units, although they were responsible for one-third of 1990-5 emission reductions.[41] A combination of fuel switching and

[40] Utilities weighed both wet and dry FGD options unsuccessfully against the low price of SO_2 allowances in the 1990-99 period [among others, see Torrens and Platt (1994)].
[41] When it became clear that Phase I retrofit installations would fall short of projections, some analysts envisioned a possible market in utilities designating their FGD-equipped units as substitute units and then upgrading those units to state-of-the-art technology in order to gain additional allowances (Feeney, 1995). The low prices of allowances and high upgrade costs in the 1990s, however, did not allow this market to grow rapidly.

blending proved to be the most popular method of compliance due to low prices for both low sulfur coal and allowances.[42, 43] The appeal of this option was slow to register with some Phase I-affected utilities, however. A number of these utilities responded to a 1996 survey that they had actually reversed initial decisions to scrub substantial capacity, with two-thirds pointing to low-sulfur coal costs and one-third to low allowance prices as the reason for their reversal (Schmalensee et. al., 1998, p. 65).

TABLE 2.11

Compliance Strategies of Units Affected in Phase I of Title IV of the 1990 CAA, as of 1995

Compliance Strategy	Number of Units	Emissions Reduction, 1990-95 (Million tons)
Table A Units		
Fuel switching/blending	162	2.550
Obtaining allowances	39	0.100
Installing FGD Equipment	27	1.410
Using Previous Controls	25	0.130
Retiring Facilities	7	0.030
Boiler Repowering	1	0.007
Total Table A	261	4.230
Substituting and Compensating Units	182	0.420
Total Phase I	443	4.650

Source: Zipper and Gilroy (1998, p. 830)

Table 2.12 lists the twenty-seven FGD units that came on-line at sixteen utilities in order to comply with Phase I, in the order in which they came on-line. Three of the dominant scrubber vendors, responsible for 81% of this capacity, remained the same in this period as in the 1970-76 and 1977-89 periods. Acquisitions continued in the 1990-99 period, as they had in earlier periods. Most noteworthy were the acquisition in the fall of 1997 of GEESI by the Canadian-

[42] The popularity of low-sulfur coal in the 1990s continued a trend: coal with less than 1% sulfur comprised more than one-half of the coal market by 1990 (compared to one-quarter of the market in the 1970s) (Munton, 1998).

[43] Fuel switching costs declined in 1990-5 due to "improved operating efficiencies" in the rail and coal industries and the expansion of low-cost, low sulfur western coal production (Zipper and Gilroy, 1998). Utilities paying greater than market value for high-sulfur coal due to "escalator clauses" in long-term contracts especially benefited from switching western coal under short-term contracts (Munton, 1998).

owned Marsulex and the acquisition of Joy Engineering by Babcock & Wilcox in the spring of 1995.

TABLE 2.12

FGD Retrofits for Compliance with Phase I

Online Year	State	Boiler Units	Plant & MWe	Utility	FGD Vendor
1992	Georgia	Y1BR	Yates* (123)	Georgia Power	Chiyoda
	Indiana	7, 8	Bailly* (844)	Northern Indiana Public Service	Pure Air, a partnership of Mitsubishi Heavy Industries and Air Products and Chemicals, Inc.
1994	Kentucky	1, 2	Elmer Smith (530)	City of Owensboro	Wheelabrator
	Ohio	1	General J.M. Gavin (1,300)	Ohio Power	Babcock & Wilcox
	Pennsylvania	2	Conemaugh (936)	Pennsylvania Electric Company	ABB = Combustion Engineering
	West Virginia	1, 2, 3	Harrison (2,052)	Monongahela Power Company	Marsulex = GEESI
1995	Indiana	2,3	F.B. Culley (333)	Southern Indiana Gas & Electric	Riley
	Indiana	4	Gibson (668)	PSI Energy	Babcock & Wilcox
	Kentucky	H1, H2	Henderson MP&L (364)	Big Rivers Electric	Wheelabrator
	Kentucky	1	Ghent (557)	Kentucky Utilities	Babcock & Wilcox
	New Jersey	2	B.L. England (163)	Atlantic City Electric Company	Marsulex = GEESI
	New York	1, 2	Milliken* (316)	New York State Gas & Electric	Saarberg-Holter-Umwelttechnik
	Ohio	2	General J.M. Gavin (300)	Ohio Power	Babcock & Wilcox
	Ohio	1	Niles (133)	Ohio Edison	ABB = Combustion Engineering
	Pennsylvania	1	Conemaugh (936)	Pennsylvania Electric Company	ABB = Combustion Engineering
	Tennessee	1, 2	Cumberland (2,600)	Tennessee Valley Authority	ABB = Combustion Engineering
	West Virginia	3	Mt. Storm (550)	Virginia Electric & Power Company	Marsulex = GEESI
1996	Indiana	1, 2	Petersburg (724)	Indianapolis Power & Light	Marsulex = GEESI

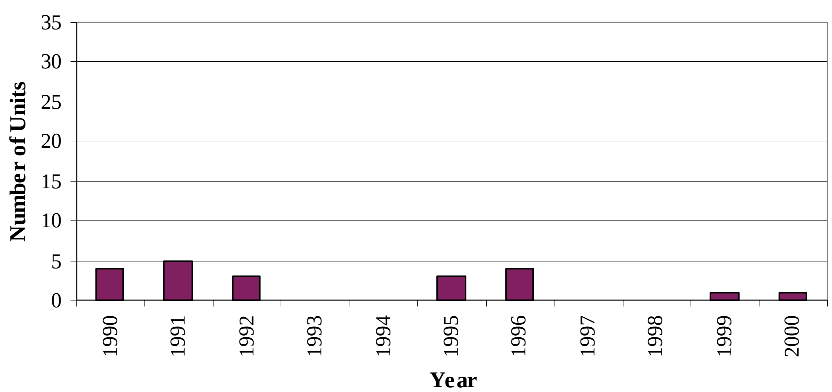
Source: Energy Information Administration (1997, P. 10), Smith and Dalton (1995), DOE (1999), Virginia (1999), Test (1995), SIGECO (1992)

Note: For consistency with previous tables in this chapter, two major scrubber vendors are listed with their post and pre-acquisition names.

The U.S. market for FGD was not completely dominated by Phase I, however. Figure 2.10 shows the extremely low level of new utility-operated coal-fired steam turbine units brought online between 1990 and 1995 and planned as of January 1, 1996. This is the market background for new FGD units that were not affected by Title IV of the 1990 CAA, and probably reflects the uncertainties of utility restructuring. Figure 2.11 shows the total number of commercial FGD units brought online between 1990 and 1993, broken down into the realized categories of new and retrofit construction. Note that new FGD units associated generally with new power plant construction comprised 52% of the FGD market in these four years, which is a more balanced proportion than in either the 1973-76 period (28%) or the 1977-1989 period (69%). Unfortunately for FGD vendors, the dearth of new power plant construction, in combination with the Phase I decisions of affected utilities to favor fuel switching over the installation of FGD, meant a very small U.S. FGD market on the basis of both new and retrofit construction.

FIGURE 2.10

Number of New Utility-Operated Coal-Fired Steam Turbine Units in 1990-2000 by Historical or Planned Year of Commercial Operation

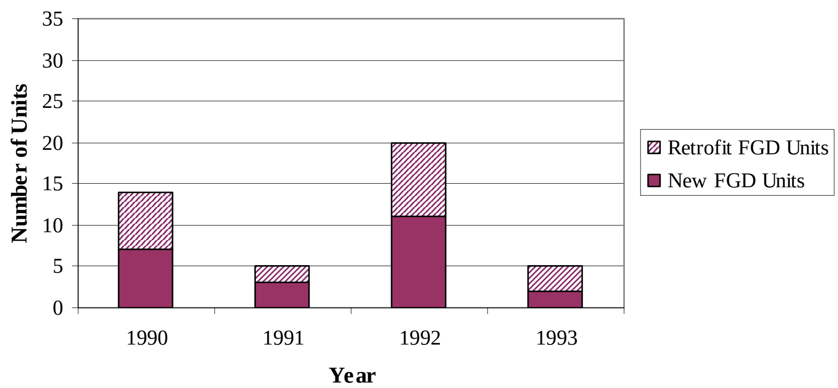


Source: Adapted from Energy Information Administration (1996)

Notes: The year of commercial operation is the year that control of the unit was turned over to the dispatcher. Includes all units active since 1990 and all units planned as of January 1, 1996.

FIGURE 2.11

U.S. Scrubber Market, 1990-93



Source: Adapted from Soud (1994)

Although the FGD market certainly appeared bleak in the early 1990s, there are a number of FGD orders that have been made since 1995 for either Phase II or NSPS compliance purposes. In 1998, orders were placed for Wheelabrator scrubbers to service 890 MWe capacity at two boiler units at Tampa Electric's Big Bend plant, and for one ABB FGD system to service 650 MWe at one boiler at Edison Mission Energy's Homer City plant in Pennsylvania. In 1999, scrubbers were ordered for two boiler units at Springfield Illinois Municipal Electric's 173 MWe Dallman plant, Marsulex scrubbers were ordered for two 550 MWe boiler units at Virginia Electric and Power Company's Mount Storm plant in West Virginia, and ABB scrubbers were ordered for Pacificorp's 1,340 MWe Centralia plant in Washington. Finally, in 2000, Public Service Company of Colorado ordered Babcock & Wilcox scrubbers for two boiler units at its 504 MWe Cherokee facility as well as for one unit at its Valmont facility. It is unclear, however, how large the utility FGD market will become as Phase II progresses while newly deregulated utilities struggle with the need to add new generating capacity.

R&D efforts in the 1990-99 period did not remain at levels as high as in earlier periods. The DOE retained its government R&D prominence in FGD through its CCT program, but EPRI reduced its R&D efforts for FGD significantly, for two reasons. First, efforts in SO_2 control R&D were reduced as "the scope for improving performance of today's reliable FGD systems, which achieve SO_2 reductions around 95% … is lessening (Row, 1994, p. 301)." Second, EPRI's overall R&D funding levels declined substantially in the 1990s in the face of growing competition in the electric utility industry. The R&D funding levels of scrubber vendors were also hurt by the decline in scrubber demand during the mid- and late-1990s.

Several developments occurred in FGD technology during the 1990-99 period that enhanced the cost-effectiveness of the technology, as measured by capital costs, operating costs, and SO_2 removal efficiency. Capital costs for scrubbers fell by almost 50% between 1989 and 1996 (Zipper and Gilroy, 1998). One important reason for this was lessening concern about scrubber reliability. As stated earlier, the FGD technology itself had become highly reliable by 1989, and since allowance sales provided an additional safety net in case of a reliability problem, costly design options such as spare absorber modules were dropped in the 1990-99 period. Additional capital cost savings resulted from several factors, including: a trend toward larger capacity modules that provided economies of scale; increased flue gas velocity in the absorber which lowered the unit cost; elimination of flue gas reheat components; and reduced reagent preparation costs (Energy Information Administration 1997; Burtraw, 1996). The potential revenue-generating allowances obtainable with greater FGD removal efficiencies sped the diffusion of higher removal efficiency scrubbers in the 1990-99 period. SO_2 removal efficiencies in excess of 98 percent were accomplished through such measures as the incorporation of additives (e.g. dibasic acid, formic acid, and magnesium compounds) in scrubber designs, and improved gas-liquid contact throughout the scrubber system via improved hydraulics and ultrafine limestone particle size.

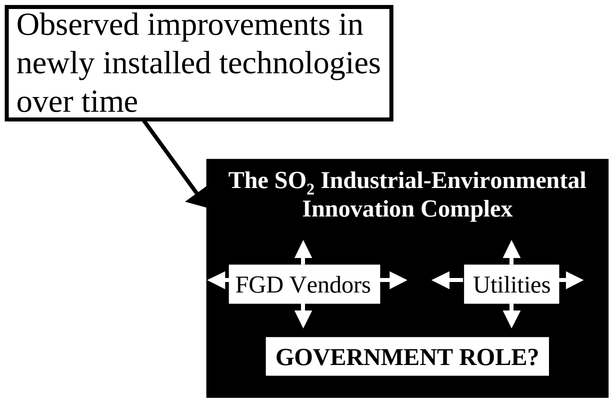
Finally, operating and maintenance costs were reduced due to a number of innovations. New materials of construction such as alloys, clad carbon steel, and fiberglass provided corrosion resistance at reduced cost, with subsequent savings in maintenance costs. Operation without gas reheat, wastewater evaporation systems, and heat exchangers that used waste heat from stack gases to increase power plant efficiency all enhanced energy efficiency. Labor costs were reduced through improvements in instrumentation and controls, while operating costs could be offset by the sale of commercial-grade gypsum from wet limestone forced oxidation processes (U.S. Environmental Protection Agency, Office of Air Quality Planning & Standards, 1997; Jozewicz et. al., 1999; Schmalensee et. al., 1998).

Outside the Black Box: Outcomes of Innovation in SO_2 Control Technologies

As the preceding discussion has shown, government actions have had a considerable influence on the SO_2 industrial-environmental innovation complex and its resulting technologies. In later sections of this dissertation, some of this influence will be quantified with respect to the innovative activities undertaken by the actors in this complex. Expert opinion about innovative outcomes in SO_2 control technologies will also be described throughout the dissertation. The remainder of this chapter, however, will focus on quantifying the innovative outcomes observed outside the black box of the SO_2 industrial-environmental innovation complex. Figure 2.12 represents the method used in this section to quantify, through the use of market and performance data, improvements in the removal efficiencies and capital costs of newly installed FGD systems over time.[44]

FIGURE 2.12

Observed Improvements as a Measure of Innovative Outcomes



The method used in this section to quantify innovative outcomes is similar to the learning curve method employed in Chapter Five, in that it charts performance improvements as the dependent variable related to the independent variable of cumulative output. The method used here differs from the learning curve method, however, in that it considers improvements in state-of-the-art FGD systems over time rather than simply the performance improvements that occur based on organizational learning at a given facility. Thus, it will be called a "generational" analysis, for the new generations of state-of-the-art FGD systems to come online over the years. Whereas the learning curve method relies on one data set for a consistent plant-level analysis that is then aggregated to derive overall trends, the generational method used here employs two data sets and a series of studies in order to assess FGD industry trends.

Both the generational analysis of SO_2 removal efficiencies and that of capital costs rely on a predictor variable that represents the cumulative output of FGD systems. The cumulative

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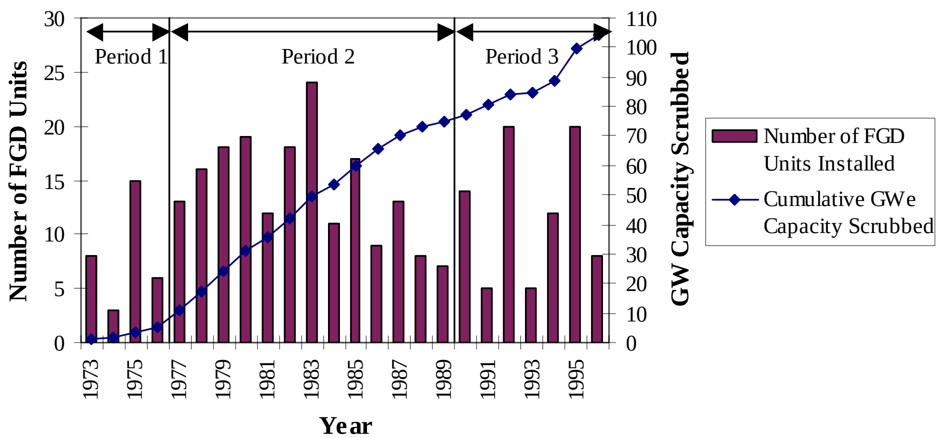
[44] Reliability and operating costs are not considered in this section. As stated previously, reliability became a negligible concern by 1989. Changes in capital costs over time incorporate reliability considerations to a large extent. Operating cost trends are examined in Chapter Five, which deals with learning curve analysis.

output of an FGD system can be considered to be the cumulative gigawatts (GWe) of electrical capacity scrubbed by all FGD systems in the U.S. For both generational analyses, the cumulative FGD capacity is taken from an International Energy Agency (IEA) dataset considered reliable on FGD capacity (Soud, 1994).[45] Figure 2.13 shows the cumulative GWe capacity scrubbed by FGD units that came online between 1973 and 1996, as calculated from this dataset (parts of this graph were shown throughout the preceding discussion of government and non-government actions in SO_2 control).

FIGURE 2.13

Number of FGD Units and Cumulative GWe Capacity of FGD Units from 1973 to 1996



Source: Adapted from Soud (1994)

Note: These numbers are archival through June 1994, then projected for 1994-96.

The generational analysis of SO_2 removal efficiencies relies on performance data for U.S. FGD units that came online between 1973 and 1996. These data are provided in a very detailed and complex DOE Energy Information Administration (EIA) form 767 dataset, which covers

[45] There is some question about reliability after the publication date of June 1994, since the 1994 to 1996 data is based on scrubber orders known at the time.

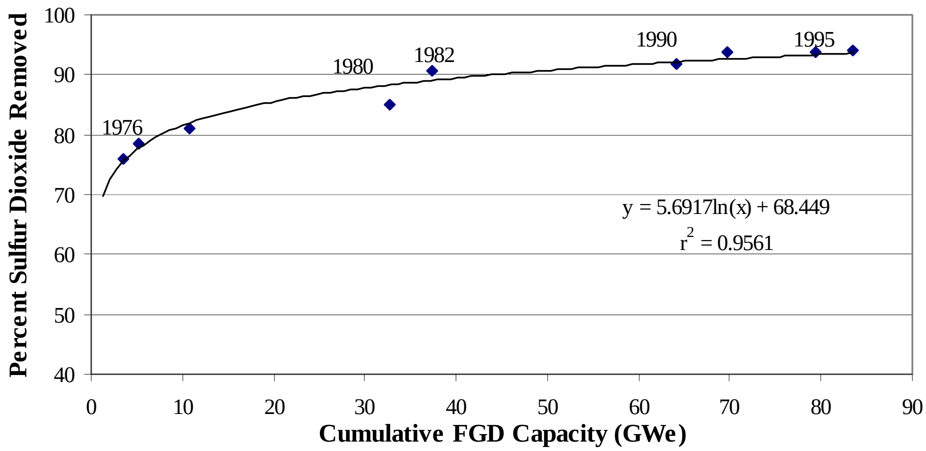
U.S. scrubbers with inservice dates as early as 1969 (see Energy Information Administration (1999) and Appendix D for details on the data and the data translation process).[46] The exact removal efficiency calculated in this analysis for each year is an average of the estimated removal efficiencies (at the annual operating factor) of each year's class of inaugural FGD units. Figure 2.14 displays the improvement in wet limestone FGD system SO_2 removal efficiencies between 1973 and 1996 as a function of cumulative FGD GWe capacity.[47] Overlaid on the average estimated removal efficiency data points is a logarithmic curve that explains over 95% of the variance. Note that the rate of SO_2 removal efficiency improvement is particularly high between 1976 and 1980, as efficiencies improved from a 1975 removal level of about 70% to a 1980 level of almost 90% removal. These years correspond with years of high FGD industry profit and entry into the utility FGD market. These years also correspond with the period of promulgation and implementation of the 1977 CAA and the FGD-promoting 1979 NSPS. In general, the logarithmic curve in Figure 2.14 indicates the "innovative life-cycle" of FGD technologies, since it shows the technology to be born and improve rapidly in the 1970s and early 1980s, then mature as removal efficiencies flatten out.

[46] This dataset has well-documented inaccuracies (see Weilert and Dyer, 1995).

[47] Because of a concern that low- to moderate-removal dry and other FGD systems might be masked as wet FGD systems due to inaccuracies and missing information in the EIA 767 dataset, data points were excluded from this figure if they showed lower removal efficiencies than the state-of-the-art in previous years.

FIGURE 2.14

Improvements in SO_2 Removal Efficiency of Commercial FGD systems as a Function of Cumulative Installed FGD Capacity in the U.S.



Source: Based on data from Soud (1994), Energy Information Administration (1999)

FGD capital costs are not as simple to analyze as SO_2 removal efficiencies because capital costs entail a great number of site-specific design factors that muddy cost trends. For this reason, the generational analysis of capital costs relied on a dependent variable based not on actual utility data, but rather on a series of capital cost studies conducted over the last three decades. As mentioned previously, TVA performed periodic utility capital cost benchmark studies in the 1970s and early 1980s. EPRI began to perform similar benchmarking studies in the mid-1980s and continued these studies into the 1990s. All of these studies incorporated systematic cost assumptions associated with contemporary technology design applied to standardized coal-fired power plants. Five of these studies, representing wet limestone scrubbing technology as it appeared in 1976, 1980, 1982, 1990, and 1995, were used to examine trends in FGD capital costs for a benchmark 500 MWe plant burning a high sulfur (3.5% sulfur) coal (McGlamery et. al., 1980; Laseke, Jr. et. al., 1982; Keeth, Ireland, and Moser, 1986; Keeth, Ireland, and Radcliffe, 1990; Keeth, Ireland, and Radcliffe, 1991).[48] The reported capital cost in each study was adjusted to a basis of 1997 dollars using the procedure described in Appendix E. Other adjustments were made to account for slight differences in the relevant assumptions of the TVA and EPRI studies. For example, one study used somewhat higher sulfur coal and smaller plant size than the reference plant design. In these cases, reported cost results were adjusted using a power plant computer model that accounts for the influence of each cost factor on total FGD cost (Rubin, Kalagnanam, and Berkenpas, 1995; Rubin et. al., 1997).

Figure 2.15 provides a systematic estimate of FGD capital cost reductions as a function of FGD GWe capacity (based on Soud, 1994; McGlamery et. al., 1980; Laseke, Jr. et. al., 1982; Keeth, Ireland, and Moser, 1986; Keeth, Ireland, and Radcliffe, 1990; and Keeth, Ireland, and Radcliffe, 1991. Overlaid on these estimated costs is a third-order polynomial equation that accounts for over 98% of the variance in these capital costs over time. Note that capital cost reductions were minimal in the 1976 to 1980 time period during which SO_2 removal efficiencies improved rapidly. Indeed, steeper improvements in capital costs occurred only after steep improvements in SO_2 removal efficiencies (capital costs improved greatly between 1980 and 1990, while removal efficiencies improved rapidly between 1976 and 1980). As in the case of SO_2 removal efficiencies, however, capital costs leveled out in the 1990s, although to a lesser extent than removal efficiencies.

[48] Note that these years were also highlighted in Figure 2.14 for purposes of comparison.

FIGURE 2.15

Reductions in Capital Cost of a New Wet Limestone FGD System for a Standardized Coal-fired Power Plant (500 MWe, 3.5% sulfur coal, 90% SO_2 removal)

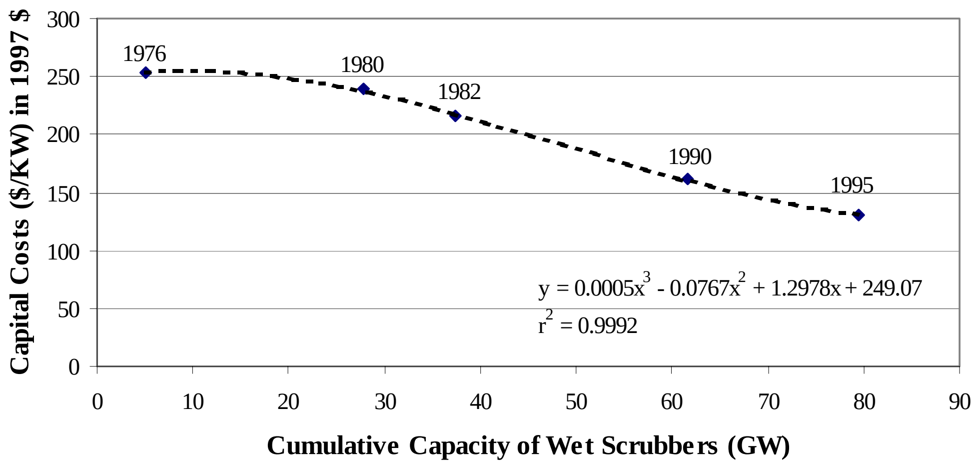


Figure 2.14 and Figure 2.15 quantify the improvements in SO_2 removal efficiencies and capital costs that were a major outcome of innovative processes occurring inside the black box of the SO_2 industrial-environmental innovation complex during the 1970s, 1980s, and 1990s. These two figures do not merely show the existence of important innovations in a heavily government-influenced technology, however. These figures also suggest innovative priorities in the SO_2 industrial-environmental innovation complex and hint at possible predictive implications about environmental technological innovation.

It appears that the priority order for SO_2 control technology development was first, to demonstrate that FGD technology could meet high removal standards, and second, to make this technology cost-competitive. This is probably a typical priority order for the development of an environmental control technology, as long as the most expensive technological solution is still cheaper than the alternative to meeting the environmental standard that created the need for the technology. This sort of calculation is considerably more uncertain in the emission-trading regime of the 1990 CAA than in earlier national environmental regulatory events.

One of the advantages of developing the logarithmic and third-order polynomial equations fitted to the data in Figure 2.14 and Figure 2.15 is that these models characterize improvements in performance and reductions in cost as a simple function of technology diffusion. The simplicity of these functions is likely to make this work accessible to models of future environmental change, which have important uncertainties related to the rate of relevant environmental technological change. Of course, finding similar functions in other case studies of environmental innovation will be important to developing a more general understanding of these rates of change. Some of this work will be done for nitrogen oxide control technologies and carbon sequestration technologies in fulfillment of the USDOE Office of Science Notice 00-08 for the Integrated Assessment of Global Climate Change Research.

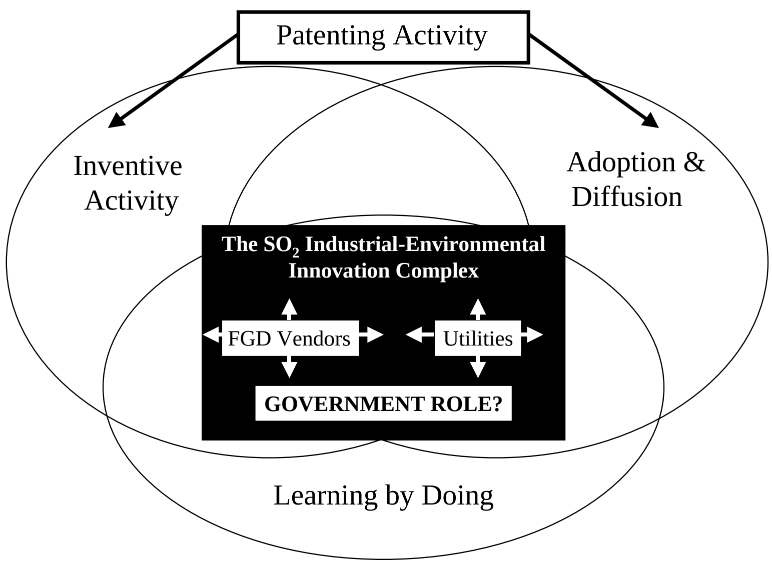
This section provided a quantitative overview of innovative outcomes in SO_2 control technologies, while the historical descriptions that comprised the majority of this chapter provided a qualitative understanding of the context in which these innovations occurred. The next three chapters each focus on ways of measuring the innovative processes of invention, adoption and diffusion, and learning by doing that take place within the SO_2 industrial-environmental innovation complex. The influence of government actions on these processes over the past three decades will be highlighted.

Chapter 3 Patent Analysis

Chapter Two described the outcomes of innovation in SO_2 control technologies between 1970 and 1999 and quantified the improvements that took place in these years with respect to SO_2 removal efficiencies and capital costs. In order to arrive at these outcomes, innovative activities occurred that were influenced by the government actions and business concerns that were also described in Chapter Two. Figure 3.1 portrays the combined innovative activities of invention, adoption and diffusion, and learning by doing that occur within the SO_2 industrial-environmental innovation complex.

FIGURE 3.1

Patents as a Measure of Inventive Activity and Adoption & Diffusion Strategy



No attempt was made in Chapter Two to quantify any of these innovative processes. This chapter focuses on measuring inventive activity in the SO_2 industrial-environmental innovation complex over time in an effort to observe the influence of government action on the innovation process. The measure used in this chapter is patenting activity, which has not only been used by many studies to gauge inventive activity, but also speaks to the marketing strategies of firms that can lead to adoption and diffusion (for published reviews of patent research, see Archibugi and Pianta, 1996; Basberg, 1987; Griliches, 1990; Pakes and Simpson, 1989; Pavitt, 1985; Schankerman, 1989).

The introductory section of this chapter defines patents and discusses the patenting process. It also explores some of the advantages and disadvantages of using patents as an innovation measure. Some of the techniques other researchers have used to compensate for these disadvantages are also discussed in this section, and an overview of how these disadvantages are accounted for in this dissertation is provided. The introductory section of this chapter concludes with expert perceptions of the role of patents in the SO_2 industrial-environmental innovation complex. The second and third sections of this chapter describe two different approaches employed in this dissertation to create patent datasets for use as a stage on which to observe the influence of government action on innovation. The results of these approaches are presented and discussed; expert opinion on these results is also included in some of the interpretations.

Patents and the Patenting Process

A patent is a government grant to an inventor of a legal right to the exclusive manufacture and sale of a useful, non-obvious, novel invention for a set period of time in exchange for making details of the invention public. In theory, a patent rewards an inventor for investing in inventive activity with a temporary monopoly right for the commercialization of the resulting invention. The societal reward for granting this monopoly right is the enhancement of the public good of "knowledge" from which new discoveries and innovations draw. In practice, the patent is not always commercially exploited by the inventor or the organization to which the inventor may assign the patent right.

Instead, the patent may be treated by its owner as an intellectual property that can be bought, sold, traded or licensed to other firms or individuals as part of the patent owner's commercial strategy. An inventor may thus file a patent application not only as the result of a new inventive effort, but also as the result of a new strategic interest in exploiting an existing invention. In general, though, researchers have observed that patenting activity occurs at a fairly early stage in a research project (Hall, Griliches, and Hausman, 1986; Stoneman, 1983).

Patents are not always applied for when a technical advance occurs that meets all the conditions for patenting and is thus "patentable," however, and certain types of technical advances are not patentable. Survey results in Mansfield (1986) show that firms apply for a patent for about 66-87% of patentable inventions. A firm's understanding of competitive conditions and the strength of patent protection in its industry determine the decision whether to file for a patent. Keeping a patentable advance secret can be more beneficial to a firm interested in appropriating the commercial benefits of inventive activity than paying patent fees and publicly revealing details of the technical advance. This is especially, but not exclusively, true in industries in which technologies develop so rapidly that inventions get quickly outdated and in industries in which patents are difficult to enforce. The attractiveness of secrecy to a firm in any industry is enhanced if a firm appreciates that it has a strong position, vis-à-vis competitors, in its firm-specific skills and know-how that will make imitation by competitors costly and time-consuming. Other firm characteristics that can make imitation difficult include the ability to quickly launch and distribute a new product and the ability to maintain especially low prices on a new product. [For more about the firm decision to patent, see Cohen, Nelson, and Walsh (1996); Ferne (1998, p. 14); Mansfield, Schwartz, and Wagner (1981); Pavitt (1985, p. 81); Scherer

(1976); Schmoch and Schnoring (1994, p. 399); Taylor and Silberston (1973); von Hippel (1982)].

Once a firm decides to apply for a patent, it faces a decision about where to file for patent protection. A patent can be filed in an industrialized country like the United States in two main ways: either directly to the national patent office or through the global Patent Cooperation Treaty (PCT) administered by the World Intellectual Property Organization (WIPO). Direct application to individual national patent offices is typically less costly than application to international mechanisms such as the PCT, but applying through the PCT can be less expensive and burdensome if the inventor is interested in filing for patent protection in multiple countries around the world. If patent protection is sought in multiple countries, it is the first application filed anywhere in the world that is considered the "priority" application. The year this application is filed is considered the priority file year, and the priority country is typically assumed to be the country in which the invention is developed. It is this priority application that is considered the basic patent in an international patent "family" consisting of all the patent documents associated with a single invention that are published in different countries (National Science Board, 1999, p. 6-23).

In general, a patent is filed in countries the patent applicant seeks to market in. The size of the U.S. market has helped to make the U.S. patent system the largest in the world and has therefore made it a useful patent system for researchers to explore international issues related to inventive activity. This chapter deals only with patent data from the U.S. system. About 100,000 patents are granted every year by the United States Patent and Trademark Office (USPTO), about half of which are invented in the United States and considered "domestic applications (Narin, 1994a; Narin, 1994b)." Between 1880 and 1989, the number of domestic patent applications in the U.S. increased at a slower rate than real GNP and investment, but the late 1980s and early 1990s demonstrated a sharp increase in U.S. patent applications (Arundel and Kabla, 1998; Griliches, 1990; Kortum and Lerner, 1997).

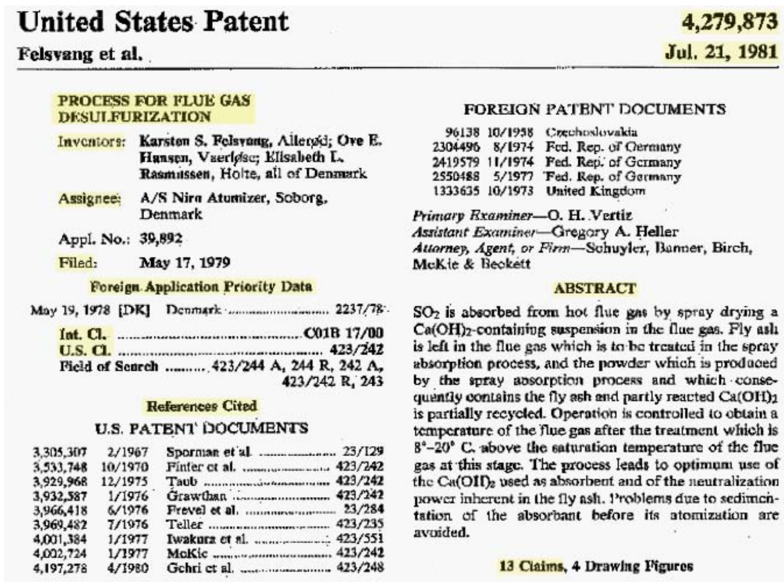
Once a patent is filed in the United States, it undergoes an examination process that ultimately leads to granting or rejecting the patent. The granting rate has varied over time in the United States (as well as in different countries). Data from domestic applications filed between 1965 and 1980 showed the U.S. granting rate varied from a low of 58 percent in 1965 to a high of 72 percent in 1967 (Griliches, 1990, p. 1663).

If a patent is granted, a publicly accessible document (available electronically for patents granted since 1975) is created with three main parts: the front page, the technical claims that form the legal heart of the patent, and associated diagrams. The front page of the patent is particularly useful for the researcher to gain information not just about the invention (in summary form), but also about the inventor, the organization the inventor may assign the patent right to (the "assignee"), and the intellectual background of the invention as evidenced in references to previous patents and other sources. Figure 3.2 displays the front page of a U.S. patent relevant to SO_2 control. Information contained on this front page includes the following fields of summary information: the patent number, grant date, title, inventor and assignee (including geographic origin), application file date, foreign application priority data, International Patent Classification (IPC), United States Patent Office Classification (USPC), patent and non-patent references, abstract, and number of claims. By convention, all patent front pages, regardless of the granting authority, contain most of the same fields of summary information in the same order as in this sample patent (Clarke and Riba, 1998, p. 2). In addition to these fields, U.S. patents sometimes have a "statement of government interest" if the U.S.

government has helped to develop the invention being patented and would like to retain the right to use (not commercialize) the invention without dealing with infringement issues.

FIGURE 3.2

Sample Patent Front Page



United States Patent **4,279,873**

Felsvang et al. **Jul. 21, 1981**

PROCESS FOR FLUE GAS DESULFURIZATION

Inventors: Karsten S. Felsvang, Allerød; Ove E. Hansen, Vaerløse; Elisabeth L. Rasmussen, Holte, all of Denmark

Assignee: A/S Niro Atomizer, Soborg, Denmark

Appl. No.: 39,892

Filed: May 17, 1979

Foreign Application Priority Data

May 19, 1978 [DK] Denmark 2237/78

Int. Cl. C01B 17/00

U.S. Cl. 423/242

Field of Search .... 423/244 A, 244 R, 242 A, 423/242 R, 243

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2550488	5/1977	Fed. Rep. of Germany
1333635	10/1973	United Kingdom

Primary Examiner—O. H. Vertiz
Assistant Examiner—Gregory A. Heller
Attorney, Agent, or Firm—Schuyler, Banner, Birch, McKie & Beckett

ABSTRACT

SO_2 is absorbed from hot flue gas by spray drying a $Ca(OH)_2$-containing suspension in the flue gas. Fly ash is left in the flue gas which is to be treated in the spray absorption process, and the powder which is produced by the spray absorption process and which consequently contains the fly ash and partly reacted $Ca(OH)_2$ is partially recycled. Operation is controlled to obtain a temperature of the flue gas after the treatment which is 8°–20° C. above the saturation temperature of the flue gas at this stage. The process leads to optimum use of the $Ca(OH)_2$ used as absorbent and of the neutralization power inherent in the fly ash. Problems due to sedimentation of the absorbant before its atomization are avoided.

13 Claims, 4 Drawing Figures

Several of the patent front page fields require additional explanation and notes. First, the title of the patent is often not as clear an indicator of the nature of the invention as might be expected, due to the use of general terms and vague language (Clarke and Riba, 1998, p. 2). In some instances, this vagueness is a deliberate attempt by patent attorneys to “hide” their clients’ patents from competitors’ search engines. Second, the “assignee” field does not always appear on a granted patent. Inventors who work for private companies, the federal government, or universities often must assign ownership of their patents to their employers. Inventors who do not assign their patent rights to another organization are considered individual inventors, and assignee fields often do not appear on the front pages of their patent applications (National Science Board, 1999, p. 6-18).

Third, a number of classification systems exist that attempt to categorize patents by their technical content according to class and subclass. In many instances, an examiner will assign more than one classification to a patent, although the first is accepted as the "main" classification. Guides are issued to understand, through keywords, which classes consist of which types of technologies. Developed and managed by WIPO, the IPC is revised roughly every five years, and contains about 20,000 terms related to the form or construction of the invention. The USPC is administered by the USPTO and contains about 370 active classes and 128,000 subclasses related to the function or purpose of the invention (Clarke and Riba, 1998, p. 4; National Science Board, 1999, p. 6-21).

Fourth, the references of a patent to previous patents are not simply a matter of the judgment of the inventor as in the case of references in articles or books. Patent references point to the "prior art" of a patent, or earlier inventions whose claims are legally determined by the patent examiner to be closely related to the claims in the citing patent (Narin, 1994b, p. 152). Generally, patent applicants and their attorneys contribute some of a patent's references, and the patent examiner will modify these citations during the examination process, often adding or subtracting citations (Jaffe, Fogarty, and Banks, 1998, p. 199).

Finally, the abstract of a patent is meant to be a brief description of the technical nature of the invention. The abstract, like the patent claims, should demonstrate the usefulness of the invention and may do so by describing a problem the current technological state-of-the-art does not solve that the patented invention claims to solve (Clarke and Riba, 1998, p. 2-3). In practice, abstracts are not always brief and, like titles, may employ non-obvious keywords.

After a patent is granted, it is in force for a set period of time. For many years, U.S. patents were guaranteed for seventeen years after the grant date. Beginning with applications filed on and after December 12, 1980, however, these seventeen years were only guaranteed contingent on the payment of patent renewal fees due 3 ½, 7 ½, and 11 ½ years from the grant date (U.S. Patent and Trademark Office, 2000a). U.S. maintenance fees for the common "utility" type patent as of December 29, 1999, are shown in Table 3.1. The "small entities" described in this table are concerns with less than 500 employees (13 CFR 121.802). Surcharges on late maintenance fee payments range between $130 and $1,640 (U.S. Patent and Trademark Office, 2000b).

TABLE 3.1

Patent Maintenance Fees

	Most Assignees	Small Entities
Maintenance Fee at 3 ½ years	$830	$415
Maintenance Fee at 7 ½ years	$1,900	$950
Maintenance Fee at 11 ½ years	$2,910	$1,455

Source: U.S. Patent and Trademark Office (2000b)

Although patent renewal rates are of interest to researchers, the subset of patents for which maintenance fee data are available is relatively small compared to the total universe of U.S. patents. In his 1990 review of patent research, Griliches (1990, p. 1681) gives some basic information on the payment of maintenance fees for patents filed in 1981-4. Unpublished tabulations from the USPTO's Office of Documentation Information showed that, as of the end of 1988, 84% of these patents were renewed after the first 3 ½ year period (83% of U.S.-owned patents and 85% of foreign-owned patents were renewed). Griliches (1990) also cites an unpublished manuscript by Manchuso, Masuck, and Woodrow (1987) on a smaller sample of the same data in which 87% of U.S.-invented patents were renewed but only 61% of individually-owned patents were renewed. When this study separated patents by technology, "chemical" patents were maintained at the highest rates, and "mechanical" patents were maintained at the lowest rate.

In 1995, the patent term was changed to twenty years from the earliest effective *filing* date claimed by the applicant, contingent on the payment of the same renewal fees as in the earlier revision. As a result of this change, the incentive of patent applicants to prolong the application process and obtain a de facto extension of patent coverage was reduced, while pressure was increased on the patent office to expedite the examination process (U.S. Patent and Trademark Office, 1999, p. 7).

Research Use of Patents

Researchers have long used patents as a measure and descriptive indicator of inventive activity because they provide considerable research advantages (for published reviews of patent research, see Archibugi and Pianta, 1996; Basberg, 1987; Griliches, 1990; Pakes and Simpson, 1989; Pavitt, 1985; Schankerman, 1989). Some of the advantages of using patents as a measure and a descriptive indicator for inventive activity are clear from the discussion of the patenting process above. The nature of the "trade-off" involved in the granting of patents to inventors benefits researchers in two ways. First, the time-consuming and costly nature of the patenting process and the monopoly right to commercialize an invention that results from the granting of a patent are reasons why researchers can expect that the inventive activity measured in patent counts is, on the whole, non-trivial. Further evidence of the non-trivial nature of patents is empirically shown in surveys by Napolitano and Sirilli (1990), Scherer et. al. (1959), and Sirilli (1987), which demonstrate that the eventual use by firms of the inventions detailed in their patent applications ranges from 40% to 60% of total applications (Archibugi and Pianta, 1996, p. 454). Second, the societal benefit of publishing patent information is good not only for enhancing technical knowledge, but also for improving the understanding of the innovation process. The public accessibility of patent information is constantly increasing, as more information is made electronically available for a growing number of countries and application years. The detailed front page summary information about the invention, the inventor, the assignee, and the intellectual background of the patent is clearly of interest to researchers studying the nature, locus, and timing of inventive activity.

Analysis of the relationship between patent data and the inventive input of research and development ("R&D") expenditures has also strengthened patent analysis as a measure of inventive activity. As stated in Griliches (1990, p. 1674), "the evidence is quite strong that when a firm changes its R&D expenditures, parallel changes occur also in its patent numbers." Since patents are an intermediate output of R&D, they are typically used by researchers as a measure of inventive output; but this close relationship between levels of R&D expenditures and levels of patents tie patents strongly to inventive input as well. This is particularly important since R&D expenditure data are not typically available for all inventing entities, especially in a detailed manner [see Cohen and Levin (1989); Griliches (1990); Lanjouw, Pakes, and Putnam (1998); Schmoch and Schnoring (1994)].

Finally, another advantage of the use of patenting activity as an invention measure is that analysis has shown that patenting activity can be linked to events that occur outside the firm. In an analysis of the relationship between patents, R&D, and the stock market rate of return, Pakes (1985) showed that about 5 % of the variance in the stock market rate of return is caused by events that change both R&D expenditures and patent applications. The implication of this is that an observation of a dramatic increase or decrease in a firm's patent activity is an indication "that events have occurred to cause a large change in the market value of its R&D program

(Griliches, 1990, 1683-4)." The Jaffe and Palmer (1997) and Lanjouw and Mody (1996) papers discussed in Chapter One of this dissertation both take advantage of this finding by attempting to relate environmental patenting to pollution abatement expenditures as a measure of severity of regulation.

Problems Encountered with the Use of Patents in Research

However useful patents are as a measure and a descriptive tool for inventive activity, they also present the researcher with difficulties that can be categorized into three problem areas. First, technical difficulties arise in both locating patents of interest and allocating these patents to relevant industrial and product groups. Second, analysis difficulties arise from variations in the strategic decisions of entities to apply for patent protection. Both these problem areas were touched upon in the discussion of patents and the patenting process above. The third problem area involves difficulties with comparing patents against each other because of a number of "qualitative homogeneity" issues related to the question of whether all patents are of equal value simply because they have unique patent numbers.

Most patent research identifies patents of interest based on a classification system such as the IPC or the USPC and then allocates these patents to relevant industry or product groups; care must be taken with both of these research tasks. The subclasses often used by researchers to identify patents can be vague and can cause a researcher to miss relevant patents; at the same time, since a patent can be assigned to multiple subclasses, irrelevant patents can be netted in subclass-based searches. Additional identification problems arise from a researcher's choice of classification system, since the IPC, USPC, and other classification systems vary according to the level and nature of technical detail they use to categorize patents. Patent identification can also be problematic when subclasses are not used as the basis for identification. Non-obvious keywords in a patent's title or abstract can foil careless electronic searches based on these front page fields. Finally, identifying patents by assignee firms and then classifying these patents according to the firm's major business lines, as was first done by Scherer (1984), is an imprecise method because of the number of firms with diverse business and technical interests and/or multiple name changes over time.

Allocation of patents to relevant industrial groupings presents other difficulties. Most patent systems do not require patent examiners to link patents directly to the standard industrial classification (SIC) digit level that would correspond with the patented invention's potential use (the Canadian patent system is an exception). Instead, researchers have to develop their own methods of allocating patents to either the industry that made the patent, the industry likely to produce the patented invention, or the industry that will use the patented invention. In the mid-1970s the USPTO established the Office of Technology Assessment and Forecast (OTAF), which developed a concordance that attempted to link patent subclasses to the three and 2 ½ digit levels of the SIC based on the industry of production. Unfortunately, the vagueness of subclass descriptions resulted in assigning many subclasses to multiple SIC codes, a practice that has limited the concordance's usefulness to researchers (Griliches, 1990, p. 1667-8).

As was mentioned earlier, a number of strategic factors influence an entity's decision to patent (its "patent propensity"). Indeed, strategic concerns can cause inventing entities to engage in such contrary actions as choosing to patent when they do not expect to commercialize an invention or choosing not to patent when they do expect to commercialize an invention. Variations in the patent propensities of firms and individuals can be a particular problem in comparative research, because such variations can occur by nation, by industry, by firm, and even by invention. Innovation survey information has provided the greatest insight into the patent propensities of various industries and has demonstrated its usefulness as an interpretive tool for patent analyses.

Finally, the patent problem area most frequently discussed in the literature involves difficulties in comparing patents without regard to their varying degrees of usefulness either to their owners or to society at large. Not all inventions are economically or technically equal, yet patent counts can give this appearance. Even in the hypothetical situation in which two inventions would be economically and technically equivalent, the claims of the two inventions could be bundled into a different number of patents so that the two inventions appear unequal. The Japanese patent system, for example, is particularly famous for granting patent status to a smaller number of claims than other patent systems. In addition to these problems with the qualitative homogeneity of granted patents, another source of error in the measurement of inventive activity by patents is the number of useful inventions that are not patentable. A technical advance may not be patentable for a variety of reasons related to such things as the type of technology invented or the incremental nature of the advance (Cohen and Levin, 1989).

Archibugi and Pianta (1996) reviews four different methods to weight patent counts that have been developed by researchers to address problems related to the apparent qualitative homogeneity of patents. The first of these methods uses the period of time over which patent maintenance (or "renewal") fees are paid in order to assess the private economic value of a patent to its owner. Research using renewal fee information includes Lanjouw, Pakes, and Putnam (1998), Pakes and Schankerman (1984), Pakes and Simpson (1989). The second method involves counting the patents that cite a given patent in their prior art in order to indicate the social value, or technological importance, of that patent. Research using citation information includes (Albert et. al., 1991; Carpenter, Narin, and Woolf, 1981; Jaffe, Trajtenberg, and

Henderson, 1993; Narin, 1994a; Narin, 1994b; Narin and Olivastro, 1988; Trajtenberg, 1990). The third method involves the use of international patent families in order to make more accurate international comparisons and also assess the private value of patents. Research using patent families includes Grupp (1993), Lanjouw, Pakes, and Putnam (1998), Schmoch and Kirsch (1993). Finally, the fourth method, which is less frequently used than the other methods, uses counts of the number of claims made in each patent in order to provide an informed basis for patent comparison. Research using patent claims includes Tong and Frame (1994).

Use of Patents in this Dissertation

In summary, there are several advantages to the use of patents as a measure of inventive activity. Patents provide publicly accessible and detailed technical and organizational information for what can be assumed to be non-trivial inventions over a long period of time. This is a particular advantage in this dissertation, since patents can help link commercially-relevant technical information with adopted & diffused innovations and the knowledge gained from operating experience with these innovations. Close parallels between levels of R&D expenditures and patenting activity are another advantage of patents as a measure of inventive activity, especially in industries – such as the FGD equipment and services industry – in which detailed R&D information is very difficult to obtain. Finally, the linkages that have been shown in the literature to occur between events external to the firm and patenting activity suggest that patents can provide insights into connections between inventive activity and government actions pertinent to SO_2 R&D, such as new legislation.

The three main research disadvantages of patents, however, need to be considered in order to utilize patents optimally in research. In this dissertation, two approaches are taken to resolve the first research problem, the technical difficulties with patent identification and allocation. In the first approach, patents are identified through a search of patent subclasses and in the second, through an electronic search of patent abstracts and the manual assignation of captured patents into technological and organizational categories. Concerns about the second research problem – the various reasons for patenting in the SO_2 industrial-environmental innovation complex – are addressed in this dissertation through interviews with experts from a range of different organizations. Finally, the third research problem – the appearance of qualitative homogeneity among patents – is addressed in this dissertation through three methods to gauge the private and social value of patents. The private value of patents is gauged using patent renewal data and a direct validation of patents against "commercially important" patents obtained from firms with large market shares in the FGD equipment and services industry. The social value of patents is gauged using patent citation data.

Perception of Patents

This section discusses one of the three problems encountered in the use of patents in research, namely concerns about the various reasons for patenting in the SO_2 industrial-environmental innovation complex. It does so in the context of expert perceptions of patenting in SO_2 control technologies. The other two problem areas involved in the use of patents in research, the technical problems involved in patent identification and allocation as well as the misleading appearance of qualitative homogeneity among patents, will be addressed in the next two sections of this chapter.

As discussed in Chapter One, twelve experts were interviewed for this dissertation through a structured two-hour interview process designed to elicit opinions about innovative activity in the SO_2 industrial-environmental innovation complex.[49] These experts were asked questions dealing with the historical development of technologies and government actions, as well as with organizational issues related to innovative activity. In addition, each expert was asked questions pertinent to the methods used in this dissertation to quantify innovation. Five questions dealt specifically with patents in the SO_2 industrial-environmental innovation complex. Three of these five questions involved the experts' perceptions of the role of patents in the SO_2 industrial-environmental innovation complex, and will be discussed in this section. These three questions addressed: the importance of patents to various organizations; the approach of organizations to the patenting process; and significant technologies that are covered by patents. The other two (of five) questions involved direct interpretation of the results of patent analysis, and will be discussed in another section of this chapter.

Levels of Patenting Activity

All twelve experts made statements in the interviews that support both the existence of a role for patents in the SO_2 industrial-environmental innovation complex, as well as the perception that this role is not currently vital to innovative activity. There was some disagreement among the experts as to the frequency of patent applications in the SO_2 industrial-environmental innovation complex. Three experts, experts B, E, and L, supported the view that many patents are applied for in FGD technologies. Expert B stated that "a lot of the vendors patent everything they do," while expert E suggested that the role of patents in the FGD equipment and services industry is growing in importance, particularly as the globalization of the industry increases. Alternatively, four other experts supported the view that patent frequency is

[49] The characteristics of these experts appear in Table 1.1, where they are listed in conjunction with their identification labels in the dissertation.

low in FGD technologies. Expert K stated that “surprisingly few patents are really out there.” Expert I stated that patents do not cover most of the technology in use today, while experts A and B explained that very few people in their organizations apply for patents. Expert K, however, agreed with the statement that the role of patents is increasingly important, as there has been a “history of patent infringement” and legal “aggravation” that has prompted SO_2 control technology innovators to be much more careful about patent protection in recent years.

The frequency of patenting activity is, of course, related to the perceived advantages of patents. Expert G stated that the advantage of some of the early patents was to allow certain organizations to attract business and then maintain market position. Experts C and D mentioned enhanced customer perceptions of patent-holding entities as an advantage of patent ownership. In support of this, expert D stated that “customers do ask what’s patented in an offering” and expert C mentioned that suppliers with strong patent portfolios achieve a temporary advantage because of enhanced customer perceptions of the supplier. Experts A and D, however, also stressed the commercial advantage of organizational “know-how.” As was mentioned earlier in the discussion of the patenting process, previous research has shown that firms with perceptions that their know-how is particularly strong often find secrecy to be an attractive approach to managing intellectual property. No expert, however, mentioned secrecy as an alternative to patent protection in SO_2 control technologies. It is an interesting feature of the FGD equipment and services industry, however, that product differentiation associated with specific scrubber vendors was considered by experts D and H to be more important to the commercial technological strategy of companies than patents. According to these two experts, this differentiation is generally respected by the other organizations in the SO_2 industrial-environmental innovation complex.

Besides product differentiation, the composition of the SO_2 industrial-environmental innovation complex and the volatility and profitability of the FGD equipment and services industry were also specifically linked by experts to relatively low levels of patenting activity in SO_2 control technologies. Regarding composition, four experts (D, G, H, K) explained that the public nature of some of the most prominent innovating organizations in the SO_2 industrial-environmental innovation complex – specifically EPA, DOE, and EPRI – reduced the importance of patents in SO_2 control technologies.[50] This was because a considerable amount of information pertinent to SO_2 control innovation was shared freely among innovators and the public. Thus, the opportunity for private intellectual property protection did not arise as much as it might have in an area dominated more by private firms. This was particularly true before the Federal Technology Transfer Act of 1986 and Executive Order 12591 of April 1987; until the enactment of these government actions, agencies like EPA and DOE were not subject to considerable pressure to obtain patents. For EPRI, also, the importance of patents has grown over time, as utility deregulation has pressured EPRI to find new ways to demonstrate its importance as a technological innovator in order to sustain EPRI membership levels. In addition to the dampening effect of considerable public sector involvement in SO_2 innovation on patenting activity, one expert (D) explained that the volatility of the FGD equipment and services industry and the length of the patent application process discouraged patent filing. Finally, one expert (E) explained that the low profitability of the industry has helped to keep R&D levels, and subsequent patents, relatively low.

[50] While not technically public, EPRI represents the shared research investments of the public monopolies of utilities (before deregulation).

Reasons for Patenting, Enforcement, and Patentability

Those entities that do patent in SO_2 control technologies do so, according to nine of the experts, for at least one of three main reasons. Six – B, C, F, G, H, L – mentioned the standard incentive of protecting important innovations of technical merit in a way that will give an advantage over competitors in the FGD equipment and services industry. Five experts – D, F, G, I, K – identified prestige as important to a variety of actors in the SO_2 industrial-environmental innovation complex, including individual researchers, sections of government agencies, and entire organizations such as EPRI.[51] Careers, funding levels, public-private partnerships, and membership levels could all be enhanced by the tangible rewards of the prestige accompanying successful patents. Finally, three experts – C, D, H – who suggested either technological importance or prestige as incentives for patenting, also mentioned blocking other innovators as an incentive for filing patent applications in the FGD equipment and services industry.

The incentives for patenting of protecting innovations from competitors and blocking competitors from innovating both depend on the level of patent enforcement in the SO_2 industrial-environmental innovation complex. Eleven of the twelve experts touched on the enforcement of patents. Nine of these experts – B, C, D, E, F, G, H, I, L – generally agreed that patent enforcement has not been extremely effective, as a number of patents have been relatively easily invented around or gotten around in other ways. Experts B and C even recalled customers retrofitting a supplier's patented invention knowing that the vendor was unlikely to enforce the patent. Experts A, B, H, I, and K, however, were able to mention specific court actions that enforced patent rights. One additional expert, expert F, who also agreed that patents could be gotten around relatively easily, explained that for some less powerful innovators in the FGD

[51] Two of these experts also mentioned the standard incentive for patenting.

equipment and services industry, the threat of patent enforcement hassles, even without the expectation of actual enforcement actions, is enough to protect their rights from more powerful innovators.

Of course, in order to enforce a patent, patent protection must be applied for, and there was a certain amount of disagreement among the experts about what inventions are patentable. For example, expert D considered some of the chemical advances in SO_2 control unpatentable; another expert, expert K, considered these same types of advances "fundamental work" and stated that this type of work is likely to result in patents. Four experts in total – A, D, J, K – addressed the issue of patentability in the SO_2 industrial-environmental innovation complex. Experts A, D, and J saw an important dichotomy between know-how and patentability (two of these three had previously touted the importance of know-how in improving SO_2 control technologies). Expert J explained that patents did not cover the way an FGD system is put together.

Patent Coverage of Specific Technologies

Nine of the experts (A, B, C, D, F, H, I, K, L) were able to mention specific SO_2 control technologies that have been patented. Four of these experts (A, B, H, K) mentioned the Niro Atomizer recycle patent on spray dryers, which was the subject of a particularly notorious court case. Other patents well-known to experts included the Babcock & Wilcox tray patent (experts B, C, D, F, H, K, L mentioned this patent), the Dravo patents on thiosorbic technology for magnesium enhanced lime scrubbing (experts A, D, F, H, L mentioned these patents), and the ABB nozzle arrangement patent (experts A, B, C mentioned this patent). Other patents mentioned included: a number of nozzle patents, a patent on reducing scaling in a two-loop scrubber using forced oxidation, a horizontal spray scrubber, patents on hydroclones, a patent on a lance-type of oxidation and air introduction system, a patent on sludge stabilization, a patent on placing a baghouse downstream from a spray dryer, a patent on buffering with formic acid, a patent on nahcolite injection used in magnesium lime injection, and a patent on a combined SO_2-NOx removal process using zinc-oxide.

Several of the experts were also able to mention a number of important SO_2 control technologies for which they believe no patent coverage exists. Experts C and D selected dibasic acid as such a technology while one of these experts also mentioned inorganic acid. Experts C, D, H, and I believe that there are no patents on forced oxidation, which has been arguably the most important advance in SO_2 control technology overall, although expert G believes that the broad coverage of earlier patents implies coverage for forced oxidation. Expert H was unaware of any patents in the area of high velocity scrubbing, an area that has been a particularly important technological focus in the last few years. Finally, expert I believed that there is no patent on how to effectively wash a mist eliminator.

Although three questions were asked of the experts regarding their perception of the role of patents in the SO_2 industrial-environmental innovation complex, not all three were equally relevant for understanding the context in which variations could occur in the patent propensities of organizations in the SO_2 industrial-environmental innovation complex. For example, that most experts could name specific patented technologies was less relevant to this overall research issue than that experts believe some important technologies have no patent coverage. According to the trend of other expert statements, this is likely to be a result of patentability issues that affect these technologies consistently, rather than a result of variations among innovating entities in SO_2 control. This consistency is important in order to have confidence in patent analysis. It is contributed to by the general agreement of experts that there is an increasingly important role, albeit not necessarily a vital one, for patents in SO_2 control technologies, and that patent ownership bestows financial advantages on both private and public innovators (despite somewhat weak enforcement).

Subclass-Based Dataset

Linkages have been shown in the literature to occur between events external to the firm and patent activity. This suggests that patents, which provide public, detailed, and consistent technical and organizational information for inventions over a long period of time, can be used to develop insights into connections between inventive activity and government actions pertinent to SO_2 R&D, such as new legislation. In order to investigate whether patent activity levels change in a corresponding manner with such government actions, it is necessary to generate a dataset that correctly identifies patents relevant to SO_2-control technologies. This dataset should be crafted with due consideration to the remaining problem areas notable in the use of patents in research, namely the technical difficulties in patent identification and allocation and the appearance of qualitative homogeneity among patents.[52] In light of the patent identification and allocation difficulties, two methods are used in this dissertation to develop such a dataset. In this section, a patent dataset is created based on USPC subclasses that are valid for over one hundred years. In the next section, a patent dataset is created based on an electronic search of patent abstracts (relevant for patents granted in the 1970s through 1990s) that is easier to refine and analyze according to technological and organizational categories. In both sections, some consideration is made for the qualitative homogeneity of patents based on either their private or social value.

[52] The second research problem area – the variety of reasons for patenting in the SO_2 industrial-environmental innovation complex – was considered in the previous section.

As discussed in the "Patents and the Patenting Process" section above, the majority of patent studies identify relevant patents through the use of a patent classification system's subclasses. This holds true in research into environmentally responsive innovation, although environmental control technology poses additional challenges in patent identification beyond those faced in most patent research.

The two most prominent (and contradictory) previous studies to use patent data to understand the relationship between environmental regulation and innovation employ class-based patent location techniques. In the first of these studies, Lanjouw and Mody (1996), the authors develop a patent dataset using IPC classes. These IPC classes are determined by first, searching IPC class descriptions, and second, using a USPC keyword index in order to determine relevant patents and backtrack these patents to their IPC classes. Lanjouw and Mody note that if too few IPC classes are used to create the inventive activity dataset, relevant patents will be left out. Yet they assume that this will not diminish the relative validity of the dataset as long as all "environmentally responsive innovation in a field responds to events in a broadly similar fashion." An obvious counterexample to this assumption is the 1979 New Source Performance Standards (NSPS) accompanying the 1977 Clean Air Act (CAA), in which the new percentage reduction requirements favored technologies with greater removal efficiencies over other technologies and approaches.

In the second of these studies, Jaffe and Palmer (1997), the authors identify patents through the use of industry patent totals based on the USPTO's OTAF concordance of USPC subclasses to 2 ½ digit levels of the SIC (based on the industry of production). As mentioned in the "Patents and the Patenting Process" section above, this concordance has had limited usefulness in patent identification because the vagueness of subclass descriptions has resulted in the inaccurate assignment of many subclasses to multiple SIC codes. Jaffe and Palmer (1997, p. 614) note that these problems are likely to be particularly harmful in developing datasets indicative of inventive activity in industries that rely heavily on equipment suppliers for research. As mentioned in Chapter One, industrial-environmental innovation complexes rely heavily on environmental equipment suppliers for research since polluting organizations often purchase control technology (such as FGD) from environmental equipment and service organizations (see Kemp 1997, p. 40).

Examiner Interview

Given the shortcomings of the patent identification methods used by these prominent previous studies of environmentally responsive innovation (particularly in the case of the SO_2 industrial-environmental innovation complex), patent identification expertise was sought from the main patent examiner in FGD control, Gary P. Straub (Straub, 1999). Mr. Straub has been either the primary or assistant examiner for at least 1,734 granted patents dating back at least to 1976, which is the earliest grant year for which USPTO electronic information is completely available. Mr. Straub recommended identifying relevant patents by searching the subclasses he regularly checks in order to determine the legal prior art of the patents he examines. Table 3.2 indicates these subclasses as well as a supplemental set of fuel treatment subclasses relevant to pre-combustion removal technologies (identified with an asterisk). For this research, a search was conducted of all USPTO patents based on the USPC subclasses contained in this table.

TABLE 3.2

U.S. Classes and Subclasses that Compose the Class-Based Dataset

USPC Class/ Subclasses	Definition of USPC Class/Subclasses
423/242.1-244.11	Class 423, the "chemistry of inorganic compounds," includes these subclasses representing the modification or removal of sulfur or sulfur-containing components of a normally gaseous mixture.
095/137	Class 095, "gas separation processes," includes this subclass representing the solid sorption of sulfur dioxide or sulfur trioxide.
110/345	Class 110, "furnaces," includes this subclass representing processes to treat fuel combustion exhaust gases, for example, in order to control pollution.
44/622-5*	Class 044, "fuel and related compositions," includes these subclasses to treat coal or a product thereof in order to remove "undesirable" sulfur.

Source: U.S. Patent and Trademark Office (2000c)

Method and Time Series Results

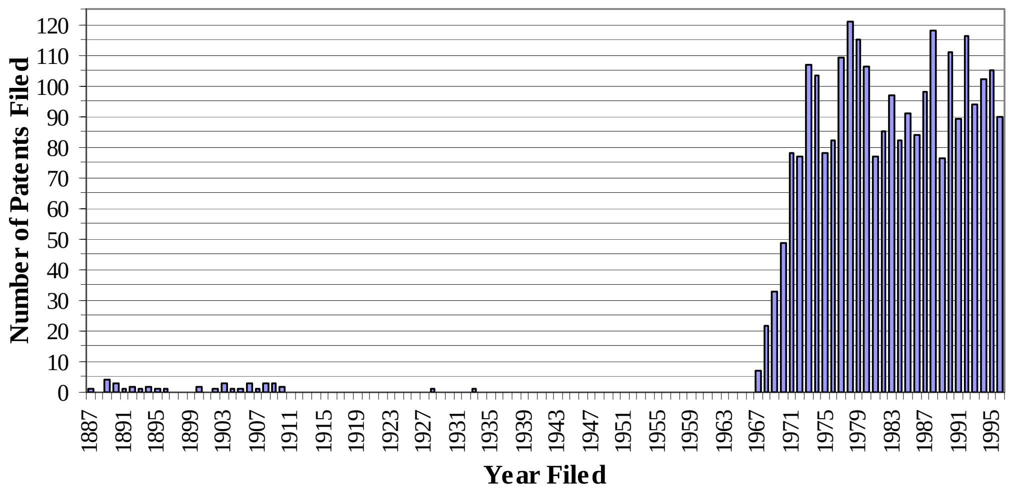
The result of this search of USPC subclasses was the capture of 2,681 patents dating back to the nineteenth century, which will be called the "subclass-based dataset." USPTO patent information for patents granted before 1976 is available through two sources: incomplete electronic information for patents beginning with patent 3,552,244, which was granted on January 5, 1971, and manual information for all patents, based on a file system organized by subclass. This subclass-based file system allows the creation of a consistent patent dataset for over one hundred years. Unfortunately, the various data formats of different segments of this dataset make detailed technological and organizational analysis a labor-intensive proposition. Without a detailed technological analysis, an overall patent activity analysis can be conducted with the accepted disadvantage of including some irrelevant patents while excluding some relevant patents filed in subclasses other than those included in the creation of the dataset. According to Mr. Straub, however, inaccuracies in patent examiner allocations to subclasses are less likely for patents filed before the advent of electronic searching because examiners had to be more careful in searching and cross-referencing patents.

Figure 3.3 displays the number of patents filed over time in SO_2 control technologies as defined by the subclasses listed in Table 3.2.[53] Note that prior to 1967, there were never more than four patents filed in a given year. This supports the idea that inventive activity in SO_2 control can be portrayed as a step-function divided into two main periods. In the first period, which includes the years before 1971, patenting activity was low despite government legislation dating back to 1955 that authorized research into air pollution abatement methods. In the second period, which includes 1971 and all the years succeeding it (here, 1971 to 1996), patenting activity never falls below the minimum activity threshold of seventy-six patents per year. The pivotal patent filing year that marks the difference between the two periods, 1971, coincides with the passage of the 1970 CAA and associated 1971 NSPS for power plant emissions. Precise correlation of patent filing activity with legislative dates is difficult as well as potentially misleading because of timing issues related both to the inventive and strategic process underlying a patent filing decision and to the various twists and turns in the legislative and regulatory process. The more than ten-fold increase in patenting activity between 1967 and 1971, however, is the type of sudden large burst in patenting activity that Griliches (1990) suggests is certain to indicate a change in external events relevant to the patented technology.

[53] File dates are used for display purposes since these dates are the earliest possible dates linked consistently to a patent application and, therefore, to the underlying invention.

FIGURE 3.3

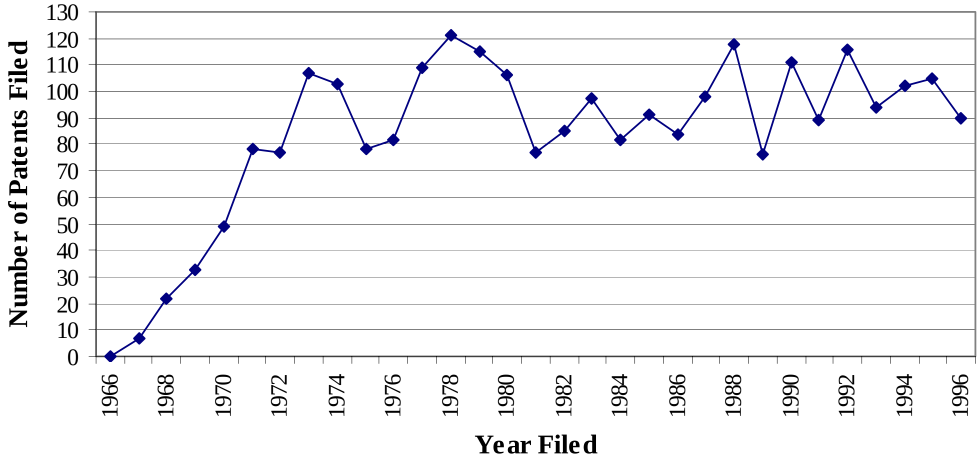
U.S. Patents Relevant to SO_2 Control Technology as Identified with the Patent Subclass Method



Unfortunately, the pattern of alternating peaks in patenting activity in the second period, 1971 to 1996 (which is revealed in greater detail in Figure 3.4), does not allow a simple identification of other obvious bursts in patenting activity. The average number of patents filed in a given year from 1971 to 1996 is ninety-six, with a standard deviation of fourteen. Of the twenty-six years represented in the 1971 to 1996 period, ten years show patenting levels that exceed the average by greater than one standard deviation, for a total of 40% of all the years represented. Attempting to associate with external events the four years with the highest patent activity levels in this period – 1978, 1979, 1988, and 1992 – is ill-advised because of this variation.

FIGURE 3.4

Second Period of U.S. Patents Relevant to SO_2 Control Technology as Identified with the Patent Subclass Method



Link to Commercial Technology

In order to gain a rough understanding of the private value of patents in the subclass-based dataset, the patents in this dataset were compared against the patents embodied in the commercial technologies of three prominent organizations in the FGD equipment and services industry. The commercially embodied patents were obtained by querying a number of FGD industry actors about the patents in their portfolios that covered their commercially successful technologies. The three companies that responded together held almost 40% of the U.S. FGD market between 1973-93, based on an analysis of Soud (1994).[54] Table 3.3 shows the moderate percentages of commercially important patents from these companies that were identified through the subclass-based search.

[54] These companies are not identified here for confidentiality reasons.

TABLE 3.3

Percent of Patents Covering "Commercially Successful" Technologies found in Subclass-Based Dataset

	Company A Commercially Successful Patents (16)	Company B Commercially Successful Patents (69)	Company C Commercially Successful Patents (15)	Total Patents From the 3 Portfolios
Subclass-Based Dataset (2,681 Patents Total) Finds:	56%	46%	87%	54%

Although the subclass-based dataset provided a very important insight into the two-period step-function of patent activity in SO_2 control (divided by the 1970 CAA and its associated 1971 NSPS), its high level of variance and only moderate success in identifying patents of private value limits its usefulness in this research. In future work, more effort may be expended to refine this dataset further. In this research, however, more detailed technological and organizational consideration is given to a dataset that does not exclude as many patents of private value in order to obtain subtler insights into the relationship between environmentally responsive invention and government actions.

Abstract-Based Dataset

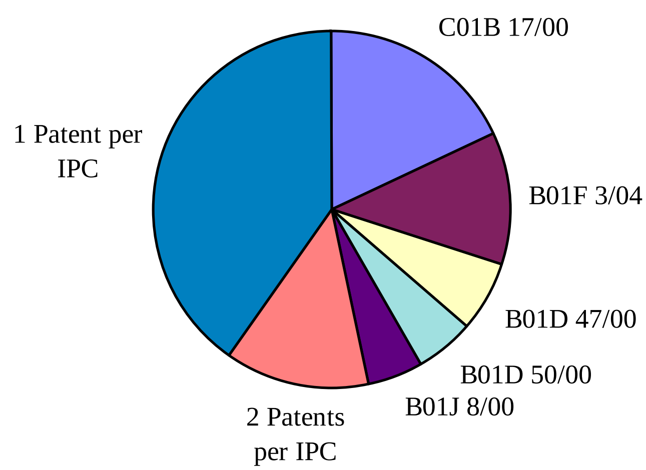
This section focuses on crafting and analyzing such a patent dataset. As mentioned previously, the dataset discussed here is created based on an electronic search of patent abstracts that is relevant for U.S. patents granted in the 1970s through 1990s. The analysis in this section spotlights correlations between patent activity and government actions as well as technological and organizational details of inventive activity that are relevant to consideration of the effects of a variety of government actions on innovation in SO_2 control.

Method and Link to Commercial Technology

The breadth of mechanical and chemical technologies embodied in FGD systems is an important foil to developing a patent dataset of SO_2 control technologies that includes a high percentage of commercially valuable patents. This breadth is illustrated in Figure 3.5, which depicts the wide range of IPC subclasses assigned to the commercially important patent portfolio of just one of the three companies that responded to queries. Over 40% of this company's seventy-seven patents are assigned to completely separate and unique IPC subclasses, while an additional 13% of its patents only share an IPC subclass with one other company-owned patent. In comparison to the thirty-six USPC subclasses used to generate the dataset graphed in Figure 3.3, this company's commercially relevant patents are filed in forty-one IPC categories (recall that IPC subclasses are more general than USPC subclasses). This indicates that a dataset based solely on subclasses, regardless of the classification system, is highly unlikely to generate a commercially validated patent dataset.

FIGURE 3.5

Distribution of One Company's Patents by IPC Subclass



Note: Total number of patents is seventy-seven.

Therefore, a different patent identification strategy was developed based on the abstracts of granted patents. With the assistance of CHI Research, a firm that specializes in using patent bibliometrics to help corporate and government clients, an electronic search was developed and conducted to filter out SO_2-relevant patents from the full set of U.S. patents granted between January 1, 1975 and December 1, 1996 (Albert, 1996; Narin, 1996).[55] After deriving likely keywords for electronic searching from a consultation of relevant chemical engineering texts on FGD process chemistry and design, the search filter algorithm was constructed in two parts. First, the search filter eliminated patents with USPC and IPC categories deemed likely to come up erroneously in searches based on these keywords. Second, the search filter identified and captured patents with abstracts in which these keywords were present in a grouping specified by advanced Boolean logic. The result was the creation of an "abstract-based" dataset of 1,593 patents, which CHI research supplemented with a secondary dataset that was accurately predicted to yield a small number of relevant patents (this dataset was based on a keyword search of subclass descriptions). Table 3.4 shows the comparative percentages of commercially validated patents that were identified in the abstract-based and supplemental datasets, in contrast with the subclass-based dataset. The abstract-based and supplemental datasets proved to be more effective in identifying relevant patents, although some patents of private value were not identified in either dataset.

[55] Complete electronic information for USPTO patents is available only for patents granted after January 1, 1975.

TABLE 3.4

Percent of Patents Covering "Commercially Successful" Technologies found in Abstract-Based and Supplemental Datasets, versus Subclass-Based Dataset

	Company A Commercially Successful Patents (16)	Company B Commercially Successful Patents (69)	Company C Commercially Successful Patents (15)	Total Patents From the 3 Portfolios
Abstract-Based Dataset (1,593 Patents Total) + Secondary Subclass Dataset (1,240 Patents Total) Finds:	64%	71%	100%	75%
Subclass-Based Dataset (2,681 Patents Total) Finds:	56%	46%	87%	54%

For each dataset, CHI Research provided summary front page patent and citation information generated by three programs run on official weekly USPTO data tapes. The citation information went beyond USPTO generated data fields, and included the number of other patents in the U.S. patent system which cite the patent in question ("successor" patents) and the number of patent and non-patent references of the patent in question ("precursor" patents). These data were obtained in a database-ready format.

Once the abstract-based patent dataset was imported into a relational database, these patents were analyzed for their relevance to SO_2 control technology. Irrelevant patents, as judged by a lengthy and labor-intensive reading of the patent abstracts on the basis of their intention (to remove SO_2 emissions from stationary sources) and their technical content, were discarded.[56, 57] This was an important process since it ensured the most accurate abstract-based dataset possible for purposes of association with external events and detailed technological and

[56] Focusing on the patent abstract as the gauge of relevance was effective since, as mentioned previously, the abstract summarizes the usefulness of the invention.
[57] In order to avoid interrater reliability problems and simplify the logistics of this process, the patent coder used for this research was the author.

organizational analysis. The total number of relevant patents in the final abstract-based dataset was 1,237. Each of these patents was coded with a general "technology type" and an "assignee type," as listed in Table 3.5. These categories were used to generate time series and histograms.

TABLE 3.5

Categories Used to Distinguish Relevant Patents

Technology Categories & Abbreviations		**Assignee Categories & Abbreviations**	
Post-combustion desulfurization	Post	Firms	Firms
Pre-combustion desulfurization	Pre	Individual	Indiv
During combustion desulfurization	During	Government agencies	Gov
Desulfurized coal gas and synthetic fuels	Gas	Universities	Univ
Fluidized-bed combustion	FBC	Contract research organizations	Joint
Desulfurizing agent modification	Sorb		
Desulfurization byproduct modification	By		
Measurement technologies	Measure		

Link between Private and Social Returns to R&D

In addition to the commercial validation of the patents in the abstract-based dataset, the qualitative homogeneity problem concerning the use of patents in research was addressed through two further approaches. In the first approach, the private value of patents in the abstract-based dataset was considered through the use of patent renewal data, in the tradition of Lanjouw, Pakes, and Putnam (1998), Pakes and Schankerman (1984), Pakes and Simpson (1989). In the second approach, the social value, or technological importance, of these patents was considered through their citation rates in other U.S. patents. This follows the tradition of Albert et. al. (1991); Carpenter, Narin, and Woolf (1981); Jaffe, Trajtenberg, and Henderson (1993); Narin (1994a); Narin (1994b); Narin and Olivastro (1988); and Trajtenberg (1990).

a) Private Returns – Patent Renewal Data

As mentioned in the "Patents and the Patenting Process" section above, patent renewal fees were first introduced for U.S. patents filed on and after December 12, 1980. A number of previous researchers have used the payment of patent renewal fees due 3 ½, 7 ½, and 11 ½ years from the patent grant date as an indicator of the private value of patenting. The payment of the renewal fee after the first 3 ½ year period was the test of private value used in this dissertation (in order to keep the sample of patents eligible for renewal fee testing large enough for a useful comparison). This limited the number of SO_2-relevant patents for which renewal data would be useful to those filed after December 12, 1980 and before April 2, 1994, for a total of 608 patents.

Table 3.6 displays the percentages of relevant patents that were renewed after the first 3 ½ year maintenance fee period, as broken down by technology type, assignee type, and inventor nation of origin. The overall percentage of patents that were renewed after the first 3 ½ year period was 84%, which is in line with the finding in Griliches (1990, p. 1681) that 84% of all USPTO patents filed between 1981 and 1984 were renewed after the same first maintenance period. A continued comparison to the Griliches (1990) data shows that a slightly higher percentage of U.S.-owned SO_2-control relevant patents were renewed compared to the USPTO average (86% versus 83%), while a lower percentage of foreign-owned SO_2-relevant patents were renewed compared to the USPTO average (80% versus 85%). Griliches (1990) also cites an unpublished manuscript by Manchuso, Masuck, and Woodrow (1987) that analyzed a smaller sample of USPTO data. A comparison to this Manchuso, Masuck, and Woodrow (1987) study shows a smaller gap between the percentage of U.S.-owned patents renewed in the SO_2-relevant and overall USPTO datasets (86% versus 87%). A wide disparity is seen, however, between the Manchuso, Masuck, and Woodrow (1987) data on the renewal of individually owned patents. In the SO_2-relevant dataset, 100% were renewed after the first 3 ½ year period while in the overall USPTO dataset, only 61% were renewed. The high percentages of SO_2-relevant patents renewed may, however, be consistent with the finding in Manchuso, Masuck, and Woodrow (1987) that “chemical” patents are maintained at the highest rates in the USPTO dataset, since SO_2-control processes are large chemical engineering systems.

TABLE 3.6

Relevant Abstract-Based Patent Renewal Percentages by Category after First 3 ½ Year Period

Percent of Patents Renewed by Technology Category		**Percent of Patents Renewed by Assignee Category**		**Percent of Patents Renewed by Inventor Nation**	
Post	85.3	Firms	83.3	U.S.	86.1
Pre	82.1	Indiv	100.0	Germany	71.9
During	86.8	Gov	78.9	Japan	97.6
Gas	82.6	Univ	95.0	Canada	90.0
FBC	78.6	Joint	84.4	Other Nations	77.1
Sorb	85.2				
By	81.0				
Measure	100.0				

b) Social Returns – Citation Data

A number of previous studies have used counts of the patents that cite a given patent in their prior art in order to indicate the social value, or importance to technological knowledge, of that patent. Those patents with higher citation rates in later patents are considered more important to the overall technical community. In this analysis, highly cited patents were used to refine the understanding of the technical focus of inventive activity as well as the locus of that activity in SO_2 control technology.

Table 3.7 indicates the range of citations the SO_2-relevant dataset received from other patents in the USPTO database at the time of this analysis. The average number of cites received by these patents was five.

TABLE 3.7

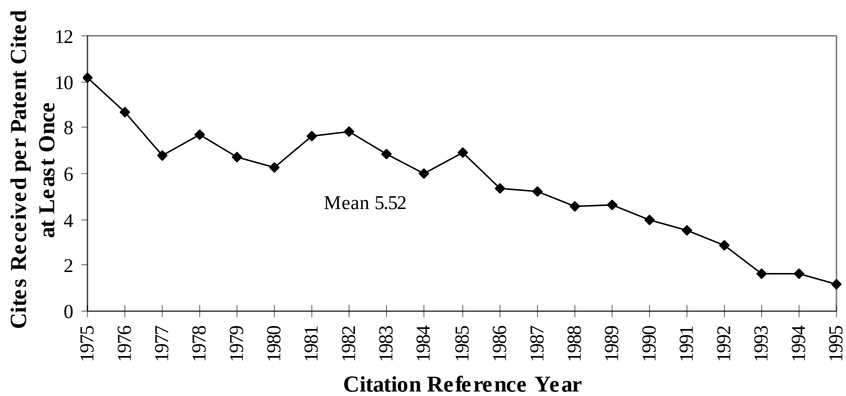
Distribution of Cites Received for SO_2-Relevant Patents

Cites Received	Number of Patents	Cites Received	Number of Patents	Cites Received	Number of Patents	Cites Received	Number of Patents
0	240	5	53	10-14	117	50-59	0
1	157	6	69	15-19	54	60-69	1
2	153	7	46	20-29	27		
3	123	8	61	30-39	3		
4	98	9	33	40-49	2		

Since patents with older grant dates have a longer period of time in the public domain than patents with newer grant dates, and thus have a greater opportunity for being cited by later patents, these citation numbers could not be used as a direct measure of the social value of patents. Scaling each SO_2-relevant patent's citation number by a "grant year specific adjuster" made it possible to create a "highly cited" patent dataset of 110 patents that could be used for comparative purposes against the technology, assignee, and geographic statistics of the overall abstract-based dataset. Two steps underlay the construction of the grant-year specific adjusters. First, for each grant year in the abstract-based dataset, the total number of references (in patents from 1975-1995) to patents granted in that year was divided by the total number of patents granted in that year that were cited at least once. The results of this stage in the adjuster creation process are displayed in Figure 3.6. Second, the mean value of the time series displayed in Figure 3.6 (5.52) was then divided by each year's Figure 3.6 y-value to derive the grant year specific adjuster.

FIGURE 3.6

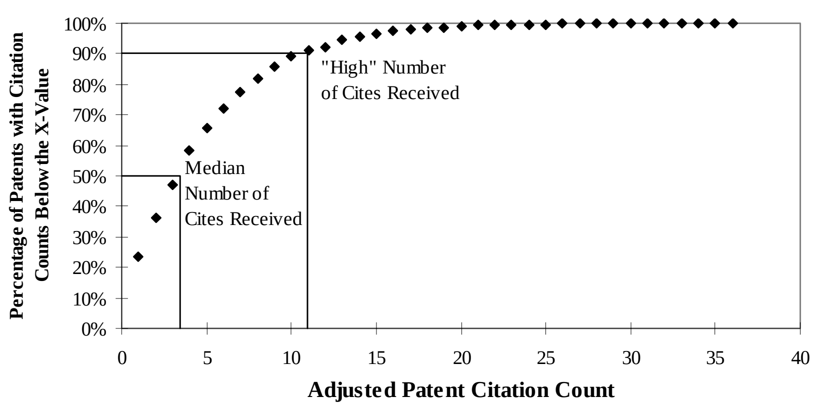
Cites Received per Patent based on Patent Grant Year



Each patent's number of cites received was then multiplied by its grant year-specific adjuster to arrive at a scaled number of cites received. The patents were then sorted by their scaled number of cites received, in ascending order, and a cumulative distribution function was created (as shown in Figure 3.7). The patents with adjusted citation numbers greater than 90% of all other patents (at an adjusted citation rate of 11 or more cites received) were chosen for the highly cited data set.

FIGURE 3.7

Cumulative Distribution Function of SO_2-Relevant Patents by Adjusted Citation Numbers



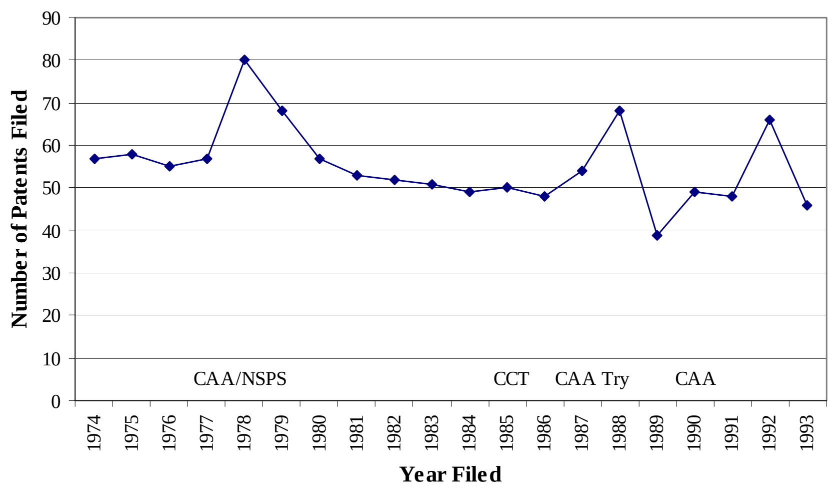
Results

a) Overall Inventive Activity

Figure 3.8 displays the time series, by file date, of overall patenting activity in SO_2-relevant technologies as identified through the manual examination of the patents in the abstract-based dataset. Although the patents in the abstract-based dataset were granted between January 1, 1975 and December 1, 1996, these patents were *filed* between 1969 and 1995. Figure 3.8 only captures those granted patents that were filed between 1974 and 1993, however, in order to avoid "lag effects" at either end of this trend line.

FIGURE 3.8

Trend in U.S. Patents relevant to SO_2 Control Technology as Identified in the Abstract-Based Dataset



These lag effects exist because of the varying length of time it takes to grant a patent after its application is first filed. Table 3.8 demonstrates the variation in the time lag between the filing and granting of patents in the SO_2-relevant abstract-based dataset. The average percent of patents granted in a given year that were filed within the previous three years is 91.2%, while the average lag for all patents in the dataset was almost two-and-a-half years. In order to avoid lag effects at either end of the trend line in Figure 3.8, patents granted in 1976 and 1977 are included only if they have a file year of 1974 or later, while patents granted in 1995 and 1996 are included only if they have a file year of 1993 or earlier.

TABLE 3.8

Lags Between File Dates and Grant Dates for SO_2-Relevant Patents Over Time

Patents Granted / Lag Between File Date and Grant Date	Over Entire Time Period	1975-80	1981-85	1986-90	1991-96
0-1 Years	88	16	13	29	30
1-2 Years	740	214	177	155	194
2-3 Years	299	103	77	60	59
3-4 Years	76	34	17	14	11
4-5 Years	21	11	2	3	5
5-6 Years	5	1	3	1	0
6-7 Years	5	1	0	4	0
7-8 Years	3	0	0	3	0
Total Patents	1,237	380	289	269	299
Average Patent Lag in Years	**2.4**	**2.5**	**2.4**	**2.4**	**2.2**

The abstract-based patent dataset depicted in Figure 3.8 for 1974 to 1993 displays considerably less variation than the second patent activity period (1971 to 1996) of the dataset of SO_2-relevant USPC subclasses depicted in Figure 3.4.[58] Of the 1,105 patents displayed in Figure 3.8, the average number of patents filed in a given year is fifty-five patents, with a standard deviation of nine. Only five of the twenty years represented in Figure 3.8 show patenting levels that exceed the average by greater than one standard deviation. This is a lower proportion (25%) than was exhibited in Figure 3.4, where 40% of the years showed fluctuations exceeding one standard deviation (fourteen) over the average number of patents (ninety-six). A further indication of the comparative lack of variation of Figure 3.8 is the fact that the highest yearly percentage increases in patent filing activity occur in 1978 (40.4%), 1988 (25.9%), and 1992 (37.5%), which coincide with the highest absolute levels of patenting activity in Figure 3.8. This

[58] This patent activity period is more useful for comparison with the abstract-based dataset than the entire subclass-based dataset because it addresses a similar time frame.

behavior was not seen in 1971 to 1996 in the subclass-based dataset, where the highest yearly percentage increases in patent filing activity occur in 1971 (59.2%), 1973 (39.0%), 1977 (32.9%), and 1990 (46.1%) while the peak patenting years occur in 1978, 1979, 1988, and 1992.

It is interesting to note a further difference between the abstract-based and subclass-based datasets. When computing an average trend line for both datasets based on the same time period (1974 to 1993), the abstract-based dataset exhibits a slightly negative slope (-0.59) while the subclass-based dataset shows a roughly flat, although positive slope (0.09).

b) Regression Analysis of the Abstract-Based Dataset

The two datasets share a very interesting similarity: both exhibit peak patent filing activity in the same four years (1978, 1979, 1988, and 1992). This lends credence to the existence of these peaks and the likelihood that they represent true "bursts" in patenting activity that Griliches (1990) suggests is indicative of a change in external events relevant to the patented technology. In this research, however, only limited attempts have been made to model patent filing activity as a result of inventor awareness of specific government actions (the change in external events predicted to be most relevant to patents in SO_2 control technology). This is because the number of valid years for the dependent variable of patent filing activity in the more refined, abstract-based dataset is only twenty. As befits the limited statistical power of a model of this dataset, a simple least-squares regression approach was used in which a dummy variable is "turned on" when the inventor is likely to be showing strong responses to a government action and then "turned off" when the situation returns to the status quo. The potential national government actions that an inventor may respond to are listed in Table 3.9, with summary information encapsulated from Chapter Two. They are also indicated on the X-axis of Figure 3.8. For the purpose of associating these government actions with the patent file years in Figure

3.8, the enactment date of each action is rounded to the nearest January, and the enactment year is defined as the year in which that January occurs.

TABLE 3.9

Government Actions with Potential for Modeling against Patent Filing Activity

Government Action Title and Abbreviation	Enactment Date and Year for Analysis	Summary and Implications
1971 New Source Performance Standard (1971 NSPS)	December 1971 (1972)	Maximum allowable emission rate for new and modified sources was 1.2 lbs of SO_2 /MBTU heat input. This effectively required a 0-85% SO_2 removal, depending on coal properties.
1977 Clean Air Act Amendments (1977 CAA)	August 1977 (1978)	Directed EPA to implement new source performance standard for SO_2 based on a percentage reduction from uncontrolled levels. This was intended to promote universal scrubbing at new plants.
1979 New Source Performance Standard (1979 NSPS)	June 1979 (1979)	SO_2 limit of 1.2 lb/MBTU and a 90 percent reduction, or 0.6 lb/MBTU and a 70 percent reduction for new sources. This sliding scale favored wet scrubbing for high sulfur coals and dry scrubbing for low sulfur coals.
1985 Clean Coal Technology Demonstration Program (1985 CCT)	December 1985 (1986)	$2.5 billion government cost-sharing program operated by DOE in order to demonstrate advanced coal technologies at a commercially-relevant scale. Some of these technologies addressed SO_2 control.
1987 Clean Air Act Amendments Senate Attempt (1987 CAA Try)	(1987)	Serious but unsuccessful attempt to overhaul the CAA, with particular emphasis on tightening acid rain precursor controls. Federal government would subsidize the capital cost of installing scrubbers.
1990 Clean Air Act Amendments (1990 CAA)	November 1990 (1991)	Uses emission allowance trading to achieve a cap in 2010 of 8.95 million annual tons of SO_2 through two phases. Phase I (1995-1999) applied aggregate emission limit of 2.5 lb/MBTU to 261 existing generating units. Phase II (2000-10) applies aggregate emission limit of 1.2 lb/MBTU to about 2,500 existing generating units.

Three sets of government actions were chosen for analysis. In the first, “Enacted” set, only enacted legislative and regulatory government actions were considered (the 1970, 1977, and 1990 CAAs were eligible for this set of government actions, along with the 1971 and 1979 NSPS). In the second, “Enacted Plus CCT” set of government actions, the enacted legislative and regulatory government actions were considered and supplemented with the government subsidy of the 1985 Clean Coal Technology Demonstration Program. In the third, “Enacted Plus Anticipated” set of government actions, enacted legislative and regulatory events were considered and supplemented with a prominent legislative action that ultimately did not succeed, the 1987 Senate attempt to reform the CAA.

Equation 3.1 depicts the regression equations of these three sets of government actions against patent activity levels, based on two inventor-awareness dummy variable windows associated with different types of government actions. These dummy variable windows were assigned based on simple assumptions about the inventive and legislative processes.[59] First, for enacted legislative and regulatory events, the dummy variable was activated both during the year of enactment and during the year directly after enactment, then deactivated for the rest of the time period. Activating the inventor-awareness window during the year of enactment allowed for one year of anticipative invention to lead to a patent application, with that year beginning one year prior to enactment (in other words, invention occurred while the legislative or regulatory event was under consideration). Continuing the inventor-awareness dummy variable activation into the year after enactment allowed the impetus for invention sparked by the government action to continue but also to be only temporary. It also reflected the two-year lag between pollution abatement expenditures and patent activity found across environmental media in Lanjouw and Mody (1996). Second, for anticipated legislative events (only considered to apply in the case of the 1987 attempt to reform the CAA), the dummy variable was activated only during the year after legislative consideration. The activation of this shortened inventor-awareness window allowed for one year of invention during the year of legislative consideration to lead to a patent application, as in the enacted legislative case. It also gave less weight to the impetus for invention sparked by the anticipation, rather than the enactment, of legislation.

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[59] Assumptions had to be made to combat uncertainties revolving around both the length of these processes and the fact that not every patent application is filed as the result of new inventive activities.

EQUATION 3.1

Regression Equations with Dummy Variables based on Sets of Government Actions

(a) Government Actions: Enacted Set. Dummy variables activated during the year of enactment and in the year following the year of enactment, as defined in Table 3.9.

$$y = \mathrm{B}_0 + \mathrm{B}_1 D_1 + \mathrm{B}_2 D_2 + \mathrm{B}_3 D_3 + \varepsilon$$

where

y = number of patents filed
D_1 = 1 for 1978 and 1979, 0 otherwise (enactment of the 1977 CAA)
D_2 = 1 for 1979 and 1980, 0 otherwise (enactment of the 1979 NSPS)
D_3 = 1 for 1991 and 1992, 0 otherwise (enactment of the 1990 CAA)

(b) Government Actions: Enacted Plus CCT Set. Dummy variables activated during the year of enactment and in the year following the year of enactment, as defined in Table 3.9.

$$y = \mathrm{B}_0 + \mathrm{B}_1 D_1 + \mathrm{B}_2 D_2 + \mathrm{B}_3 D_3 + \mathrm{B}_4 D_4 + \varepsilon$$

where

y = number of patents filed
D_1 = 1 for 1978 and 1979, 0 otherwise (enactment of the 1977 CAA)
D_2 = 1 for 1979 and 1980, 0 otherwise (enactment of the 1979 NSPS)
D_3 = 1 for 1986 and 1987, 0 otherwise (enactment of the 1985 CCT)
D_4 = 1 for 1991 and 1992, 0 otherwise (enactment of the 1990 CAA)

(c) Government Actions: Enacted Plus Anticipated Set. Dummy variables activated during the year of enactment and in the year following the year of enactment, as defined in Table 3.9. In the case of the anticipated government action, dummy variable activated in the year after legislative consideration.

$$y = \mathrm{B}_0 + \mathrm{B}_1 D_1 + \mathrm{B}_2 D_2 + \mathrm{B}_3 D_3 + \mathrm{B}_4 D_4 + \varepsilon$$

where

y = number of patents filed
D_1 = 1 for 1978 and 1979, 0 otherwise (enactment of the 1977 CAA)
D_2 = 1 for 1979 and 1980, 0 otherwise (enactment of the 1979 NSPS)
D_3 = 1 for 1988, 0 otherwise (the 1987 CAATry)
D_4 = 1 for 1991 and 1992, 0 otherwise (enactment of the 1990 CAA)

Note: In each dummy variable set, the 1970 CAA and 1971 NSPS were excluded from consideration because they were outside the Figure 3.8 time frame.

The results of this model for the three sets of government actions are shown in Table 3.10. For the Enacted and Enacted Plus CCT sets of government actions, the square of correlation (r^2 value) shows that almost half of the variance in Figure 3.8 can be explained by the (a) and (b) dummy variable regressions depicted in Equation 3.1. Interestingly, the fraction of the variance accounted for (0.49) does not change regardless of whether the 1985 CCT subsidization program is included in the set of government actions. The Enacted Plus Anticipated set of government actions, however, demonstrates that a higher fraction of the variance in Figure 3.8 (0.64) can be explained through the (c) dummy variable model in Equation 3.1. In addition, note that the Enacted Plus Anticipated set of government actions also has a higher (and more significant) ANOVA F-Statistic result than the other two sets of government actions (6.64 versus 5.13 and 3.67).[60] Both results indicate that this set of government actions appears to correlate more strongly with patent activity levels than the other two sets of government actions.

TABLE 3.10

Model Results for Regressions in Equation 3.1

	Regression (a)	**Regression (b)**	**Regression (c)**
Government Action Set	**Enacted**	**Enacted Plus CCT**	**Enacted Plus Anticipated**
Intercept	52.76	53.03	51.70
Coefficients	$ß_1 = 21.82$ $ß_2 = -1.17$ $ß_3 = 4.24$	$ß_1 = 21.65$ $ß_2 = -1.35$ $ß_3 = -2.03$ $ß_4 = 3.98$	$ß_1 = 22.53$ $ß_2 = -0.47$ $ß_3 = 16.30$ $ß_4 = 5.30$
Square of Correlation (r^2)	0.49	0.49	0.64
ANOVA F-Statistic	5.13	3.67	6.64
F-Statistic Significance	0.01	0.03	0.00

[60] Recall that the ANOVA F-Statistic is a test of structural change in which the estimated model is compared against a model in which the dependent variable is regressed on a constant.

c) Expert Analysis of the Abstract-Based Dataset

Because the regression analysis of patent filing activity as a result of government actions is somewhat limited by the small number of observations in Figure 3.8, expert opinion was solicited to help interpret the pattern exhibited in Figure 3.8. Only one of the twelve experts interviewed, expert D, refused to make any suppositions about Figure 3.8. For both the 1978 peak and the 1992 peak in patent filing activity, ten of the remaining eleven experts supported the regression results by suggesting independently that the peaks were due to related legislative and regulatory events (for the 1978 peak, the 1977 CAA and the 1979 NSPS, and for the 1992 peak, the 1990 CAA).[61] In the case of the 1978 peak, the eleventh expert (expert E) suggested that this peak could have resulted from inventive activity from a few years earlier when there was a strong expectation of a big potential SO_2 control market in the U.S., as described in Chapter Two. In the case of the 1992 peak, the eleventh expert (expert H) did not attempt to explain it.

The peak in patent filing activity in 1988 elicited a more varied range of explanations from experts, however. In the context of this peak, nine of the eleven experts – A, C, E, F, H, I, J, K, L – mentioned a heightened public and legislative awareness of acid rain in the mid- to late-1980s. Eight of these experts (all but expert I) mentioned an anticipation of legislation related to this problem (that might potentially take the form of an overhauled CAA), and explained that the result of this anticipation was an intensification of technological demonstrations and testing of moderate SO_2 removal technologies. Expert K directly related the 1988 peak to an anticipation

[61] In addition, experts A and G gave the 1990 CAA credit for renewing interest in SO_2 control technologies, especially in the area of lowering costs to compete with fuel switching, while expert K attributed the drop-off in patenting activity after 1992 to the growing awareness that the scrubber market was not going to be as large as had been initially anticipated.

of legislation that was likely to result from the findings of the National Acid Precipitation Assessment Program.[62] Although no expert specifically mentioned the 1987 Senate effort to overhaul the CAA, these statements about the anticipation of legislation lend support to the regression results based on the Enacted Plus Anticipated set of government actions. Two experts did not mention acid rain legislation in the context of the 1988 peak in patent filing activity, however. One had no suggestion to explain the peak (expert B) and the other tied the peak to the R&D results of EPRI and Radian (a major architect and engineering firm) at the time (expert G). Expert G's statement, of course, does not exclude the possibility that anticipation of acid rain control legislation was behind some of this R&D.

In addition to these explanations of the peaks in patent filing activity, in their discussion of the trend line in Figure 3.8 the experts spoke to a limited extent on what factors contribute to patent activity in the SO_2 industrial-environmental innovation complex. The experts appear to believe both that patent filing activity in SO_2 control reflects the perception of demand for SO_2 control technologies (which is shaped by government actions), while it also reflects the level of new ideas and technological changes in SO_2 control. This is particularly clear in the statements of two experts who discussed the overall negative slope of patent filing activity in Figure 3.8. Expert A explained the gradual decline of patenting activity after the peak in 1978 as representing a dearth of new technological changes, while expert J explained the phenomenon as representing an absence of new technological ideas worth patenting. These same two experts, however, concur with the interpretation of the majority of the experts that patent peaks were related to government actions or the anticipation of government actions. This raises the question

[62] The U.S. National Acid Precipitation Assessment Program (NAPAP) was established in the Acid Precipitation Act of 1980. The NAPAP program was a ten-year, $500 million, multidisciplinary study of the science and technology issues involved in acid precipitation (Irving, 1990).

of whether government actions inspire new ideas beyond simply motivating profit-seeking inventors to escalate inventive activities in the anticipation of an increased government-action-induced demand for SO_2 control technologies.

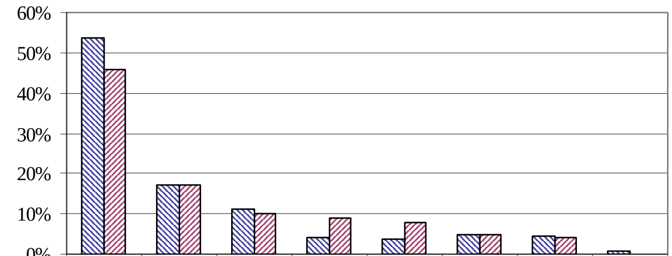
d) Inventive Activity by Technology, Assignee, and Inventor Nation of Origin

This section considers the technologies and organizations underlying the patents in the SO_2-relevant dataset. It specifically pursues the question of how inventive activity in SO_2 control differs by technology and assignee type, as well as by the inventor's nation of origin. Figures 3.9 through 3.11 show the proportional representation, according to technology, assignee, and geographic categories, of the 1,237 abstract-based patents in comparison with the 110 highly cited patents.[63] Note the dominance of post-combustion control technology as the major focus of inventive activity among the various technology categories, with pre-combustion technology the second most important type of patented technology. Also note the dominance of firms among the various assignee types granted SO_2-relevant patents (although the U.S. Department of Energy is the specific assignee with the highest number of patents).

[63] Recall that these categories are listed in Table 3.5 and that highly-cited patents are considered to be particularly important technologically.

FIGURE 3.9

Proportions of Abstract-Based and Highly Cited Patent Datasets by Technology Type

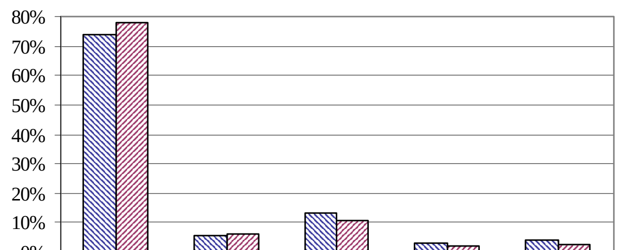


	Post	Pre	Gas	During	FBC	Sorb	By	Measure
% of 1237 Patents	54%	17%	11%	4%	4%	5%	4%	1%
% of 110 Highly Cited Patents	46%	17%	10%	9%	8%	5%	4%	0%

Patented Technology Types

FIGURE 3.10

Proportions of Abstract-Based and Highly Cited Patent Datasets by Assignee Type

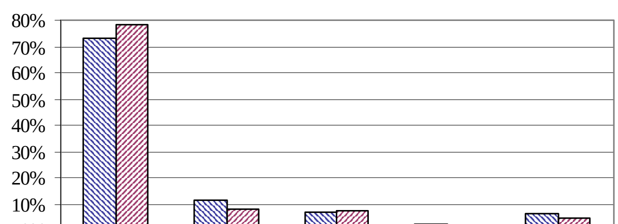


	Firm	Gov	Indiv	Joint	Univ
% of 1237 Patents	74%	5%	13%	3%	4%
% of 110 Highly Cited Patents	78%	6%	11%	2%	3%

Patent Owner Type

FIGURE 3.11

Proportions of Abstract-Based and Highly Cited Patent Datasets by Inventor Nation of Origin



	USA	Germany	Japan	Canada	All Other Nations
% of 1237 Patents	73%	11%	7%	2%	6%
% of 110 Highly Cited Patents	78%	8%	7%	2%	5%

Inventor Nation of Origin

In Figure 3.9, the abstract-based dataset and the highly cited dataset demonstrate that they consist of roughly similar proportions of patents related to specific technologies. Z-tests were conducted to determine the statistical significance of the differences between the two datasets of values for a given technology type.[64] Only during-combustion technology and fluidized-bed combustion technology exhibited statistically significant differences in proportions between the two datasets (at the 99% and 98% confidence levels, respectively). While there is no definitive explanation for this, one possible reason for the smaller percentages in the larger dataset is the absence of many new or major technical changes in these technologies. Those technical changes that do occur in these technologies appear to be important, however, considering the greater proportion of highly cited patents attributed to these technologies. Another possible explanation for the proportional discrepancy is that patenting activity in these technologies may reveal more information to other innovating entities than patenting activity in other types of technologies, so patent protection is only sought for important innovations.

In both Figure 3.10 and Figure 3.11, the abstract-based dataset and the highly cited datasets demonstrate that they consist of quite similar proportions of patents related to specific types of assignee and inventor nations of origin. According to Z-tests, no differences in proportions between these two datasets were statistically significant for any type of assignee or specific inventor nation of origin.

The USPTO reports statistics for individually-owned, government-owned, and university-owned patents for the overall USPTO dataset based on assignee categories defined in the same way as in this research. Data in National Science Board (1999) reveal some differences in the

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[64] The Z-statistic calculation is: $Z = (\hat{p} - p) / \sqrt{\frac{p(1-p)}{n}}$. In this calculation, the proportion of the sample population (the highly cited dataset) with a characteristic of interest is standardized by subtracting the mean of the sampling distribution. The result is then divided by the standard deviation of the sampling distribution, with the final Z-statistic compared against the standard normal distribution in order to determine significance (Moore, 1995, 269-71).

proportions of these assignee categories with respect to all USPTO patents versus SO_2-relevant abstract-based patents. First, after business entities, individuals are the preeminent owners of USPTO patents with origins in the U.S., with an average of 24% of all patents granted prior to 1982 and 23-27% of patents granted since then (National Science Board, 1999). In contrast, only 13% of SO_2-relevant patents are assigned to individuals. Second, in the 1963-82 period, government-owned patents consisted of 3.4% of U.S. originated patents in the USPTO, with declining proportions since 1982. In contrast, government-owned patents consist of 5% of SO_2-relevant patents. Finally, about 3.3% of the U.S.-owned patents granted in the USPTO in 1995 were assigned to universities and colleges, while 4% of SO_2-relevant patents are thus assigned.

Table 3.11 summarizes the proportions of individual, government, and university-owned patents in the USPTO dataset and in the SO_2-relevant abstract-based dataset. The proportion in parentheses in Table 3.11 is the value used to run z-statistic tests of significant differences between the two datasets. These differences are indeed significant at the 99% level for all three assignee categories. Although there are no definite explanations for these differences, two hypotheses seem plausible. First, the lower proportion of patent ownership by individuals in the SO_2-relevant dataset is probably attributable to the size and complexity of FGD systems. Second, the higher proportion of patent ownership by government agencies and universities in the SO_2-relevant dataset is probably due to the importance of non-market incentives for innovation in SO_2 control.

TABLE 3.11

Proportions of U.S.-Owned USPTO and SO_2-Relevant Patents by Assignee Type

Assignee Type	Proportion in Overall USPTO Dataset[a]	Proportion in SO_2-Relevant Abstract-Based Dataset
Individuals	23-27% (25%)	13%
Government	~3% (3%)	5%
Universities	~3% (3%)	4%

[a] Data from National Science Board (1999)

Just as the USPTO reports patent statistics for assignee categories, it also reports patent statistics for various inventor nations of origin. Table 3.12 indicates the comparative proportions of American, Japanese, and German-owned patents in the overall USPTO dataset and in the SO_2-relevant abstract-based dataset. The differences between the proportions in the two datasets are all statistically significant. One particular difference between these two datasets is interesting: the SO_2-relevant abstract-based dataset exhibits a much higher percentage of U.S.-invented patents than the USPTO dataset. This is of note since Japanese and German innovations and companies played important roles in the development of SO_2 control technology. Japan was an early user of FGD systems in the 1960s and 1970s, while Germany became a major FGD user in the mid-1980s. Despite these important roles, however, archival information and expert testimony support the U.S. dominance in SO_2-related patents when they point to the leadership role of the EPA, EPRI, and U.S. FGD equipment and services organizations in R&D and in meeting U.S. electric utility needs.

TABLE 3.12

Proportions of USPTO and SO_2-Relevant Patents by Inventor Nation of Origin

Inventor Nation of Origin	Proportion in Overall USPTO Dataset[a]	Proportion in SO_2-Relevant Abstract-Based Dataset
U.S.	54%	73%
Japan	23%	7%
Germany	15%	11%

[a] Data from National Science Board (1999)

e) Technology-Specific Inventive Activity

This section further investigates the question of how inventive activity in SO_2 control differs by technology type. In previous sections, analysis was based either on the subclass-based patent dataset, the SO_2-relevant abstract-based patent dataset, the highly cited abstract-based patent dataset, or the entire USPTO system. In this section, analysis is based only on the SO_2-relevant abstract-based patent dataset as broken down by technology category. Table 3.13 displays the breakdown of each technology type by assignee type and inventor nation of origin. Boldfaced figures in this table indicate the highest percentages achieved by each assignee type or inventor nation in any of the seven technology type datasets. Italicized numbers in this table indicate the lowest percentages.

TABLE 3.13

SO_2-Relevant Abstract-Based Dataset Technology Types Broken Down by Assignee Type and Inventor Nation of Origin

	Post	Pre	Gas	During	FBC	Sorb	By
Assignee Types							
Firm	75%	66%	**84%**	77%	63%	*60%*	78%
Gov't	*3%*	8%	9%	4%	**17%**	12%	4%
Indiv	15%	16%	*5%*	15%	7%	7%	**19%**
Joint	3%	2%	2%	4%	**11%**	3%	*0%*
Univ	4%	8%	*0%*	*0%*	2%	**18%**	*0%*
Inventor Nations							
U.S.A.	69%	**91%**	68%	77%	65%	75%	*57%*
Germany	13%	*3%*	9%	6%	4%	10%	**26%**
Japan	9%	1%	7%	*0%*	**11%**	7%	7%
Canada	2%	2%	1%	**8%**	2%	3%	*0%*
Others	6%	*2%*	16%	10%	**17%**	5%	9%

From these data, two main observations can be made regarding the nature of inventive activity and how it differs according to the type of SO_2 technology. The first relates to the nature of patenting in SO_2 control technologies by the federal government. Of the various assignees in the abstract-based dataset, the U.S. Department of Energy (DOE) directly holds the highest number of patents (38), while the U.S. Environmental Protection Agency (EPA) directly holds a non-negligible number of patents (4).[65] Table 3.13 shows the types of technology patents that government actors hold in the abstract-based dataset. Note that the government owns only 3% of all patents in the commercially dominant post-combustion control technology category, but owns 17% of the patents in the much less commercially prevalent fluidized-bed combustion SO_2 technology. Figure 3.12 casts light on this finding, as it demonstrates the percentages of DOE and EPA R&D spending on basic research, applied research, and development in 1985 to 1995.[66] Note the large proportions of DOE and EPA R&D spent on (officially non-commercial) basic research (DOE 16%, EPA 25%).[67] These percentages are much higher than the 7% of R&D spending on basic research during this time period for all U.S. industry (based on similar National Science Board (1999) figures in millions of constant 1987 dollars).[68] The most commercial R&D activity, development, shows the converse relationship between government and industry expenditures (DOE 26%, EPA 51%, industry 70%). These expenditure figures

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[65] Recall that prior to the Federal Technology Transfer Act of 1986 and Executive Order 12591 of April 1987, agencies like EPA and DOE were not subject to considerable pressure to obtain patents. In the case of the EPA, its history of engaging in cooperative R&D activities with utility/vendor teams influenced its typical patent strategy. According to expert K, the EPA prefers to have private partners assigned its patented inventions (with a statement of government interest at the bottom of the patent that gives the government the right to retain use of the invention). Either the private partner will be identified before the patent application is filed or a partner will be found after the patent application is filed and then announced to the public through publications such as the Federal Register.

[66] The National Science Board (1999, p. 4-9) provides definitions of these R&D activities, which are based on the somewhat unrealistic linear model of the innovation process (origins in Bush, 1945) that is still used in government data collection. Basic research "advances scientific knowledge but does not have specific immediate commercial objectives, although it may be in fields of present or potential commercial interest." Applied research is "oriented to discovering new scientific knowledge that has specific commercial objectives with respect to products, processes, or services." Development is "the systematic use of the knowledge or understanding gained from research directed toward the production of useful materials, devices, systems, or methods, including the design and development of prototypes and processes."

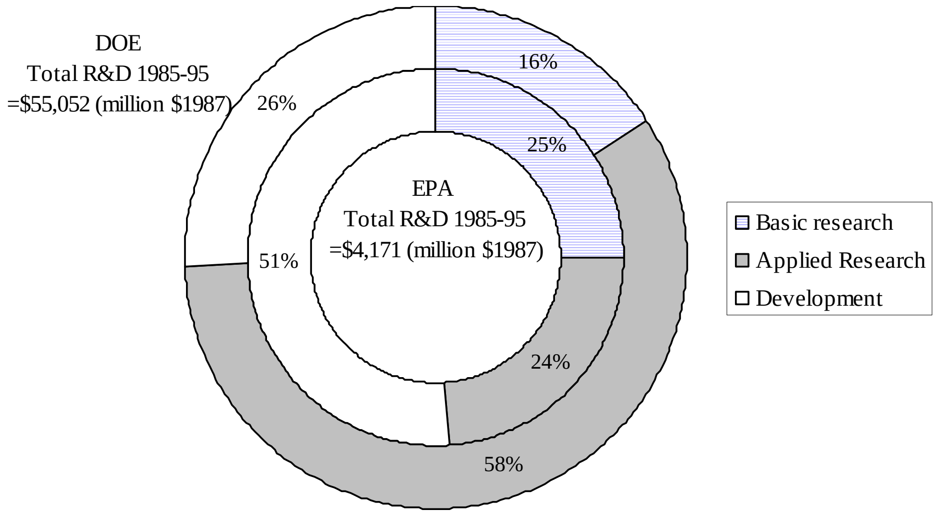
[67] In more complex views of the relationship between science and the commercialization of technology than the linear model of basic research, applied research, and development that originated with Bush (1945), basic research is seen to have potential practical application beyond that gained from pure science (see, among others, Stokes, 1997).

[68] Data are not available solely for utilities and FGD equipment and services organizations.

point to a stronger interest by the DOE and EPRI in research with less immediately practical implications, and this interest is born out in the patent ownership figures above.

FIGURE 3.12

DOE and EPA R&D by Character of Work, 1985-95



Source: National Science Board (1999)

Table 3.13 also provides the opportunity to consider the nature of patenting in SO_2 control technologies by various countries. Note that the highest percentage of SO_2-related patents invented in the U.S. is in pre-combustion technology (91%), while the lowest U.S. percentage is in byproduct modification (57%). This is particularly interesting since German inventive activity shows the exact opposite pattern (3% of pre-combustion patents, 26% of byproduct modification patents). These inventive activity patterns support a consistent story behind innovation in these technological pathways. The U.S. has historically relied on eastern coal reserves that have relatively high sulfur content, with a high proportion of pyritic sulfur that is amenable to physical separation (or coal cleaning). Germany, on the other hand, has predominantly low pyrite coals that are not readily cleanable. It is to be expected, then, that U.S. inventors would be disproportionately interested in researching ways to remove sulfur from U.S.

coal. Meanwhile, Germany, unlike the U.S., has geographic and political constraints against large landfills of FGD by-product. Germany also has a dearth of natural gypsum, and has found a good use for FGD byproduct as a substitute for this resource. It is to be expected, then, that German inventors would engage in a higher level of research into the technologies that would make FGD byproduct useful.

f) Regression Analysis of Technology-Specific Inventive Activity

Inventive activity in SO_2 control by technology type varies not just according to assignee type and inventor nation of origin, but also across time. Table 3.14 provides some basic statistics for each technology type for the 1974 to 1993 time period. This table demonstrates that, with the exception of sorbent modification technologies, each of these technology datasets exhibits the same overall degree of variation as the full dataset of SO_2-relevant abstract-based patents depicted earlier in Figure 3.8.

TABLE 3.14

Size and Noise of Datasets Based on Technology Type drawn from SO_2-Relevant Abstract-Based Dataset

Technology Type in Patent Dataset	Patents, 1974-93 (out of 1,105 Total)	Years (out of 20) when Patents exceed Average by at least one Standard Deviation
Post-combustion desulfurization (Post)	574	5
Pre-combustion desulfurization (Pre)	196	5
During combustion desulfurization (During)	126	5
Desulfurized coal gas and synthetic fuels (Gas)	49	5
Fluidized-bed combustion (FBC)	44	5
Desulfurizing agent modification (Sorb)	55	7
Desulfurization byproduct modification (By)	50	5
Measurement technologies (Measure)	6	5

Each of these technology types (except for measurement technologies, due to their small number of observations) can be a patent dataset analyzed according to regression techniques such as those in section (b) above. Recall that three sets of government actions were defined in that section, the Enacted, Enacted Plus CCT, and Enacted Plus Anticipated sets.[69] In addition, two inventor-awareness dummy variable windows were defined in Equation 3.1 that corresponded with either enacted or anticipated government actions. Overall, three regression equations were run against the dependent variable of the total number of patents filed in a given year. Table 3.10 demonstrated that regression (c), which corresponded with the Enacted Plus Anticipated set of government actions, best explained the variance of patent activity in the overall abstract-based dataset.

Even though the Enacted Plus Anticipated set of government actions proved most explanatory for the combined set of technologies in the abstract-based dataset, this set of government actions might not explain the variance in individual technologies equally well. For this reason, regression equations identical to those in Equation 3.1 (except for the dependent variable) were run against the total number of patents filed in a given year in each technology-specific dataset. Table 3.15 indicates the results of these regression analyses. The Enacted Plus Anticipated set of government actions explains a high fraction of the variance in the pre-combustion technology dataset (0.66) and a moderate level of the variance the fluidized-bed combustion technology dataset (0.41) at a 95% confidence level or better. In addition, the Enacted Plus CCT set of government actions significantly explains a high fraction of variance in both the pre-combustion (0.66) and the fluidized-bed combustion (0.59) technology datasets. The Enacted set of government actions significantly explains an even higher fraction of the

[69] Again, the Enacted set of government actions includes only the enacted legislative and regulatory government actions of the 1977 and 1990 CAAs and the 1979 NSPS. The Enacted Plus CCT set includes these enacted legislative and regulatory actions in addition to the government subsidy of the 1985 Clean Coal Technology Demonstration Program. The Enacted Plus Anticipated set includes the enacted legislative and regulatory events as well as the prominent attempt to reform the CAA in the Senate in 1987.

variance in the pre-combustion technology dataset (0.68). Unfortunately, none of these sets of government actions explains at a 95% confidence level or better the variance in post-combustion, gasification, during-combustion, sorbent modification, or by-product technology patents as defined in this research. This may well be because of the fairly simple regression equations executed here (due to the small number of observations in these patent datasets over time), which are only able to take into consideration the existence, rather than the characteristics, of government actions.

TABLE 3.15

Model Results for Regressions in Equation 3.1, According to Technology Type

	Regression (a): Enacted Gov't Action Set	Regression (b): Enacted Plus CCT Gov't Action Set	Regression (c): Enacted Plus Anticipated Gov't Action Set
Intercept and Coefficients			
Post Tech. Type	Intercept = 27.93 $ß_1$ =5.04; $ß_2$ = -1.96; $ß_3$ = 4.57	Intercept = 27.70 $ß_1$ = 5.20; $ß_2$ = -1.80; $ß_3$ = 1.80; $ß_4$ = 4.80	Intercept = 27.51 $ß_1$ = 5.33; $ß_2$ = -1.67; $ß_3$ = 6.49; $ß_4$ = 4.99
Pre Tech. Type	**Intercept = 8.95** **$ß_1$ =15.70; $ß_2$ = -2.30;** **$ß_3$ = -5.95**	**Intercept = 8.86** **$ß_1$ = 15.76; $ß_2$ = -2.24;** **$ß_3$ = 0.64; $ß_4$ = -5.86**	**Intercept = 9.25** **$ß_1$ = 15.50; $ß_2$ = -2.50;** **$ß_3$ = -4.25; $ß_4$ = -6.25**
Gas Tech Type	Intercept = 6.74 $ß_1$ = 0.17; $ß_2$ = -0.83; $ß_3$ = -3.74	Intercept = 6.70 $ß_1$ = 0.20; $ß_2$ = -0.80; $ß_3$ = 0.30; $ß_4$ = -3.70	Intercept = 6.65 $ß_1$ = 0.23; $ß_2$ = -0.77; $ß_3$ = 1.35; $ß_4$ = -3.65
During Tech Type	Intercept = 2.43 $ß_1$ = -0.96; $ß_2$ = 0.04; $ß_3$ = 1.07	Intercept = 2.58 $ß_1$ = -1.05; $ß_2$ = -0.05; $ß_3$ = -1.08; $ß_4$ = 0.93	Intercept = 2.26 $ß_1$ = -0.84; $ß_2$ = 0.16; $ß_3$ = 2.74; $ß_4$ = 1.24
FBC Tech Type	Intercept = 1.80 $ß_1$ = 2.13; $ß_2$ = 1.13; $ß_3$ = 0.70	**Intercept = 1.55** **$ß_1$ = 2.30; $ß_2$ = 1.30;** **$ß_3$ = 1.95; $ß_4$ = 0.95**	**Intercept = 1.86** **$ß_1$ = 2.09; $ß_2$ = 1.09;** **$ß_3$ = -0.86; $ß_4$ = 0.64**
Sorb Tech Type	Intercept = 2.50 $ß_1$ = 0.00; $ß_2$ = 0.00; $ß_3$ = 2.50	Intercept = 2.58 $ß_1$ = -0.05; $ß_2$ = -0.05; $ß_3$ = -0.58; $ß_4$ = 2.43	Intercept = 2.40 $ß_1$ = 0.07; $ß_2$ = 0.07; $ß_3$ = 1.60; $ß_4$ = 2.60
By Tech Type	Intercept = 2.26 $ß_1$ = -2.17; $ß_2$ = 2.83; $ß_3$ = 1.74	Intercept = 2.23 $ß_1$ = -2.15; $ß_2$ = 2.85; $ß_3$ = 0.28; $ß_4$ = 1.78	Intercept = 2.28 $ß_1$ = -2.19; $ß_2$ = 2.81; $ß_3$ = -0.28; $ß_4$ = 1.72
ANOVA F-Statistic (with Significance); Square of Correlation (r^2)			
Post Tech. Type	1.16 (0.26); 0.28	0.90 (0.49); 0.19	1.47 (0.35); 0.18
Pre Tech. Type	**9.76 (0.00); 0.68**	**6.85 (0.00); 0.66**	**7.57 (0.00); 0.66**
Gas Tech Type	0.97 (0.58); 0.16	0.69 (0.61); 0.15	0.74 (0.43); 0.15
During Tech Type	0.39 (0.51); 0.19	0.43 (0.79); 0.10	0.87 (0.76); 0.07
FBC Tech Type	3.64 (0.07); 0.43	**5.48 (0.01); 0.59**	**2.78 (0.04); 0.41**
Sorb Tech Type	2.67 (0.08); 0.40	2.02 (0.14); 0.35	2.55 (0.08); 0.33
By Tech Type	1.69 (0.35); 0.24	1.20 (0.35); 0.24	1.19 (0.21); 0.24

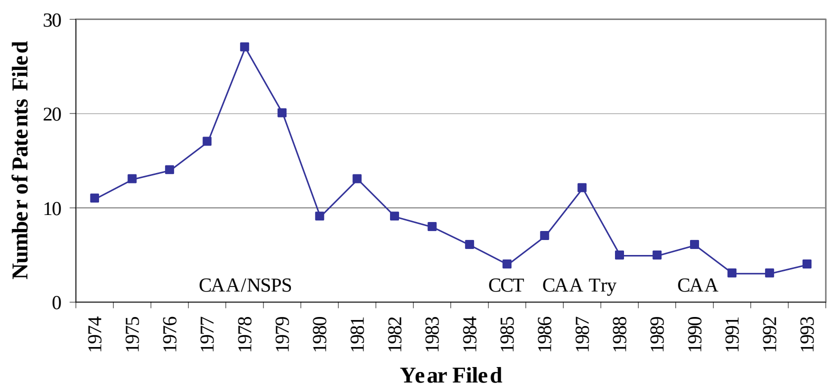
Note: Regression results are given in boldface if the ANOVA F-Statistic is statistically significant at a confidence level of at least 95%.

g) Expert Analysis of the Pre-Combustion Dataset

Since the pre-combustion patent dataset appears to be tied most closely to the existence of government actions, it is worth further discussion here in an attempt to better understand the relationship of government actions to this type of technology. Figure 3.13 displays the trend of pre-combustion patenting activity in 1974 to 1993. During the 1974 to 1978 period, pre-combustion patenting activity increased annually. At its highest point in 1978, inventive activity in pre-combustion technologies (which comprise only 17% of the abstract-based patent dataset), almost reached the level of inventive activity of post-combustion technologies (which comprise 54% of the abstract-based patent dataset). After 1978, however, pre-combustion patenting activity dropped off dramatically and never returned to the levels seen in 1974 to 1978.

FIGURE 3.13

Trend in Pre-Combustion Patents Identified in the SO_2-Relevant Abstract-Based Dataset



The years 1974 to 1978 occurred not only after the passage of the 1970 CAA and 1971 NSPS (which could be met with a range of SO_2-control technologies, as detailed in Chapter Two) but also after the Arab oil embargo of October 1973. This time period is particularly known for heightened and continuing national energy concerns that were responded to in part by the promotion of coal as a fuel source by the federal government. Thus, pre-combustion, or coal cleaning, technologies were favored by both the environmental and energy situations of this time period. The 1979 NSPS significantly altered the environmental situation, however, by requiring more stringent SO_2 removal efficiencies than those achievable by pre-combustion technology alone. In effect, the 1979 NSPS required the use of post-combustion technology.

Experts, although not as familiar with pre-combustion technology as with post-combustion FGD technologies, tended to agree with this description of the situation of pre-combustion control technology when discussing the patent activity pattern exhibited in Figure 3.13. Eight of the twelve experts – A, C, D, G, H, I, J, K – discussed the pre-1978 period in the development of pre-combustion control technology (the other four experts contributed to discussions of the 1979-93 period). Seven of these eight experts (all but C) explained that pre-combustion technologies were pursued as one of many possible SO_2-control technologies in the early 1970s. In addition, expert K also mentioned that the Arab oil embargo provided an incentive for these technologies as part of alternative fuel scenarios while experts I and J explained that the promise of these technologies was economic, since sulfur removal from coals was potentially less costly than cleaning stack gas or buying lower sulfur coals. Expert C suggested that government was probably funding much of the R&D activity in pre-combustion control, a view supported by expert H when he mentioned that the EPA had a coal-cleaning program during this time period. The existence of government funding enhances the idea that these technologies were favored by the environmental and energy situations of the early 1970s.

Three experts – B, K, L – specifically discussed the role of the 1977 CAA and 1979 NSPS in pre-combustion inventive activity, and two of these three described incentives for pre-combustion inventive activity inherent in these legislative and regulatory events.[70] Expert B suggested that the lower SO_2 removal threshold in the 1979 NSPS of 0.6 lb/MBTU and a 70 percent reduction might have provided an incentive for inventors with chemical cleaning technologies. Expert L suggested that the 1978 peak, which occurs during the period in which the NSPS was being developed, could be due to the fact that the NSPS allows polluters to take

[70] Four other experts (A, F, G, I) described the period immediately following these government actions without mentioning them specifically.

credit for any coal cleaning performed. Neither of these suggestions seems to suit fully the chronology of the evolution of the 1979 NSPS as described in Chapter Two. Expert K, however, explained that universal scrubbing and continuous compliance was an enormous deterrent for pre-combustion technologies, which typically have removal efficiencies of less than 30%. These pre-combustion technologies were too limited to offer much towards the effort to reach the higher SO_2 removal level required in the 1979 NSPS. For eastern coals, the effective emissions limit was 0.6 lbs SO_2/MBTU, requiring removal efficiencies of 85 to 90 percent (Rubin, 1989).

The limitations of pre-combustion technologies were well understood by the experts, and expert statements about these limitations imply the deterrent effect of the 1979 NSPS without mentioning it specifically. The four experts who did not specifically mention the 1979 NSPS discussed the technological and economic limitations of pre-combustion technologies and explained that these technologies did not meet utility needs in the post-1979 NSPS period. According to experts F and G, utilities realized this in the late 1970s and early 1980s. Expert A further explained that pre-combustion control never “worked out,” and expert I explained that the utilities realized that with scrubbing, no pre-combustion control was necessary. Three of these same four experts (A, G, I) had earlier explained that pre-combustion technologies were being explored in the early 1970s, with the implication that they *were* meeting utility needs in this earlier period. Utility needs had apparently changed as a result of the 1977 CAA and its associated 1979 NSPS, although none of these four experts mentioned either government action specifically. In addition to these four experts, expert B, who described the positive influence of the lower threshold of SO_2 removal in the 1979 NSPS for chemical coal cleaning, also recalled doing a lot of work evaluating (with a negative outcome) physical and chemical coal cleaning in the 1978-81 period.

Finally, four experts – B, C, E, L – discussed the status of pre-combustion patenting activity in the late 1980s and early 1990s. Experts B, C, and L focused on the 1987 peak in pre-combustion patenting activity and explained that it was due to anticipation of a new CAA for acid rain. Experts C and L supplemented their statements by stating that the DOE's work in limestone furnace injection technologies and other mid-level removal technologies helped shape anticipation of the direction the new CAA would take. The anticipated direction was for low cost, low- to mid- level removal technologies, which could potentially have provided a market for pre-combustion technologies. Expert E focused on the reduced level of patenting activity in the 1990-93 period. He explained that this was not surprising, since incremental increases in SO_2 removal such as those achieved by pre-combustion technology would be particularly disadvantaged by the flexible trading concept of the 1990 CAA, in which "getting one more plant at 99% would offset five plants [using pre-combustion control technologies]."

Conclusions

The first part of this chapter defined patents and discussed the patenting process, explored some of the advantages and disadvantages of using patents as an innovation measure, and discussed expert perceptions of the role of patents in the SO_2 industrial-environmental innovation complex. The second and third sections of this chapter described two different approaches pursued in this dissertation to create and analyze patent datasets as indicators of the influence of government action on inventive activity. The subclass-based patent dataset described in the second section of this chapter demonstrated that, despite the existence of government legislation dating back to 1955 that authorized research into air pollution abatement methods, patent activity in SO_2 control did not really begin until after the introduction of a regulatory regime. Patent activity levels for this consistent dataset of over one hundred years can be portrayed as a step-function divided into two main periods by the 1970 CAA and its associated 1971 NSPS. In the first period, no more than four patents were filed in a given year, while in the second period, 1971 to 1996, patenting activity never fell below a minimum activity threshold of seventy-six patents per year. The subclass-based dataset also demonstrated that patent activity in the second period peaked in the years 1978, 1979, 1988, and 1992. These peaks were not modeled against government actions because of the lack of refinement of the subclass-based dataset.

The third section of this chapter introduced an abstract-based search methodology in order to obtain a clean dataset of commercially validated SO_2-relevant patents. Three sets of analyses of this dataset provided several insights into the inventive processes involved in SO_2 control technologies over time. First, a time series of these patents was analyzed both through simple models based on government actions and through expert elicitation. Both types of analyses arrived at similar conclusions that the existence of government actions positively, although temporarily, affected SO_2-relevant patenting activity.

Second, the abstract-based patent dataset was also analyzed in order to gain insights into the sources of innovation in SO_2 control and how these sources might differ according to the social value of patents. A dataset of 110 highly cited patents was developed to represent technologically important patents. Few differences were seen between the proportion of patents attributed to technology type, assignee type, and inventor nation of origin in the overall SO_2-relevant dataset and the highly-cited dataset. Significant differences were seen, however, between certain assignee and inventor nation of origin proportions of patents in the abstract-based SO_2-relevant dataset versus the overall USPTO dataset. Individuals owned less and government and universities owned more SO_2-relevant patents than their share of all USPTO patents. Similarly, U.S. inventors patented more and German and Japanese inventors patented less in SO_2 control than they patented in the overall USPTO dataset.

In a third set of analyses, SO_2-relevant patents were broken down into datasets based on technology type in order to investigate how the inventive process differs among the various technological pathways pursued to address SO_2 pollution. Patenting activity in these technology types was shown to vary according to assignee type and inventor nation of origin. In addition, regression analysis showed that not all technological pathways could be explained equally well by the various sets of government actions analyzed. Patent activity in pre-combustion control technology was particularly well explained, however, by the existence and nature of government actions both in regression analysis and in interviews with experts.

All of these results contribute to a growing understanding of inventive activity in SO_2 control technologies, as measured by patents, and how this activity relates to government actions. The next chapter will address the importance of government actions in inventive activity and the diffusion of SO_2 control technology by focusing on the evolution of technical papers presented at conferences sponsored by EPA, EPRI, and DOE in order to advance this technology.

Chapter 4 Network Analysis

Activity in Technical Conferences as a Method of Evaluating Invention and Diffusion

Chapter Three focused primarily on invention in SO_2 control technologies, as measured through patenting activity. In the innovation literature, other approaches have been taken to investigate inventive activities that do not necessarily meet the strict conditions required for a patent to be granted. Instead of patents, researchers focus on such indicators of innovative activity as journal articles or advertisements in trade publications (for a brief review of literature-based innovation research and some of the difficulties involved in its use for measuring innovative output, see Santarelli and Piergiovanni, 1996).

This chapter focuses on activity in technical conferences as a measure of inventive activity and technology diffusion (see Figure 4.1).[71] In particular, this chapter highlights the evolution of technical papers presented at an important SO_2 control technology conference held regularly between 1969 and 1995. This conference, the "SO_2 Symposium," brought together such technological actors as government, utilities, FGD equipment vendors, architect-engineering firms, university researchers, and other contract researchers in order to share information on the use of SO_2 control technologies. Table 4.1 lists the dates and locations of these symposia. In its early years, the U.S. Environmental Protection Agency (EPA) sponsored the SO_2 Symposium by itself; in 1982 the Electric Power Research Institute (EPRI) joined EPA as a co-sponsor; and in 1991, U.S. Department of Energy (DOE) also became a co-sponsor. In 1997, the SO_2 Symposium was folded into a broader conference, known as the "Mega

[71] Technical conferences and consortia have been previously considered as knowledge transfer mechanisms in such studies as Appleyard (1996) and Browning, Beyer, and Shetler (1995).

Symposium," that included control technologies dealing with other air pollutants, such as nitrogen oxides, particulates, and toxics. The Mega Symposium was held in 1997 and 1999.

FIGURE 4.1

Activity in Technical Conferences as a Measure of Inventive Activity and Adoption & Diffusion Strategy

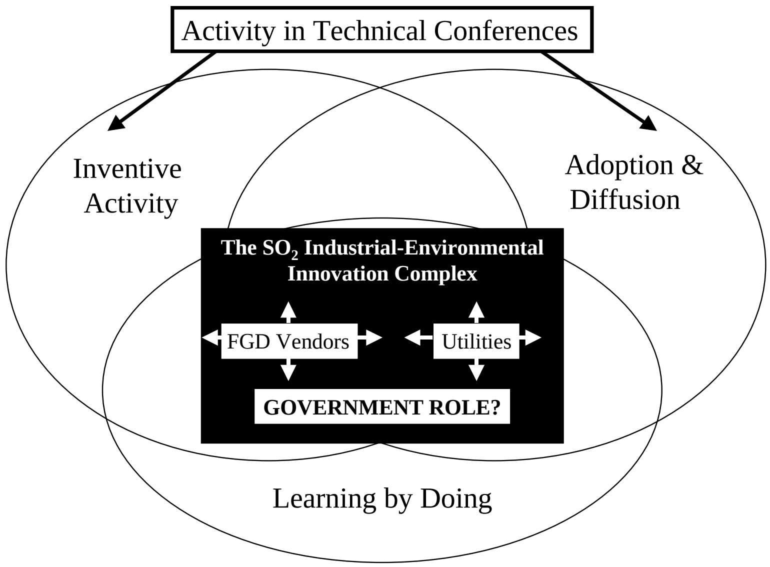


TABLE 4.1

Year and Location of SO_2 Symposium Conferences Considered in this Chapter

Year	Location	Year	Location
1973	New Orleans, LA	1985	Cincinnati, OH
1974	Atlanta, GA	1986	Atlanta, GA
1976	New Orleans, LA	1986[D]	Raleigh, NC
1977	Hollywood, FL	1988	St. Louis, MO
1979	Las Vegas, NV	1990	New Orleans, LA
1980	Houston, TX	1991	Washington, D.C.
1982	Hollywood, FL	1993	Boston, MA
1983	New Orleans, LA	1995	Miami, FL
1984[D]	San Diego, CA		

[D] A separate conference was held in this year to focus entirely on dry and combination SO_2/NO_x technology rather than the wet FGD technology that was the mainstay of the SO_2 Symposium.

The SO_2 Symposium conveys two types of information that provide useful backdrops for observing the government role in innovation in SO_2 control technologies. First, the number and topics of the technical papers presented over the years at the SO_2 Symposium reflect changing inventive activity that is not necessarily captured by patents. Second, the individuals and organizations involved in the SO_2 Symposium form a technical communication network. The knowledge-based interactions that can be observed through co-authorship patterns in the SO_2 Symposium over time provide insights into the diffusion processes occurring in the SO_2 industrial-environmental innovation complex. This second type of information is better understood in the context of the SO_2 Symposium rather than in the context of selected trade or technical journals, because the participation of the various public and private actors involved in SO_2 control is assured in the SO_2 Symposium.

These two types of information – the number and topics of technical papers and the patterns of coauthorship in these papers – will be the focus of the second and third sections of this chapter. In the rest of this introductory section, expert opinion will be related as it pertains to the role of the SO_2 Symposium in the SO_2 industrial-environmental innovation complex and in advancing the technology.

Perception of the Role of the SO_2 Symposium in Advancing the Technology

As discussed in Chapter One, twelve experts were identified for extended interviews as part of the research methods used in this dissertation.[72] During the structured two-hour interview process, the twelve experts were asked their informed opinion about the impact of the SO_2 Symposium on the SO_2 industrial-environmental innovation complex and on SO_2 control technology. Ten of the experts – A, B, D, F, G, H, I, J, K, L – described the conference as having a positive influence on the development of the technology. The high regard of these

[72] The characteristics of these experts appear in Table 1.1, where they are listed in conjunction with their identification labels in the dissertation.

experts for the conference can be seen in the excerpts in Table 4.2. Expert C did not have considerable experience with FGD technology before 1990 but attributed a probable positive role to the symposium before 1990 in terms of international information exchange and the dissemination of information from FGD vendors to utilities. Expert E did not address this question.

TABLE 4.2

Excerpts of Expert Statements on the Importance of the SO_2 Symposium

"A tremendous resource." (A)	"I've been to all of them over the past 10-20 years. … There isn't any other meeting where the same level of exchange occurs." (H)
"… it was excellent, it had a big impact back in the '70s and early '80s." (B)	"Over the years, it's been very helpful." (I)
"It's been fabulous." (D)	"If you were in the business, this would certainly be the one to go to." (J)
"The [SO_2] Symposiums were essential to the whole evolution of the technology..." (F)	"…Major impact …" (K)
"…A good interchange … the biggest help [is that] some of the people have already walked the path and can share information." (G)	"This symposium and its predecessors really have been significant in terms of the free exchange of information …"(L)

In order to organize the discussion of expert opinion on the SO_2 Symposium, this introductory section explores the following three general theses derived from the expert interviews. First, the influence of the SO_2 Symposium on the industrial-environmental innovation complex and the technology varied over time. Second, there was variation in the level, type, and manner of information exchange facilitated by the SO_2 Symposium. Third, the SO_2 Symposium was especially important in the evolution of SO_2 control technology when compared to other relevant conferences.

The first thesis derived from the expert interviews is that the conference had a shifting role in the SO_2 industrial-environmental innovation complex over time. A number of experts agreed with expert B that the SO_2 Symposium had an especially important impact in the 1970s and 1980s, although they believed that its influence diminished in the 1990s. Expert K provides one perspective of the changing role of the conference over the last three decades. In the 1970s, expert K described the SO_2 Symposium as the main information dissemination source on the status of research for FGD vendors and utilities. During this period, the Japanese and Germans attended the Symposium to gain information. In the 1980s, as other information outlets like reports from subscription newsletters and government organizations (e.g., EPA, the International Energy Agency (IEA)) emerged, the conference evolved to a forum for new and emerging developments in FGD technologies. In this time period, the Japanese and Germans became important contributors of information to the SO_2 Symposium. Expert K explained that by the 1990s, other air pollutants had increased in importance over SO_2 at the same time that FGD technologies had generally matured into reliable, efficient systems. At the 1999 Mega Symposium, expert K described the admission of a utility representative, "We're all going to have scrubbers in twenty years anyway," as a dramatic development made possible by the maturing of FGD. In expert K's opinion, the Mega Symposium is now less important as a technology forum for SO_2 than as an issues forum for upcoming regulation on other pollutants.

The view that the SO_2 Symposium has become less important in the 1990s is also supported by experts B, C, D, F, G, I, and L. Experts B, D, and F agree with expert K in their emphasis on the maturing of the technology, which in their view has led to less important technical work being needed or done in SO_2 in the 1990s. Experts D and F also placed emphasis on the relatively lower maturity of technologies designed to combat other air pollutants as a reason for the decline of the SO_2 Symposium and the emergence of the Mega Symposium. Expert F, however, emphasized the continued importance of the Mega Symposium for SO_2, since it is now "almost the only place where people who are interested in FGD get together anymore on a regular basis." Experts C, D, G, and L also pointed to changes in the SO_2 industrial-environmental innovation complex as contributing to the decreased importance of the SO_2 Symposium in the 1990s. Expert L mentioned that downsizing, competition, and cost-cuts in the utility industry as a result of deregulation have reduced SO_2 Symposium attendance in the 1990s, although the level of information exchange has been as high as ever. In contrast, experts D and G pointed to deregulation as potentially contributing to a reduction in the level of information exchanged in the conferences in the 1990s. Expert D stated that now that utilities are paying more directly for research (instead of DOE and EPRI), less know-how is being shared than in the first twenty years of the conference. Expert G pointed to similar utility self-interest in a competitive industry as a potential threat to cooperation among FGD operators. Expert C pointed to increased FGD vendor competition in a tighter market since 1990 as a reason why FGD vendors are concerned more about competitor intelligence in the late 1990s than in previous years. According to expert C, this concern about competitor intelligence is reducing the vendors' willingness to share know-how in presentations, rather than simply share the results of research efforts.

One final expert observation about the changing importance of the SO_2 Symposium over time deserves particular attention. Expert L noted that the conference was particularly popular right before and during the implementation of the 1977 and 1990 Clean Air Act Amendments (CAA), when utilities needed to determine their technological options. This observation is important because it potentially ties changes in the nature of the researcher network created by the SO_2 Symposium to the existence of government actions to control SO_2. This point will be explored further in section three of this chapter.

The second thesis derived from expert discussions about the SO_2 Symposium is that there was variation in the level, type, and manner of information exchange in the SO_2 Symposium over time. Opinions about the level of information exchanged, particularly with regard to know-how, are generally described above. More can be said, however, about expert opinion on the level of *international* information exchange in the SO_2 Symposium. Experts G and L both refer to the value that international FGD vendors have placed (and continue to place) on the information exchanged in the SO_2 Symposium and its successor, the Mega Symposium. Expert G described an incident in which a materials problem he described at an SO_2 Symposium prompted action by a European company within a week of the conference. Expert L related discussions with international FGD vendors who said that they considered the SO_2 Symposium to be "the most important symposium that they can possibly come to or participate in." Expert H, on the other hand, considered the information exchange with Germany and Japan to be somewhat incomplete in the SO_2 Symposium. He believed that a fuller exchange of information probably occurs between U.S. FGD vendors and their European and Japanese peers, since U.S. vendors have had to survive almost solely on the international market since the U.S. market tightened ten to fifteen years ago.

Experts generally categorize the type of information exchanged through the SO_2 Symposium as either operating experience (and sometimes related know-how) or new developments in FGD. Experts A, F, G, I, and K particularly identified operating experience as an important type of information shared through the SO_2 Symposium, while experts A, D, F, I, and K particularly mentioned new developments in FGD technology. In addition to these two main types of information, expert G also mentioned what could be deemed a third type of information exchanged in the SO_2 Symposium: information on the research activities of EPA, DOE, and EPRI that assisted the coordination of these activities.

Experts F, G, J, and H touched upon the manner with which the SO_2 Symposium facilitated high levels of information exchange of at least these three different types. Expert G, who described the speed with which information about his materials problem was diffused internationally after his description of the problem at an SO_2 Symposium, also related an instance of a similar rapid technology diffusion event that occurred domestically. According to expert G, the SO_2 Symposium made it possible for the use of thiosulfate additives as an oxidation inhibitor to diffuse across roughly thirty utilities within a year or two of theoretical and practical information exchange among utilities, EPRI, FGD vendors, and academic researchers. Experts F, J, and H identified elements of the SO_2 Symposium that were particularly important for supporting such an effective technology-based knowledge network. All three of these experts pointed to the venues for informal interpersonal information exchange at the conferences as very important. Expert F also identified the technical research in conference papers as important. Expert H, however, saw these papers as considerably less important than the "rubbing of noses" of researchers, both at the conference and more importantly *after* the conference when more know-how could be transferred effectively [see von Hippel (1988) on informal trading of technical know-how among rivals; also Argote (1999) pg. 146, on conference presentations as an important source of knowledge]. Expert A also observed a "flurry" of innovative activity after every symposium, although he did not specifically mention enhanced researcher cooperation as an aspect of this activity.

The third and final thesis that can be derived from expert discussions is that the SO_2 Symposium appears to be more relevant to the evolution of research in SO_2 control than other conferences. Experts G, H, and J specifically mentioned the existence of other conferences that were germane to SO_2 control technology. Expert G has been a regular attendee of a utility FGD user's group conference (the "FGD User's Conference") at which no government actors were present. He considered the FGD User's Conference to be more open to an uncensored discussion of operating experience problems, and thus found it very useful in transferring operational know-how. The current need for the FGD User's Conference seems strong since expert G described a considerable recent turnover of utility FGD operators due to restructuring in the power sector. Unfortunately, this same restructuring has made organizing the FGD User's Conference more difficult in recent years. The SO_2 Symposium (and its successor, the Mega Symposium), on the other hand, is designed to interest multiple actors in the SO_2 industrial-environmental innovation complex, as shown by the co-sponsorship of these symposia by EPA, EPRI, and DOE. Expert G expressed a hope that the joint sponsorship of these symposia would demonstrate to regulatory agencies that the utility industry is really trying to work with environmental control technologies. The opportunity the SO_2 Symposium and the Mega Symposium have provided for the utility industry to demonstrate its cooperativeness is a continuing incentive for utility operator participation in these symposia. This participation also ensures consistency in the coverage of symposia program topics relevant to these operators, and makes the SO_2 Symposium an effective source of information on the evolution of FGD technology.

Experts H and J underscored two other reasons why the SO_2 Symposium is the most relevant conference to understand the evolution of the technology. Expert H mentioned that the DOE and EPA used to hold industry briefings in the 1970s to disseminate information from completed research topics. Although these meetings were undoubtedly important in diffusing innovative information, the SO_2 Symposium has covered not only the same time frame as these meetings, but has outlasted them by a considerable amount. This demonstrates the long-standing interest in and relevance of the SO_2 Symposium. Expert J, meanwhile, indicated that the SO_2

Symposium was the conference with the greatest depth on the topic of SO_2 control. Whereas other technical conferences might have had a couple of sessions on SO_2 control over several days, the SO_2 Symposium has been distinguished by its length and the intensity of its spotlight on this topic.

According to expert E, responsibility for the research presented at the SO_2 Symposium over time tended to shift to the organizations that were most influential in FGD research funding at different time periods, which further indicates that the SO_2 Symposium reflected leading SO_2 control research. For example, the period in which the EPA was the sole sponsor of the SO_2 Symposium was only slightly longer than the period in which EPA had a large budget for FGD research, as discussed in Chapter Two.[73] Similarly, the DOE was brought into the SO_2 Symposium as a co-sponsor at about the same time that EPRI funding for FGD was considerably diminished. Prior to that, expert E stated that EPRI "pretty much controlled the symposium program, and certainly controlled the funds" of both the conference and much of the research presented at the conference in the 1980s. In the 1990s, there is some intimation from expert C that the architect and engineering (A&E) firms probably dominated "what comes out of these symposia." It was not clear from expert C's discussion, however, whether this dominance was exercised over the formal content of the SO_2 Symposium or simply the projects that were awarded as a result of marketing opportunities arising from the conference. It does make intuitive sense that A&E firms would be prominent in the more private market of the utility industry in a time of deregulation and minimal public funding for SO_2 control research.

Expert F bypassed specific arguments as to why the SO_2 Symposium was the most relevant conference to the understanding of the evolution of FGD technology. Instead, he simply

[73] Besides the transfer of a major FGD research program from EPA to DOE in 1979, recall that EPA's operating budget was cut by more than one-third between 1981 and 1983, with personnel cuts of 20%.

stated that the story of FGD research is in the tables of contents of the SO_2 Symposium over time. This statement prompted a follow-up question about what happened in the history of FGD research when the SO_2 Symposium briefly split into two smaller conferences focusing on dry and combined SO_2/NO_x technologies in the period between 1984 and 1986. Expert F related this split to an exceptional market that emerged for dry SO_2 technologies as a result of the 1979 NSPS.[74] In expert F's opinion, spray dryer technologies held a unique position in the history of FGD because the diffusion of these technologies was very different from the normal adoption and diffusion process among electric utilities. According to expert F, utilities "simply don't install systems [that] don't have a track record, [but] they probably had seven or eight spray dryers being installed before one of them was demonstrated on a full scale." Different actors were involved in this exceptional market, which dissipated due to skepticism about the technology's effectiveness on high sulfur coal applications.

In conclusion, most interviewed experts perceived the SO_2 Symposium to have had an important positive impact on the SO_2 industrial-environmental innovation complex and on advancing FGD technology, although the influence of the conference did change over time. The level of information exchanged in the SO_2 Symposium through the researcher network established by this conference was generally considered to be high and of two types: the results of operating experience, with various degrees of accompanying know-how, and new developments in FGD research. Experts have observed that information can traverse the knowledge-network defined by the SO_2 Symposium with considerable speed. Experts also observed that informal meetings of researchers were particularly important to the successful information exchange facilitated by this conference. Finally, expert opinion supports the thesis

[74] When asked a similar question, expert E attributed this split to increased funding by EPRI for dry and combination SO_2/NO_x technology during this time period.

that the SO_2 Symposium is the most relevant conference to study in order to understand the evolution of FGD technology, and several experts suggested that the tables of contents of the SO_2 Symposium reveal the history of SO_2 control research. The second section of this chapter attempts to use these tables of contents to investigate this history to a limited extent, while the third section explores changes in the network of researchers defined by the SO_2 Symposium over time.

Inventive Activity Analysis

The purpose of this section is to understand changes in inventive activity over time, as analyzed by the topics of session papers presented at the SO_2 Symposium. In addition, this section deals with attribute data regarding authorship statistics. This section's efforts to link the content analysis of text with authorship analysis is in the tradition of Lievrouw (1987) and Hill (1999).[75] Relational data about authorship are dealt with in the next section on network analysis.[76]

Method

Analysis of the tables of contents of the SO_2 Symposium over time required a lengthy process of interlibrary loan requests and coding of the resulting conference proceedings. Each of the 1,116 papers presented in the eighteen conference proceedings obtained in this process was coded by year, session topic, paper number, paper title, authors, affiliations of authors, and geographic location of authors. Author affiliations were further coded for the following six

[75] Attribute data refers to "the behavior of agents … regarded as the properties, qualities, or characteristics which belong to them as individuals or groups (Scott, 1991, pg. 2)."
[76] Relational data are "the contacts, ties and connections, the group attachments and meetings, which relate one agent to another (Scott, 1991, pg. 2)." Network analysis techniques are a common method of analyzing relational data.

"affiliation types": trade associations, firms (general), universities, contract nonprofit research and development organizations, government agencies, and utilities.

The eighteen conference proceedings obtained included every SO_2 Symposium between 1973 and 1995, as well as the 1997 Mega Symposium and the 1984 and 1986 conferences on dry FGD and combined SO_2/NO_x removal technologies ("Dry Symposium"). Since the Mega Symposium cannot be directly compared with the SO_2 Symposium for many attributes because of its considerably reduced focus on SO_2, it was dropped from consideration for the results that follow. Similarly, the Dry Symposium cannot be directly compared with the SO_2 Symposium; some information about the session titles and number of papers presented in these conferences, however, was relevant to the history of FGD research emphases and will be included in selected results as indicated later. In addition, it might be expected that the 1985 and 1986 SO_2 Symposium conferences that were contemporary with the Dry Symposium conferences would not be comparable with other years of the SO_2 Symposium, since they were ostensibly missing the dry and combined SOx/Nox technologies of other symposia. In fact, these two conferences still included some sessions on dry technologies, and for this reason were considered comparable to the other SO_2 Symposium conferences.

Results and Implications

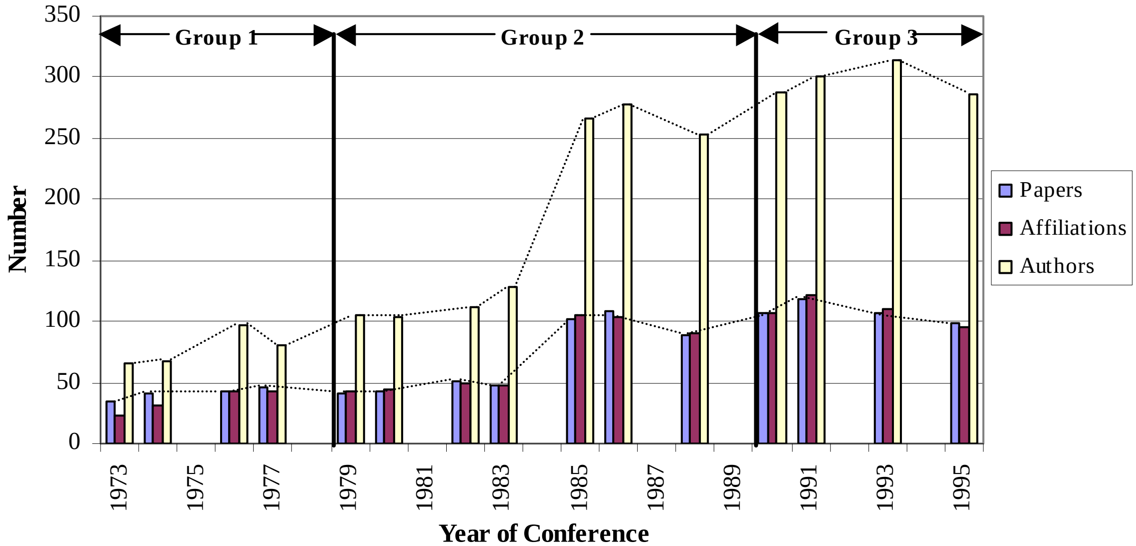
The influence of government actions on inventive activity in the SO_2 industrial-environmental innovation complex is likely to be seen in the research activity reported at the SO_2 Symposium, and particularly at those conferences that occurred around the time of a real or anticipated government action. In order to determine this effect, the fifteen conference proceedings under general consideration were divided into three groups demarked by the dates of the 1979 NSPS and 1990 CAA. These two government actions were selected because they had particular importance to the dominant technological options in SO_2 control in different periods of time. Thus, Group 1 conferences include those in 1973, 1974, 1976, and 1977, before serious consideration of the details of the 1979 NSPS. Group 2 conferences include those in 1979, 1980, 1982, 1983, 1985, 1986, and 1988, before serious consideration of the 1990 CAA.[77] Group 3 conferences include those in 1990, 1991, 1993, and 1995.

Three consistent indicators of research activity in the SO_2 industrial-environmental innovation complex and the size of the SO_2 researcher community over time are the number of papers presented in a symposium, the number of authors involved in the writing of papers, and the number of affiliations that these authors represent.[78] Figure 4.2 shows the breakdown of the 1,075 papers presented in the conferences in time periods 1-3. These 1,075 papers were written by 1,825 authors representing 501 affiliations.[79]

[77] When included in the results, the Dry Symposium conferences in 1984 and 1986 are part of Group 2.
[78] Another measure of the scale of the SO_2 researcher community over time is attendance figures at the various conferences. Unfortunately, these figures are not available for all the SO_2 Symposium conferences.
[79] Affiliations could not be determined for twenty-nine of the 112 coauthors in 1979.

FIGURE 4.2

Time Series of SO_2 Symposium Papers, Affiliations, and Authors



In Figure 4.2, the Dry Symposium conferences are merged with the two SO_2 Symposium conferences that occurred contemporaneously. The result is that the largest increase in conference activity occurred between 1983 and 1985, when the number of papers, affiliations, and authors more than doubled (i.e., increased from 200 to 220% for all three measures). When the SO_2 Symposium is considered alone (without the Dry Symposium conferences), conference activity doubles between 1986 and 1988 (i.e., increases 170% in the number of papers, 210% in the number of affiliations, and 190% in the number of authors). It is interesting to note that this increase in conference activity corresponds with the 1988 peaks seen in overall and pre-combustion patenting activity (seen earlier in Figure 3.8 and Figure 3.13).

It is clear from the above results that research activity in SO_2 control technology increased significantly between 1973 and 1995, with the largest rate of increase occurring in the mid- to late-1980s. The interview testimony in this chapter and in Chapter Three supports the idea that the mid-1980s was a time of growing anticipation of new acid rain regulation that was expected to focus on low to moderate SO_2 removal requirements. This would explain the split between the main SO_2 Symposium and the Dry Symposium at this time, since dry FGD technologies were of particular interest for low- to mid-level SO_2 removal (i.e., removal efficiencies of roughly 30-70%).

Table 4.3 demonstrates that the average number of conference papers, author affiliations, and authors all increased sharply between each of the three time periods of the SO_2 Symposium. The number of authors involved in conference presentations grew most rapidly, followed by growth in the number of affiliations they represent (which tripled over the full time period of interest). Table 4.4 shows the number of papers in each time period that had various numbers of authors. This table demonstrates that just as the total number of papers increased and the total number of authors increased, the total number of authors per paper also increased across the three time periods.

TABLE 4.3

Change in Number of Papers, Affiliations, and Authors between Groups Bounded by Government Actions

Conference Group	Average No. of Papers per Conference	Percent Increase from Previous Group	Average No. of Affiliations	Percent Increase from Previous Group	Average No. of Authors	Percent Increase from Previous Group
Group 1	41		35		78	
Group 2	69	69%	69	96%	178	128%
Group 3	108	57%	108	57%	297	67%

TABLE 4.4

Distribution of Paper Authors Across Time Period Groups

Conference Group Papers	Number of Authors								
	One	**Two**	**Three**	**Four**	**Five**	**Six**	**Seven**	**Eight**	**Nine**
Papers in Group 1	76 (47%)	42 (26%)	27 (17%)	12 (7%)	6 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Papers in Group 2	97 (20%)	109 (23%)	131 (27%)	72 (15%)	40 (8%)	24 (5%)	5 (1%)	2 (0%)	1 (0%)
Papers in Group 3	62 (14%)	87 (20%)	123 (29%)	86 (20%)	35 (8%)	23 (5%)	8 (2%)	5 (1%)	2 (0%)

Note: Percentages in parentheses are of all papers in a time period group.

Since the purpose of the SO_2 Symposium was to bring together actors in the SO_2 industrial-environmental innovation complex to tackle technical problems and advance the technology (primarily wet FGD), the research session titles of the SO_2 Symposium indicate the most important technical issues in SO_2 control as determined by contemporary experts. The majority of session titles reflect technical aspects of wet FGD lime/limestone systems, although some deal with other types of systems. Besides the technical session titles, some session titles reflect the concern of the SO_2 industrial-environmental innovation complex about SO_2 control economics and new and anticipated regulation. Table 4.5 displays the compiled list of eighteen recurring session titles of the SO_2 Symposium that are of interest for understanding the changes in research emphasis in SO_2 control over time. These session titles are grouped in Table 4.5 first by titles that cut across the three time period groups, and then by titles specific to each of these groups.

TABLE 4.5

Recurring SO_2 Symposium Session Titles of Interest, with Appearances and Notes

Session Focus	Number of Conference Appearances	SO_2 Symposium Appearances and Notes
Group 1, 2, and 3 Conferences (1973 to 1995)		
Byproduct (or waste) disposal and utilization	16	1973-95, except for 1979
Group 2 and 3 Conferences (1979 to 1995)		
Dry FGD technologies	12	1980 to 1995, including Dry Symposia
Combined SO_x/NO_x technologies	7	1982, 1983, 1990, 1991, 1995, Dry Symposia
Furnace sorbent injection technologies[a]	5	1983, 1988, 1990, 1991, 1984 Dry Symposia
Materials of FGD construction	5	1982, 1983, 1985, 1993, 1995
Organic acid/wet FGD additives	4	Organic acid 1983, 1985; additives 1986, 1993
"Reliability" specifically in session title	4	1982, improvements reported in 1985, 1986, 1990
Economic issues (not opening sessions)	8	1979, 1983, 1986, 1988, 1990, 1995, Dry Symposia
Legislation/regulation (not opening sessions)	5	1979, 1980, 1991, 1993, 1995
"Clean Coal" demonstrations	3	1986, 1991, 1993
"International Overview"	2	1988, 1990
Group 1 Conferences Only (1973 to 1977)		
Non-regenerable, regenerable processes	4	1973 to 1977
Group 2 Conferences Only (1979 to 1988)		
"Acid deposition" specifically in session title[b]	1	1986
Industrial applications	3	1979, 1980, 1986
Dual alkali	3	1982, 1983, 1985
"Chemistry" specifically in session title	2	1983, 1985
"Retrofitting" specifically in session title	3	1985, 1986, 1988
Group 3 Conferences Only (1990 to 1995)		
Air toxics	2	1993, 1995

[a] Two sessions on this topic occurred in both 1988, 1990.
[b] Two sessions on this topic occurred in 1986.

These session titles illustrate the changing technological focus of the SO_2 industrial-environmental innovation complex over time. "Byproduct (or waste) disposal and utilization" is a recurring topic throughout the time period, while furnace sorbent injection technologies and related dry technologies for SO_2 removal appeared only during the 1980s. The prevalence of these three subjects as research areas in the conference proceedings was not implied by the small share of patents assigned to these technologies. For example, 9% of the papers presented at the SO_2 Symposium over time occurred in a byproduct (or waste) disposal and utilization session, while only 4% of the 1,237 SO_2-related patents in the abstract-based dataset were attributed to desulfurization byproduct modification patents. According to a Z-test performed on these relative percentages, this difference is statistically significant at greater than a 99% confidence level.[80] Although materials of construction were not similarly separated out in the patent analysis, it is clear from these session titles that improvement in materials was an important research emphasis of the SO_2 control community. In addition, session titles focusing on dry FGD and furnace sorbent injection enhance the qualitative understanding of the 4% of patents assigned to sorbent modification for use in SO_2 removal systems.

SO_2 Symposium sessions regularly addressed economic and political issues relevant to the SO_2 control community over time. These issues were typically featured in the opening plenary sessions of each conference. Economic issues were further elaborated on as a separate session beginning in 1979, after the passage of the 1977 CAA. It is interesting to note the recurrence of specific legislation- and regulation-based sessions in the first conferences to follow the August 1977 CAA, the June 1979 NSPS, the November 1990 CAA, and the January 1995 start of Phase I of the 1990 CAA. In light of this phenomenon, the appearance in 1986 of the only SO_2 Symposium sessions with “acid deposition” in the titles seems to indicate that the research community in that year was considering SO_2 as a regional air pollutant that might soon be regulated to control acid rain. This supports the view that the peak in patent filing activity in 1988 was likely due to anticipation of an impending revised CAA that addressed SO_2 regulation in the context of acid rain.

For more details on these session titles and how they changed over time, Appendix F contains a complete list of the SO_2 Symposium session titles and the number of papers presented per session for each of the conferences in the three time period groups (including the Dry Symposium conferences).

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[80] The Z-test calculation is given in footnote 64 in Chapter Three.

Network Analysis

Background

The discussions of quantitative measures of innovation in this chapter and in Chapter Three have focused primarily on various inventive activities that helped to bring about the improvements in performance and cost of the commercially deployed FGD technologies documented in Chapter Two. The SO_2 Symposium, however, provides an opportunity for the study of diffusion in the SO_2 industrial-environmental innovation complex. Many researchers consider diffusion to be a process of communication and influence through which potential users become informed about the availability of new technologies and are persuaded to adopt these technologies. This occurs, in part, through interaction with previous users [for reviews, see Attewell (1996); Rogers (1995); and Tornatzky and Fleischer (1990); also see Carley (1990); (1995); and (1996)].

Classical diffusion studies that emphasize how diffusion is limited by the timing and pattern of communication, such as Coleman, Katz, and Menzel (1966), have been criticized for not distinguishing between two types of information that may be communicated in the diffusion process. In the first, "signaling" information, the existence and potential gains of a particular innovation are communicated. In the second, "know-how" information, the technical knowledge needed to use a complex innovation – such as FGD – is communicated.[81] A number of studies in the innovation literature demonstrate that know-how about complex technologies is not easily transferred between individuals at different organizations; often, supplemental productivity-enhancing know-how must be developed within the user organization [see Argote (1999, 144-88)

[81] In the innovation literature, scientific or technical "tacit knowledge" can be seen as an important element of know-how (see discussion in Senker and Faulkner (1996), which also includes a discussion of the importance of informal networks in the transfer of tacit knowledge from public-sector research institutions).

for a review]. Chapter Five will discuss one method by which this know-how is developed within a user organization: organizational learning by the operators of FGD technologies.

Earlier in this chapter, expert perceptions were related concerning the value of the SO_2 Symposium as a forum for the exchange of information about operating experience and technical know-how. From expert comments, it appears that the opportunities the conference provided for informal interpersonal meetings between researchers were particularly useful for this information exchange. Although studies have been done to assess cooperative research and development in the form of informal know-how trading [a classic example is von Hippel (1988)], the SO_2 Symposium proceedings do not provide archival information on informal interactions at the many hospitality suites, luncheons, and other informal gatherings at the conference. The coauthorship patterns of papers presented at the SO_2 Symposium, however, provide a proxy source of information on the channels of interpersonal and interorganizational knowledge flow facilitated by the conference over time.[82] For previous research use of paper coauthorship as a measure of collaboration, see such articles as Cockburn and Henderson (1998); Liebskind et. al. (1995); Tijssen and Korevaar (1997); Zucker, Darby, and Armstrong (1994); Zucker and Darby (1995); and Zucker, Darby, and Brewer (1997).

The various coauthorship arrangements of each SO_2 Symposium can be used to define a network of technological collaborators. Networks and collaboration have been extensively discussed in the innovation literature in the 1980s and 1990s. Networked, rather than independent, organizations have been particularly shown to have opportunities to benefit from knowledge transfer [see discussion in Argote (1999, pp. 166-68)]. Also in the 1980s and 1990s,

[82] Many studies have addressed knowledge flow channels, including Carley and Hill (forthcoming) and Carley (1999). One of the seminal works to address coauthorship networks across scientists as important for generating new innovation and new technology was Crane (1969). Argote (1999) reviews many other studies involving the mechanisms of knowledge transfer.

evolutionary economic models of science and technology policy emerged that analyzed developments in terms of “interacting and coevolving networks of institutions and technoeconomic infrastructures (Tijssen and Korevaar, 1997).” For a good review of both the sociological and economic approaches to networks and technological collaboration, see Coombs et. al. (1996).

Relatively little use has been made in the innovation literature, however, of the formal network analysis techniques developed originally in the fields of ethnology and sociometry [exceptions include such articles as Coleman, Katz, and Menzel (1957); Leoncini et. al. (1996); Rogers (1979); and Tijssen and Korevaar (1997)]. As defined in Leoncini et. al. (1996), “network analysis uses quantitative techniques derived from graph theory to study and describe the structure of interactions between given entities.” A comprehensive explanation of network analysis techniques will not be attempted here, since there are excellent reviews of the development of network analysis and guides to its use in research in sources such as Lincoln (1982), Scott (1991), and Wasserman and Faust (1997). Instead, these techniques will be discussed only in relationship to the method and results of the present analysis of the patterns of coauthorship within the SO_2 Symposium, and their relationship to government actions regarding SO_2 control.

Method

In this analysis, the basic relational data analyzed are the ties between the 1,825 authors of SO_2 Symposium papers between 1973 and 1995 that form as a result of paper coauthorship.[83] For a paper with three authors, there are three distinct ties between these authors because each

[83] The papers considered include those of the Dry Symposium conferences, which here are lumped together with the nearest SO_2 Symposium (as in Figure 4.2).

author is connected to each of the authors except him or herself. This is expressed mathematically in Equation 4.1.

EQUATION 4.1

Definition of Ties between Paper Authors

$$Ties = \frac{n*(n-1)}{2}$$

where

n = The number of authors on a paper

Table 4.6 echoes Table 4.4 in its depiction of the distribution of the potential number of ties between paper authors across the three time period groups. Yet this table does not reflect the actual number of ties between all the paper authors of the SO_2 Symposium because it does not take into consideration the fact that some authors write papers for more than one conference. Those authors that present papers at greater numbers of conferences can be considered more "important" to the direction and content of the SO_2 Symposium over time than other authors.

TABLE 4.6

Potential Ties between Paper Authors Across Time Period Groups and in Total

Potential Ties between Paper Authors across Time Period Groups										Total Number of Potential Ties (Discounting Authorship in Multiple Conferences)
	Number of Authors on Papers									
	One	*Two*	*Three*	*Four*	*Five*	*Six*	*Seven*	*Eight*	*Nine*	
Group 1	0	42	81	72	60	0	0	0	0	255
Group 2	0	109	393	432	400	360	105	56	36	1,891
Group 3	0	87	369	516	350	345	168	140	72	2,047
Total										4,193

Table 4.7 shows the incidence of authorship in multiple conferences of the SO_2 Symposium, in decreasing order of author importance. Table 4.7 also demonstrates the potential

size of networks defined by authors of varying importance.[84] Note the very large network that results if all 1,825 authors are considered. This network is also quite sparse across time, as 74% (1,355) of the 1,825 authors only write papers in one conference. A standard network analysis practice when dealing with a potentially very large and sparse network is to limit the number of authors considered in analysis (Carley, 2000). As a first step in this limitation process, agents with no ties to other agents, known as "isolates," are typically discarded. As a first step in limiting network size in this analysis, 92 authors who never had paper coauthors were discarded. As a second step, the 1,355 authors who presented papers in only one conference were also discarded. The total number of discarded authors at this stage was thus 1,366 authors, since 81 of the isolates also presented in only one conference.

TABLE 4.7

Authorship in Multiple Conferences (Listed in Decreasing Order of Author Importance to the SO_2 Symposium) and Effect on Potential Network Size

Number of Conferences Author Wrote Papers for	Percent of All Conferences Author Wrote Papers for	Number of Authors	Cumulative Number of Authors, according to Importance (= a)	Size of Potential Network between Cumulative Number of Important Authors (= a * (a - 1))
13	81%	1	1	0
12	75%	2	3	6
11	69%	1	4	12
10	63%	1	5	20
9	56%	9	14	182
8	50%	6	20	380
7	44%	9	29	812
6	38%	20	49	2,352
5	31%	29	78	6,006
4	25%	46	124	15,252
3	19%	100	224	49,952
2	13%	246	470	220,430
1	6%	1,355	1,825	3,328,800

[84] A network's size is defined by: (the number of authors) times (the number of authors minus one).

Ultimately, the core group of authors analyzed in this dissertation (labeled the "important" innovative actors, with their corresponding affiliations) was defined as those authors involved in writing papers for at least 50% of the SO_2 Symposium conferences held between 1973 and 1995. Table 4.8 lists these important innovative authors and their affiliations, as well as the six affiliation types represented by all of the authors in the network. These six affiliation types are assigned abbreviations in this table; these abbreviations are then used to help identify the important affiliations and authors in Table 4.8. An additional piece of data in Table 4.8 is the number of SO_2-related patents each affiliation or author holds in the abstract-based dataset. The majority of important affiliations hold patents in this dataset, although most important authors do not hold patents.

TABLE 4.8

Affiliation Types, Important Affiliations, and Important Authors in the SO_2 Symposium

Affiliation Types with Affiliation Type Abbreviations		Important Affiliations with Affiliation Type Abbreviation and Number of Abstract-Based Patents			Important Authors with Affiliation Type Abbreviation and Number of Abstract-Based Patents		
Trade Assoc.	(A)	Acurex Corp.	F	2	Ando, Jumpei	R	0
Contract R&D	(C)	Babcock & Wilcox Co.	F	33	Blythe, Gary M.	F	0
Firm	(F)	Bechtel Corp.	F	7	Dene, Charles E.	C	0
Government	(G)	Burns & McDonnell	F	0	Ellison, William	F	0
University	(U)	Chiyoda Corp.	F	4	Hargrove Jr., O.W.	F	0
Utility	(P)	Chuo University	U	0	Jones, Julian W.	G	0
		Combustion Engineering	F	25	Kaplan, Norman	G	0
		DOE Pittsburgh Energy Technology Ctr	G	38[a]	Laseke, Bernard A.	F	0
		Dravo Lime Co.	F	14	Maxwell, Michael A.	G	0
		EPA	G	4	Owens, David R.	U,F,C	0
		EPRI	C	18	Rhudy, Richard G.	C	0
		Ellison Consultants	F	0	Rochelle, Gary T.	U	2
		Louisville Gas & Electric	P	0	Rosenberg, Harvey S.	C,F	3
		Northern Indiana Public Service	P	0	Sedman, Charles B.	G	0
		Northern States Power Co.	P	4			
		Radian Corp.	F	0			
		Southern Company Services, Inc.	P	0			
		Stone & Webster Engineering Corp.	F	0			
		Tennessee Valley Authority	P	4			
		University of Texas at Austin	U	3			

[a] These patents are held by the entire DOE, rather than just the Pittsburgh Energy Technology Center.

Despite their lack of patented inventions, the fourteen important authors listed in Table 4.8 are clearly significant actors in the SO_2 research community. These fourteen authors not only presented in at least 50% of the SO_2 Symposium conferences, but were also coauthors on one-sixth of all the papers presented in the history of the SO_2 Symposium. Collectively, they coauthored with one-eighth of the 1,825 authors of SO_2 Symposium papers.

The following three sections present network analysis results concerning the strength of coauthorship ties among the affiliation types, important affiliations, and important authors listed in Table 4.8. The process of constructing network graphs for these data is described in Appendix G. Note that the full set of 1,825 authors is only considered in the analysis of the affiliation type by affiliation type network.

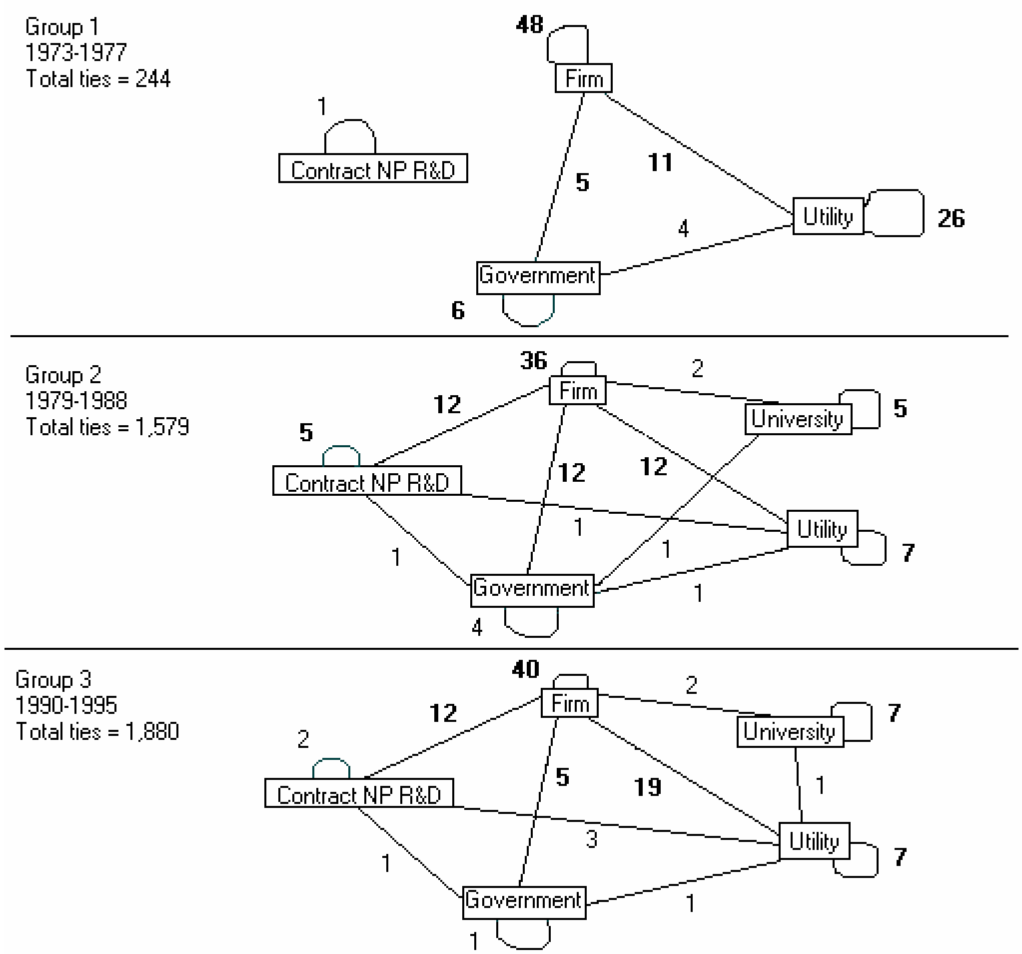
Affiliation Type by Affiliation Type Network Results

Figure 4.3 shows coauthorship ties between affiliation types, where each affiliation type is connected either reflexively (to the same affiliation type) or relationally (to other affiliation types) for at least 1% of all the coauthorship ties in each of the three time periods.[85] The numbers shown in this figure are the percentages of all coauthorship ties that occurred between researchers in the tied affiliation types during each time period. Group 1 conferences encompass 244 affiliation type ties, Group 2 conferences encompass 1,579 affiliation type ties, and Group 3 conferences encompass 1,880 affiliation type ties. Numbers in bold in Figure 4.3 indicate "strong" ties, which represent greater than 10% of all the coauthorship ties in each time period.

[85] Because they do not account for 1% of the ties in each period, trade associations are do not appear in this figure.

FIGURE 4.3

Evolving Coauthorship Ties between Affiliation Types for Three Time Period Groups



Notes: Numbers are percentages of total affiliation type coauthorship ties in each period. Numbers in bold are strong ties (greater than 10% of affiliation type ties).

The affiliation type network in the Group 1 conferences is quite different from that in the Group 2 and 3 conferences. In the Group 1 conferences (1973 to 1977), not every affiliation type is connected to others through coauthorship ties on papers. This is perhaps to be expected in this time period, which was marked by a particularly competitive SO_2 control market and litigation between regulated utilities and government.[86] In the affiliation type network in the Group 2 conferences (1979 to 1988), however, most affiliation types are connected, which provides evidence that a community of researchers is forming. It is interesting to note that this community emerged just after the passage of the 1977 CAA, which effectively required the utility industry to install FGD technology on all new and substantially modified capacity. The network formed in the Group 2 conferences remains fairly stable in the Group 3 conferences (1990 to 1995), although some density (defined here simply as the number of ties in the network) is lost. Nevertheless, no major changes are evident in the network after passage of the 1990 CAA, regardless of the initially high anticipated demand for FGD or the later absence of that demand.

With regard to specific features of the affiliation type network, the dominant characteristic is the consistently large reflexive coauthorship ties among private firms. Reflexive coauthorship ties among firm authors, which range from 36% to 48% of ties in all three conference time periods, are the strongest by far in the network. Reflexive coauthorship among utility authors is also strong in the Group 1 conference time period (26% of all ties), although it is diminished in the Group 2 and Group 3 conference time periods (7% of ties in both periods). The strength of utility coauthorship shifts from reflexive to relational ties between firms and utilities in these latter two periods, when this relational tie accounts for 12% of all ties in the Group 2 conferences and 19% of all ties in the Group 3 conferences.

[86] The perception of the scrubber market, which had experienced a tenfold increase in commercial scrubber unit installations between 1971-76 and a low but growing profitability between 1976-78, was that it would continue to improve due to new regulatory initiatives. This was an impetus to FGD equipment and services industry acquisitions and new entry (the number of firms in the utility FGD market between 1971-77 increased from one to thirteen).

It is interesting to compare the combined strength of firm and utility authorship to firm and utility patenting. In the patent analysis, firms and utilities were grouped together in one category, "firms," which accounted for 74% of the abstract-based SO_2-relevant patents. In comparison, reflexive firm ties, reflexive utility ties, and ties between firms and utilities alone account for 85% of the ties in the Group 1 conferences, 55% of the ties in the Group 2 conferences, and 66% of the ties in the Group 3 conferences. Firms and utilities have an even greater influence in coauthorship ties overall. If all the ties of firms and utilities are summed, these two affiliation types account for 94% of all Group 1 conference ties, 83% of all Group 2 conference ties, and 90% of all Group 3 conference ties.

In contrast with consideration of the strongest actors in the network, it is interesting to note which affiliation types are weak in a given time period. In the Group 1 conferences, researchers at contract nonprofit research and development organizations have no relational ties and relatively low reflexive ties. This is most likely due to the relative youth during the Group 1 conference years of the main contract nonprofit research and development organization involved in SO_2 control, EPRI.[87] Also in the Group 1 conferences, researchers at universities have no presence in the SO_2 Symposium coauthorship network. The emergence of both reflexive and relational ties between university researchers and other affiliation types is seen in the Group 2 conferences. This may have been the result both of trends in academic research and the contribution of one important author.

Table 4.9 presents the percentages of each affiliation type's total ties that are relational in nature, and how these percentages changed over the three time periods. It therefore provides information about the changing connectedness of this network and the changing influence of

[87] EPRI was founded in 1973 and it instituted its first FGD research program in 1974.

different affiliation types in this network. For example, it makes clear how involved in coauthorship the non-profit contract R&D organizations became over the years of the SO_2 Symposium. In both the Group 2 and 3 conferences (1979 to 1995), this affiliation type was one of the most connected to the overall coauthorship network. Table 4.9 also shows that utilities became more connected to other affiliation types through each of the three conference time periods. Firms similarly become more connected between the Group 1 (1973 to 1977) and Group 2 (1979 to 1988) conference time periods, although, as conveyed in the expert comments earlier in this chapter, firms became slightly less connected in the Group 3 (1990 to 1995) conference time period. Universities' connectedness level in the Group 2 conferences also declined in the Group 3 conferences.

TABLE 4.9

Relational Ties of Each Affiliation Type

	Group 1 Conferences 1973 to 1977 94 relational ties (39% of 244 total ties)	**Group 2 Conferences 1979 to 1988** 1,366 relational ties (87% of 1,579 total ties)	**Group 3 Conferences 1990 to 1995** 1,658 relational ties (88% of 1,880 total ties)
Contract Nonprofit R&D	0 (0%)	245 (76%)	296 (89%)
Firm	38 (25%)	598 (51%)	721 (49%)
Government	21 (58%)	237 (79%)	126 (89%)
University	NA	60 (43%)	65 (35%)
Utility	35 (36%)	226 (67%)	450 (78%)

Note: Percentages are of all of the ties of an affiliation type in a given time period.

According to Table 4.9, the most connected affiliation type throughout all three conference time periods was government. The importance for government of working together with utilities, equipment vendors, and others in research in SO_2 control technology is evidenced not only in this table, but also in the research histories of the EPA and DOE. The EPA's research history shows two good examples: first, it has been the longest sponsor of the SO_2 Symposium, and second, it was responsible for establishing the Shawnee test facility in April

1972. This facility, which was equipped with three 10 MW boilers and operated in partnership with Bechtel and TVA, was responsible for much of the early research in SO_2 control. The DOE's research history also shows a good example of government cooperation with industries in its management of the Clean Coal Technology (CCT) program beginning in December 1985. Industries provided over 50 percent of the cost of the CCT demonstrations and also played a major role in project definition and in ensuring eventual commercialization.

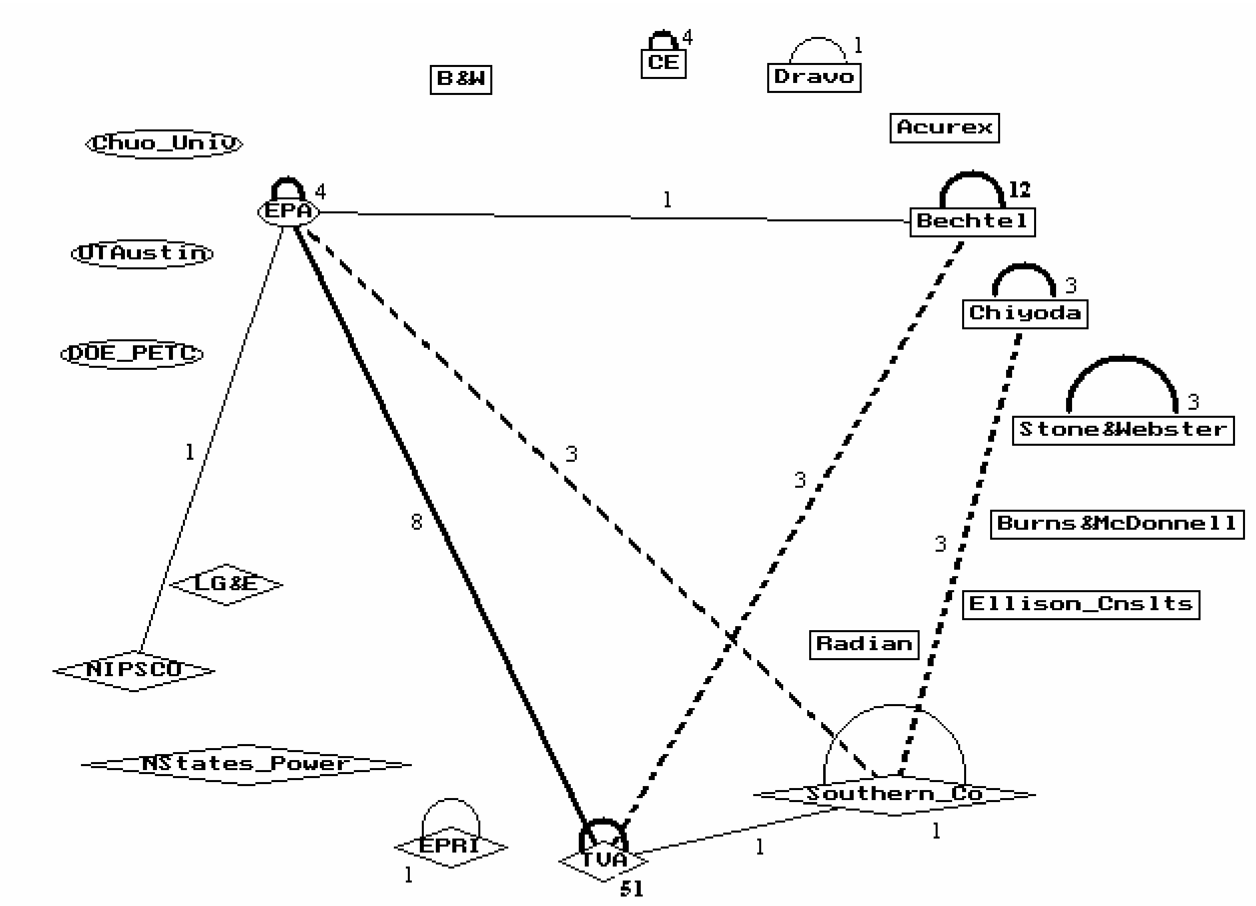
Important Organization by Important Organization Network Results

Figure 4.4, Figure 4.5, and Figure 4.6 are Krackplot 3.0 versions of the changing coauthorship patterns among the important affiliations listed in Table 4.8. The numbers accompanying various interorganizational ties in these figures again are the percentages (if at least equal to 1%) of all coauthorship ties that occurred between researchers in the important affiliations during each time period. Group 1 conferences encompass 75 important affiliation ties, Group 2 conferences encompass 481 important affiliation ties, and Group 3 conferences encompass 682 important affiliation ties. Numbers in bold indicate "strong" ties, which again are ties between important affiliations that represent at least 10% of all such ties in each time period. The boxes around the various affiliations indicate types of affiliations, in the following order (going clockwise): elliptical boxes indicate either universities or government agencies, rectangular boxes indicate firms including FGD vendors, boiler manufacturers, and consultants, and diamond boxes indicate utilities and contract nonprofit research and development organizations.[88]

[88] Krackplot 3.0 only has the graphic capability to show boxes of three different shapes.

FIGURE 4.4

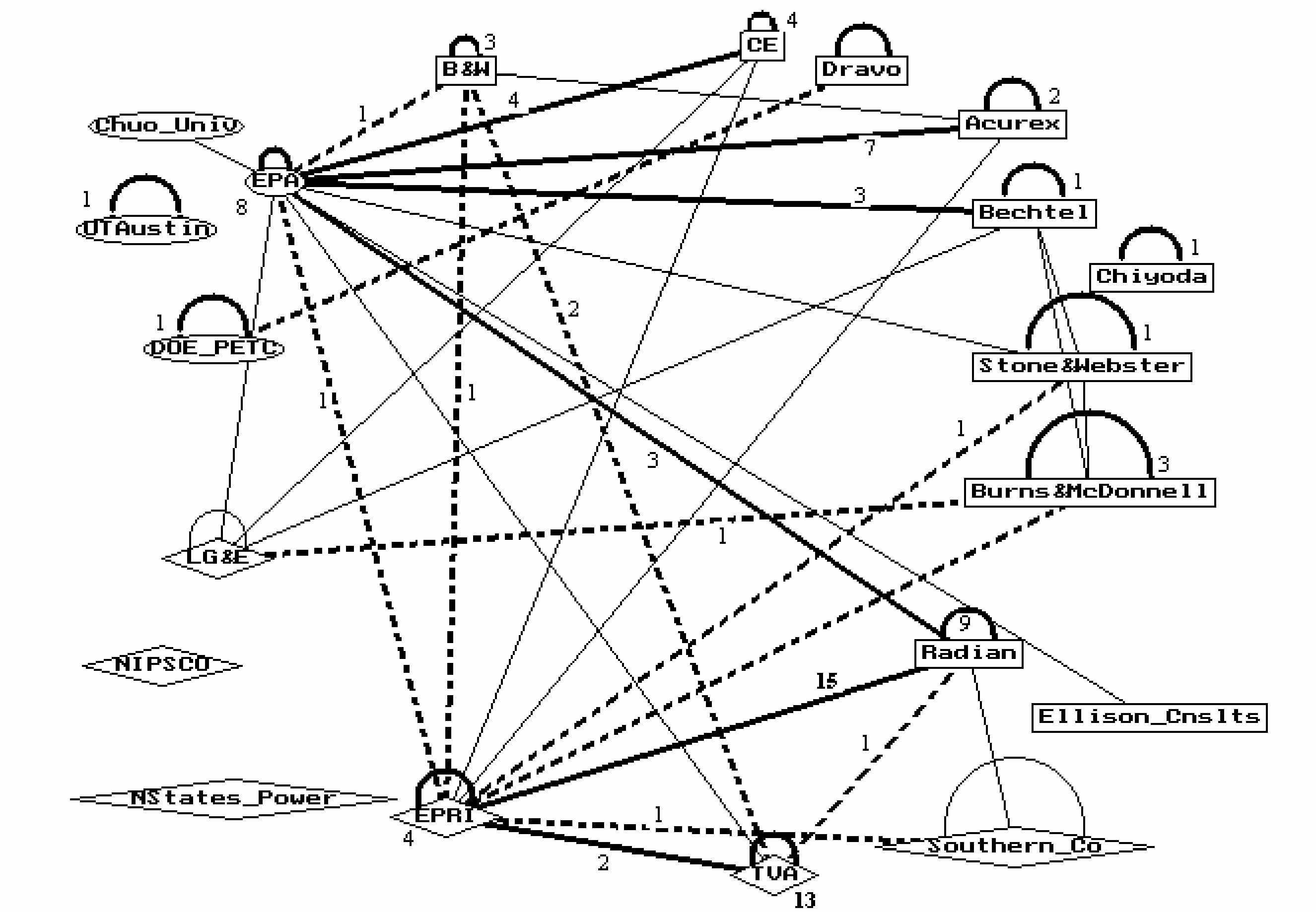
Coauthorship Ties between Important Affiliations in Group 1 Conferences (1973 to 1977)



Notes: Numbers are percentages of 75 total important affiliation coauthorship ties in this period. Numbers in bold are strong ties (greater than 10% of important affiliation ties).

FIGURE 4.5

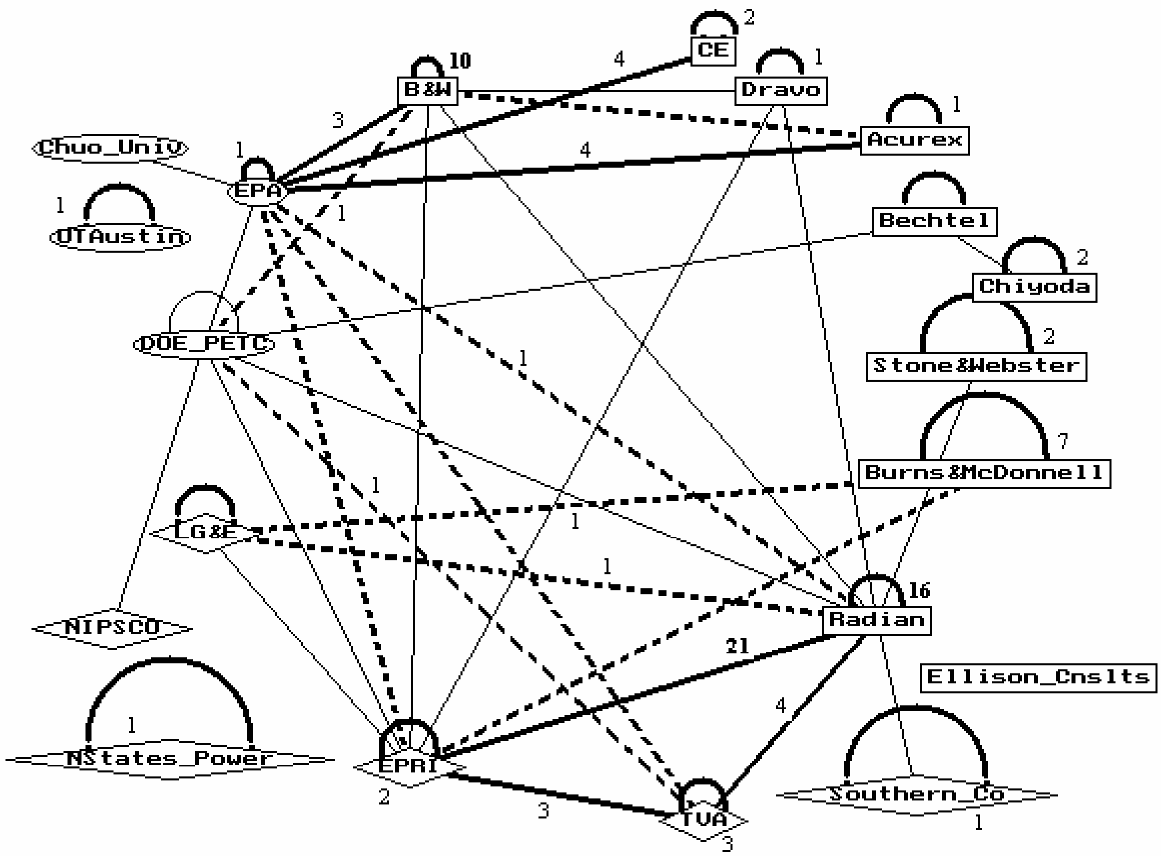
Coauthorship Ties between Important Affiliations in Group 2 Conferences (1979 to 1988)



Notes: Numbers are percentages of 481 total important affiliation coauthorship ties in this period. Numbers in bold are strong ties (greater than 10% of important affiliation ties).

FIGURE 4.6

Coauthorship Ties between Important Affiliations in Group 3 Conferences (1990 to 1995)



Notes: Numbers are percentages of 685 total important affiliation coauthorship ties in this period. Numbers in bold are strong ties (greater than 10% of important affiliation ties).

As was the case with Figure 4.4, Figure 4.5, and Figure 4.6, these figures show network relations becoming denser between the Group 1 and Group 2 conferences, and then stabilizing between the Group 2 and Group 3 conferences. The most prominent feature of these figures is the changing nature of strong ties, as summarized in Table 4.10. By far, the most dominant set of ties in any period is among researchers at the Tennessee Valley Authority in the 1973 to 1977 conference time period (51% of all important affiliation ties). Together with ties to other important government agencies, firms, and utilities, TVA accounts for two-thirds of all the important affiliation ties at the Group 1 conferences. TVA, again, partnered with EPA and Bechtel on the Shawnee test facility in the 1970s, and both of these partners are also strong players in the important affiliation coauthorship pattern of the Group 1 (1973 to 1977) conferences. EPA accounts for 17% and Bechtel accounts for 16% of all the ties between important affiliations in the Group 1 conferences (Bechtel's reflexive coauthorship ties alone account for 12% of important affiliation ties).

TABLE 4.10

Strong Coauthorship Ties between Important Affiliations

Group 1 Conferences (1973 to 1977)	**Group 2 Conferences (1979 to 1988)**	**Group 3 Conferences (1990 to 1995)**
TVA reflexive ties 38 (51%) of 75 important affiliation coauthorship ties (16% of 244 affiliation type ties of >1%)	TVA reflexive ties 63 (13%) of 481 important affiliation coauthorship ties (4% of 1,579 affiliation type ties of >1%)	Babcock & Wilcox reflexive ties 70 (10%) of 682 important affiliation coauthorship ties (4% of 1,880 affiliation type ties of >1%)
Bechtel reflexive ties 9 (12%) of 75 important affiliation coauthorship ties (4% of 244 affiliation type ties of >1%)	Radian to EPRI relational ties 74 (15%) of 481 important affiliation coauthorship ties (5% of 1,579 affiliation type ties of >1%)	Radian to EPRI relational ties 144 (21%) of 682 important affiliation coauthorship ties (8% of 1,880 affiliation type ties of >1%)
		Radian reflexive ties 111 (16%) of 682 important affiliation coauthorship ties (6% of 1,880 affiliation type ties of >1%)

TVA's dominance begins to fade in the Group 2 conference time period, and disappears altogether in the Group 3 conference time period. Meanwhile, the Radian-EPRI tie increases in dominance, from non-existent in the Group 1 conferences, to the most dominant tie in the Group 2 and 3 conferences. Radian's reflexive ties also become a strong factor in the Group 3 conferences. These observations indicate that TVA was a very significant player in the SO_2 industrial-environmental innovation complex in the 1970s, while EPRI and Radian were very significant players in the 1980s and 1990s.

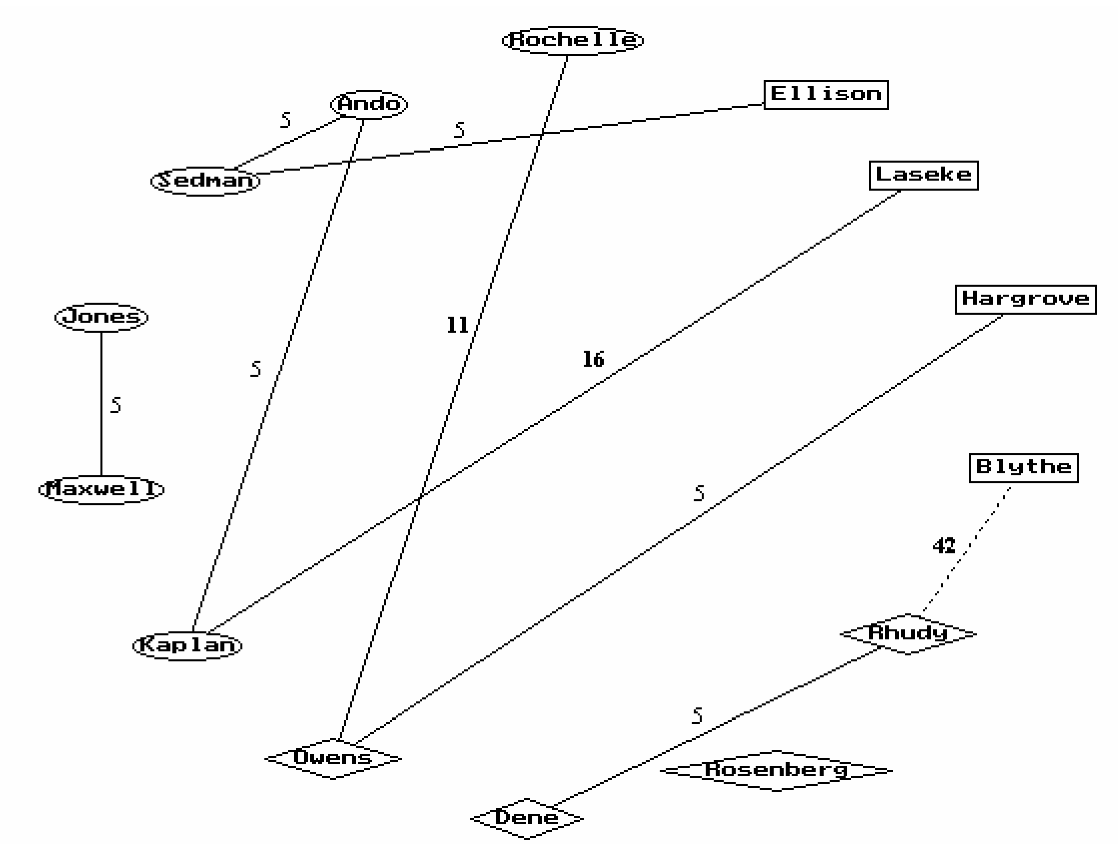
Another observation is that in both the Group 2 and 3 conferences, a few important affiliations were not connected to other important affiliations. In addition, several important organizations appear only in one or two time periods.

Important Author by Important Author Network Results

Figure 4.7 and Figure 4.8 show Krackplot 3.0 versions of the changing coauthorship pairings between the fourteen important authors listed in Table 4.8. Recall that these authors presented papers in over half of the SO_2 Symposium conferences and coauthored one-sixth of the conferences' 1,075 total papers with one-eighth of its 1,825 total authors. As these figures show, while these authors are highly connected within the general SO_2 research community, they had relatively little coauthorship interaction amongst themselves. The numbers accompanying various ties in these figures again are the percentages of all coauthorship ties that occurred between important authors during each time period. The Group 1 conferences had no coauthorship ties between these fourteen important authors; hence, there is no figure for the Group 1 conference time period of 1973 to 1977. The Group 2 conferences encompassed nineteen important author ties and the Group 3 conferences encompassed ten important author ties. Numbers in bold again indicate "strong" ties, which represent at least 10% of all the important author ties in the Group 2 conferences and at least 50% of these ties in the Group 3 conferences.[89] The boxes around the various author names indicate the affiliation types they were primarily associated with, in the following order (going clockwise): elliptical boxes indicate either universities or government agencies, rectangular boxes indicate firms including FGD vendors, boiler manufacturers, and consultants, and diamond boxes indicate utilities and contract nonprofit research and development organizations.

FIGURE 4.7

Coauthorship Ties Among Important Authors in Group 2 Conferences (1979 to 1988)

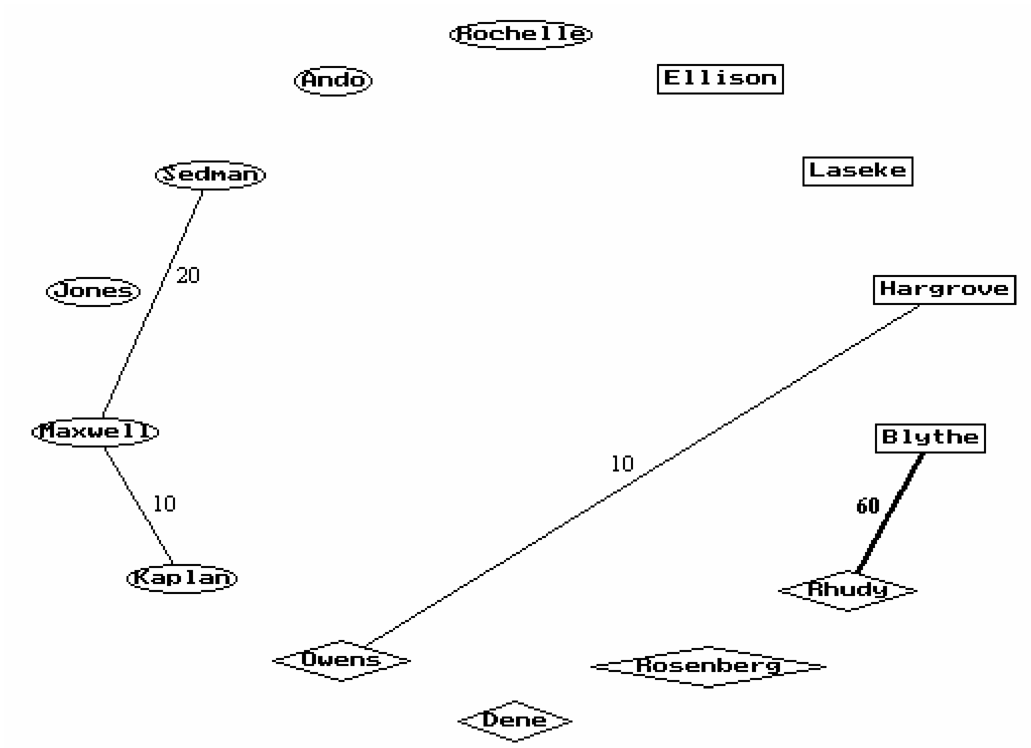


Notes: Numbers are percentages of nineteen total important author ties in this period. Numbers in bold are strong ties (greater than 10% of ties).

[89] This higher percentage cut-off for strong ties is a result of the concentration of strong important author ties in the Group 3 conferences.

FIGURE 4.8

Coauthorship Ties Among Important Authors in Group 3 Conferences (1990 to 1995)



Notes: Numbers are percentages of ten total important author ties in this period. The number in bold is a strong tie (greater than 50% of ties).

Whereas important affiliations coauthor papers together, important authors generally do not. Besides not coauthoring any papers together in the Group 1 (1973 to 1977) conference period, the important authors only coauthor together in the Group 3 (1990 to 1995) conference period in four distinct pairings. The most prominent of these pairings is that between Gary Blythe at the Radian Corporation and Richard Rhudy at EPRI. In the Group 2 (1979 to 1988) conference time period, important authors coauthor with one another a bit more often, with nine pairings of varying frequency strengths. The strongest tie in this period, as in the Group 3 (1990 to 1995) conference period, is the tie between Blythe and Rhudy. There are other strong ties in this period, however. Gary Rochelle at the University of Texas at Austin and David Owens at EPRI form one of these strong pairings, as do Bernard Laseke of PEDCo-Environmental Consultants, Inc. and Norman Kaplan at the EPA. The Laseke-Kaplan link is somewhat expected, since PEDCo-Environmental Consultants, Inc. ran a long-term database for the EPA on the commercial status of FGD technologies that frequently issued reports at the SO_2 Symposium.

Conclusions

In order to gain insights into the effects of government actions on the innovation process, this chapter has focused on research activity and communication patterns for the group of SO_2 control technology researchers that presented at the SO_2 Symposium between 1973 and 1995. Conference proceedings show that a large and diverse population of researchers presented papers in the SO_2 Symposium, with this population (and the number of papers they presented) increasing throughout the 1973 to 1995 time period. This population of authors was affiliated with such organization types as government, contract nonprofit research and development organizations, universities, utilities, and other types of firms.

As attested to by experts, the SO_2 Symposium was very important to the evolution of FGD technology. Although it was probably more influential before the 1990s, this conference facilitated a high level of information exchange in the SO_2 industrial-environmental innovation complex in such areas as operating experience, technical know-how, and new research. The information exchange facilitated particularly by the SO_2 Symposium's venues for informal meetings between researchers was observed to be fast and to have an international reach throughout the 1973 to 1995 time period.

The information contained in the SO_2 Symposium conference proceedings provides technical, organizational, and political insights into this information exchange and how it has and has not changed over the years. Technically, one constant throughout the 1973 to 1995 time period was the emphasis contemporaneous researchers placed on the disposal or utilization of FGD byproducts, a topic that has rated sessions in all but one of the SO_2 Symposium conferences analyzed. This fact adds another qualitative dimension to the understanding of technical change in SO_2 control as measured by patenting activity in Chapter Three, as does the prominence of session titles pertaining to furnace sorbent injection technologies, materials of construction, and chemical additives. The prominence of dry FGD technologies in the SO_2 Symposium, particularly in the 1979 to 1988 period when these technologies and combined SO_2/NO_x technologies were split into their own conference, is another important insight into inventive activity provided by these conference proceedings.

Organizationally, fourteen authors and twenty organizations emerged as consistently important to the diffusion of SO_2 control technology research due to their coauthorship of research papers presented in over 50% of the SO_2 Symposium conferences. The fourteen important authors further excelled both in the total number of papers they coauthored (one-sixth of the total 1,075) and in the total number of authors they wrote papers with (one-eighth of the 1,825 total). The number of authors that presented over time increased faster than the number of papers that were presented, which shows that the research community defined by the SO_2 Symposium grew over time.

Network analysis of conference paper coauthorship data provided further insight into the growth of this research community. In the Group 1 (1973 to 1977) conference time period, not every type of innovating organization reached beyond its boundaries in writing papers for the SO_2 Symposium.[90] This was not true in the Group 2 (1979 to 1988) or Group 3 (1990 to 1995) conference time periods, which is further evidence of SO_2 community growth over time. Information about important organizations also shows changes in the SO_2 community. Analysis showed that TVA was a very significant player in the SO_2 industrial-environmental innovation complex in the 1970s, while EPRI and Radian were very significant players in the 1980s and 1990s.[91] Analysis of coauthorship patterns among important authors revealed that important authors generally do not coauthor papers together, despite their centrality in the overall coauthorship network.

Politically, the SO_2 Symposium provides three lines of evidence that the information exchange that occurred through the conference was consistently influenced by the actions of government. The first line of evidence for this is the observation by expert L that the SO_2 Symposium was particularly popular right before and during the implementation of the 1977 and 1990 CAAs, as utilities needed to determine their technological options. The second line of evidence is the growth of coauthorship networks from the Group 1 (1973 to 1977) conferences to

[90] For example, universities and contract non-profit R&D organizations like Battelle and EPRI only had reflexive connections in this time period.
[91] Bechtel played a strong, but less significant role in the 1970s, as did Babcock & Wilcox in the 1990s.

the Group 2 (1979 to 1988) conferences for all affiliation types, important organizations, and important authors. This growth in the SO_2 research community after the 1977 CAA and 1979 NSPS befits a time period in which FGD technologies had been basically mandated for all new and significantly modified sources.

The third, and most important, line of evidence that the knowledge shared at the SO_2 Symposium was influenced by government actions is the existence of specific legislation- and regulation-based session titles in the proceedings of each conference that followed the passage of a national SO_2-related legislative or regulatory event.[92] The 1986 sessions on acid deposition retrofit applications and acid deposition issues are particularly informative on this account, as they were the only sessions in the history of the conference to treat acid rain in the session title. This fact, as well as the particularly large increase in conference research activity in the mid- to late-1980s, corresponds well with the attempts made in Congress in 1982, 1984, 1986, and 1987 to strengthen U.S. air legislation with respect to acid rain. All of these facts help to build the case, first posed in Chapter Three as an explanation of a 1988 peak in patent filing activity, that the SO_2 industrial-environmental innovation complex greatly anticipated pending acid rain-related regulation in the mid-1980s.

The SO_2 Symposium session titles and coauthorship patterns have been used in this chapter to increase the understanding of the technological and organizational changes accompanying the historical innovation processes underlying SO_2 control technologies. The next chapter will attempt to address the importance of government actions in innovation in SO_2 control by focusing on knowledge gained from operating experience and its contribution to innovative outcomes.

[92] These sessions were in addition to any discussions of government activity held in the opening plenary sessions.

Chapter 5 Learning Curve Analysis

Studies have shown that a considerable amount of innovative activity can be traced to the experience of operating personnel [for a discussion, see Cohen and Levin (1989)]. The information about technical operations developed by these personnel is likely to be especially important for both potential and actual utility adopters of FGD systems.[93] For potential utility users, operating experience information could contribute to the adoption decision and thus facilitate technology diffusion. For current utility users, this information could help them modify the operations of systems they already own in order to improve performance and/or reduce operating costs. It is this latter innovative activity – a type of post-adoption innovative activity referred to here as "learning by doing" – that is the focus of this chapter.

As mentioned in Chapter One, this type of innovative activity is discussed under a variety of names in the literature, including "learning by doing," "learning by using," or "reinvention." Learning by using or doing is the result of the observation of "difficulties or opportunities that emerge during the operation" of new equipment (Rosenberg, 1994). "Reinvention" is "the degree to which an innovation is changed or modified by the user in the process of its adoption and implementation (Rogers, 1995)." The basic principle behind learning by doing, however, is that production experience creates knowledge that improves productivity (Arrow, 1962). An important part of this knowledge acquired through organizational experience is tacit know-how (see Nonaka, 1991; Polanyi, 1966; Berry and Broadbent, 1984).

The SO_2 industrial-environmental innovation complex is a good candidate for studying learning by doing. According to Argote (1999, p. 199), learning by doing is especially effective

[93] The importance of this type of information to the development of FGD technology was indicated in Chapter Four in the expert discussions about the types of information exchanged in the SO_2 Symposium.

in industries in which "knowledge is uncertain, not well-understood, and highly dependent on the organizational context." The FGD equipment and services industry appears to be such an industry. The FGD operating problems of the 1970s and the fact that the knowledge required to simulate the effects and interactions of specific FGD process variables did not accumulate until the mid-1980s indicate that the knowledge base for FGD was historically uncertain and poorly understood. As discussed in the interview testimony to follow in this chapter, FGD operators were known for helping to improve the technology through trial and error, a behavior that fits the "improvisational approaches" proven to be effective in firms with an uncertain knowledge base. FGD-related knowledge is also highly "context-dependent," or likely to vary as a function of features which vary significantly from firm to firm, such as the structures and technologies in place at a given utility. The context-dependent nature of SO_2 control technology is also elaborated upon in interview testimony in this chapter. For example, one expert explained that FGD performance sometimes varies even at the plant level within a given utility company.

Given that post-adoption innovation appears likely to occur in the FGD equipment and services industry, it is important to find a measure that will capture it. Technological change attributed to operating experience is often measured through "learning curves," in which unit costs (or other features) of production decrease at a decreasing rate with increasing cumulative output.[94] As reviewed in Argote (1999, p. 1), learning curves have been found in a variety of industries, including those in which discrete products like ships, aircraft, trucks, and semiconductors are produced, as well as in industries in which continuous products like refined

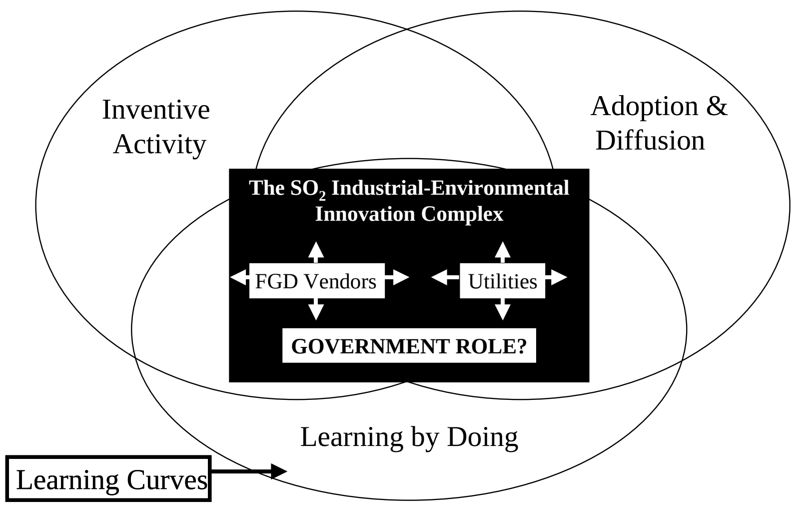
[94] This phenomenon is also sometimes given the names "progress curves" and "experience curves."

petroleum and chemicals are produced. In the electric power industry, learning curves have been found to characterize the construction cost of power plants (Joskow & Rose, 1985; Zimmerman, 1992) and plant operating reliability (Joskow & Rozanski, 1979).

This chapter focuses on searching for the existence of learning curves in the SO_2 industrial-environmental innovation complex in order to gain insight into the innovative activity of learning by doing in this complex (see Figure 5.1). If learning curves can be demonstrated in FGD technology and learning by doing is thus shown to have an important role in innovation in SO_2 control, it may ultimately be possible to link learning by doing to government actions ranging from regulation to knowledge transfer mechanisms such as the SO_2 Symposium.

FIGURE 5.1

Learning Curves as a Measure of Post-Adoption Innovation



The classical form of an organizational learning curve (Argote, 1999, pg. 13) is given in Equation 5.1. The estimation of this equation allows the empirical assessment of whether organizational behavior has changed as a function of experience. The estimation of the learning rate, b, in this equation can be used to calculate the progress ratio ($P = 2^{-b}$), or the rate at which unit costs decline each time cumulative output doubles (Argote, 1999, pg. 18). A progress ratio of 80%, for example, means that unit costs are reduced to 80% of their value each time cumulative production doubles. In a study by Dutton and Thomas (1984), progress ratios were shown to vary from 55% to 107% for over one hundred field studies in a variety of production programs in industries including electronics, machine tools, papermaking, aircraft, steel, and automotive.[95] The most frequently observed progress ratio in these industries, however, was 80% (Argote, 1999, p. 19).

EQUATION 5.1

The Classical Form of an Organizational Learning Curve

$$y_i = a x_i^{-b}$$

where:

y = the number of labor hours required to produce the ith unit
a = the number of labor hours required to produce the first unit
x = the cumulative number of units produced through time period i
b = the learning rate
i = a time subscript

It is important to note that learning curves typically use the predictor variable of cumulative output to reflect operating experience at a particular organization (or unit of an organization). As discussed in Argote (1999, pg. 15), as organizations acquire operating experience, "members might learn who is good at what, how to structure their work better, or how to improve the layout of the production area." These and other types of learning by doing activities are generally not included in direct organizational investments in technology. Predictor variables other than cumulative output have the potential to confuse the effects of learning by doing activities with the effects of other innovative processes that may be the result of more direct organizational investments. For example, the predictor variable of calendar time reflects

[95] Progress ratios over 100% indicate situations in which unit costs increase rather than decrease with cumulative output.

general technological advances in the external environment that may result in unit cost improvements at an organization that are indistinguishable from the effects of learning by doing (Solow, 1957).[96]

In this dissertation, learning curve analysis focuses strictly on the effects of learning by doing activities (resulting from operating experience) on FGD performance improvements by limiting the predictor and performance variables of Equation 5.1 to installed technologies. This is a departure from the way "learning curves" are often analyzed in the environmental technology literature. For example, Harmon (2000, pg. 8) attributes the cost decline in the learning curve equation to "a combination of production improvements (process innovations, learning effects, and scaling efforts), product development (product innovation, product redesign, and product standardization), and decreases in process input costs (parts and materials)." Harmon thus lumps together many innovative processes for consideration in his learning curve analysis, rather than limiting his analysis to the effects of the post-adoption innovative activity of learning by doing. As a result, his analysis of performance improvements does not distinguish between learning by doing effects over time on a single generation of technology versus overall innovation effects that manifest themselves in multiple generations of technology. In the framework of this dissertation, however, this distinction is made. Learning by doing effects on a single generation of technology are considered in this chapter, while the effects of the full set of innovative processes relevant to SO_2 control technologies on multiple generations of technology are considered at the end of Chapter Two in what is referred to as a "generational analysis."

The remainder of this chapter is divided into three sections. The first section relates expert opinion about the "big picture" behind the evolution of FGD technology, particularly as it

[96] As "general technological improvements," Argote (1999) gives the examples of improvements in materials properties and increases in computing power as time passes.

pertains to the role of operating experience in advancing the technology. The second section uses a learning curve methodology to analyze the operating experiences in the 1985 to 1997 period of U.S. FGD systems brought into service between 1971 and 1985. The third and final section discusses conclusions and possible future work in understanding the role of learning by doing in the SO_2 industrial-environmental innovation complex.

Perception of the Importance of Operating Experience

Operating experience was considered an essential part of the experts' descriptions of the story behind improvements in SO_2 control technology over the last thirty years.[97] As part of the interview protocol, therefore, experts were prompted for information regarding the importance of operating experience only if they did not address it fully in the course of relating this story. Of the twelve experts interviewed, nine had to be prompted.

In the experts' discussions of operating experience – ranging from the problems of the 1970s (touched upon by experts A, B, E, F, G, H, I, J, K, and L) to the building of a positive track record that is helping to change perceptions about FGD today – one major theme emerges. The experts describe complementary and interacting roles for both the operators and designers of FGD systems in advancing the technology over the last thirty years. Experts B and H characterized this relationship between operators and designers as *essential* to the advancement of FGD technology.

The experts paid special attention to the actions of FGD operators when faced with the operating problems of the 1970s. Utilities were credited with two major technological developments during this time period. First, expert E related that the Canadian utility Ontario

[97] The characteristics of the twelve experts interviewed appear in Table 1.1, where they are listed in conjunction with their identification labels in the dissertation.

Hydro developed the very important spray tower absorber that was later sold by General Electric Environmental Services (GEESI, now Marsulex) after the inventor went to work for GEESI.[98] Second, expert I explained that an engineer at Louisville Gas & Electric, either "by accident or by extremely clever intuition," was the first in the U.S. to get a scrubber working without scaling by using the inhibited oxidation effect. This scrubber, which expert I explained was built as a result of a county-level regulation, used carbide lime, a byproduct of a method of acetylene manufacture, as a reagent. Battelle, EPA, and Radian all later investigated carbide lime to understand its properties. This led to better understanding of inhibited oxidation and the usefulness of thiosulfate as a reagent.

Most of the other activities of utility personnel faced with the operating problems of the 1970s did not have as clearly identified benefits as the activities in these two examples, according to the experts. Expert D observed that FGD operators at plants within a utility sometimes learned to operate FGD systems more effectively than those at other plants owned by that utility. This knowledge was not always transferred across the utility either because of "islands" or "one plant wanting to be more efficient than the other."[99] Expert H identified operating personnel as helping to improve FGD technology through trial and error and testing in such areas as mist eliminator improvements and the development of corrosion-resistant materials and equipment. The testing of systems was a particularly important technology research area in which operators and designers interacted. As related by expert K, real time data on emissions and FGD chemistry were not available in the 1960s and 1970s, which hindered the development of more reliable and efficient scrubbers. Expert K explained that standard chemical technologies

[98] He was clearly appreciated by his new employer since he eventually became executive vice president.
[99] Note that competition among organizational subunits is a primary factor in impeding knowledge transfer within an organization [see Argote (1999, p. 177) for a brief review and discussion].

developed in the laboratory were unable to work for long in harsh scrubber environments, so cooperation between operators and outside FGD researchers was essential to developing better understanding of FGD chemistry.

A barrier to this cooperation was operator distrust of outside researchers. Expert H related that operators did not always believe that researchers "knew what we were talking about." This is not surprising considering the great efforts to which utility operators had to go to compensate for the operating problems of the early scrubbers. Experts G, H, and K all described some of the physical activities involved in this compensation and how these activities translated into higher maintenance costs for the utilities. Expert G explained that annual maintenance costs were "tremendous" and unpredictable in the early days, as "things dissolved away and pieces of ductwork fell off and we found big holes in them." Manpower needs were also particularly high when utilities treated scrubbers "as a piece of auxiliary equipment" that the boiler operators were told to make run. Expert G described scrubbers running for a few days at a time until they plugged up and then had to be shoveled out and worked on by maintenance personnel for one to two weeks in order to make them run again. Experts H and K similarly described high maintenance costs in the 1970s due to the large number of operating personnel needed to take scrubbers down, clean them, and replace parts. In one case, expert K told of a utility using about forty people in a shift, each with different jobs such as replacing nozzles or fan blades, in order to take a module off-line and service it for twenty-four hours before its next use. Expert K also related that utilities used jackhammers or small dynamite charges to clear out clogged scrubbers.[100]

[100] This was not a radical process for boiler operators, since they used similar charges to remove slag from the heat transfer surfaces inside boilers.

The magnitude of the operating problems experienced in the 1970s provided a strong incentive for utilities to resolve these operating problems. This incentive was reflected in the research priorities of many organizations involved in the SO_2 industrial-environmental innovation complex, and especially in those of EPRI (which was responsible for conducting research for its utility members). Experts A, F, J, and L all explained that the research priorities thus established in SO_2 control technology resulted in the development of a better understanding of the process chemistry of the scrubber system. Expert A specifically mentioned that an improved understanding of phase equilibria, dissolution kinetics, and precipitation resulted from these research priorities. Additional improvements occurred in materials, according to expert J, and in instrumentation, according to expert L.

New technologies evolved from these improvements. Experts E and J described a simplification in design that made the next generation of scrubbers (following early systems such as those using marble bed absorbers) much easier for utilities to operate. Expert A also stated that spray drying became popular in part because it demanded less of operators: "the liquid-based chemistry was less important and you could control it basically just by turning the knob, by adding more lime, [and] running high recycle rates." In the 1980s, utilities particularly considered ease of use important and were willing to pay higher capital costs for reliable wet systems. Expert A described "gold plated" scrubbers installed in this period that employed both higher quality alloys to reduce operating problems and more redundant designs than earlier scrubbers. As scrubbers evolved in the 1990s and reliability increased, however, capital costs declined since firms were able to dispose with redundancy.[101] Operating and maintenance costs for later scrubbers were also considerably lower than in earlier models.

[101] According to expert K, some of these cost savings were negated a bit by the addition of sophisticated equipment.

Experts D, G, and K explained that as FGD technology evolved, the training and selection of operating personnel changed. Expert G participated in this trend. In the early 1980s, he created a more dedicated staff that would treat the scrubber as a chemical plant and achieve higher reliability and slightly higher removal efficiencies. He took people who had been rotating through power plant operations and created a separate job category for them as chemical operators. This entailed specialized training on how to run a scrubber and how the chemistry behind it worked. Expert K similarly described a transition to a more dedicated staff in the utilities he visited. In 1978, the utility teams he met typically involved a mechanical engineer who supervised boiler-operating personnel to also run scrubbers. In the late 1990s, utility FGD teams involve chemists, chemical engineers, and trained instrument technicians, among others, which is a team composition that Expert K first saw in Germany in the 1980s.

Experts H and K also mentioned that the size of operating personnel teams has decreased over the years. This yielded operating cost savings; but in expert H's view, the number of engineers assigned to support FGD systems is "notoriously" low when compared to the engineering support provided for chemical plants of similar value in the chemical industry. Expert H stated that he believed that employing more engineers would likely result in money-making opportunities for the utilities, which have based their engineering staffing decisions not on these opportunities but on the smaller number of "fires" (i.e., problems) that FGD operators had to put out in the 1990s.

The additional enhancements that operating personnel can potentially make in the functioning of scrubbers are now being threatened due to increased personnel turnover as a result of utility deregulation and restructuring, according to experts D and G. Expert D explained that turnover is high both in operating personnel within utilities as well as in personnel within vendor firms. Particularly in Southeast Asia, where new scrubbers are being installed and no track record exists, mistakes from the past are being repeated, according to expert D. Both experts D and G, however, argued that this phenomenon is occurring in the U.S. as well.

Both experts emphasized that a mechanism of technology transfer for new operators is very important, and both mentioned conferences as one such mechanism. Both experts saw the apparent success of conferences as a technology transfer mechanism as under threat, however, due to restructuring in the electric utility industry. Expert D explained that plant cutbacks have changed the audience at the SO_2 (now Mega) Symposium, so that considerably fewer power plant superintendents, FGD superintendents, and FGD operators attended in the 1990s than in the early 1980s. Similarly, utility deregulation has made it more difficult to organize the "FGD User's Conference" expert G described in Chapter Four.

In summary, experts perceive that operating experience was important to the evolution of FGD technology. They relate that both major and incremental technological developments arose from operating experience, and particularly from the difficulties FGD operators faced in the 1970s. Such developments are reflected in the performance improvements and cost reductions for new systems seen earlier in Chapter Two (Figure 2.14 and Figure 2.15). These are the "generational" improvements noted previously. It is not clear, however, if measurable FGD performance improvements can be observed as a result of learning by doing activities. The next section deals with this issue in the effort to identify learning curve effects in utility FGD systems.

Learning Curve Analysis

The purpose of learning curve analysis for SO_2 control technology is to investigate whether FGD operating experience resulted in a measurable improvement in technological performance. Such a demonstration of the importance of learning by doing to innovation in FGD technology is the first step in investigating the influence of government action on learning by doing activities in SO_2 control. Unfortunately, this first step is highly dependent on the data available for learning curve analysis and the potential predictor and performance variables these data provide.

The data source used in this analysis was the EIA-767 form collected by the Energy Information Administration (EIA) of the Department of Energy since 1974 from all utility boilers above 50 MWe in size (Energy Information Administration, 1999). These data are currently available in computerized format from the EIA only for the operating years 1985 through 1997. This limits the scope of analysis for three reasons. First, the number of annual data points available to generate time series is small, which restricts the statistical power of learning curve regressions. Second, these annual data points fall relatively late in the development of FGD technology, which limits the opportunities to observe FGD performance improvements. Third, the time frame of analysis constricts the applicability of the potential findings of this analysis if these findings are to be directly compared to the major government regulatory actions in SO_2 control. Only one of these actions, the 1990 CAA, occurred during this time period.

Despite these problems, the EIA-767 dataset was analyzed for learning curves because it provided a wide range of consistent data. Table 5.1 lists some of the data in the EIA-767 dataset that were considered potentially relevant to the choice of predictor and performance variables that might result in demonstrable effects of learning by doing on FGD technological improvements. The cumulative output of an FGD system can be considered as the desulfurized gas that results from the combustion of fuel in the output of electrical generation. From the EIA-767 data, three potential information sources emerged that were hypothesized to be useful in expressing this output. For each power plant boiler unit, these were: (1) the amount of coal burned, (2) the amount of sulfur in the coals burned, and (3) the amount of electricity generated. Similarly, four potential information sources were hypothesized to be useful for the FGD performance variables that might demonstrate learning curve effects. For each FGD unit, these were: (1) the amount of sorbent used, (2) the electrical energy consumed, (3) the operating and maintenance costs experienced in the area of "labor and supervision," and (4) the operating and maintenance costs experienced in the area of "maintenance and all other costs."

TABLE 5.1

Some of the Relevant Data in the EIA-767 Dataset

Type of Data	Specific Information
Identifiers	Plant, boiler, and FGD units
Non-FGD Operating Data	Total annual coal burned
	Total sulfur content of coal
	Maximum generator nameplate rating
	Annual electrical generation
FGD Operating Data	Manufacturer and type of FGD
	Type of sorbent
	Operating status
	Initial inservice date
	Annual total hours inservice
	Estimated removal efficiency under full load
	Estimated removal efficiency under annual operating factor
	Amount of sorbent used
	Electrical energy consumed
	Operating & maintenance expenditures broken down by category
	Installed cost broken down by category
	Estimated FGD waste and salable byproduct produced
	Annual pond and landfill requirement
	Design fuel specifications for ash and sulfur
	FGD specifications at 100% load broken down by category

Source: Energy Information Administration, 1999

The first step in analysis was to translate these variables from the raw EIA-767 dataset into usable form.[102] The next step was to estimate learning curve effects using these variables on data for power plants with FGD system inservice dates before January 1, 1986. This set of eighty-eight plants had thirteen years of operating data in the years 1985 through 1997, which was the longest continuous operating period available in the EIA-767 dataset. Learning curve estimation of this full set of plant data using predictor and performance variable combinations based on the seven variables chosen might prove inefficient, however, if the variables chosen did not give signals of sufficient size. For this reason, a pilot set of eighteen utility plants with the popular spray tower, limestone sorbent type of FGD (the largest group of plants likely to exhibit similar effects based on operating parameters specific to the type of FGD unit) was analyzed first.

Equation 5.2 gives the learning curve equations estimated for some of the different variable combinations considered in analysis of these eighteen plants. Missing data affected the total number of plants considered in a number of variable combinations, as noted. Equation 5.2 also gives the condition for acceptance of the existence of a learning curve; if the coefficient of the X-variable (the value of the learning rate) is negative and statistically significant, learning is said to occur (see Argote, 1999). Note that the basic equation in Equation 5.2 is a logarithmic form of Equation 5.1 that facilitates ordinary least-squares regression. The X-variable in this equation is a proxy for knowledge acquired through production. It is computed by summing the total units of output produced from the start of production up to, but not including, the current year. In order to generate the appropriate X-variable data points, annual power plant data were

[102] Note that the original computer programs designed to tabulate the EIA-767 data were written for computers circa 1974, so the EIA-767 data had to be translated into a database-accessible format using the process described in Appendix D.

summed over the appropriate part of the 1985 to 1997 period, and the logarithm was computed. Each data point was lagged so that the value for year *i* was the value of year (*i*-1). The Y-variable data points were computed first by dividing the *i*th year's FGD performance variable by the cumulative output for the *i*th year, then by taking the logarithm.

EQUATION 5.2

Learning Curve Equation Estimated in this Analysis

$$\log y_i = c - b \log x_i$$

$$H_0 : b \geq 0$$

where:

y = the performance variable as the ith unit is produced
x = the cumulative number of units produced through time period i
b = the learning rate

(a) y = sorbent used in the FGD unit
x = coal burned by the boiler unit
For these variables, eighteen pilot plants of continuous data were analyzed.

(b) y = power consumed by the FGD unit
x = coal burned by the boiler unit
For these variables, thirteen pilot plants of continuous data were analyzed.

(c) y = sorbent used in the FGD unit
x = sulfur processed in the boiler unit
where sulfur processed = (the amount of coal burned) * (the amount of sulfur in the coal)
For these variables, seventeen pilot plants of continuous data were analyzed.

(d) y = power consumed by the FGD unit
x = sulfur processed in the boiler unit
where sulfur processed = (the amount of coal burned) * (the amount of sulfur in the coal)
For these variables, thirteen pilot plants of continuous data were analyzed

(e) y = sorbent used in the FGD unit
x = power generated by the boiler
For these variables, eighteen pilot plants of continuous data were analyzed.

(f) y = power consumed by the FGD unit
x = power generated by the boiler
For these variables, thirteen pilot plants of continuous data were analyzed.

(g) y = adjusted "labor and supervision" costs
These were adjusted to constant 1997 dollars using the procedure given in Appendix E
x = power generated by the boiler
For these variables, eighteen pilot plants of continuous data were analyzed.

(h) y = adjusted "maintenance and all other costs"
These were adjusted to constant 1997 dollars using the procedure given in Appendix E
x = power generated by the boiler
For these variables, eighteen pilot plants of continuous data were analyzed.

(i) y = summation of adjusted "labor and supervision" and "maintenance and all other costs"
This summation, in constant 1997 dollars, is referred to as "LA+ MA"
x = power generated by the boiler
For these variables, eighteen pilot plants of continuous data were analyzed.

Table 5.2 displays the results of these pilot analyses. For each combination of predictor and performance variables in Equation 5.2, the percentage of pilot plants for which the estimation coefficient (learning rate b) is negative at the 90% confidence level is listed.[103] These plants exhibit learning curves. For most of the variable combinations in Equation 5.2, however, some plants definitely do exhibit learning curves while some plants definitely do not exhibit learning curves. Those plants that do not exhibit learning curves are seen in Table 5.2 in the percentage of pilot plants for which the estimation coefficient (learning rate b) is greater than or equal to zero at the 90% confidence level. The variable combinations that resulted in high percentages of learning curve plants with low percentages of non-learning curve plants, all of which deal with the FGD performance variable of operating and maintenance costs, are listed in boldface. The variable combination that resulted in the greatest percentage of learning curve plants and a very small percentage of non-learning curve plants, combination (i), was chosen for further analysis.[104]

TABLE 5.2

Results of Learning Curve Estimation using Combinations of Predictor and Performance Variables for Subset of Eighteen Plants

Learning Curve Variable Combination	Number of Plants of Total Relevant Pilot Plants for which b < 0 at 90% Confidence Level (Null Hypothesis Rejected)	Number of Plants of Total Relevant Pilot Plants for which b ≥ 0 at 90% Confidence Level (Null Hypothesis Accepted)
(a)	3/18 (17%)	3/18 (17%)
(b)	5/13 (38%)	3/13 (23%)
(c)	3/17 (18%)	3/17 (18%)
(d)	3/13 (23%)	4/13 (31%)
(e)	3/18 (17%)	3/18 (17%)
(f)	5/13 (38%)	3/13 (23%)
(g)	**8/18 (44%)**	**0/18 (0%)**
(h)	**5/17 (29%)**	**0/18 (0%)**
(i)	**10/18 (56%)**	**1/18 (6%)**

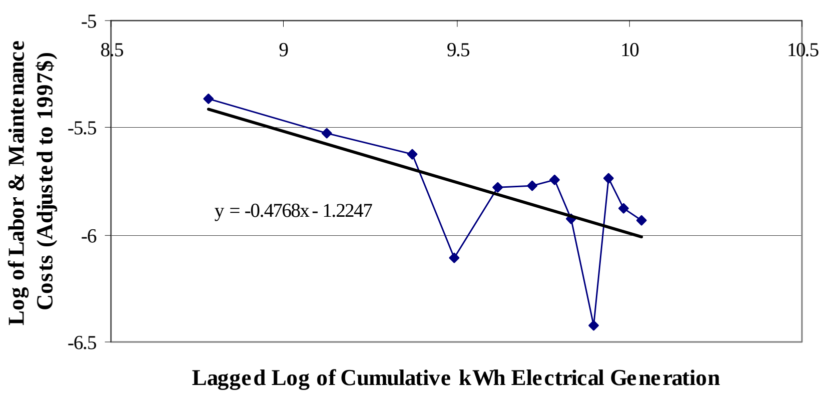
103 The 90% confidence level was chosen because it indicates statistical significance, albeit at a somewhat forgiving level that befits a pilot analysis of plant data with a fairly small number of yearly observations. For explanation of the computation of the confidence level, see Appendix H.

104 Recall that this combination uses the LA+MA summation of adjusted “labor and supervision” and “maintenance and all other costs” as the performance variable and power generation as the predictor variable.

The set of eighty-eight plants with thirteen years of operating data in the years 1985 through 1997 were estimated in two ways using the learning curve analysis variable combination (i). In the first method, estimation was performed on each plant separately.[105] Forty-five plants (51%) of the eighty-eight plants of various types analyzed exhibited statistically significant learning curve effects based on the predictor variable of cumulative electricity generation and the FGD performance variable of LA+MA for a given year. For these forty-five plants, the mean slope of the regression line (or learning rate) was -0.47, the median was -0.37, the maximum was -0.13, and the minimum was -1.48. Figure 5.2 displays the learning curve of the plant with the slope closest to the mean of the forty-five plants with significant learning curve effects. For this plant, the annual FGD-related labor and maintenance costs decreased by 52% from 1985 to 1997 as cumulative generation steadily increased.[106]

FIGURE 5.2

Sample Plant Time Series with Slope Closest to the Mean of the 45 Plants Exhibiting a Learning Curve Effect



In the second estimation method, the set of eighty-eight plants with thirteen years of operating data were pooled together. By running a fixed-effects model on these pooled

[105] Note that these estimations ignored missing data at the beginning or end of a given plant's time series.
[106] This increase was relatively steep, since cumulative generation at the end of these thirteen years was twenty times that at the beginning of the period.

observations, the learning rate b was observed to be -0.265, which was statistically significant at the 99% confidence level.[107] The progress ratio P that results from this learning rate was therefore $2^{-0.265}$, or 0.83. This means that as cumulative output (power generation) doubles, the LA+MA operating and maintenance costs decline to 83% of their original level. This is in line with the Dutton and Thomas (1984) progress ratios for production programs in industries including electronics, machine tools, papermaking, aircraft, steel, and automotive, that were discussed earlier. The most frequently observed progress ratio in these industries, which arguably have less government influence on their innovative activities than the SO_2 industrial-environmental innovation complex, was 80% (Argote, 1999, p. 19).

Conclusion and Future Work

In this chapter, the presence of a learning curve effect was quantitatively demonstrated for the first time for FGD operations in the U.S. for the period 1985 to 1997. The progress ratio of 83% was determined for the FGD performance variable of combined labor and maintenance costs (adjusted to 1997 dollars) and the predictor variable of power generation. This progress ratio is very much in line with progress ratios determined in other industries.

The existence of the learning curve effect in the SO_2 industrial-environmental innovation complex was not totally unexpected. Experts interviewed in this dissertation noted the importance of operating experience in SO_2 control technology and the value of shared operating experience and know-how conveyed at forums like the heavily government-sponsored SO_2 Symposium. In addition, previous studies of learning by doing suggest that this effect is likely in industries in which the knowledge base is uncertain, poorly understood, or highly context-dependent, like the FGD equipment and services industry for much of its history.

[107] For more on the use and calculation of this model, see Appendix H.

Nonetheless, the finding of significant post-adoption learning activity in the SO_2 industrial-environmental innovation complex in the 1985-97 period is important for two reasons. First, policy-makers interested in promoting environmental technological innovation may find this information useful for predictions or assessments of technological change in other environmental areas. Second, identifying plants with learning curve effects is a useful first step in understanding whether and how government environmental actions affect successful learning by doing activities by utility plants.

In future research, the plants for which significant learning curves were identified in this analysis could be investigated using other analytic techniques such as surveys and interviews in order to gain insight into the influence of government actions on learning by doing activities in SO_2 control technology. One potentially interesting use of these analytic techniques would be to show whether facilities with greater learning effects participated heavily in the SO_2 Symposium or in government-sponsored R&D projects. If such correlations exist, they support the effectiveness of non-regulatory government actions in promoting the innovative activity of learning by doing in an environmental control technology. The converse correlations would also be interesting, as would a correlation between plants with strong learning effects and facilities that felt they gained the most knowledge from the FGD User's Conference, which did not include the input of government regulators. Another potentially interesting correlation would be between plants with strong learning effects and plants with low employee turnover, which may have weathered the storms of utility deregulation more successfully than other plants. The exact follow-up measurement techniques chosen for this follow-up work would be based on the identification and understanding of any common factors exhibited by these plants. Power plants that did not exhibit learning curves could also be useful in the process of identifying the factors necessary for successful learning by doing in this domain.

Finally, there is some possibility that a learning curve analysis similar to the one performed here but for a longer time series could provide the framework for a direct estimation of the effect on learning by doing activities of the major government regulatory actions in SO_2 control. For example, it might be possible to construct learning curves (either through the discovery and use of missing EIA-767 data from 1974 to 1984 or through estimates of FGD performance across this period) for the early years of FGD installation, when both SO_2 regulation and the SO_2 industrial-environmental innovation complex were young. If a progress rate based on this earlier period proved to be different from the progress rate calculated here, it would suggest that a predictive use of learning curves in models of environmental innovation would have to consider the maturity of the market for that technology. In addition, combining the data from 1974 through 1997 would make it easier to see if short-term "shocks" correlated with government regulatory actions occur in learning curves. These shocks might occur as a side effect of the temporary but intense interest in FGD operations that regulatory changes might spur in utility management. Such an analysis would not have been useful in this chapter because only one of the main government regulatory actions considered in this dissertation, the 1990 CAA, occurred during the time period analyzed here.

Chapter 6 Conclusions

When the New Source Performance Standards for the 1970 Clean Air Act were issued in December 1971, only three commercial scrubber units were operating in the United States. In hearings held in 1973, systems brought into service in 1972 and 1973 reported operating difficulties related to chemical scaling, demister pluggage, corrosion, reheater problems, and mechanical failures in equipment such as fans, pumps, and dryers. These early scrubbers had problematic reliability and low SO_2 removal efficiencies. A 1976 study by PEDCo-Environmental Consultants, Inc., reported that SO_2 removal efficiencies ranged from 40 to 90% during the 1970 to 1976 period. Figure 6.1 and Figure 6.2, however, demonstrate how quickly SO_2 control technologies diffused and improved as a result of innovative activities that occurred inside the black box of the SO_2 industrial-environmental innovation complex, as supported and spurred on by government actions.

FIGURE 6.1

Improvements in SO_2 Removal Efficiency of Commercial FGD systems as a Function of Cumulative Installed FGD Capacity in the U.S.

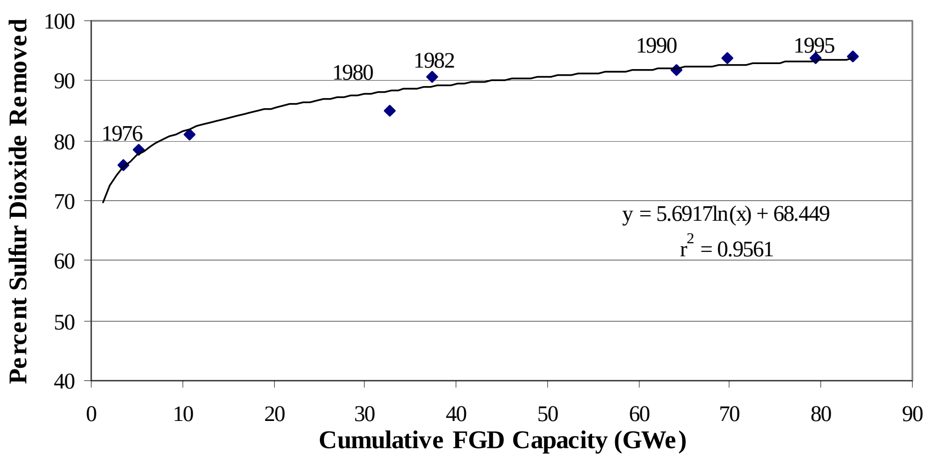
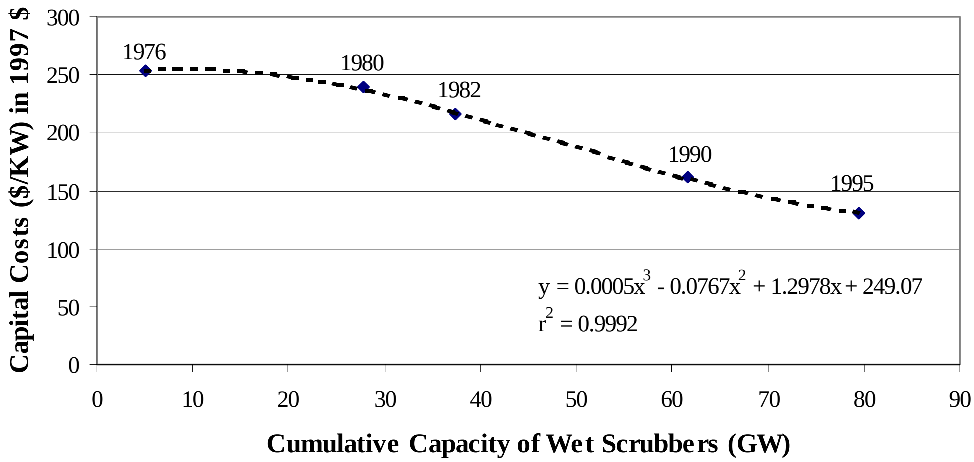


FIGURE 6.2

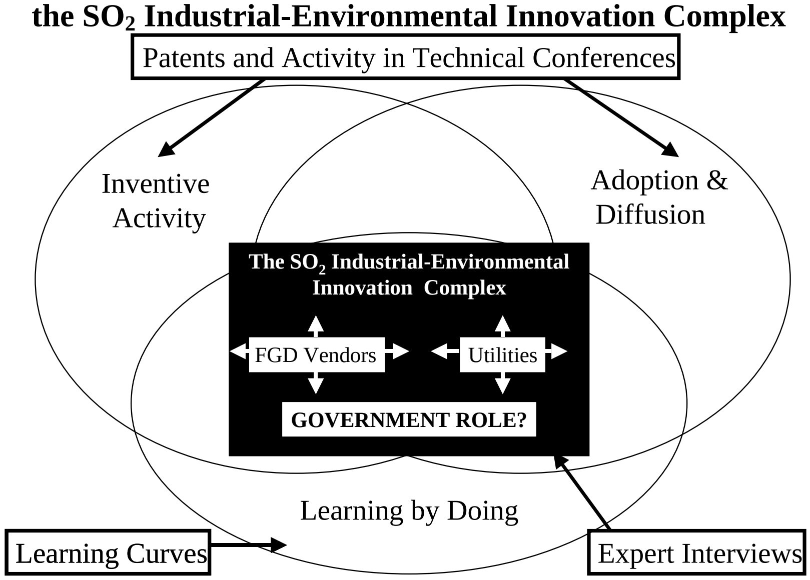
Reductions in Capital Cost of a New Wet Limestone FGD System for a Standardized Coal-fired Power Plant (500 MWe, 3.5% sulfur coal, 90% SO_2 removal)



This dissertation has explored the relationship between government actions and innovative activities in the industrial-environmental innovation complex built around the control of SO_2 emissions from electric power plants. It has applied complementary evaluation methods to the overlapping innovative activities of invention, adoption and diffusion, and learning by doing in this system. This research approach is depicted in Figure 6.3.

FIGURE 6.3

Dissertation Methods Used to Understand Innovative Activities in the SO_2 Industrial-Environmental Innovation Complex



In previous chapters, insights into the influence of government actions on innovative activities were related according to the three primary quantitative evaluation methods used in this dissertation: patenting activity, activity in technical conferences, and learning curves. In this chapter, however, these insights are integrated according to innovative activity in order to gain the greatest understanding of the influence of government actions on the innovative process. The final section of this dissertation discusses policy implications and future research.

Invention, Adoption, and Diffusion

The various data sources analyzed in this dissertation demonstrate the existence of inventive activity and characterize the adoption and diffusion of SO_2 control technologies. Figure 6.1, Figure 6.2, and much of Chapter Two demonstrate that SO_2 control technologies were adopted and diffused among electric utility plants. Chapter Three demonstrated that inventive activity occurred in SO_2 control technologies (at least as captured by patents), since thousands of patents exist in these technologies. These patents are also relevant for understanding the adoption and diffusion of these technologies, since firms typically anticipate commercial returns from patents. The research papers in the SO_2 Symposium also speak to invention, adoption, and diffusion. This conference's session titles are relevant for inventive research and operating experience in the industrial-environmental innovation complex, while the coauthorship patterns of the SO_2 Symposium touch on the communication channels for knowledge transfer in the diffusion of SO_2 control technologies.

Several veins of evidence discussed in this dissertation support the thesis that the existence of national government regulation for SO_2 emissions control affected innovation in SO_2 control technologies. Two different approaches to the creation and analysis of patent datasets showed patenting activity to be an indicator of the influence of regulation on inventive activity. First, the subclass-based patent dataset (which was consistent for over one hundred years) demonstrated that, despite the existence of government legislation dating back to 1955 that authorized research into air pollution abatement methods, patent activity in SO_2 control did not really begin until after the introduction of a regulatory regime. Patent activity levels for this dataset can be portrayed as a step-function divided into two main periods by the 1970 CAA and its associated 1971 NSPS (which effectively mandated the existence of a national market for FGD in the U.S.). In the first period, no more than four patents were filed in a given year, while in the second period, 1971 to 1996, patenting activity never fell below a minimum activity threshold of seventy-six patents per year. The subclass-based dataset also demonstrated that patent activity in the second period peaked in the years 1978, 1979, 1988, and 1992. This pattern of peaks was also exhibited in the second, abstract-based, patent dataset. Models of the abstract-based patent dataset and interview testimony support the idea that inventive activity, as measured by patents, is spurred temporarily by the existence and anticipation of government regulatory actions. These temporary spurts of patenting activity (associated with the 1977 and 1990 CAAs, as well as an anticipated CAA in the mid- to late-1980s) enhance the public good of knowledge from which new discoveries and innovations draw.

More evidence for the importance of government regulatory actions on the invention, adoption, and diffusion of SO_2 control technologies comes from the government-sponsored technology transfer mechanism of the SO_2 Symposium. For example, paper sessions specific to a new national legislative or regulatory event were held during the SO_2 Symposium that immediately followed the passage of the event. This implies that the SO_2 control community was quite aware that the details of government actions affected the direction of SO_2 control technologies. This supposition is supported by the heightened attendance at these post-government action conferences that was observed by one expert.

One particular technological pathway for SO_2 control, pre-combustion control technologies, was very strongly affected by the stringency and flexibility of SO_2 regulatory actions and their implications for potential technology markets. First, both models and expert testimony concerning patenting activity in pre-combustion control technology link the precipitous drop in this activity in 1978 to the 1979 NSPS. Although pre-combustion control technology was somewhat favored by the relatively flexible 1970 CAA and the government promotion of coal use after the Arab oil embargo of 1973, the stringency of the 1979 NSPS permanently and adversely altered this situation. Pre-combustion technologies were simply not robust enough to meet the new regulations; consequently, innovative activity in this technology declined markedly.

Ironically, other legislative details of the 1979 NSPS supported sustained innovative interest along a different technological pathway, dry FGD technologies. Throughout the time period between the 1979 NSPS and the 1990 CAA, but especially during a period of anticipation of acid rain regulation in the mid- to late-1980s, presentations at the SO_2 Symposium demonstrated a particular emphasis on these technologies. This emphasis, which was supported in expert testimony, was not prevalent before the 1979 NSPS and was greatly reduced after the more technologically “flexible” 1990 CAA was implemented. Incidentally, the effect on innovative outcomes of the 1990 CAA was not ultimately the commercialization of a greater variety of technological responses to the problem of SO_2 control. Instead, it resulted in a general utility industry convergence to fuel switching and to wet limestone forced oxidation FGD technologies. These FGD technologies had lower cost designs and operations made possible primarily through pre-1990 innovations and the legislative safeguard for utility reliability concerns of emissions trading.

The details of government actions did not simply affect innovative activities directed toward particular technological pathways. They also apparently affected the size of the innovative audience interested in sharing knowledge about SO_2 control technologies as well as the composition of inter-organizational coauthorship patterns. In the wake of the relatively less stringent and more flexible 1970 CAA, when considerable operating problems were experienced by FGD utility operators, analysis of the SO_2 Symposium from 1973 to 1977 reveals that not every type of innovating organization reached beyond its boundaries for research paper coauthorship. As seen in Chapter Four, those organizations that did cross affiliation boundaries did so at much lower levels in conferences held in the 1973 to 1977 time period than in later years. Litigation between regulated utilities and government during this time period was probably one cause of this. Litigation, however, would be an unlikely reason for researchers from Bechtel and TVA not to write papers with each other or with the EPA in these years, as all three organizations were partners in the influential Shawnee test facility that ran in the 1970s. Yet reflexive ties amongst Bechtel and TVA authors were dominant in the conferences held between 1973 and 1977.

With the implementation of the relatively more stringent 1979 NSPS, which affected a larger number of utilities than the 1971 NSPS, the innovative audience for knowledge about SO_2 control technologies grew. In the SO_2 Symposium conferences held between 1979 and 1988, the number of papers that were presented, the number of organizations and authors that presented, and the number of cross-affiliation coauthored papers grew. The largest increase in all of these numbers occurred in the mid- to late-1980s, during the same period of anticipation of acid rain regulation discussed above as important to patenting activity and to the interest in dry FGD technologies. The growth in cross-affiliation paper coauthorship in the conferences held between 1979 and 1995 is evidence that a denser communication network emerged during this time period for knowledge transfer relevant to the diffusion of SO_2 control technologies. The SO_2 Symposium conferences held between 1990 and 1995 were also characterized by a disproportionate growth in the number of authors that presented papers. This change may reflect heightened innovative interest in SO_2 control technologies during these years, which were marked by considerable uncertainty about the market implications of the 1990 CAA for FGD technologies.

Uncertainty about the implications of government actions for SO_2 control technology was not limited to the 1990 CAA. Archival evidence shows that, as early as the 1970s, firms entered the FGD equipment and services industry rapidly either through new ventures or acquisitions as a result of anticipated, although uncertain, growth in the industry due to potential new regulatory initiatives. These predictions of industry growth were partially based on the tenfold increase in commercial scrubber unit installations that occurred between 1971 and 1976 and the low but growing profitability of the industry between 1976 and 1978. This FGD industry growth did continue in the early 1980s (the peak years for commercial scrubber installations occurred between 1979 and 1983).

Rates of commercial FGD installation in the U.S. declined in the mid- to late-1980s, however, although levels of patenting and activity in technical conferences grew during this time period (almost certainly due to anticipation of new acid rain regulation). This anticipation is evidenced by expert testimony and the existence of SO_2 Symposium sessions in 1986 on “acid deposition retrofit applications” and “acid deposition issues” (the only sessions in the history of the conference to allude explicitly to acid rain in a session title). It can also be inferred from congressional attempts in 1982, 1984, 1986, and 1987 to strengthen U.S. air legislation with regard to SO_2. It thus appears that the anticipatory response of firms to the timing and market potential of predicted government regulatory actions can be seen in overall and technology-specific inventive activity, as well as in organizational aspects of innovation.

Innovative activities in SO_2 control are not limited solely to government regulation. Such institutionally focused environmental government actions as R&D support, research collaborations, and financial support for the SO_2 Symposium clearly had large effects on the evolution of SO_2 control technologies. The strongest evidence of the importance of these other government actions in the development of SO_2 control technologies (particularly the SO_2 Symposium) arose in expert testimony, although the network analysis of the SO_2 Symposium provided in Chapter Four also supports this conclusion.

In addition to these environmental government actions, there is one other type of government action that had implications for the SO_2 industrial-environmental innovation complex. Government actions that affect the utility industry have a strong potential influence on innovative activities in this complex. According to expert interviews, utility deregulation reduced the willingness of actors to share know-how and financial support for the SO_2 Symposium. In addition, reductions in EPRI funding due, in part, to utility deregulation, served to reduce its financing of general R&D efforts in the SO_2 industrial-environmental innovation complex as well as its support of the SO_2 Symposium. On the positive side, individual post-deregulation utilities continue to fund R&D in SO_2 control technology. These utilities also continued to collaborate with other affiliation types in the SO_2 Symposium in the 1990 to 1995 time period.

Learning by Doing

Unlike invention, adoption, and diffusion, the existence of learning by doing in the SO_2 industrial-environmental innovation complex is difficult to demonstrate. Qualitative evidence from expert interviews suggested that learning by doing, or performance improvements that occur as a result of a user's modifications of behavior or adopted equipment so as to correct difficulties observed during operation, occurred in SO_2 control technology. Numerous experts stated that operating experience was one of the most important types of knowledge shared as a result of the SO_2 Symposium and that both major and incremental technological developments arose from operating experience. Yet learning by doing is difficult to quantify.

This dissertation quantitatively demonstrated the existence of learning by doing in U.S. utility FGD operations for the period 1985 to 1997 as a necessary first step to understanding the influence of government actions on learning by doing. The progress ratio of 83%, which is very much in line with progress ratios determined in other industries, was determined for the FGD performance variable of combined labor and maintenance costs (adjusted to 1997 dollars) and the predictor variable of power generation.

By itself, the existence of learning by doing in SO_2 control technology is a useful finding for policy-makers interested in promoting environmental technological innovation. It shows that, unlike the curves depicted in Figure 6.1 and Figure 6.2 that result from new generations of equipment, quantifiable technological improvements can be shown to occur solely on the basis of the experience of operating an environmental control technology forced into being by government actions. It is important for policy-makers to note, however, that these improvements come at some pain to polluters and therefore involve a certain amount of political risk. As interview testimony, archival information about litigation and policy hearings, and perhaps the low incidence of cross-affiliation coauthorship in the 1973 to 1977 SO_2 Symposium conferences demonstrate, the high expense of maintaining early FGD systems at electric utilities generated considerable distrust and antagonism between utilities and government actors. This antagonistic relationship was less useful for FGD performance improvements than the more cooperative climate that developed later. Cooperation among utility operators and outside researchers, particularly as supported through institutions such as EPRI, the EPA, and their jointly sponsored SO_2 Symposium, was cited by most experts as important to FGD performance improvements.

The quantification of learning by doing through learning curves in the SO_2 industrial-environmental innovation complex for the years 1985 to 1997 provides some insights into the influence of government actions on environmental technological innovation. Richer insights may yet be obtained through future research. For example, it might be possible to construct learning curves (either through the discovery and use of missing EIA-767 data from 1974 to 1984 or through estimates of FGD performance across this period) for the early years of FGD installation, when both SO_2 regulation and the SO_2 industrial-environmental innovation complex were young. It is quite possible that a progress rate based on this earlier period would be different from the progress rate calculated here for the more mature SO_2 industrial-environmental innovation complex. If true, this would suggest that any predictive use of learning curves for future estimates of the characteristics of an environmental control technology would have to consider the maturity of the market for that technology. In addition, combining the data from 1974 through 1997 would make it easier to see if short-term "shocks" correlated with government regulatory actions occur in learning curves. These shocks might occur as a side effect of the temporary but intense interest in FGD operations that regulatory changes might spur in utility management. Finally, a more in-depth investigation of the plants that exhibited strong learning effects may reveal the effectiveness of non-regulatory government actions, such as facilitating technology transfer and funding R&D activities, in promoting the innovative activity of learning by doing in SO_2 control technologies.

Policy Implications and Future Work

This dissertation integrated several established and repeatable quantitative and qualitative innovation research methods and applied them to an extended case study of innovative responses to multiple U.S. government actions centered on the abatement of SO_2 emissions from stationary sources. This approach allowed the specifics of government actions, environmental technology features, and affected organizations within the industrial-environmental innovation complex to be considered in this analysis. Although these insights are particularly relevant to the case study of SO_2 control technologies and may not be considered fully generalizable, they do appear to have policy implications that may be reinforced in future research.

As stated in Chapter One, one instance in which case studies can have a generalizable impact is when a relatively large number of such studies show similar findings. The research methods used in this dissertation were chosen in part so that this case study could serve as a model for the conduct of similar case studies of other environmental control technologies. The findings of these future studies would then be able to be synthesized more readily with those of this dissertation, and the combined insights could then have a more generalized impact on policy discussions related to innovation, particularly in the environmental area. Two of these additional case studies, which focus on nitrogen oxide control technologies and carbon sequestration technologies, are newly underway in a follow-on study funded by the USDOE Office of Science (under Notice 00-08 for the Integrated Assessment of Global Climate Change Research).

Some of the major policy implications of this dissertation already appear to be generalizable because they are supported by other case studies. For example, this dissertation has shown that the existence of national government regulation for SO_2 emissions control stimulated innovation. This is supported by the case studies analyzed in Ashford, Ayers, and Stone (1985). It is interesting to note, however, that the patent analysis in this dissertation shows that national regulation is a more effective stimulant of inventive activity than national legislation in support of air pollution abatement research alone, with no regulatory requirements. This may well be particularly relevant to policy-makers interested in stimulating innovation in support of global warming mitigation, for which regulatory stimulus is lacking but research support is not.

A second policy implication of this dissertation is that regulatory stringency appears to be particularly important as a driver of innovation, both in terms of inventive activity and in terms of the communication processes involved in knowledge transfer and diffusion. In the Ashford, Ayers, and Stone (1985) case studies, they found that "a relatively high degree of [regulatory] stringency appears to be a necessary condition" for inducing higher degrees of innovative activities (Ashford, Ayers, and Stone, 1985, note 36 at 429). In this dissertation, regulatory stringency appeared to be particularly important in driving the innovative direction of technologies to control SO_2 emissions. The high stringency of the 1979 NSPS for high-sulfur coal applications ended the viability of one technological pathway that innovation had centered upon, pre-combustion control technology with low removal efficiencies. Meanwhile, the moderate degree of stringency of this regulatory event for low-sulfur coal applications focused innovative attention on dry FGD technologies. With the relatively less stringent 1990 CAA, coupled with the lower cost of non-technological alternatives (i.e., low-sulfur coal), this innovative attention faded.

Increased regulatory stringency may have helped stimulate the formation of communication channels important to knowledge transfer in the diffusion of SO_2 control technology. The 1979 NSPS, which was more stringent and affected a larger number of utilities than the 1971 NSPS, thereby creating a larger market for FGD in the U.S., coincided with the growth in cross-affiliation paper coauthorship in the conferences held between 1979 and 1995. In addition, it corresponded with the beginning of a major increase in the number of papers that were presented and the number of organizations and authors that presented at the SO_2 Symposium. All of these findings about the effects of regulatory stringency on innovation appear to be related to the finding in the mainstream innovation literature that demand is a major driver of innovation (see Mowery and Rosenberg, 1982). In an industrial-environmental innovation complex, the demand for various types of pollution control equipment is almost inseparable from the details of environmental legislation (see Kemp, 1997). The findings in this dissertation about regulatory stringency and innovation may be especially relevant to policy-makers considering a new national regulatory regime for a pollutant for which a dominant environmental control technology has not been established. Mercury air emissions from power plants might be considered such a pollutant today.

A third policy implication of this dissertation is that inventive activity, as captured by patents, is spurred temporarily by the existence and anticipation of government regulatory actions. This temporary spurt in inventive activity thus provides a brief burst in the stock of the public good of knowledge from which new discoveries and innovations (especially in SO_2 control technology) draw. Ashford, Ayers, and Stone (1985) also found that "anticipation of regulation stimulates innovation," and that while "excessive regulatory uncertainty may cause industry inaction, too much certainty will stimulate only minimum compliance technology" (Ashford, Ayers, and Stone, 1985 pg. 426). Taken together, these findings make a case for policy-makers to not be overly concerned with mapping many years' worth of environmental standards into law at a given time.

This dissertation also has other policy implications that have not arisen in previous environmental innovation case studies. First, it has shown that federal funding of a technology transfer mechanism such as the SO_2 Symposium has been extremely valuable to environmental innovation, according to experts in SO_2 control technologies. More specifically, these experts cited cooperation among utility operators and outside researchers as particularly important to FGD performance improvements. The facilitation of research cooperation and knowledge transfer of a variety of valuable forms, including operating experience, appears to be an important aspect of a well-designed effort on the behalf of policy-makers to drive environmental innovation. Policy-makers interested in driving environmental innovation for use in the electric power sector should pay particular attention to this recommendation, especially in light of the findings of this dissertation that utility deregulation has reduced the willingness of innovative actors in SO_2 control technologies to share technical know-how.

A second stand-alone finding of this dissertation that is relevant to policy-makers is the determination that as electric power generation doubles, the operating and maintenance costs of FGD systems decline to 83% of their original level. This finding, which is very much in line with progress ratios determined in other industries, shows that quantifiable technological improvements can be shown to occur solely on the basis of the experience of operating an environmental control technology forced into being by government actions. This finding, especially if reinforced by other case studies, can be useful to policy-makers interested in making cost projections about environmental technologies.

A third stand-alone finding of this dissertation, the logarithmic and polynomial equations fitted to the data in Figure 6.1 and Figure 6.2, may also be useful to policy-makers interested in projecting aspects of environmental innovation. These models characterize improvements in FGD performance and reductions in cost as a simple function of technology diffusion. Again, finding similar functions in other case studies of environmental innovation will be important to developing a more general, policy-relevant understanding of these rates of environmental innovation.

This dissertation has provided several insights into the complex influence of government actions on innovative activities and outcomes in an environmental control technology, but additional work could provide further insight. There are several avenues of future work, besides applying the research methods used in this dissertation to nitrogen oxide control and carbon sequestration technologies. First, it would be interesting to note how patent activity in SO_2 control changes as Phase II of the 1990 CAA progresses. Second, it would be interesting to see if the findings in this dissertation about the influence of government regulation on patenting activity hold true when considering the patent datasets of other countries. For example, while it might be expected that Germany would exhibit a patenting spike in the mid-1980s, to tie with its stringent 1983 acid rain program, both its government and its innovation patterns could confound the results.[108] Third, it would be interesting to observe whether learning curves change as their underlying data are updated to reflect an increasingly deregulated electric utility industry. Fourth, it would be interesting to see if an in-depth investigation of the plants identified in this

[108] This program resulted in 35,000 MWe of FGD systems being installed in four years, 33% of which was licensed from U.S. companies.

analysis as exhibiting learning curve effects demonstrated positive or negative correlations between high rates of learning and non-regulatory government actions. Finally, it would be interesting to observe whether learning curves that span the 1974 to 1997 period exhibit slope changes between the early and later years of FGD technological maturity or exhibit shocks correlated with government regulatory actions.

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Appendix A. Previous Case Studies of Technological Responses to Regulation

Substance	Application	Overview of Regulation	Regulatory Categories	Technology Response
PCBs	All	Prohibition of the manufacture of PCBs after January 1, 1980 by EPA under Toxic Substances Control Act (TSCA) after 12 years of regulatory surveillance	Product Regulation, Very Stringent	• Voluntary restriction by PCB manufacturer of PCB sales to closed electrical systems 10 years before prohibition of PCBs, based on anticipation of government concern • Introduction of a new, more biodegradable PCB mixture for use in capacitors together with a new capacitor design reducing PCB use by two-thirds • Development of PCB substitutes by outsiders
CFCs	Aerosol	Ban of use of CFCs in 1978 by Consumer Product Safety Commission and EPA under TSCA	Product Regulation, Very Stringent	• Product substitution in the form of a non-fluorocarbon propellant (CO_2) by non-CFC manufacturers • Development of a new pumping system without propellant by outsider firms
Lead	Paint	Limitations of lead content of household paint in 1970s under various acts that effectively prohibited the use of lead pigments after 1973 and the use of lead dryers in 1977	Product Regulation, Very Stringent	• Non-innovative substitution of lead by paint industry
	Fuel Additive	Requirement by EPA under Clean Air Act Amendments in 1970 for large gasoline retailers and oil producers to market by July 1, 1974 at least one grade of lead free gasoline to protect catalytic converters in automobiles; followed by requirement of reduction in the lead content of regular gasoline after October 1, 1979	Product Regulation, Very Stringent	• Unsuccessful substitution of existing manganese-based additive MMT for lead; banned by EPA due to damage to catalytic converters • Development of lead trap to capture the lead in exhaust; no commercial success • The use of new catalysts for cracking process

Substance	Application	Overview of Regulation	Regulatory Categories	Technology Response
	All Manufacture	Permissible exposure limits to lead of 50 $\mu g/m^3$ in working site under Occupational Safety and Health Act (OSHA) with ten year exemptions for primary smelting and five year exemptions for secondary smelting and battery manufacture	Process Regulation, Very Stringent	• Combination of source-reducing controls, worker isolation and improved work practices • Use of new direct smelting process • Development of new process technologies that reduce lead exposure • Acceleration of development of smaller batteries containing less lead relying on lead-calcium rather than lead-antimony alloys
Mercury	Paint	Ban by EPA in 1976 of phenyl mercurials in oil-based paint	Product Regulation, Very Stringent	• Substitution of existing organic compounds for mercurials
	Chloralkali	Establishment of effluent standards for chloralkali plants limiting mercury discharges to maximum of 0.28 grams per 1000 kg of products per day by July 1977 under Federal Water Pollution Act plus promulgation of emission standards limiting mercury under the Clean Air Act	Process Regulation, Stringent	• Separation of process and cooling water • Treatment of process water and cleaning of sewer pipes • Series of housekeeping improvements
Vinyl Chloride (VC)	All Manufacture	Setting of VC exposure limits under OSHA in 1970s plus emission standards for VCM and PVC after 1976 under Clean Air Act	Process Regulation, Very Stringent	• Acceleration of incremental process innovations
Cotton Dust	All Manufacture	Introduction of differing exposure limits for cotton dust in 1984 under OSHA	Process Regulation, Very Stringent	• Modernization of textile industry through diffusion of superior textile technology
Asbestos	All Manufacture	1972 OSHA limit of airborne asbestos to five fibers per cubic centimeter	Process Regulation, Mildly Stringent	• Adoption of pollution control technology

Source: Adapted from Ashford, Ayers, and Stone (1985) and Kemp (1997)

Appendix B. Expert Selection Procedure

The first step in the expert selection process was to analyze the SO_2 Symposium conference proceedings for 1973 to 1995 in order to understand the distribution of papers presented according to affiliation type. This distribution was used to suggest a likely distribution of expert affiliation types that should be represented in interviews. Organizations that presented often at the SO_2 Symposium were then categorized by affiliation type. Each of these organizations was then ranked according to its presentation frequency (versus other top organizations of similar type) in individual conferences in order to get a sense of the importance of various organizations over time. Based on these rankings, dominant organizations in each affiliation type category were targeted for interviews.

Prominent individual presenters for these dominant organizations were then listed and ranked across time for their presentation frequency at the SO_2 Symposium. These rankings were the basis of the initial list of experts to contact for potential interviews. In some cases, multiple individuals from an organization were listed as contacts if they were prominent presenters in a subset of the SO_2 Symposium conference years that was complementary to that of another expert from the same organization. In cases where more than one individual met the basic selection criteria, other factors were used to determine whether an individual would be contacted for an interview. One such factor was whether the individual was also listed as an inventor on an SO_2 control patent, since such individuals would bring additional insights to the overall dissertation.

The initial list of potential interviewees that emerged from this process included twenty experts. Due to a number of logistical difficulties, not all of these experts were interviewed for the dissertation. In two cases, experts were interviewed who had lower presentation frequency than experts on the initial list; these experts represented the same dominant organizations as the initially targeted experts and were active in the SO_2 control community for a similarly long period of time.

Finally, a few experts were interviewed who were not chosen primarily on the basis of presentation frequency at the SO_2 Symposium (although they were very active in this conference). These experts were identified by other experts as important to interview because of their knowledge about the SO_2 industrial-environmental innovation complex.

Appendix C. Interview Protocol

This interview protocol was informed by research on qualitative research methods (Rosenthal and Rosnow, 1991) and developed through an iterative process that included pilot testing.

The Influence of Government Action on Technological Change in SO_2 Control Technologies

Introduction

Thank you for taking the time to meet with me today. As I mentioned before, I would like to talk with you for a little over an hour about your experiences with the development of sulfur dioxide control technologies over the last three decades.

1. Why don't we start with you telling me about how you got involved in sulfur dioxide control technologies in the first place?

2. Did your formal schooling prepare you for the demands of working on these technologies?

3. Looking back at your experience with these technologies, if you had it all to do again, would you get involved in this area of research?

Technological change questions

I'm interested in getting expert opinions about how the technologies have changed over time, especially as regards the removal efficiencies, reliability, and cost aspects of some of the dominant technologies. Let's start by drawing some graphs.

ASK FOLLOWING QUESTIONS WHILE DRAWING GRAPHS AGAINST TIME AND CUMULATIVE OUTPUT ON X-AXIS.

1. What is your sense of the removal efficiencies of wet limestone scrubbers in the early days, say in the early 1970s? How about the late 1970s? The early 1980s? The late 1980s? The beginning of the 1990s? The end of the 1990s?

2. What is your sense of the reliability of wet limestone scrubbers in the early days, say in the early 1970s,? How about the late 1970s? The early 1980s? The late 1980s? The beginning of the 1990s? The end of the 1990s?

3. What is your sense of the capital costs of wet limestone scrubbers in the early days, say in the early 1970s,? How about the late 1970s? The early 1980s? The late 1980s? The beginning of the 1990s? The end of the 1990s?

4. What is your sense of the operating costs of wet limestone scrubbers in the early days, say in the early 1970s,? How about the late 1970s? The early 1980s? The late 1980s? The beginning of the 1990s? The end of the 1990s?

5. Are there other features of these technologies that have changed over time? If so, how would this (these) feature(s) have looked in the early 1970s, late 1970s, early 1980s, late 1980s, early 1990s, and late 1990s?

LOOKING AT GRAPHS WITH SUBJECT. So, how would you explain some of these trends?

6. Can you pinpoint the technological advancements that have affected these technological features?

MAKE LIST BASED ON THESE TECHNOLOGICAL GOAL AREAS:
Removal efficiencies
Reliability
Capital costs
Operating costs
Other

7. What research trajectories were followed by the industry that are not reflected in these improving trends? In other words, what was tried but not commercialized?

ADD TO LIST

NOW, BASED ON TECHNOLOGY LIST, ASK QUESTIONS 8-16 FOR EACH ITEM ON THE LIST:

8. Which organizations and individuals have been responsible for these technological advancements?

9. How did these organizations/individuals communicate with the greater technical community working on these problems in SO2 control? Did they work in cooperation with individuals at other organizations (TYPES OF ORGANIZATION LIST TO REMIND, ALSO COUNTRIES)?

10. Were any individuals in the organizations you were involved with working on this technological advance? If so, what were their names and positions?

11. What is your recollection of the amount of research money directed towards the work these individuals were doing? If you had to estimate the amount of money devoted to research in these areas over time, what would the graph look like? Early 1970s, late 1970s, early 1980s, late 1980s, early 1990s, late 1990s? MAKE GRAPH

12. Why not extrapolate out to the universe of organizations working on these issues. What would a research money graph look like for this universe, with data points in the early 1970s, late 1970s, early 1980s, late 1980s, early 1990s, late 1990s? MAKE GRAPH

13. Would you be able to get any archival data on the amounts of research money directed toward these areas?

14. What recollections do you have about hiring and firing decisions on these technological advancements within the organizations you worked in?

15. Would you be able to get any archival data on hiring/firing trends?

16. What rationale do you recall there was for the research budget and hiring decisions for these technological advancements over time? Early 1970s, late 1970s, early 1980s, late 1980s, early 1990s, late 1990s.

Government action questions

17. What do you consider the major landmarks in legislation affecting SO_2 control over the last 30 years?

MAKE LIST, HELPING REMIND THEM IF NECESSARY (INCLUDING GOING OVER TIME PERIOD).

18. Were there other legislative events that were widely believed to occur that never actually materialized.

ADD TO LIST
GO THROUGH LIST, ONE-BY-ONE

19. When did the organization you worked in first become aware that this legislative action was being considered?

20. How did the organization respond to first seeing this legislative action on the horizon? Formal procedures, informal procedures? R&D budgets or hiring?

21. When did the organization you worked in first become aware of the final stage details that were emerging about this legislative action?

22. How did the organization respond to first seeing this legislative action on the horizon? Formal procedures, informal procedures? R&D budgets or hiring?

23. After this legislative action was passed, how did your organization respond? Within 1 year, 2 years, 3 years, etc.

Patent questions

24. SHOWING PATENT CORRELATIONS I have conducted a patent search on the set of technologies pertaining to removing SO2 from stationary sources. There seem to be correlations between the timing of major legislative events and peaks in patenting activity in these areas. Do you have any possible explanations for why this pattern is observed?

25. How are patents applied for, seen, and used in the organizations you have worked in?

26. How important are patents to the organizations you have worked in? To the overall community, to the best of your knowledge?

27. Another finding from the patent study I did is that pre-combustion (coal cleaning) technologies were not patented in as much after 1979. Yet articles and books in the early 1980s were still very positive about these technologies and their potential importance in acid rain control. Do you have any ideas why these patents show this pattern?

End

Thank you for being so helpful today. Do you have any other major thoughts on this topic that you'd like to share?

If you have any thoughts on this later and you'd like to contact me, my contact info is:

Reference

Rosenthal, Robert, and Ralph L. Rosnow. *Essentials of Behavioral Research: Methods and Data Analysis*. Second ed. New York: McGraw-Hill, Inc., 1991.

Appendix D. Notes on Data Translation Process for Form EIA-767

In Chapter Two and Chapter Five, data were used from the EIA-767 form collected by the Energy Information Administration (EIA) of the Department of Energy since 1974 from all utility boilers above 50 MWe in size (USDOE/EIA, 1999). These data are currently available in computerized format only for the operating years 1985 through 1997.

The programs designed to tabulate the EIA-767 data originally were written for computers circa 1974, so these data needed to be translated into a more database-accessible format before any analysis could begin. Of the sixteen pages of data each utility plant contributes annually, of particular interest for translation and later analysis were the data on utility generators, boilers, and flue gas desulfurization systems. Translation and analysis focused on coal-fired boilers burning a non-zero amount of coal each year and employing a single FGD unit.[109]

The data-translation task posed some difficulties. First, typographical errors were encountered. For example, errors were occasionally detected in the FGD boiler identifier provided in form EIA-767 and were either corrected based on other information or the data associated with these errors were abandoned. Second, missing or impossible values were sometimes encountered, so null values had to be generated as placeholders in the translated data. Third, discrepancies were sometimes seen between an annual total and the monthly data underlying that total. As a rule, manually calculated summations of the monthly data were treated with greater respect than the stated annual totals. Fourth, the total sulfur content of coals is an important context variable for a utility FGD system, but this information was not given on

[109] No boilers that shared an FGD unit were considered in this analysis.

the annual basis needed for the learning curve analysis in Chapter Five. For this reason, monthly coal tonnage was multiplied by the percent sulfur content given for these coals and then summed to get annual sulfur.

Finally, in order to generate the variable of cumulative kilowatt-hours scrubbed as well as several of the FGD performance variables required for the learning curve analysis, plant generator, boiler, and FGD unit data needed to be linked by a one-to-one relationship. In cases with multiple boilers or FGD units, where it was impossible to relate plant power generation to FGD activities, these links could not be established. Only a small number of boilers were thus affected.

Appendix E. Cost Adjustment Process

The formula given here was used to adjust current dollar costs to constant 1997 dollar costs, based on two *Chemical Engineering* cost indices. Since an FGD unit is a type of chemical plant, the *Chemical Engineering* plant index, as previously compiled by Mike Berkenpas of Carnegie Mellon University for 1977-98, was used to adjust capital costs, maintenance costs, and "other" costs. Similarly, the *Chemical Engineering* hourly earnings index, updated on a semi-monthly basis, was collected for the years 1985-1998 and used to adjust labor costs.

$$Cost(1997\$) = Cost(i) * \frac{Indexvalue(1997)}{Indexvalue(i)}$$

i = the year of interest for adjustment
Cost = the labor or capital or maintenance cost
Indexvalue = the appropriate Chemical Engineering index (hourly earnings or plant cost)

Year	Labor Index (1977=100)	Plant Cost Index (1957-59=100)
1977	Not applicable to analyses	204.1
1978	Not applicable to analyses	218.8
1979	Not applicable to analyses	238.7
1980	Not applicable to analyses	261.1
1981	Not applicable to analyses	297.0
1982	Not applicable to analyses	314.0
1983	Not applicable to analyses	316.9
1984	Not applicable to analyses	322.7
1985	180.2	325.3
1986	186.1	318.4
1987	192.1	323.8
1988	196.9	342.5
1989	203.2	355.4
1990	210.6	357.6
1991	218.4	361.3
1992	224.8	358.2
1993	229.4	359.2
1994	235.8	368.1
1995	243.6	381.1
1996	251.7	381.7
1997	257.8	386.5
1998	263.4	386.5

Appendix F. SO_2 Symposium Session Titles

SO_2 Symposium Session Titles in Three Groups, as Delimited by the Implementation Dates of the 1979 NSPS and the 1990 CAA, with Parentheses Indicating the Number of Papers Presented in Each Session. Asterisks indicate difficulties identifying the exact number of presenters in a specific session.

Group 1			
May 1973	**Nov. 1974**	**March 1976**	**Nov. 1977**
Opening Session (**4**)	Opening Session (**4**)	Opening Session (**5**)	Opening Session (**8**)
Throwaway Processes (**10**)	Non-Regenerable Processes (**11**)	Non-Regenerable Processes (**14**)	Non-Regenerable Processes (**10**)
Regenerable Processes (**8**)	Regenerable Processes (**7**)	Regenerable Processes (**4**)	Regenerable Processes (**7**)
Disposal and Use of Byproducts from FGD Processes: Introduction & Overview (**6**)	FGD Byproduct Disposal/Utilization Panel (**6**)	Byproduct Disposal/ Utilization (**4**)	Byproduct Disposal/Utilization (**8**)
Advanced Processes (**6**)	Second Generation Processes (**8**)	Advanced Processes (**6**)	Advanced Processes (**7**)
		Unpresented Papers (**3**)	Unpresented Papers (**5**)

Group 2

March 1979	**October 1980**	**May 1982**	**Nov. 1983**	**Nov. 1984 Dry & SOx/NOx**	**June 1985**	**Nov. 1986**	**June 1986 Dry & SOx/NOx**	**October 1988**
Opening Session: Energy and the Environment (**4**)	Opening Session (**4**)	Opening Session (**5**)	Opening Session (**4**)	Introduction (**5**)	Opening Session (**3**)	Opening Session: Clean Coal Programs (**3**)	Introduction (**4**)	Opening Remarks (*****)
Impact of Recent Legislation (*****)	Impact of Recent Legislation/ Regulations (*****)	Materials of Construction (**5**)	Economics (**4**)	Fundamental Research (**8**)	Commercial Status of FGD (**4**)	Status of FGD (**4**)	Sorbents - Selection, Preparation, and Performance (**7**)	International Overview (**6**)
Economics and Options (**4**)	FGD R&D Plans (**3**)	Dual Alkali (**4**)	Materials of Construction (**4**)	Pilot-Scale Development of Furnace Injection (**7**)	Limestone FGD/Organic Acid Enhancement (**4**)	FGD Economics: General (**2**)	Sorbents - Promoters and Additives (**3**)	Retrofit Economics (**3**)
Utility Applications (**22**)	Utility Applications (**13**)	Special Studies (**4**)	Dry Furnace Absorbent Injection (**3**)	Burners for Simultaneous SO_2/NOx Control (**3**)	FGD Reliability Improvement (**3**)	FGD Economics: Acid Deposition Retrofit Applications (**3**)	Sorbents - Fundamentals (**2**)	Spray Dryer Technology (**6**)
FGD Current Status and Future Prospects - Vendor Perspectives (*****)	Byproduct Utilization (**6**)	Panel: Reliability and Maintenance (**6**)	Dual Alkali (**2**)	Post-Furnace SO_2 Removal (**4**)	Chemistry/ Reagent Preparation (**4**)	Acid Deposition Issues (**2**)	Process Research (**5**)	Furnace Sorbent Injection: Demonstra-tions (**8**)
Industrial Applications (**6**)	Dry Scrubbing (**6**)	Flue Gas Treatment (Combined SOx/NOx Removal) (**3**)	Flue Gas Treatment (Combined SOx/NOx Removal) (**2**)	Process Integration and Economics (**8**)	Materials of Construction (**5**)	Industrial Applications (*****)	Mixing/ Dispersion (**3**)	Integration/ Byproduct Utilization (**8**)

Unpresented Papers (**4**)	Industrial Applications (**5**)	Limestone/ Organic Acid (**3**)	Panel: The A&E: Middleman Between Utility and FGD Supplier (*****)	Sorbent Availability and Costs (**3**)	Panel Discussion on Retrofitting FGD Systems (*****)	Wet FGD: Additives (**4**)	Economics, Power Plant Integration and Commercial Applications (**4**)	FSI Impacts/ Enhancements (**8**)
	Unpresented Papers (**4**)	Lime/ Limestone Utility Applications (**2**)	FGD Chemistry (**6**)	Field Applications and Full-Scale Testing (**8**)	Dual Alkali (**4**)	Wet FGD: Operations and Flexibility (**3**)	Post-Furnace SO_2 Removal (**7**)	Wet FGD Operation (**16**)
		Byproduct Disposal/ Utilization (**4**)	Limestone/ Organic Acid (**2**)	Unpresented Papers (*****)	Emerging Technologies (**5**)	Wet FGD: Operations and Reliability (**2**)	System Impacts (**6**)	Municipal Solid Waste Facilities (**4**)
		Dry FGD Systems (**7**)	Waste Disposal/ Utilization (**4**)		Spray Dryer FGD (**7**)	Spray Dryer FGD (**4**)	Commercial Scale Applications (**8**)	Dry FGD Fundamentals (**6**)
		Unpresented Papers (**7**)	Dry FGD: Pilot Plant Test Results (**5**)		FGD Byproduct Disposal/ Utilization (**6**)	Dry FGD Technologies (**5**)	Unpresented Papers (**2**)	New Technologies (**6**)
			Dry FGD: Full Scale Installations (**5**)		Unpresented Papers (**7**)	FGD Byproduct Disposal/ Utilization (**6**)		FGD Improvement (**6**)
			Unpresented Papers (**5**)			Poster Session (**16**)		Post-Combustion Dry Technologies (**8**)
								Unpresented Papers (**3**)

Group 3			
May 1990	**Dec. 1991**	**August 1993**	**March 1995**
Opening Remarks (**3**)	Opening Session (**6**)	Clean Air Act Regulatory Strategies (**3**)	Regulatory and Economic Issues (**4**)
International Overview (**4**)	Clean Air Act Compliance Issues Panel (**4**)	Phase I Designs (**7**)	Full-Scale Optimization (**6**)
Economics (**8**)	Clean Air Act Compliance Strategies (**9**)	Additives for High Efficiency FGD (**6**)	Phase I Startups (**7**)
Furnace Sorbent Injection – Demonstrations (**8**)	Wet FGD Process Improvements (**8**)	Materials for FGD (**7**)	Dry FGD (**6**)
FSI Recycle (**4**)	Furnace Sorbent Injection (**4**)	Clean Coal Demonstrations (**7**)	Operating Experiences and Recent Design (**6**)
Wet FGD Reliability (**8**)	Wet FGD Design Improvements (**8**)	Applied Research (**7**)	Emerging Processes (**6**)
Spray Dryers (**5**)	Dry FGD Technologies (**12**)	Dry FGD Technologies (**7**)	Wet FGD Advanced Design Issues (**7**)
Wet Full Scale Operation (**10**)	Wet Full Scale FGD Operations (**8**)	Wet FGD Process Issues (**6**)	Air Toxics (**7**)
Emerging Technologies (**7**)	Combined SOx/NOx Technologies (**8**)	Air Toxics Removal in FGD Systems (**7**)	Modeling and Fundamental Research (**6**)
Combined SOx/NOx Technologies (**7**)	Wet FGD Operating Issues (**8**)	Wet FGD Process Issues (**7**)	Combined SOx/NOx Removal (**6**)
Wet FGD Vendor Designs (**7**)	Clean Coal Demonstrations (**8**)	Emerging Technologies (**6**)	Materials for FGD (**8**)
Post Combustion Dry Technologies (**8**)	Emerging Technologies (**21**)	Waste Utilization and Disposal (**6**)	Byproducts and wastewater (**5**)
Wet FGD Research (**7**)	Commercial FGD Designs (**7**)	Poster Papers (**18**)	Poster Papers (**12**)
Byproduct Utilization (**8**)	Byproduct Utilization (**7**)		
Poster Session (**13**)	Poster Papers (**7**)		

Appendix G. Network Graph Construction Procedure

The first step in the process of constructing network graphs was to develop a computer program that was run on the coded SO2 Symposium data in order to list the year and the various authors on each paper in permuted pairs. The output of the program replaced the author names with their affiliation types. In Microsoft Excel, pivot tables were then created using these pairings in order to show reflexive ties (to the same affiliation type) and relational ties (to other affiliation types) for each year of the conference. The next step was to sum the various pivot tables into affiliation-type-by-affiliation-type, important organization by important organization, and important author by important author matrices for each of the three time period groups. The resulting matrices could then be graphed manually or with software such as Krackplot 3.0.

Appendix H. Statistics in Learning Curve Analyses

(1) The confidence levels associated with the learning curve analyses are computed in Microsoft Excel 2000 and listed as part of the regression results. They are based on the two-sided p-value obtained through the t-test of the null hypothesis of no linear relationship between the x and y variables in Equation 5.2. The t-statistic is:

$$t = \frac{b}{SE_b}$$

where:

b = the slope of the least-squares regression line

SE_b = the standard error of this slope

where: $$SE_b = \frac{\sqrt{\frac{1}{n-2}\sum (y-\hat{y})^2}}{\sqrt{\sum (x-\bar{x})^2}}$$

(2) Given that there is a relatively large number of power plants with relevant FGD operating data (88) and there is a relatively small number of observations for each power plant (13 years), a more powerful estimation technique is to consider these data as panel data. Recall that panel data are repeated observations on the same set of cross-sectional dependent and explanatory variables. The simplest estimation method for panel data is to essentially ignore the panel structure of the data and stack the data in the linear regression model with the assumptions that for a given plant, observations are serially uncorrelated and across plants and time, the errors are homoscedastic. The result is the pooled estimator.

There are two extensions to the pooled estimator. If the first, "random effects" model were applied to these data, it would be based on the assumption that the individual power plant is uncorrelated with the explanatory variables. Instead, we assume that the individual power plant is correlated with the explanatory variables and we use the second, "fixed effects" model, which has two important advantages. One is that the ordinary least-squares regression on the transformed data yields unbiased estimates of the coefficients on the X-variables. Another is that the fixed effects estimator is robust to the omission of any relevant time-invariant regressors.

The fixed effects model was run in Stata 6.0 for the pooled set of eighty-eight power plants with thirteen years of FGD operating data, with a group variable based on the plant-FGD identifier. For more information, see Johnston and DiNardo (1997, Ch. 12) and StataCorp (1999).

References

Johnston, J., & DiNardo, J. 1997. *Econometric Methods*. New York: McGraw Hill.

StataCorp. 1999. *Stata Statistical Software: Release 6.0*. College Station, TX: Stata Corporation.