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Gains from Trade in the Optimal Control of Environmental Externalities: Evidence from Acid Rain Abatement in the Eastern United States and Canada

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Abstract

In this paper I investigate the properties of a system of internationally traded "licenses to pollute" for the control of acid rain in in the Eastern United States and Canada. I report estimates of the costs to the United States and Canada of achieving a 15 percent reduction in acid rain concentrations under a joint tradeable permit system for sulfur dioxide emissions. I use point-source data for the 200 largest sulfur dioxide emitters in each of Canada and the United States, transfer coefficients that relate emissions in different regions to acid rain concentrations in specified "sensitive receptor" regions, and fitted cost functions for each point source, to estimate the costs facing each country under different acid rain abatement programs. The estimates show (1) that an autarkic program of abatement in either country induces significant spillover benefits in the other that lead to the potential for "free-riding", and (2) that, contrary to widespread beliefs, a joint program of abatement would lead to substantial cost savings for *both* the United States and Canada. The results also document, however, large differentials in the gains that would accrue to each country, suggesting that there may be serious obstacles, in the form of difficulties in arriving at a division of the gains from trade, to achieving agreement on a joint program of abatement.

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I. Introduction

As theory has filtered into the realm of policy, the past 20 years have witnessed increasing sophistication in dealing with environmental externalities, as reflected in the system of tradeable licenses for sulphurous oxide emissions ("emissions licenses") among electric utilities, authorized by the 1990 amendments to the U.S. Clean Air Act. Even so, market-based programs that have been implemented to date remain well behind the state of the art. A system of tradeable *emissions* licenses, in its conception, is at least two steps removed from addressing the matter of ultimate economic interest: achieving an optimized level of *ambient pollution*. One key missing feature is that even cost-minimized reductions in *emissions* do not translate directly into the attainment of objectives specified in terms of levels of *ambient* pollution (that is, in terms of environmental *quality*). Likewise missing is any effort to equate marginal damage from ambient pollution with the (minimized) cost of abating the emissions that give rise to that pollution.

We may yet be some way from having the information needed to implement programs to achieve optimized levels of ambient pollution. But, though virtually unutilized to date, we do possess the techniques and are beginning to develop the data to address the problem of optimizing the cost of achieving *exogenously* specified environmental objectives expressed in terms of levels of ambient pollution. Doing so would be an important advance. It is rarely the case, especially with airborne contaminants, that emissions reductions translate in a straightforward manner into improvements in ambient environmental quality. Emissions, even from a single source, can have spatially differentiated effects. When emissions from multiple sources affect environmental quality differentially in different regions, the problem of efficiently achieving specified improvements in ambient air quality will depend in a complex way both on the cost structures of abatement at the different sources of emissions and also on the ways in which emissions from those sources disperse. That second dimension may render efficient attainment of environmental *quality* objectives very different from efficient abatement of *emissions*.

In theory, we know that a system of marketable "licenses to *pollute*" can be used to decentralize the problem of minimizing the cost of attaining ambient environmental objectives in spatially distinct regions. The existence and efficiency of the solution was first established by Montgomery (1972). Its implementation, however, is more informationally demanding than a simple system of tradeable emissions licenses. It requires, in particular, estimates of the mappings from each source of pollutants to ambient environmental quality in each target region of interest. To *study* this possibility realistically requires, in addition, data about actual sources of pollutants in the emitting regions under study. Such data are only now starting to become available on any large-scale basis. Since they are, however, the time seems ripe to begin exploring seriously the optimized pursuit of environmental *objectives*, rather than merely controlling the release of environmental contaminants.

This paper reports an investigation of precisely that sort. I exploit a recent, comprehensive inventory of North American sources of acid rain precursors, developed under the auspices of the U.S. Environmental Protection Agency ("EPA"), to study the implementation of a program of acid rain control in the Northeastern United States and Eastern Canada through a system of marketable licenses to pollute. My objective in pursuing this investigation is not merely confined to studying the gains to be achieved with a system of this sort.[1] There are collateral, but nevertheless important advantages to such systems, advantages that have been almost entirely overlooked by reason of the fact that their actual implementation has so infrequently been explored.[2] *Spatially* differentiated regions of concern may fall under differ-

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[1] It should be reasonably apparent that, for a given set of ambient environmental objectives, minimizing the cost of achieving those objectives, rather than minimizing the cost of reducing emissions, is the appropriate way to proceed. It provides an additional margin to work with, stemming from the fact that, even with costs of abatement held constant, abating emissions from some sources will more efficiently reduce ambient *pollution* than will emissions abatements from others.

[2] Atkinson (1983) and Atkinson & Tietenberg (1982), are two small scale exceptions.

ent *legal* jurisdictions, a fact that may be of particular importance when the jurisdictional boundaries happen to be national. Since airborne pollutants are not in the habit of respecting national boundaries, domestic efforts to achieve given ambient environmental quality objectives through the control of domestic emissions may sometimes not even be feasible. Even when they are, autarkic programs of environmental management are quite likely to be inefficient when compared to coordinated, multi-jurisdictional efforts. Nevertheless, it has often proved difficult to arrive at international agreements for the control of transboundary pollution. It might prove more feasible to coordinate multi-jurisdictional environmental management through the formation of international markets in *permits*.

In this paper I explore both of these issues in the context of the acid rain problem in the Northeastern United States and Eastern Canada. At a technical level this particular problem is characterized by complex relationships between emissions of acid-rain precursors and resulting ambient pollution, involving bilateral international flows of the pollutants of interest. As a political matter, it is a problem on which, despite 20 years of effort, the parties have been unable to arrive at an agreement. That inability apparently has been attributable to U.S. apprehensions that the costs of any coordinated solution to the problem would fall disproportionately on it.

I first estimate the optimized costs to each country of achieving specific environmental objectives using decentralized but *domestic* markets for licenses to pollute. I then compare the costs under these *autarkic* policies with the costs of a decentralized *joint* program of abatement, showing that, because of substantial bilateral spillover benefits to both the U.S. and Canada from the abatement of emissions in the other country, there are sizeable gains -- on the order of 70 percent annually over a 30-year period -- to be achieved from simply internationalizing and integrating those markets. One striking insight that emerges from these estimates is that the conventional beliefs that apparently have forestalled a U.S.-Canadian agreement are unfounded. When properly optimized, the U.S. has more to *gain* than to lose from a coordinated but decentralized program of acid rain abatement.

A second, equally striking finding is that the spillover benefits, while sizeable for both the U.S. and Canada when compared to autarkic programs of abatement, would be far more substantial for Canada. They are in fact so disproportionate as to render it tempting for *Canada* to refrain from reaching agreement and simply to "free ride" of U.S. abatement efforts. These findings suggest, then, that there might be serious obstacles to negotiating the gains to be achieved from trade. Indeed, in the face of potential incentives for Canada to "hold out," my findings suggest that it might actually be in the United States' interest simply to shoulder the cost of Canadian participation in a cost-minimized joint program of abatement.

The balance of the paper is divided into six sections. Section II provides background on the acid rain problem in the United States and Canada. Section III describes the methodology that I use in simulating a marketable permit system to abate sulfur dioxide emissions, including a brief discussion of the role of "transfer matrices" in specifying the crucial source-receptor mappings. Sections IV and V describe the data that I used in fashioning the simulations, and the methodology used to fit abatement cost functions for each point-source emitter in my sample. Section VI sets out the results of the simulations, and compares the estimated abatement costs facing each country under autarky and an internationally tradeable permit system. Section VII discusses methods used to test the sensitivity of the results presented in Section VI. A concluding section summarizes the findings of the simulations and discusses some policy implications of the findings.

II. Background and Motivation

The primary components of acid rain are sulfur oxides and nitrogen oxides, denoted (respectively) SO_x and NO_x. When SO_x and NO_x are released into the atmosphere from either natural or anthropogenic sources, they can settle as either dry or wet ("acid rain") deposition. In solution, SO_x and NO_x are responsible for the acidification of lakes and the resulting death of fish, the destruction of crops, and the degradation of man-made structures. Wet deposition has become especially serious in the Northeastern regions of the United States and in Eastern Canada. Eight "sensitive receptor" regions have been identified in the eastern regions of both countries, four in each country.[3]

Programs for the mitigation of acid rain have focused primarily on the reduction of sulfur dioxide emissions. Anthropogenic sources of sulfur dioxide vary greatly between Canada and the United States. Since the 1960s, the bulk of U.S. emissions has been generated by coal-fired electric generating plants.[4] Because Canada relies more heavily on other sources (such as hydro-electricity) for power, Canadian sulfur dioxide emissions come primarily from industrial and manufacturing sources, in particular from non-ferrous smelters. During 1985, electric power generation accounted for approximately 69 percent of total U.S. sulfur dioxide emissions, but only 20 percent of Canadian emissions. In contrast, industrial and manufacturing processes accounted for 67 percent of Canadian emissions and for less than 13 percent of U.S. emissions. In the aggregate, Canadian emissions were less than 20 percent of U.S. emissions. These national differences in the sources of sulfur dioxide emissions will prove to be important, because they lead to differences in the two countries' overall cost structures for the abatement of sulfurous oxide emissions. See Tables I and II, below.

(Tables I and II somewhere near here)

One major difficulty in controlling acidic deposition stems from the complex nature of the "source-receptor" relationship between the emitters of precursors to acid rain and the resulting acidic precipitation. Evidence for the bilateral nature of these flows has been developed from studies using "long-range transportation" (or "LRT") modelling of the migratory patterns of acid rain precursors and the resulting "source-receptor" relationships.[5] Although these models have not been perfected, and the choice of methodology to some extent remains controversial, LRT modelling has afforded policy makers improved insights into the importance of both inter-state (or inter-provincial) and transnational spillovers of pollution in achieving domestic ambient pollution objectives.

To date, North American acid rain abatement programs have not come to grips with *either* the transboundary nature of the problem *or* the differences in composition of sources of sulfur dioxide emissions in Canada and the United States. Efforts by the two countries to reach a joint agreement on the mitigation of acid rain have extended over nearly twenty years, but have been uniformly unsuccessful. With the Reagan Administration, whatever limited progress had been achieved to that point apparently came to a halt.[6] Political considerations aside, two technical considerations have hindered progress towards any joint U.S.-Canadian agreement: gaps in the scientific understanding of acid rain, and a lack of actual data on sources of sulfur dioxide emissions. Perhaps more importantly, anecdotal evidence suggests that the reluctance of the United States to reach a joint agreement has been fueled by the simultan-

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[3] A "sensitive receptor" region is simply a region that, for ecological reasons, has been identified as particularly sensitive to damage from acid rain.

[4] Before that time, the largest source of sulfur dioxide emissions in the United States was industrial/manufacturing processes (including non-ferrous smelters).

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[5] In general, there are two classes of LRT models currently in use. The first is based on a "Eulerian" grid, that models air masses moving over a fixed grid of points. The second is based on a "Lagrangian" method, which traces out the trajectory of moving air masses. Each type of LRT model takes into account such factors as the elevation (usually denoted "stack height") of emissions sources, the surface contours of the terrain, temperature, and general weather patterns that prevail in the areas of interest. Each also takes into consideration rates at which chemical reactions occur in the atmosphere in predicting where the dry or wet deposition will occur.

[6] In a 1982 memorandum, Mr. Raymond Robinson, then Executive Chairman of Canada's Federal Environmental Assessment Review Office, wrote regarding the U.S. stand on acid rain research and policy development that:

> . . . A pattern of external interference or inadequate support of the work has continued over the past year and a half. Our scientific experts have attended scheduled meetings and had virtually no one turn up on the United States' side or had people arrive whom they had never before seen. Despite the frustration of operating under such conditions, our people have occasionally succeeded in laboriously putting together a draft only to have it greatly changed by United States officials who had not been involved in the discussions that produced it. . .

Robinson, R.M., *The Rule of Law Between Nations - An Acid Test*, presented at the Seventh Symposium on Statistics and the Environment, National Academy of Sciences, Washington, D.C., October 4-5, 1982.

eous apprehension that the abatement costs would be enormous, and that they would produce no significant improvement in environmental quality, despite the fact there has been no concrete evidence to suggest that either supposition is so. With recent improvements in scientific understanding of the problem, and the recent availability of appropriate data, we are now in a position to begin investigating the extent to which such apprehensions are founded in fact or in fear.

III. A System of Tradeable "Licenses to Pollute"

The system of tradeable "licenses to pollute" that I use in this study draws heavily on theoretical work by Montgomery (1972). The distinguishing feature of a system of permits of this form is that it confers on the holder of permits the right to pollute, but *only* as long as doing so does not lead to an increase in ambient *concentrations* of the externality of interest above some exogenously specified level, in any receptor region specified by the administering authority as being of concern.[7] Such a system allows the administrator not merely to prescribe the levels of emissions to be permitted, but also, conditional on availability of the requisite data, to fix those levels in a manner calculated to achieve a prespecified improvement in ambient environmental quality in one or more regions, taking into account the natural migratory patterns of the pollutant.

Consider, then, a region in which there are n point-source emitters of sulfur dioxide, indexed by $i \; (= 1, \ldots, n)$. Total annual emissions of sulfur dioxide from point source i is denoted by e_i, and the vector of emissions from all point sources is given by $E = (e_1, \ldots, e_n)'$. There are m sensitive receptor areas in the region, indexed by $j \; (= 1, \ldots, m)$. Exogenously determined ambient air quality standards for sulfur dioxide for *each* of the m sensitive receptor areas are given by $S^* = (s_1^*, \ldots, s_m^*)'$, which I shall take to be measured in micrograms/cubic meter/year (μg/m^3/year). Average concentrations of sulfur dioxide in receptor region j are related to emissions at point source i by a "source-receptor" coefficient, h_{ji}. The array of source-receptor coefficients is thus an m x n matrix H with non-negative entries each of which relates the contribution of one unit of sulfur dioxide *emission* from point source i to the average sulfur dioxide *concentration* in receptor region j:

$$H = \begin{pmatrix} & \cdot & \\ \cdot \; \cdot & h_{ji} & \cdot \; \cdot \\ & \cdot & \end{pmatrix}_{m \times n \;\; (m<n)} \qquad (1)$$

Given a vector of emissions (E), *ambient pollution* in the vector of receptor regions is given by $S = H \cdot E$.

The program objective is to construct a policy such that an emissions vector will be chosen that will bring air quality standards into compliance in each of the m receptor regions, at *least total cost* for the entire geographic system. The emissions vector, E^*, that achieves these objectives will then be efficient *for the given ambient air quality standards, S^*.*[8] The standards imposed by S^* imply that, if all sensitive receptor areas are in compliance with the prescribed environmental standards, then $H \cdot E \leq S^*$.

The level of emissions from each point source is bounded above by a maximum that (at each level of output) assumes that *no* abatement technology were to be adopted (the "base" level of emissions, denoted $\bar{e}_i$); and is bounded below by the maximum reduction that could be achieved, using the most efficient available abatement technology, expressed as a percentage of the base level:

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[7] Emissions licenses allow the holder to produce a specific level of emissions, irrespective of the actual impact of those emissions on ambient environmental quality. Such permits produce efficient outcomes only if there is a one-to-one relationship between emissions and ambient pollution, a situation unlikely to arise when multiple jurisdictions are involved. In contrast, a system of "licenses to pollute" requires each emitter to hold a *portfolio* of licenses, relating its activities to ambient environmental quality in *each* target region.

[8] I emphasize that I am *not* attempting to simulate cost-minimized implementation of an *optimal* program of abatement, which would entail equating the marginal costs of abatement to the marginal *damage* from ambient pollution. I instead take the program objective (captured by S^*) as exogenously determined and seek optimal *implementation* of *that objective*.

$$(4) \qquad (1-\bar{\pi}_i)\bar{e}_i \le e_i \le \bar{e}_i,$$

where $\bar{\pi}_i$ is the maximum feasible percentage reduction in sulfur dioxide emissions using the best available control technology.

Associated with each point source is a cost function, denoted C_i, a minimum value function that gives the least total cost of achieving emissions e_i with output level y_i:[9]

$$(2) \qquad C_i = C_i(e_i, y_i).$$

Each cost function is assumed to be convex and twice differentiable in each of its arguments.

In general, the *actual cost* to each point source of attaining emissions level e_i (given a price, p_i, for its output) is the difference between the profits it *would* realize by choosing both an output *and* emissions level (e_i^*, y_i^*) to maximize profits, and the profits realized by choosing a profit-maximizing level of output ($\hat{y}_i$) *given* the emissions level e_i, or:

$$(3) \qquad F_i(e_i) = [p_i y_i^* - C_i(e_i^*, y_i^*)] - [p_i \hat{y}_i - C_i(e_i, \hat{y}_i)].$$

(As discussed in Section V-B, in estimating abatement costs I actually use a more restricted formulation in which output is constrained to remain fixed at 1985 levels.)

The least-cost strategy is then given by the solution to:

$$(5a) \qquad Min_{\{e_1,\ldots,e_n\}} \sum_{i=1}^{n} F_i(e_i)$$

$$\textit{Subject to} \quad H \cdot E \le S^*_{m \times 1}, \textit{ and}$$

$$(5b) \qquad (1-\bar{\pi}_i)\bar{e}_i \le e_i \le \bar{e}_i,$$

$$(i = 1,\ldots,n).$$

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[9] This represenation may also be extended for the multiproduct firm.

With a modest set of assumptions, the solution vector of emissions E^* may be attained through a system of marketable licenses to pollute, using a competitive market for the licenses, from any initial allocation of those licenses. The assumptions, and proofs of the existence and efficiency of the market, can be found in Montgomery (1972). Given the existence of a decentralized solution E^*, one can calculate the aggregate (optimal) cost of the program by solving the minimization problem (5). Solving that problem obviously requires both an inventory of sources of emissions and an estimate of each inventoried source's contribution to ambient concentrations of pollution in each receptor region (the entries in the matrix H). It also requires information about the cost of abatement at each point source.

IV. Data: The 1985 National Acid Precipitation Assessment Program

Emissions Source Data. Much of the data was derived from sources compiled by the EPA as part of the *1985 National Acid Precipitation Assessment Program, Version 2* ("NAPAP"). A series of studies under this program led to the compilation of over 93 data tapes that contain detailed information on *every* emitter of more than 100 tons of any criterion pollutant, located in *either* the United States or Canada, as of 1985. (The compiled data started to become available in 1991.)

North American sources of sulphurous oxides in the NAPAP inventories, by country and major category, are reported in Table I. More generally those sources can be divided into "area" sources and "point" (or "stationary") sources. The former include locations like bridges and tunnels that concentrate emissions from atomistic transient sources, while the latter (as the name implies) consist of fixed installations. While not broken down in Table I, point sources accounted for approximately 92 percent of all U.S. and 90 percent of all Canadian sulfur dioxide emissions in 1985. Because point sources account for the bulk of North American sulfur dioxide emissions, area sources were excluded from this study.

U.S. point sources were further restricted to electric utility generating plants, which by themselves accounted for 69 percent of all U.S. sulfur dioxide emissions in 1985 (as can be seen from Table

I). Detailed data on this subset of U.S. point sources was obtained from a NAPAP study denoted the 1985 National Utility Reference File ("NURF"). NURF contains information on electric utility generating plants that had never been previously available. It includes detailed, unit-level data for 10,778 electric generating units in the United States (of which 9,755 were existing units, and 1,023 had been announced at the time of the study).[10]

In contrast, Canadian sulfur dioxide emissions are not dominated by electric utility plants. As reported in Table I, electric utility generating plants account for only 20 percent of all Canadian sulfur dioxide emissions, while industrial and manufacturing processes (in particular, non-ferrous smelters) account for about 67 percent. Consequently, Canadian point source data used in this study were not further restricted by source. Data on the point sources actually used were obtained primarily from the 1985 NAPAP Annual Canadian Point Source Inventory ("ACPSI").

The actual sub-sample of the source data used in the simulations consists of a total of 400 point source emitters of sulfurous oxides. It includes the 200 largest *utility* generating point source emitters in the United States; and the 200 largest *general* point sources in Canada. This sub-sample accounts for 65 percent of all sulfur dioxide emissions from U.S. electric utility generating plants, and over 45 percent of all U.S. sulfur dioxide emissions; it accounts for over 95 percent of Canadian emissions. Thus, despite the relatively small sample size, it accounts, in the aggregate, for over 53 percent of *all* 1985 U.S.-Canadian point source emissions of sulfur dioxide.

Source-Receptor Data. To create the matrix *H*, source-receptor transfer coefficients were obtained from a study conducted by the Canada - United States Atmospheric Modelling Work Group 2 ("Group 2"), for the *Canada - United States Memorandum of Intent on Transboundary Air Pollution*. Several LRT models were developed by Group 2 to study the impact of sulfur dioxide emissions in both the United States and Canada on eight regions in the eastern halves of the two countries, four each in Canada and the United States.[11] Although different models generally did not yield identical transfer coefficients for each of those regions, the relative magnitudes of importance of the different contributing states and provinces proved to be fairly stable across models. In this study, I use the transfer coefficients developed by the Ontario Ministry of the Environment to simulate long-term ambient concentration and wet deposition patterns on a regional scale for eastern North America. Those coefficients, arrayed in Table III, relate the concentration of sulfur dioxide in wet deposition (micrograms per meter cubed per year) from a one teragram (10^{12} grams) emission of sulfur dioxide from a source in a given emitting region. So, for example, one teragram of sulfur dioxide emitted from Ohio would lead to an annual average increase in wet sulfur dioxide deposition in Region I by 0.22 micrograms per cubic meter, 0.51 micrograms per cubic meter in Region II, and so on. The source-receptor coefficients indicate that there are potentially significant transboundary flows of acid rain between the two countries in *both* directions -- which, if they can be exploited, may play an important role in a joint program for acid rain abatement.

(Table III somewhere near here)

V. Estimating Control Costs

In general, the term "point source," as used in the files from which the data for this study were derived, denotes a single boiler unit or smoke stack. In contrast, a "facility" -- a utility, industrial, or residential installation as a whole -- may often consist of more than a single point source. It seems to be agreed on within the engineering community that it is more efficient, in terms of both cost and process, to adopt abatement technologies point source by point source, at least as long as each point source is reasonably large, rather than routing all emissions from all point sources in a given installation through a centralized pollution abatement facility. This is especially true of pre-existing sources of emissions, to which pollution abatement equipment must be retrofitted.

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[10] A more detailed description of the NURF files is available from the author upon request.

[11] The eight regions are Algoma, Muskoka, Quebec, Southern Nova Scotia, Vermont/New Hampshire, the Adirondacks, Pennsylvania, and the Smokie Mountains.

I therefore estimated cost functions separately for each *point source*. The cost functions actually estimated for each point source *i* relate the aggregate annual cost of abatement to the *percentage* reduction in sulfur dioxide emissions (π_i) from the "base level" ($\bar{e}_i$), defined (as above) as the level of emissions in the absence of *any* abatement technology. To estimate cost functions for the reduction of sulfur dioxide emissions, the emissions source data were separated into one of three categories: (1) utility-owned electric generating plants, (2) non-ferrous smelters, and (3) other industrial or manufacturing processes. Different abatement technologies were assumed to be adopted within each category. In each case the choice of technology and determination of costs drew on engineering estimates and methodology, and included the costs of installing the basic control equipment (*e.g.*, a "scrubber," together with auxiliary equipment such as fans, hoods, and ductwork), annualized over the equipment's operating life; operating and supervisory labor costs; maintenance costs; and raw material inputs and electricity. "Retrofit factors," which scale up basic installation costs for the additional expense of outfitting pre-existing sources, were used in appropriate cases. In many instances there is a range of feasible technologies by which to achieve a given level of abatement, so that assumptions were required about the technology actually adopted at each category of point source. The justification for the assumptions actually adopted are described in detail in Appendix B and summarized briefly below.

A. Technological Assumptions

1. Electric Utility Generating Facilities

From among the *feasible* processes or technologies by which to reduce sulfur dioxide emissions from coal-fired electric facilities, I assumed the adoption of one of two general types of "flue gas desulfurization" ("FGD") -- or "scrubber" -- systems,[12] which remove sulfur dioxide from

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[12] In particular, I assumed that abatement was *not* achieved either by switching to low-sulfur coal, or by resorting to chemically cleaning high sulfur coal in advance of combustion.

waste gas streams. So-called "dry" scrubbers are generally installed in facilities with design capacities of under 100MW and that characteristically use low sulfur coal. Since, however, the sample of source data actually used in the simulations includes only the largest emitters -- which tend to use *high* sulfur coal -- I assumed that "wet" scrubbers would instead be installed. In terms of scrubber operation, I assumed that the least expensive substance, limestone -- the more expensive alternative is lime -- would be used as the primary reagent.

2. Non-Ferrous Smelters

For purposes of abating sulfur dioxide emissions, non-ferrous smelters are generally classified into those having gas streams with more than a 5 percent acid concentration ("strong" gas streams), and those with "weak" gas streams. For the former, the cheapest means of abating sulfur dioxide emissions is through the construction of an on-site plant that concentrates the waste gas stream into sulfuric acid, and for such smelters I assumed that method of abatement was used. That option generally is not available for smelters with weak gas streams, unless they were first to install equipment to strengthen the acid concentration in their waste gases. For them, abatement costs were estimated on the assumption that they installed wet scrubbers.

Available information[13] was used to match the NAPAP point source data on non-ferrous smelters with their company name to identify any equipment currently in use. For smelters that already had sulfuric acid plants in operation as of 1981, I assumed that the same technology would continue to be used. For smelters with no abatement technology, acid concentrations typical for the type of process in place were used to determine whether or not the installation of an acid plant would be feasible. That information was then used to guide the choice of abatement technology and to estimate pollution abatement costs.

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[13] Data were obtained from the *Canadian Mining Handbook* (1985), and the *Canada - United States Memorandum of Intent on Air Pollution, Emissions Costs and Engineering Assessment Interim Report, Work Group 3B* (1981).

3. Other Industrial/Manufacturing Processes

In contrast with utilities and (to some extent) non-ferrous smelters, there is little general information available on the costs of pollution abatement technology for industrial sources. I therefore relied heavily on engineering cost estimates and the methodologies outlined in Vatavuk (1990). One principal difficulty when dealing with sulfur dioxide abatement costs in manufacturing and industrial installations is allocating costs among pollutants when several are removed using a single abatement technology. From the range of possibilities, wet scrubbers of either a "venturi" or "double venturi" sort (see Appendix B), which are suitable for removing *both* particulates and gaseous emissions, but are somewhat less efficient at gaseous removal than other scrubbers, were generally used. The choice between the two types was (following engineering considerations) guided by the maximum flow rate of the emitter's exit gas. I also chose to allocate all costs of installing and operating the equipment to sulfur dioxide removal, even though the technology assumed is suitable for the removal of other pollutants as well. Clearly, that assumption will imposes an upward bias on the resulting estimate of the cost of sulfur dioxide alone. For each choice of technology, data from Vatavuk (1990) were used in determining equipment costs.

B. Estimating the Cost Functions

Once the choice of abatement technology had been fixed for each point source, I fitted a linear function to relate that point source's total annualized costs of abatement to its percentage reduction in sulfur dioxide emissions. In general, the cost of abatement is not linear in abatement: kinks may exist beyond a particular level of abatement, particularly when a technology is pushed beyond its maximum reliable level of abatement. Because, however, the simulations restrict the levels of abatement to be no greater than the maximum reliable efficiency level for each technology's design, it is reasonable to linearize the cost of abatement function in this area.

Estimates (generally based on information from engineering sources) were developed of the costs of installing and operating abatement equipment. These estimates include the capital outlay to install the abatement system (including any auxiliary equipment); fixed operating and maintenance costs (*i.e.* those incurred at any positive level of abatement, once the equipment is installed) (*FOMC*); and operating and maintenance costs that varied with the level of abatement (*VOMC*). To annualize the capital cost of the abatement system, I used a capital recovery factor (*CRF*) of the form:

$$CRF = \frac{k(1+k)^m}{(1+k)^m - 1}, \tag{6}$$

where *k* is the (allowed) rate of return and *m* is the lifespan of the project in years.[14] The proper value for *m* is typically taken to be the *lesser of* (1) the estimated remaining operating life of the point source, or (2) the estimated operating life of the abatement system itself.[15]

Total *annualized* costs (*TAC*) are therefore given by:

$$TAC_i = ACC_i + FOMC_i + VOMC_i, \tag{7}$$

where *ACC* is simply the product of the initial capital outlay for the equipment and the appropriate *CRF* (as given in (6)).

Operating cost estimates are typically given in the engineering literature for operating an abatement system at its *maximum* reliable level of efficiency. To estimate the costs of operating each abatement technology at lower levels of efficiency, a number of assumptions (outlined in Appendix B) were made for each of the different technologies used. In short, however, I assumed that, to operate at a lower

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[14] A capital recovery factor of this form sums to more than 1 over the life of the equipment, since it includes the cost of replacement parts. The rate of return was assumed to remain constant at 5 percent over the period covered by the estimates, but the results were not sensitive to this assumption.

[15] Note, also, that by annualizing the capital acquisition expenditures, the estimated *cost* functions do not capture the actual pattern of *outlays* to implement the simulated programs of abatement.

efficiency, smaller amounts of reagents would be used in the case of the wet scrubber technology.[16] Reduced reductions in emissions were more generally assumed to bear a linear relation to *variable* operating and maintenance costs[17] (but not, obviously, to fixed operating costs or to annualized capital costs).

Consequently, I estimated total annualized costs of abatement at levels of abatement below the maximum reliable level of efficiency (computed by five percent decrements), by adding reduced variable costs to annualized capital costs and fixed operating and maintenance costs. Each estimated cost function was then re-written in terms of percentage abatement:

$$TAC_i = \alpha_i + \beta_i \Pi, \quad i = 1, \ldots, n, \tag{8}$$

where Π is percentage abatement of emissions, determined by reference to the maximum reliable operating efficiency for the technology assumed to be adopted by point source *i*. By restricting the cost function to this form, I am assuming a constant marginal cost of abatement. Furthermore, linearizing the cost functions in this manner allows me to formulate the problem in (5) as a linear programming problem.[18] Note that I assume that the operating load at each point source remains *constant* (at 1985 levels) for the entire period over which the abatement equipment is depreciated. As such, the cost functions give the minimized cost of achieving a specified percentage abatement of emissions *at the (1985) level of output* given in the NAPAP inventories. Hence, setting $y_i^* = \hat{y}_i = \bar{y}_i$ in (3), the cost functions actually used in the simulations take the form:[19]

$$F_i = C_i(e_i, \bar{y}_i) - C_i(\bar{e}_i, \bar{y}_i) \tag{3A}$$

where $\bar{y}_i$ = 1985 operating load and $\bar{e}_i$ = 1985 base level of emissions. Accordingly, I do not consider the possibility of reducing emissions by reducing output levels (or by shutting down any point source). I consider the sensitivity of the results to this assumption in Section VII.

VI. Simulations and Results

I report results for three basic sets of simulations. In the first, I estimate the costs to the United States and Canada of achieving at least a 15 percent reduction in average annual acid rain concentration in *each* of *its own* four sensitive receptor regions by means of a domestic, "autarkic" program of abatement.[20] In the second I estimate the savings in abatement costs to each country from the "spillover" effects, attributable to transboundary flows of pollutants, from the autarkic policy pursued by the other (as calculated in the initial simulations). This second set assumes a Stackelberg-like behavior in which each country is assumed to take the other's autarkic program as given and to free ride off the other's abatement efforts. Finally, I estimate the costs to each of the two countries under a joint tradeable permit system. Two different calculations were carried out. In the first, I estimate the total cost of achieving at least a 15 percent reduction in acid rain concentration in all eight sensitive receptor regions. In the

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[16] This includes variations in other raw material inputs. For contact sulfuric acid plants, the plants are simply shut down (not producing) for short periods of time.

[17] For example, if limestone were to account for 20 percent of variable operating and maintenance costs of a wet scrubber, and if engineering estimates of all variable costs were $1 million for a 90 percent reduction, the calculated variable costs for an 80 percent reduction were taken to be $0.2 million*(8/9) + $0.8 million.

[18] Note that corner solutions for each source will dominate the solution for the cost minimization problem due to the linearization of the cost function with constant marginal cost.

[19] Note that (8) is given in terms of percentage abatement whereas (3A) is in terms of emissions level. To transform (3A) into (8), I use the relationship that:

$$\Pi_i = \frac{\bar{e}_i - e_i}{\bar{e}_i}$$

[20] The choice of a 15 percent across-the-board reduction in acid rain concentrations as an objective was necessarily arbitrary. Lacking an explicit damage function with which to value reductions in acid rain, the abatement *level* cannot be optimally selected.

second I estimate the total cost of achieving the *largest* reduction in acid rain concentration, in *each* of the eight sensitive-receptor regions, that was achieved under *either* country's initial autarkic program.

Each simulation consists of the solution to a linear version of the constrained cost minimization problem in (4) and outlined in Section III. All were solved using linear programming.[21] One preliminary calculation was carried out before running any of the simulations. Using the 200 largest (electric utility) point source emitters in the United States and the 200 largest emitters in Canada (as given by the 1985 NAPAP data), I calculated the concentrations of acid rain attributable to those point sources in each of the eight sensitive receptor regions based on 1985 levels of emission. To do this, I utilized the source-receptor coefficients summarized in Table III. I applied the appropriate coefficient to each point source, multiplied it by that point source's *actual* 1985 emissions, and then summed over all point sources for each receptor region. In effect I compute $H\hat{E}$ using the matrix H (expression (1)) and the vector of 1985 base level emissions ($\hat{E}$). This yields the average annual acid rain concentration, attributable to all point sources in the sample, in each receptor region under study. [[(See Table A.I in Appendix A.)]]

The key results for all simulations are summarized in Table IV. More detail on each set of simulations, including shadow values on the program constraints, can be found in separate tables for each simulation included in Appendix A.

(Table IV somewhere near here.)

A. Autarkic Simulations

In estimating the cost of the autarkic programs of abatement, I assume in each case that:

(1) the program objective is to reduce average acid rain concentrations in each of the four sensitive receptor regions *in the implementing country* by at least 15 percent from 1985 levels, and

(2) each country, in formulating its program, takes the other country's emissions as fixed at 1985 levels.[22]

Thus, each country is concerned exclusively with its own environmental quality, and cannot rely on spill-over benefits, due to transboundary flows of pollutants, from abatement efforts by the other. The results are reported in Columns 1 and 2 of Table IV.

Under an autarkic program of marketable licenses to pollute, the total annualized cost to the United States of achieving a 15 percent reduction in acid rain concentrations in Regions V - VIII is $0.977 billion, an *average* cost per ton reduction in sulfur dioxide of approximately $381.[23] In the solution to the program, Regions V and VIII achieve the minimum reduction in acid rain concentration of 15 percent from base 1985 levels. Region VI achieves a reduction of nearly 25 percent, and Region VII of more than 45 percent. The annual cost to Canada of an autarkic policy is $1.186 billion, or an average cost per ton reduction of sulfur dioxide of approximately $1091.[24] The resulting concentration in Region I reflects the minimum 15 percent reduction; whereas for Regions II - IV, final concentrations are reduced by between 20 and 40 percent over base 1985 emissions levels.

The autarky results by themselves exhibit some intriguing features. The annual cost to the United States of an autarkic policy is almost $200 million, or 20 percent, lower than the annual cost to Canada. In part, this can be explained by the volume of U.S.-generated emissions polluting Canadian receptor regions, beyond the control of the Canadian authorities. To meet its autarkic objectives, it appears that Canada must reduce *domestic* emissions by significantly more than would otherwise be necessary if foreign pollution did not contribute to Canadian acid rain.

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[21] A simplex algorithm furnished by MATLAB™ was used in carrying out all the simulations.

[22] The four sensitive receptor regions in Canada are regions I-IV; those in the United States are regions V-VIII.

[23] Under the U.S. autarky policy, this corresponds to a 2,566,000 ton reduction in sulfur dioxide emissions.

[24] Under the Canadian autarky policy, this corresponds to a 1,085,800 ton reduction in sulfur dioxide emissions.

Also striking are the substantial spillovers from both autarkic policies. The U.S. autarkic program produces a spillover reduction in acid rain concentration of more than 15 percent in all but one (Region III) of the Canadian sensitive receptor regions. The Canadian autarkic policy leads to significantly more than a 15 percent reduction in two of the U.S. sensitive receptor regions -- Region V and VI -- but has negligible effects in the others.

B. Estimating Spillover Effects

I next measure the cost savings from these spillover effects by estimating the "free-rider savings," by which I mean the costs country *j* would incur to implement an autarkic policy, *knowing* that country *i* will *also* implement an autarkic policy (with a 15 percent reduction), and *knowing also* how country *i*'s policy will affect country *j*'s acid rain concentrations. Under this "Stackelberg"-type simulation, country *j* is "free-riding" off of the reductions in acid rain that occur from country *i*'s program of abatement, and can therefore reduce its own abatement *effort*, while still achieving an aggregate reduction of at least 15 percent in acid rain concentration in each of its own sensitive-receptor regions.

The results for the two "free-rider" estimates are summarized in Table IV, columns 3 and 4. When the U.S. assumes that Canada will implement a 15 percent reduction in each if the Canadian regions, the U.S. need only reduce acid rain concentrations in U.S. Regions VII and VIII to obtain a 15 percent reduction (from 1985 levels) in all four of its receptor regions. The annualized costs to the U.S. under this simulation decline to approximately $231 million, a savings of more than $700 million over the U.S. autarkic program. The average cost per ton reduction of sulfur dioxide falls to $288, or by nearly $100 per ton. When the situation is reversed -- that is, when Canada assumes that the U.S. will implement its own autarkic policy, and free-rides off the U.S. spillover reductions -- the annualized costs facing Canada drop to $1.8 *million*, or an average cost per ton reduction of sulfur dioxide of only *$23*, with aggregate annualized savings of over $1.0 billion. These findings suggest that there may exist powerful incentives for each country to free-ride off the other, creating possibly substantial hold-up obstacles to the achievement of a joint U.S.-Canadian agreement on acid rain reduction.

C. Joint Programs of Abatement

Here, I present estimates of the costs of abatement facing the United States and Canada under two different *joint* programs of abatement, each involving a system of *internationally* tradeable permits. The objective of the first program is at least a 15 percent reduction in acid rain concentration in each of the eight North American sensitive receptor regions. That is, I re-estimate the cost of abatement, carried out jointly, holding the original program *objective* constant. But each of the separate autarky programs actually achieved substantially greater reductions in one or more of those regions. So it is also useful to compare the joint costs of achieving the reductions in acid rain concentration *actually realized* under the autarkic programs. Hence, I also estimate the cost of a joint program to achieve a reduction in acid rain concentration in each region *at least* equal to the maximum reduction for that region achieved under *either* the Canadian or U.S. autarky programs. In both instances the savings are dramatic.

Table IV, column 5, reports the costs of the first of these programs. The *aggregate* annualized cost of a joint program to achieve at least a 15 percent reduction in each region is estimated to be only $632 million, of which about $608 million is incurred by the United States (average cost of reduction per ton sulfur dioxide of $408) and $25 million by Canada (average cost of reduction per ton of sulfur dioxide of $50). Aggregate savings over the two autarkic policies are more than $1.5 billion annually, of which $389 million are enjoyed by the United States and about $1.157 billion by Canada. Joint action spares both countries the unnecessary effort they would otherwise have had to expend to achieve improvements in domestic environmental quality that were due largely to foreign spillovers of pollutants. By so doing it reduces the aggregate cost of achieving the original program objectives by more than 70 percent.

Table IV, column 6, summarizes the findings from a joint U.S.-Canada program of abatement that seeks to achieve acid rain concentrations in each receptor region *at least as low* as the lowest concentration under either autarkic program. The aggregate annualized cost of this program is only $1.145 billion, $1.09 billion incurred by the United States (average cost per ton of reduction of sulfur dioxide is $311) and $55 million by Canada (average cost per ton of reduction of sulfur dioxide is $91). Canada achieves larger reductions in acid rain concentration in each of its sensitive receptor region despite a $1.13 billion reduction in annual cost. The United States experiences *substantial* gains in reducing acid rain concentration in all but one of its regions. The price of these gains is modest, not (as commonly supposed) substantial: a $100 million increase in annualized cost. Overall, the two countries can jointly produce results at least as good as those *actually achieved* under the autarkic programs, at about 50 percent of the aggregate cost.

The comparison of either joint program with the costs of the autarkic programs makes a compelling case for coordinated abatement policies. The comparisons implied by all three sets of estimates are summarized in matrix form in Figure I. Aggregate combined costs of achieving a 15 percent over-all reduction of acid rain concentration is clearly minimized by joint effort and maximized through separate autarkic programs. That is not especially surprising. What is striking, however, is the very substantial difference in annualized savings to the two countries from free-riding off the other country's autarkic policy, displayed in the off-diagonal elements of Figure I. Canada's annualized costs become trivial (approximately $2 million) if it acts on the assumption that the U.S. will implement a 15 percent reduction through an autarkic policy. In this instance, Canada need only be concerned with Region III, the only Canadian region in which, under a U.S. autarkic policy, a 15 percent reduction does not occur. In terms of aggregate joint costs, this is the second least costly solution overall.

(Figure I somewhere near here)

For the United States, reliance on a Canadian autarkic policy produces savings of over $600 million annually over a U.S. autarkic policy that is implemented on the assumption that Canadian emissions remain fixed at 1985 levels. The savings are less dramatic than in the Canadian "free-rider" case.

D. Autarkic Control of All Point Sources

Given the existence of both gains from trade and incentives to free-ride off the other country's autarkic policy, a natural final question is: how much would country *i* pay country *j* to assist country *i* in achieving a 15 percent reduction in acid rain concentration in country *i*'s sensitive receptor regions. To estimate the "pay-offs" that might take place, I return to autarkic programs implemented by each country to achieve a 15 percent reduction in acid rain concentration in each of its *own* receptor regions. Now, however, I estimate the aggregate costs to each country acting separately, but assuming that in can implement a tradeable permit system that involves *all 400 point sources* in the sample, and compare those costs with the costs facing that country under an autarkic policy optimized only over its domestic sources of emissions.

Column 7 of Table IV summarizes the results of achieving a 15 percent reduction in acid rain concentration in each U.S. receptor region. The aggregate annualized cost is $454 million, of which $443 million is incurred for abatement at U.S. point sources and $11 million at Canadian sources.[25] The difference between this figure and the annualized cost to the United States of its domestic autarkic policy for a 15 percent reduction ($0.977 billion) is $523 million. Column 8 summarizes the results of a comparable simulation, this time to achieve a 15 percent reduction in acid rain at each Canadian region. With all 400 point sources participating, the total annualized cost of the Canadian program is $385 million (of which about $350 million consists of abatement at U.S. sources), a savings of about $800 million over the cost to Canada of a pure autarkic program.[26]

One possible way of looking at these final simulations is that, in principle (and for a 15 percent reduction in U.S. domestic acid rain), the United States should be willing to pay up to $523 million

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[25] The average cost per ton reduction of sulfur dioxide in the United States is $315 and in Canada is $27.

[26] The average cost per ton reduction of sulfur dioxide for the United States is $283 and for Canada is $67.

(annually) to obtain Canadian participation in abatement; conversely, Canada should be willing to pay as much $800 million to obtain U.S. participation. But the simulation results exhibit several other features that suggest that neither of those outcomes is likely. Looking first at Canada, the results confirm that, consistent with the fact that much Canadian ambient pollution arises from U.S. sources, Canadian ambient air quality is most efficiently improved by abating emissions at U.S. point sources. A program involving Canadian control over all point sources would be more costly than free-riding off U.S. abatement, but it would also bring all four Canadian regions into compliance. On the other hand, simply free-riding leaves only Canadian Region III out of compliance, a shortcoming that Canada could rectify at negligible cost. Hence, whether Canada would be willing to pay *anything* for U.S. abatement would turn on a strategic judgment about the likelihood of U.S. abatement in the absence of any agreement.

For the United States, efficient abatement still involves reducing emissions predominantly at U.S. point sources. Nevertheless, the United States can reduce its program cost by more than 50 percent by securing a relatively trivial measure of abatement at Canadian sources. So it would be extremely advantageous to the United States to secure Canadian participation in any joint program of abatement. Short of -- and less expensively than -- outright cash transfers, the United States might attempt to secure Canadian participation by offering to allocate initially to *all* Canadian point sources permits sufficient to allow them to continue emitting at baseline levels. In effect, some U.S. *emitters* would compensate Canadian emitters for any abatement they undertook. Such a scheme would pareto-improve the cost of abatement, since the net cost to Canada would be zero.

That arrangement would not have the property of bringing all *Canadian* regions into compliance with the program objective. But an additional annualized expenditure of about $150 million, mostly at U.S. point sources, would. That is, if the United States could elicit Canadian participation, *and if* it undertook a program calling for a 15 percent reduction in *all eight* receptor regions, the total annualized cost to the United States -- the cost of the 15 percent reduction joint simulation -- would still be only $632

million. It is not obvious whether Canada might successfully insist that the United States specify a 15 percent reduction in *all* eight regions as part of the price of its participation; or whether, on the other hand, the United States might be in a position to insist that Canada bear the annualized costs of that respecification of the objective. The bargaining position implied by these estimates is both clearly at odds with conventional wisdom and potentially quite complex.

VII. Sensitivity Tests and Other Considerations

In interpreting the results reported in Section VI, it is important to keep three significant underlying assumptions in mind. The first two are that, over the 30-year period during which the abatement technology is in place (and the equipment depreciated), (1) output remains fixed at 1985 levels, and (2) industrial processes (including fuel mixes) remain stable. Both assumptions are needed for estimated base-level emissions to remain constant over the lifespan of the abatement equipment. Third, I have assumed that firms do not engage in activities that alter the coefficients that relate their emissions to ambient pollution in each of the sensitive receptor regions.

In general, options available to polluters do include reducing output or even shutting down. Under the permit system that I use in this paper, shut down should occur if the value of output from any point source is less than the cost of the portfolio of permits that point source is required to hold. If it were, it would be more profitable simply to sell the permits and discontinue operation. By assuming that output remains fixed at 1985 levels, I clearly do not allow for that possibility.[27] Imposing this condition does allow us to side-step the more complex welfare considerations that arise when facilities actually are shut down in response to a tradeable permit system. For that very reason, moreover, shut down decisions can

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[27] For electric utilities, this is not necessarily a bad assumption. The demand for electricity will generally not decline over time, however, due to technology that allows electricity to be transported very efficiently over long distances, one may want to allow changes of output amongst plants within a region so long as over-all output remains constant within that region. Regional boundaries, however, would be determined wholly on the state of transmission technology, and may be somewhat arbitrary.

(and, in some instances, probably would) be affected not just by purely economic but by political considerations, taking the form (for example) of special exemptions for particular facilities.

Assumption (2) ensures that technological changes do not occur that affect the way in which the base emissions are calculated. Changes in industrial processes *can*, of course, affect emissions levels dramatically, as can sometimes simple alterations in fuel mix. Allowing the base level of emissions to change over time would complicate the calculations significantly. Since, moreover, I have no way of predicting what changes in process design or fuel mix might actually occur, I have not allowed for flexibility in either of these conditions.[28]

The third assumption restricts the h_{ji} to being constant over time. So, for example, I do not allow for the possibility of firms moving, or even making relatively simple changes like altering smokestack heights, that almost surely would produce time-variation in some of the h_{ji}. This assumption warrants caution in any long-run interpretation of the results. Location issues will be important if over time firms can with relative ease reduce the costs of abatement they face by relocating to a region from which they will have less of an impact on environmentally sensitive regions.

Beyond these considerations, shortcomings in data and other information about actual abatement costs limits the number and quality of the sensitivity tests that can usefully be conducted on the results. The greatest concern lies with the estimates of the cost of abatement functions. Some simple tests that I did carry out included examining how robust the results were to changes in the rate of return, which affects the capital recovery factor I used to annualize the capital outlays. The base cost of abatement functions were estimated using a 5 percent rate of return. No significant changes resulted from the substitution of a 7 percent rate of return. I also calculated upper and lower bounds on the cost estimates, using the general rule of thumb that engineering cost estimates are accurate to within ± 20 percent. Allowing

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[28] As discussed earlier, there is anecdotal evidence for the proposition that there may exist local political obstacles to the relatively simple step of switching from high to low sulfur coal.

the estimated (constant) marginal cost of abatement to vary by that amount, I re-ran the simulation for a joint program with the objective of a 15 percent reduction in acid rain concentration in all eight sensitive receptor regions testing eight different combinations of cost functions.[29] The reductions in acid rain concentrations remained the same as in the reported simulations in each of the seven variations; the only differences were in the shadow values of some of the constraints. The basic cost savings from moving from autarky to a joint program remained robust in all variations.[30]

VIII. Conclusion and Implications

In an important respect, however, the degree of precision with which the costs of abatement have been estimated is not the decisive consideration. In the final analysis the real objective of a study of this sort is not to arrive at precise estimates of actual costs. It is, rather, to study the qualitative nature of the gains to be achieved from using techniques geared to the efficient attainment of environmental objectives in a multi-jurisdictional setting. At an intuitive level, what drives the results reported in this paper is a combination of (1) the complex relationships between emissions and ambient pollution captured in the source-receptor coefficients, and (2) the *differences* in U.S. and Canadian cost structures for abatement of sulfur dioxide emissions stemming from differences in the primary sulfur dioxide producers operating in the two countries. Hence, as long as the *relative* costs of abatement between U.S. and Canadian

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[29] That is, allowing both U.S. and Canadian marginal costs to take on the values +20%, 0, and -20% (where zero denotes no change from the marginal cost used in the reported simulations), I reran the simulation using each possible combination of costs.

[30] Two other considerations warrant mention. First, electric utilities are regulated in the United States and may not necessarily cost minimize. The simulations assume that all polluters will behave in a cost-efficient manner. If this assumption were violated, the reported results will underestimate the costs of tradeable permit programs. I have also assumed that trades only occur between polluters; I do not allow for the possibility that interested outsiders (such as the Sierra Club) might choose to participate in the market for permits. If individuals or organizations were allowed to buy and sell permits, and had higher valuations for less acidic rain, then the price of the permits could be driven upward and the cost of abatement would also be expected to rise.

emitters have been captured with reasonable accuracy by my estimated cost of abatement functions, and the source-receptor coefficients remain relatively stable to improvements in LRT modelling, the qualitative *insights* from the estimates presented above should remain robust to strengthening of the data.

Those insights tend strongly to contradict the belief that it would be prohibitive for the United States to participate in a joint program of acid rain abatement with Canada. To the contrary, my findings suggest that *both* the U.S. *and* Canada would experience substantial reductions in annualized abatement costs through joint action. The evidence, however, is also consistent with the possibility that the two countries *might* thus far have been unable to reach agreement on a joint program of abatement because of substantial *differences* in the magnitude of the savings that would accrue to each. Given the differences disclosed by the simulations, both countries -- but especially Canada -- may be confronted with substantial incentives to "free-ride" off an autarkic program of acid rain pursued by the other. This may create potential hold-up problems, turning on difficulties in allocating the gains to be realized from trade. All this suggests that arriving at a joint agreement may prove to be far more complicated than would be suggested by the simple magnitude of the cost savings that are there to be realized. Unfortunately, if whatever differences that have forestalled agreement to date are driven by an inability to allocate gains from trade, and if it should prove politically infeasible for each country simply to free-ride off the other, the worst-case scenario might be what we ultimately observe. Each country might end up implementing an autarkic program of abatement, a course that would, at least on the evidence presented here, *maximize* the joint costs of achieving target reductions in acid rain concentration in each country's sensitive regions.

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Figure I:

Annualized Costs (in $1990 Billions) For Different Options to Achieve a Minimum 15 Percent Reduction in Acid Rain Concentration[31]

	Canada	
United States	($0.977, $1.185) (Autarky, Autarky)	($0.977, $0.002) (Autarky, Stackelberg)
	($0.231, $1.185) (Stackelberg, Autarky)	($0.608, $0.025) (Joint Policy)

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[31] Note that the upper left entry to the pay-off matrix is *not* an equilibrium, whereas the other three entries are, in fact, possible equilibrium outcomes.

Table I

1985 NAPAP Emissions Inventory Version 2[32]
Point and Area Source Emission by Major Category

Source	SO_2 Emissions (10^3 tons/year)	
	United States	Canada
Electric Utilities	16,055	819
Industrial Combustion	2,679	340
Comm. / Res. / other Combustion	613	69
Industrial / Manuf. Processes	2,931	2,731
Transportation	864	99
Other	4	0
Total	23,146	4,058

Table II

Estimates of the Incremental Costs of Removing Pollutants From New Sources[33]

Sulfur Dioxide Source	1980 Dollars per Metric Ton Removed
Electric Utilities: Eastern Coal Western Coal	265-298 1,167-1,414
Iron and Steel Coking	184-579
Primary Copper	22
Primary Lead	315
Primary Zinc	222
Paper	92 - 12,437

Table III

Source-Receptor Coefficients for
Annual Sulfur Dioxide Concentration ($\mu g/m^3$)
per unit emission (Tg.S/yr)

	Sensitive Receptor Areas							
Source Region	RI	RII	RIII	RIV	RV	RVI	RVII	RVIII
Michigan	0.70	1.70	0.50	0.57	0.91	1.50	3.30	0.16
Illinois Indiana	0.34	0.49	0.19	0.22	0.31	0.46	1.30	0.80
Ohio	0.22	0.51	0.25	0.40	0.48	0.78	4.00	0.37
Penn.	0.17	0.46	0.30	0.62	0.63	0.99	9.20	0.16
New York to Maine	0.10	0.33	0.40	1.90	1.00	1.60	0.62	0.06
Kentucky Tennessee	0.12	0.19	0.10	0.15	0.17	0.23	0.74	3.20
W. Virg. to N.C.	0.10	0.22	0.17	0.40	0.33	0.46	1.70	0.26
Florida to Mo. to Minn.	0.68	0.55	0.20	0.18	0.28	0.38	0.62	1.90
Ontario	1.00	3.20	1.90	0.91	2.00	2.20	0.96	0.06
Quebec	0.30	0.57	3.00	1.30	4.70	1.10	0.18	0.03
Atlantic Provinces	0.03	0.07	0.26	1.50	0.26	0.15	0.05	0.01

RI: Algoma; RII: Muskoka; RIII: Quebec; RIV: Southern Nova Scotia; RV: Vermont/New Hampshire; RVI: Adirondacks; RVII: Pennsylvania; RVIII: Smokies (Southern Appalachians).

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[32] Source: U. S. Environmental Protection Agency; *1985 National Acid Precipitation Assessment Program, Version 2.*

[33] Environmental Protection Agency, "The Incremental Cost Effectiveness of Selected EPA Regulations;" (EPA, January 23, 1981).

Appendix A

This Appendix contains tables that summarize the simulation results that were presented in Section VI of the text. All dollar values are given in constant $1990 values.

Table IV

Summary of Total Annualized Costs and
Changes in Acid Rain Concentrations from 1985 Base Levels
for All Program Options

	Percentage Change in Acid Rain Concentration from 1985 Base levels							
Region	U.S. Autarky	Canada Autarky	U.S. Free-Rider	Canada Free-Rider	Joint Action: 15% Reduction	Joint Action: Max Reduction	15% U.S. Reduction (All Point Sources)	15% Can. Reduction (All Point Sources)
Region I	- 15.44	- 15.00	-15.49	- 16.42	- 17.98	-26.81	-10.16	-16.23
Region II	- 16.07	- 24.20	-23.39	- 17.43	- 15.00	-28.45	-8.89	-15.00
Region III	- 10.99	- 39.65	-38.72	- 15.02	- 24.50	-15.00	-22.07	-25.59
Region IV	- 24.24	- 20.37	-22.52	- 26.30	- 17.74	-43.29	-20.98	-16.52
Region V	- 15.00	- 37.07	-40.32	- 16.32	- 27.91	-46.21	-26.18	-27.49
Region VI	- 24.20	- 20.20	-25.11	- 22.64	- 16.52	-40.37	-15.00	-15.61
Region VII	- 45.42	- 2.66	-15.00	- 44.64	- 15.00	-62.44	-15.00	-10.07
Region VIII	- 15.00	- 0.40	-15.00	- 18.35	- 15.00	-16.22	-15.00	-9.41
Total Cost: U.S. Point Sources (Annual)	$0.977 B		$0.231 B	$0.977 B	$0.608 B	$1.090 B	$0.443 B	$0.349 B
Total Cost: Canadian Point Sources (Annual)		$1.185 B	$1.185 B	$0.002 B	$0.025 B	$0.055 B	$0.011 B	$0.036 B

Table A.I

1985 Acid Rain Concentrations Derived from Sample Data

Sensitive Receptor Region	Total Canadian Contribution (%)	Total U.S. Contribution (%)	Concentration ($\mu g/m^3$/year)
RI: Algoma	30.88	69.12	0.4165
RII: Muskoka	51.20	48.80	0.7613
RIII: Quebec	70.06	29.94	0.5452
RIV: Southern Nova Scotia	43.29	56.71	0.4734
RV: Vermont/New Hampshire	58.97	41.03	0.7818
RVI: Adirondacks	37.15	62.85	0.7673
RVII: Pennsylvania	4.74	95.26	2.0817
RVIII: Smokie Mountains	0.42	99.58	0.9458

Table A.II

U.S. Autarky Policy for a 15% Reduction of Acid Rain Concentrations in Regions V-VIII

Region	1985 Base Concentration ($\mu g/m^3/yr$)	Autarky Limit ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change from Base
Region I	0.41646		0.3521	- 15.44
Region II	0.76132		0.6389	- 16.07
Region III	0.54510		0.4851	- 10.99
Region IV	0.47328		0.3585	- 24.24
Region V	0.78181	0.66450	0.6645	- 15.00
Region VI	0.76740	0.65219	0.5816	- 24.20
Region VII	2.08182	1.76946	1.1362	- 45.42
Region VIII	0.94559	0.80390	0.8039	- 15.00
Total Cost: $0.977 Billion				

Table A.III

Canadian Autarky Policy for a 15% Reduction of Acid Rain Concentrations in Regions I-IV

Region	1985 Base Concentration ($\mu g/m^3/yr$)	Autarky Limit ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change from Base
Region I	0.4165	0.3540	0.3540	- 15.00
Region II	0.7613	0.6471	0.5770	- 24.20
Region III	0.5451	0.4634	0.3289	- 39.65
Region IV	0.4733	0.4024	0.3768	- 20.37
Region V	0.7818		0.4920	- 37.07
Region VI	0.7674		0.6123	- 20.20
Region VII	2.0818		2.0263	- 2.66
Region VIII	0.9456		0.9416	- 0.40
Total Cost: $1.185 Billion				

Table A.IV

Dual Values of Sensitive Receptor Constraints in $/($\mu g/m^3/yr$)

Region	Shadow Value From U.S. Autarky Policy	Shadow Value From Canada Autarky Policy
Region I		6.17801×10^8
Region II		0
Region III		0
Region IV		0
Region V	0.19923×10^8	
Region VI	0	
Region VII	0	
Region VIII	0.01707×10^8	

Table A.V

Estimated Value to the United States of the Spillover Effects From the Canadian Autarky Policy on U.S. Sensitive Receptor Regions V-VIII

Region	Spillover Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	Dual Value ($\$/\mu g/m^3/yr$)
Region I		0.1501	
Region II		0.4042	
Region III		0.3835	
Region IV		0.2217	
Region V	0.4920	0.4963*	0.7571
Region VI	0.6123	0.3374	0
Region VII	2.0263	0.3006	0
Region VIII	0.9416	0.1016	0
Total Cost: $3.00 Billion			

Table A.VI

Estimated Value to Canada of the Spillover Effects From The United States Autarky Policy on Canadian Sensitive Receptor Regions I-IV

Region	Spillover Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	Dual Value ($\$/\mu g/m^3/yr$)
Region I	0.3521	0.3515	0
Region II	0.6389	0.5709	0
Region III	0.4851	0.3128	0
Region IV	0.3585	0.3585	0
Region V		0.4704	
Region VI		0.6046	
Region VII		2.0241	
Region VIII		0.9413	
Total Value: $2.851 Billion			

Table A.VII

Annual Costs under "Free-Rider" Assumptions

	United States (μg/m^3/yr)			Canada (μg/m^3/yr)		
	Resulting Concentration Under Canadian Autarkic Policy	15 Percent Reduction of Base	Final	Resulting Concentration Under U.S. Autarkic Policy	15 Percent Reduction of Base	Final
RI	-	-	0.3520	0.3521	0.3540	0.3481
RII	-	-	0.5832	0.6389	0.6471	0.6286
RIII	-	-	0.3341	0.4851	0.4634	0.4633
RIV	-	-	0.3668	0.3585	0.4024	0.3489
RV	0.4920	0.6645	0.4666	-	-	0.6542
RVI	0.6123	0.6522	0.5746	-	-	0.5936
RVII	2.0263	1.7695	1.7695	-	-	1.1525
RVIII	0.9416	0.8039	0.8039	-	-	0.7722
Cost	$0.231 Billion			$0.002 Billion		

Table A.VIII

Joint U.S. - Canada Policy For a 15% Reduction in Acid Rain Concentrations in all Eight Sensitive Receptor Regions

Region	Maximum Allowable Concentration (μg/m^3/yr)	Final Concentration (μg/m^3/yr)	% Change From Base	Dual Values (\$/μg/m^3/yr)
Region I	0.3540	0.3416	- 17.98	0
Region II	0.6470	0.6470	- 15.00	9.8052×10^6
Region III	0.4634	0.4061	- 24.50	0
Region IV	0.4023	0.3893	- 17.74	0
Region V	0.6445	0.5636	- 27.91	0
Region VI	0.6522	0.6406	- 16.52	0
Region VII	1.7696	1.7696	- 15.00	0.3826×10^6
Region VIII	0.8039	0.8039	- 15.00	1.3385×10^6
Total Cost for the U.S.: $0.608 Billion				
Total Cost for Canada: $0.025 Billion				

Table A.IX

Joint U.S. - Canada Policy For a Maximum Reduction in Acid Rain Concentrations in all Eight Sensitive Receptor Regions as Determined Under the Two Autarkic Policies

Region	Maximum Allowable Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change From Base	Dual Values ($\$/\mu g/m^3/yr$)
Region I	0.3521	0.3048	- 26.81	0
Region II	0.6389	0.5447	- 28.45	0
Region III	0.4851	0.3289	- 15.00	3.7574×10^7
Region IV	0.3585	0.2684	- 43.29	0
Region V	0.4920	0.4205	- 46.21	0
Region VI	0.6123	0.4576	- 40.37	0
Region VII	1.1362	0.7819	- 62.44	0
Region VIII	0.8039	0.7922	- 16.22	0
Total Cost for the U.S.: $1.090 Billion				
Total Cost for Canada: $0.055 Billion				

Table A.X

Achieving a 15 Percent Reduction in U.S. Sensitive Receptor Regions Using all 400 Point Sources

Region	Maximum Allowable Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change From Base	Dual Values ($\$/\mu g/m^3/yr$)
Region I		0.3742	-10.16	
Region II		0.6936	-8.89	
Region III		0.4248	-22.07	
Region IV		0.3740	-20.98	
Region V	0.6645	0.5771	- 26.18	0
Region VI	0.6522	0.6522	- 15.00	6.6892×10^6
Region VII	1.7695	1.7695	- 15.00	0.1734×10^6
Region VIII	0.8039	0.8039	- 15.00	1.8005×10^6
Total Cost (U.S. sources): $0.443 Billion				
Total Cost (Canadian sources): $0.011 Billion				

Table A.XI

Achieving a 15 Percent Reduction in Canadian Sensitive Receptor Regions
Using all 400 Point Sources

Region	Maximum Allowable Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change From Base	Dual Values ($\$/\mu g/m^3/yr$)
Region I	0.3540	0.3489	- 16.23	0
Region II	0.6471	0.6471	- 15.00	1.3663×10^7
Region III	0.4634	0.4056	- 25.59	0
Region IV	0.4024	0.3951	- 16.52	0
Region V		0.5669	- 27.49	
Region VI		0.6476	- 15.61	
Region VII		1.8722	- 10.07	
Region VIII		0.8566	- 9.41	

Total Cost (U.S. sources): $0.349 Billion

Total Cost (Canada sources): $0.036 Billion

Appendix B

This section outlines some of the assumptions that were used in order to construct estimates of the cost functions for each point source used in the simulations presented in the text. Appendix B is presented in three sections -- one section for each category of point source: (1) utility generating facility, (2) non-ferrous smelters, and (3) other industrial/manufacturing processes.

B.a Utility Generating Facilities

A number of *feasible* technologies and processes to reduce sulfur dioxide emissions are available to electric generating facilities. These include switching from high-sulfur coal to low-sulfur coal; physically cleaning coal to remove pyritic sulfur; and installing dry or wet scrubbers, which may use either lime or limestone as a primary reagent, to remove the SO_2 from the waste gas stream prior to its release into the environment. Each of these alternatives has varying capacities for reducing sulfur dioxide emissions, and each carries its own characteristic costs. Various studies conducted by ICF and the EPA have shown that the least cost abatement choice would be to switch from high sulfur coal to low sulfur coal. Anecdotal evidence supports this finding, as indicated by an article appearing in the "Environment" column of the *Wall Street Journal* which reported that high sulfur coal producing states were offering tax incentives to industries that would install scrubber technology to reduce sulfur dioxide emissions in lieu of switching to low sulfur coal.[34]

Other than the political opposition to coal switching, there are also difficulties due to the long term contracts that exist between most utility plants and coal mines. In 1985, more than 78 percent of electric utility plants with larger than 50 MW capacity purchased *under* 30 percent of their coal on the

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[34] Rosewicz, Barbara; "Environment;" *Wall Street Journal*, Tuesday November 12, 1991.

spot market.[35] All other coal was purchased through long term contracts. Given these circumstances, I do not consider coal switching to be a viable alternative for electric utility plants.

Coal scrubbing is another possible alternative for electric utility plants. Chemically cleaning coal can remove up to 20 percent of the pyritic sulfur content of high pyritic content coal. This process requires that the coal be crushed and a chemical "wash" be applied to the pulverized coal. Unfortunately, this process is prohibitively expensive for low and medium sulfur coals. The cost per ton of coal cleaned increases by a factor of more than 900 percent for these categories of coal.[36] Given the limited ability to remove sulfur from the coals and the costs associated with physically cleaning coal, scrubber technologies are assumed to be adopted by all electric utility point sources, unaccompanied by any switch to low-sulfur coal.

There are two general categories of "flue gas desulfurization" (FGD) or scrubber technologies that are used to remove sulfur dioxide from electric utility waste gas streams -- a dry scrubber system and a wet scrubber system. Dry scrubber systems are generally installed in small facilities ($\leq$ 100 MW design capacity) that use low sulfur coal. Given that the sample data that are used in this paper consist of only the largest emitters of sulfur dioxide that also tend to use high sulfur coal, I assume that a wet scrubber system will be installed. Furthermore, I assume that the cheapest reagent, limestone, will be used.

Several factors can affect the cost of installing and operating a wet scrubber system that uses limestone. The most important (apart from the sulfur content of the coal being used) are (1) the design capacity of the scrubber; (2) the scrubber's operating load; (3) the percentage removal rate of the sulfur dioxide, and (4) the "retrofit factor." The design capacity is simply the maximum capacity (in MW) for which the scrubber was designed. Scrubber systems are always sized as to be able to process emissions produced at maximum operating capacity of the unit on which it is installed. Installation costs vary with design capacity. The load factor (or operating load) describes the percentage of that maximum capacity that is utilized (on average) during a given year. The load factor will affect the costs of operating and maintaining the scrubber. The maximum percentage removal of sulfur dioxide varies with the abatement technology, which in this setting includes not only the kind of device being installed, but also both the choice and amount of primary reagent employed. For wet scrubbers the maximum reliable removal rate is 90 percent. A reduction in the amount of limestone will produce a lower removal rate, and will reduce the costs of operating the system.

Data on the design capacity of each U.S. utility unit is found in the 1985 NURF. Similar data are not available for Canadian utility point sources, however, throughput values are available for 1985. In order to estimate the design capacity for the Canadian utility sources, I start by assuming a 60 percent load factor for 1985. By using the average BTU content for the coal found in the Province in which the point source is located, and by assuming an 8760 hr/year operating schedule, an estimate for the design capacity can be found using the following equation:

$$\text{(B.1)} \qquad \textit{Design Capacity (MW)} = \left(\frac{\textit{Average BTU}}{\textit{ton of coal}}\right) \textit{throughput} * \left(\frac{1}{8700\ hrs}\right)\left(\frac{292.88\,W}{BTU/hr}\right)10^{-6}$$

where throughput is measured in tons of coal.

Retrofit factors are provided for only a select number of units in the 1985 NURF. For point sources where actual estimated retrofit factors were not available, general "rule of thumb" retrofit factors, developed by ICF and the EPA, were used. Retrofit factors are used to adjust 100 percent of the capital

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[35] See 1985 *Cost and Quality of Fuels for Electric Utility Plants.*

[36] See *United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B,* February 1981.

costs and 75 percent of the fixed operating and maintenance costs. Engineering estimates of the installation and equipment costs of wet scrubber systems were also taken from an ICF report prepared for the EPA. These estimates are set out in Table B.I. The costs in Table B.I are reported in early 1986 dollars, but are escalated to 1990 dollars using the CPI for the actual simulation experiments.

Annualized costs are calculated in the following manner.[37] The average lifetime of a wet scrubber system is 50 years. The "correct" time period over which the scrubber system should be depreciated is the shorter of the remaining lifespan of the plant and the lifetime of the scrubber. When the data for the remaining lifespan of the plant (as measured from 1992) was available I used this time period as the relevant period over which to calculate the annualized capital costs. When data were not available, or if the remaining lifespan data were questionable (e.g. negative years reported as remaining lifespan measured from 1985), the full lifespan of the scrubber system of 50 years was used. The cost of capital was assumed to be constant at 5 percent over the relevant time period.

To determine the annualized costs associated with different levels of abatement I use the fact that one simple way of altering abatement levels is to change the amount of limestone used in the abatement process. Reductions in the level of abatement are assumed to vary directly with the variable operating and maintenance costs.[38]

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[37] The capital recovery factor is given by:

$$CRF = \frac{[k(1 + k)^m]}{[(1 + k)^m - 1]}$$

[38] This includes the cost of the reagant (limestone), which accounts for approximately 20% of the variable operating and maintenance costs, as well as electricity, waste management, and other raw materials.

Table B.I

Wet Scrubber Costs for New Utility Power Plants

	Sulfur Level						
	Very Low	Low	Low Medium	Medium	High Medium	High	Very High
Capital Costs ($/kw)	108	110	110	124	133	145	154
Fixed O&M Costs ($/kw)	4.92	4.98	5.00	5.45	5.74	6.11	6.39
Variable O&M Costs (mills/kwh)	0.25	0.32	0.46	0.69	0.92	1.36	1.80

Sulfur Level	Lbs. SO_2/mmBtu
Very Low Sulfur	< 0.80
Low Sulfur	0.80-1.08
Low-Medium Sulfur	1.09-1.66
Medium Sulfur	1.67-2.50
High-Medium Sulfur	2.51-3.33
High Sulfur	3.34-5.00
Very High Sulfur	> 5.00

Size	Capital Cost Relative to a New Scrubber	Fixed O&M Cost Relative to a New Scrubber
Greater than 400 Mw	110%	107.5%
Between 150 - 399 Mw	140%	130.0%
Less than 150 Mw	200%	175.0%

Source: EPA estimates as reported by ICF Resources Inc. for 90% removal of sulfur dioxide using a Wet Limestone FGD system.

B.b Non-Ferrous Smelters

Air pollution control for non-ferrous smelters has primarily been focused on the control of sulfur dioxide emissions. For the purpose of controlling sulfur dioxide emissions, non-ferrous smelters fall into two general categories: strong gas stream smelters and weak gas stream smelters. Strong gas stream smelters are generally categorized as smelters with gas streams of greater than 5 percent acid concentration. Typically for this category of smelter, the cheapest abatement technology for sulfur dioxide removal is the construction of an on-site metallurgical sulfuric acid plant. The drawbacks of this technology are related to whether there exists a market for the sulfuric acid from the smelters (which may be of a higher cost than sulfuric acid from other sources). Neutralization disposal costs of the sulfuric acid may substantially raise the costs of this technology.

Costs for three different control options on a single contact acid plant for a strong off-gas smelter are used. The first option assumes a continuous gas stream and requires a minimum of 12 percent gas concentration, the second is for a variable gas stream which requires between 5 and 8 percent gas concentration, and the third option is for both a continuous and variable gas stream which requires between 6 and 12 percent gas concentration.

Smelters with weak off-gas streams (acid concentrations < 5 percent) do not have the option of using an on-site sulfuric acid plant to control for sulfur dioxide emissions unless they wish to put into place technology that will strengthen the acid concentration of their exit gas. Another option that is available to these smelters is a flue gas desulfurization system (FGD) which uses wet scrubber technologies.

Data from the *Canadian Mining Handbook* (1985) and the *Canada - United States Memorandum of Intent on Air Pollution, Emissions Costs and Engineering Assessment Interim Report, Work Group 3B* (1981) were used to match the NAPAP point source data from the non-ferrous smelters to their company name in order to identify the process equipment used at the site. For smelters that had sulfuric acid

plants in operation as of 1981, I assumed that this technology would continue to be used. For smelters with no abatement technology in place, typical acid concentration figures from each type of process equipment was used to determine whether or not an acid plant facility *could be used* for the particular point source. If the typical off-gas stream acid concentration was larger than 5 percent, I then determined which control option for the acid plant could be used. Cost information for each control option is given in at the end of this Appendix. It is assumed that if an acid contact plant is used, to reduce the efficiency level from the assumed optimal level, the plant would simply be closed down.

Point sources from non-ferrous smelters that could not be outfitted with an acid plant were assumed to install a wet scrubber system. Costing for the scrubbers were assumed to be the same as for other industrial and manufacturing processes and is described briefly below. Costs are annualized using the same methodology described in Section B.a. Sulfuric acid plants are taken to have a maximum reliable removal rate of sulfur dioxide of 90 percent. The average lifetime of an acid plant is given to be 30 years.

B.c Other Industrial/Manufacturing Processes

Unlike utilities and to some extent, non-ferrous smelters, there is very little general information available on the costs for pollution abatement technology for industrial sources. For this section, I rely heavily on the engineering cost estimates and methodology outlined in Vatavuk, (1990). One of the difficulties involved with determining the costs associated with the reduction of sulfur dioxide emissions in the manufacturing and industrial sectors is in the appropriate allocation of costs between various pollutants that are removed using the same abatement technology. For example, electric static precipitators (ESPs) are often used to remove particulates, but can also remove sulfur dioxide from exhaust gases. For point sources associated with industrial and manufacturing processes, I allocate abatement costs for sulfur dioxide by accounting for the *full* cost of the primary technology associated with sulfur dioxide removal, regardless of whether this technology is also responsible for the removal of other pollutants. Clearly, this will bias the cost of abatement for sulfur dioxide upward.

There are numerous technologies available to remove sulfur dioxide emissions from different industrial and manufacturing processes. For purposes of this paper, I concentrate only on wet scrubbers, which in general, can be categorized as particulate scrubbers or gaseous scrubbers. Particulate scrubbers (e.g. spray towers or venturis) are designed primarily to remove particulate matter from the exhaust stream, however, are also capable of removing gaseous emissions. Gaseous scrubbers (packed or tray-type columns) are designed to be more effective at removing gases of low concentrations.

Packaged scrubber systems are priced according to the "maximum gas volumetric flowrate" (measured in actual cubic feet per minute, ACFM) that the system can accommodate. Equipment costs include the actual scrubber system along with auxiliary equipment such as pumps, internal piping, and separators. The costing procedures for equipment (add-on controls and auxiliary equipment), operation, and maintenance are taken from Vatavuk (1990). Typical gas flow design rates are assumed for each process design and are given in later in this Appendix. Gas flow rates are usually given in standard cubic feet per minute (SCFM), which describes the volumetric flow rate at standard temperature and pressure. Conversion from SCFM units to ACFM units are necessary and was done by assuming typical temperature and pressure values for each process for each point source.

Each point source was assumed to be retrofitted with either a Venturi or Double Venturi scrubber system. The choice between the two technologies was determined by the estimated maximum volumetric flow rate of the waste gas stream measured in ACFM. Those with estimated ACFM larger than 59,000 ACFM were assumed to install Double Venturi systems. This is a technical assumption, that takes into account the capacity of the point source. Once the abatement technology was chosen, linear cost estimates from Vatavuk were used to determine equipment costs. The estimated equipment costs for Venturi and Double Venturi systems (including auxiliary equipment) is given (in June 1988 dollars) by:

Venturi Scrubber:

$$P(\$) = 8180 + 1.41Q$$

where $600 \leq Q$, ACFM $\leq 19{,}900$

or

$$P(\$) = 84.2Q^{0.612}$$

where $19{,}000 \leq Q \leq 59{,}000$.

Price includes venturi, mist eliminator, fan (direct or belt driven), recirculation liquid pump, and sump. Construction material is carbon steel.

"Double Venturi" Collision Scrubber:

$$P(\$) = 492Q^{0.450}$$

where $2000 \leq Q$, ACFM $\leq 120{,}000$.

Price includes Collision Scrubber throat, diffuser, entrainment separator, and all internals. Construction material is carbon steel.

To calculate the total cost of the scrubber system, I use the "adjustment" factors given in Table B.II, below:

Table B.II

Total Cost Calculations Used for Venturi and Double Venturi Scrubber Systems*

Total Capital Investment (installation factor and purchased equipment cost)	1.91 times equipment cost
Labor: Operating Maintenance Supervisory	 4 hrs/shift 2 hrs/shift 15% of operating labor costs
Maintenance Material	100% of maintenance labor
Electricity, Waste Management, Raw Materials	50% of all labor costs

* Vatavuk (1990)

The maximum reliable removal rate for Venturi and Double Venturi scrubbers is taken to be 80 percent. Reductions in abatement efficiency levels are assumed to vary directly with the costs of electricity, waste management and raw materials. Total costs are annualized using the methodology described earlier in Section B.a. The average lifetime of a scrubber is 30 years.

Table B.III

Summary of Canadian Copper and Nickel Smelter Statistics

Smelter Location	Process Equipment	Control	% Containment
Hudson Bay Mining and Smelting Company Ltd. Flin Flon, Manitoba	13 Multihearth roasters 1 Reverberatory furnace 3 Converters	Nil	
Inco Limited Thompson, Manitoba	5 Fluid Bed Roasters 5 Electric Furnaces 7 Converters	Nil	
Inco Limited Copper Cliff, Ontario	33 Multihearth roasters 6 Reverberatory furnaces 1 Inco Oxygen Flash 19 Converters	Liquid SO_2 Plant, Acid Plant	44
Falconbridge Nickel Mines, Ltd. Sudbury, Ontario	2 Fluid Bed Roasters 2 Electric Furnaces 4 Converters	Acid Plant	56
Noranda Mines, Ltd. Noranda, Quebec	2 Reverberatory furnaces 1 Noranda reactor 5 Converters	Nil	
Noranda Mines, Ltd. Murdochville, Quebec	1 Fluid Bed Roaster 1 Reverberatory furnace 2 Converters	Acid Plant	59
Afton Mines Ltd. Kamloops, B.C	1 Top Blow Rotary Converter	Scrubber	80
Kidd Creek Mines Ltd., Timmins, Ontario	Mitsubishi Continuous Smelting Process	Acid Plant	95+

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).

Table B.IV

Summary of Canadian Lead - Zinc Smelter Statistics

Smelter Location	Process Equipment	Control	% Containment
Cominco, Ltd. Trail, British Columbia	2 Sinter Machines 2 Fluid Bed Roasters 2 Blast Furnaces	Acid Plants	94+
Brunswick Mining & Smelting Corporation, Ltd. Belledune, New Brunswick	1 Sinter Machine 1 Blast Furnace	Acid Plants	95+
Kidd Creek Mines, Ltd. Timmins, Ontario	2 Fluid Bed Roasters	Acid Plants	95+
Canadian Electrolytic Zinc, Ltd., Valleyfield, Quebec	4 Fluid Bed Roasters	Acid Plants	95+

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).

Table B.V

Abatement Costs: Sulfuric Acid Plants (1981 $s)

Control Options (Single Contact Acid Plant)	SCFM	% SO_2 in Gas Stream	Capital Cost (10^6 $)	Operation Cost (10^6 $)
Continuous Gas Only	27 000	12	17	1.5
Variable Gas Only	49 000	5 - 8	28	2.2
Continuous Gas and Variable Gas	36 000	6 - 12	22	1.8

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).

Table B.VI

Canadian Copper - Nickel Smelter SO_2 Off-Gas Strength by Emitting Equipment

Metal	Emitting Equipment	SO_2 Off-Gas Strength %	
		Min - Max	Typical
Copper	Multiple Hearth Roaster	1 - 3	less than 2
	Fluid Bed Roaster	10 - 14	12
	Reverberatory Furnace	0.5 - 2.5	1.5
	Electric Furnace	4 - 8	-
	Inco Flash Furnace	10 - 14	-
	Mitsubishi 3 - Furnace System	10	-
	Noranda Furnace	8 - 20	13
Nickel	Multi-Hearth Roaster	1 - 3	less than 2
	Reverberatory Furnace	1 - 2	1.5
	Fluid Bed Roaster	10 - 14	-

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).