THE UNIVERSITY OF CALGARY

# MARKETABLE PERMITS FOR SULFUR DIOXIDE

BY

VICTORIA JEAN STEWART

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF ARTS

DEPARTMENT OF ECONOMICS

CALGARY, ALBERTA

SEPTEMBER, 1990

ISBN 0-315-66982-9

THE UNIVERSITY OF CALGARY

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Marketable Permits for Sulfur Dioxide", submitted by Victoria Jean Stewart in partial fulfillment of the requirements for the degree of Master of Arts.

Elizabeth Wilman

Chairman, Dr. E. A. Wilman
Department of Economics

A J MacFadyen

Dr. A. J. MacFadyen
Department of Economics

Dianne Draper

Dr. D. L. Draper
Department of Geography

Date Sept 26, 1990

ABSTRACT

Today, a strong movement exists in both the United States and Canada to control pollutants responsible for the incidence of acid rain. In the northeastern region of North America the control problem is primarily one of limiting the level of sulfur dioxide emissions from a large number of fossil fuel utility plants which are responsible for approximately 71% of total emissions. Canada is particularly concerned with the difficulty of the control task faced by American authorities in this regard, since it is estimated that 50% of wet sulfate deposition experienced in eastern Canada originates from sources located in the northeastern United States.

Traditionally, U.S. control policy has relied on a purely regulatory approach to pollution control which requires that polluting sources meet imposed emission standards. However, because this approach is not cost effective, considerable interest has recently been directed towards the use of markets in emission rights as an alternative control mechanism to achieve desired air quality levels. The advantage of this approach is that it directly limits the quantity of pollution released into the atmosphere while minimizing the cost burden imposed on emitting sources.

This thesis examines the viability of implementing a market in sulfur dioxide emission rights for coal fired utility plants in 25 eastern states, in terms of both cost effectiveness and changes in air quality at 25 sensitive receptor sites in both Canada and the United States. A linear program which constrains the aggregate level of emissions over all 25 states, is used to determine the optimal distribution of control among utility plants, and the total control costs imposed on these plants under a market approach which allows for the trading of emission rights among all sources in the 25 states. In order to evaluate the cost effectiveness of this approach, these costs are compared to those incurred under a market approach which allows for the trading of emission rights between sources within each state only. The difference in control costs between these two market approaches reflects the minimum cost saving which can be achieved by moving from a purely

regulatory approach to emissions control to an interstate emission market. The results of the analysis indicate that substantial costs savings in the order of $646 million ($1985) or greater may be realized by introducing increased flexibility in control options available to sources in the context of an interstate emission market. Given these savings, the implementation of an interstate market in emission rights clearly warrants consideration.

Furthermore, by translating control allocations assigned to each state into changes in sulfur dioxide concentration levels at receptor sites, it is established that no significant increases in sulfur dioxide levels will be experienced by introducing an interstate emissions market in place of a regulatory approach. U.S. receptors generally experience small increases in sulfur dioxide levels while Canadian receptors, with the exception of one, enjoy small decreases. Although the changes in air quality realized by moving from a regulatory approach to an interstate emission market are relatively small, concern may arise over the fact that those sites which experience increases are specifically those sites which continue to receive significant levels of sulfur dioxide from utility plants after controls are implemented. However, from the Canadian perspective, any concerns that air quality will be adversely affected by the distribution of control responsibility when interstate trading is introduced are not justified.

This thesis also examines whether a more complex market system in pollution rights can achieve those air quality improvements achieved under an interstate trading market at much less cost. A linear programming model which imposes constraints on air quality levels as opposed to aggregate emission levels is used to evaluate control costs incurred by utility plants for this type of market approach. The analysis indicates that an additional cost saving of $3 million ($1985) relative to the interstate emissions market would be realized. In view of the fact that such a system is extremely complex to implement and enforce, this cost saving does not justify the consideration of a market in pollution rights as a viable alternative to sulfur dioxide control in the United States.

## ACKNOWLEDGEMENTS

I would like to extend my thanks to Dr. E. A. Wilman whose thoughtful advice and suggestions have been immensely helpful to me in completing this thesis. I would also like to thank Dr. D. L. Draper and Dr. A. J. MacFadyen for their constructive comments.

My heartfelt thanks also goes to my husband, John, who has always encouraged me to strive for greater heights, and to my parents, Jean and Ken, for their support and encouragement throughout my course of study at the University of Calgary.

CONTENTS

LIST OF TABLES

## LIST OF FIGURES

# CHAPTER 1

# OVERVIEW OF THE STUDY

## INTRODUCTION

Historically, western capitalist countries have maintained faith in the merits of a market based economy which allows individuals to freely pursue their own self-interests. Such faith rests on the belief that in a market economy where private ownership is extended to the means of production, the self-interested individual will employ his private resources in their most productive use. In this way the actions of all individuals in society are believed to contribute to the welfare of society as a whole because resources will be allocated in the most efficient manner.

Perhaps the interests of society would best be served in this way were it not for the fact that quality of life is not determined exclusively by the satisfaction of demand for those goods and services controlled by the marketplace. Though the satisfactions provided by increasing levels of economic activity in both the consumption and production sectors of our economy have been tremendous over the past forty-five years, quality of life has been adversely affected by the effects of the damage to the environment which has inevitably accompanied these activities. Indeed, increased material productivity has caused enormous damage to our environment to the point where such damage is now perceived as too great to justify complete individual freedoms to act. Market incentives in many cases are seen to be socially destructive as evidenced by the increasing public pressure to restrict the operation of the marketplace and to introduce new policies for government and business which serve to protect rather than abuse the environment.

Indeed, the perception that our environmental amenities are available to all users in unlimited supply is changing. Traditionally, our air and water resources have been viewed as examples of free goods in that they existed in such abundance that every individual could use all he desired without depriving others. However, the effect of increasing populations and increasing levels of industrial production over the past decades has been to place significant pressures on the capacity of these resources to assimilate waste from both consumption and production processes. Consequently, these so called "free goods" are today more appropriately regarded as common property resources of significant and increasing marginal value, and as such their efficient allocation among potential users is essential.

The problem is that the marketplace alone is not able to efficiently control use of our vital air and water supplies. Indeed, the problem of environmental abuse may be attributed to the failure of the marketplace to recognize and internalize those costs imposed on the environment by human activities. This failure is reflected in the actions of industrial operations which continue to dump excessive quantities of raw waste into the air and water supplies with little regard for the high social costs (externalities) of their actions in terms of environmental degradation. They operate in this way because it is economically advantageous for them to do so since they are not required under the free market system to internalize these costs. The inevitable abuse and overuse of our most vital air and water supplies which results from such behavior, clearly demonstrates the need for some form of intervention in the operation of the marketplace. The behavior of individuals and industry must be changed if we are to accommodate the social need for a clean environment. The question remains, however, as to the form such intervention should take.

In response to this question, governments have considered a number of policy instruments developed by economists in order to deal with the problem of overuse of environmental amenities. Among these, the creation of markets in pollution rights has recently generated considerable interest. The advantage of such an approach is that it directly limits the quantity of pollution which is released into the atmosphere (or water supply) while minimizing the cost burden imposed on emitting sources. It is the intent of this thesis to examine the viability of implementing such markets in pollution rights as a means of promoting a healthy environment for present and future generations.

## OBJECTIVES OF THE STUDY

In order to meet the social need for a healthy environment, governments have traditionally been assigned the task of setting legal ceilings on the concentration levels of potentially dangerous pollutants in the atmosphere, and ensuring that that these ceilings are maintained. In response to these task assignments, government control authorities have typically allocated emission control responsibility among the major sources of pollution by imposing emission standards for each point of discharge. However, under this purely regulatory approach to control, the cost burden imposed on emitting industrial sources can be formidable and, consequently, considerable interest has recently been directed towards alternative control mechanisms which are more cost efficient in achieving pollution reduction targets.

Marketable permit systems in pollution rights have recently generated particular interest in this area because they allow for greater flexibility in the control options available to emitting sources, thereby avoiding the cost rigidities of the traditional regulatory approach and promising the potential for cost efficient control allocations. In light of the potentially substantial benefits of this approach, the Bush administration has recently proposed that a market in sulfur dioxide emission rights be established for all fossil fuel utility plants in the United States. The objective of the program is to reduce sulfur dioxide emissions by approximately 50% in order to mitigate the damages caused by acid deposition in North America, while at the same time minimizing the economic impacts of the program on emitting sources.

This thesis will address two issues which arise in response to the proposed legislation. The first issue addresses the question of cost effectiveness. Specifically, are the cost savings realized under the proposed emission permit system substantial enough to justify implementation of the program? Furthermore, can the air quality improvements achieved under the proposed system be achieved at less cost by an alternative type of market system which recognizes the spatial complexities of the control problem for sulfur dioxide?

The second issue addresses the concern that the flexibility offered by an emission permit system which allows for the trading of emission rights between states, may adversely affect ambient air quality levels in sensitive receptor areas in both the U.S. and Canada. In other words, if the economic incentives provided under the program encourage those emitting sources located close to sensitive receptor sites, to purchase emission permits and increase their level of discharge, the benefits of the program may be far less than anticipated. This thesis will examine the potential distribution of emission licences across the eastern United States which could result from an emissions trading market comparable to the one proposed, and the ramifications of this distribution in terms of air quality changes for important receptor areas.

## OUTLINE OF THE STUDY

In order to address these issues the course of study outlined below is followed:

Chapter 2 provides a background to the acid rain issue. A review of the biological impacts of increasing levels of acid deposition in the United States and Canada is first examined. Second, the importance of sulfur dioxide control in the United States from the Canadian perspective is addressed followed by a review of current American control policy.

Chapter 3 provides a review of the theoretical literature on markets in pollution rights. The nature of the control problem for uniformly mixed pollutants and the desirability of using markets in emission rights to achieve agregate emission control targets at least cost is first addressed. For the case of nonuniformly mixed pollutants, the spatial complexities of the control problem are considered. It is shown that a more complex ambient market system in pollution rights is required to achieve air quality targets at least cost for this class of pollutants. Finally, the desirability of using less complex alternative market approaches for achieving ambient quality standards for nonuniformly mixed pollutants is addressed.

Chapters 4 and 5 provide an economic analysis of alternative market approaches for controlling sulfur dioxide emissions in the eastern United States. Market systems in emission rights which are comparable to those proposed in Phase I and Phase II of the currently proposed American legislation are evaluated in terms of their cost effectiveness in achieving aggregate emission control targets and in terms of their influence on sulfur dioxide concentration levels at sensitive receptor areas in both Canada and the United States. Finally, an analysis of a more complex market system in pollution rights which recognizes the importance of the relationship between source location and air quality levels is provided. The cost effectiveness of this market approach in achieving air quality improvements is compared to that of the more simple market in emission rights.

Chapter 6 provides conclusions regarding the viability of market approaches to pollution control based on the results reported in Chapter 5.

# CHAPTER 2

# THE ACID RAIN PROBLEM

## BIOLOGICAL IMPACTS OF ACID RAIN

Today, a strong movement exists in both the United States and Canada to control pollutants responsible for the incidence of acid rain. Indeed, the biological effects of acid rain in southeastern Canada and northeastern United States are considered to be significant, and the long term impacts serious.

The most obvious effect of acid deposition in North America is the reduction and elimination of fish populations in lakes which have become acidic. Studies have indicated that acid waters may prevent fish from spawning and for this reason lakes which have become increasingly acidic are generally populated only with mature adults or with no populations whatsoever. Numerous lakes which exist at high elevations of the Adirondack Mountains have become extremely acidic, and of these lakes, 45% no longer support any fish populations at all (ReVelle and ReVelle, 1984, p. 403). Although the economic consequences of these effects are small relative to the value of all freshwater sport fishing in North America, a 1984 study conducted by Menz and Mullen estimated that the 1982 value of the Adirondack lake and pond sport fishery losses to licenced fishermen was between $1.7 million and $3.2 million (Crocker and Regens, 1985). In Ontario, Canada, it has been estimated that 140 lakes have become fishless and that 48,000 more lakes are sensitive to acidification. Such findings have important implications for the over half billion dollar sport fishing industry for the province as well as the quarter million dollar commerical fishing industry. In Quebec, 30% of the salmon potential (2% of Canadian potential) is threatened by acidity levels in several rivers (Cooley, 1981). The issue of acidification becomes of even greater concern when one considers that over the long term as fish populations decline in areas sensitive to the effects of acid rain, species which depend upon fish populations for food, such as the eagle, the loon, the mink and others, will also decline.

Acid rain is also believed to have an effect on plant species over long periods of time. Although such effects are not well understood, evidence suggests that acid deposition may leach plant nutrients from soils in which these elements are plentiful, remove soil binding agents, increase heavy metals in soils to toxic levels and harm plant foliage. Given these suspicions it is not unreasonable to attribute some of the reductions in forest growth in eastern North America to acid deposition. In fact, one study conducted by the National Academy of Sciences attributed 5% of the reduction in annual growth rates of eastern United States forests to acid deposition . Assuming timber prices at the 1977 average level, a $600 million (gross) loss in timber production has been estimated in addition to losses in other forest services including recreation, water storage and wildlife habitats (Crocker and Regens, 1985).

Although the direct effects of acid deposition on human health are not easily established it is known that acid deposition can affect human health indirectly through either bioaccumulation of chemicals in human food or contamination in drinking water. Both these effects may be attributed to the increased ability of acid water to dissolve or act on minerals. For example, under acidic conditions, the mercury in bodies of water may be converted into monomethyl mercury, a human poison which may accumulate in edible fish tissue. Further, if our water reserves which supply drinking water were to become acidic, toxic metals from the watershed may dissolve in water being used for human consumption. For example, aluminum has recently become a health concern because of its increased mobilization in acid waters and because it is associated with various disorders of the central nervous system even at relatively low levels. Concern also exists that acidic drinking water may dissolve greater quantities of lead, copper, and cadmium found in plumbing systems. For all of these contaminants a known association exists with serious health problems including neurophysiological dysfunction and IQ deficiencies in children.

The damages caused by acid deposition to materials such as mortar, stone and iron are generally assigned very high monetary values. Severe economic damage has been linked particularly to public and private structures valued for their cultural heritage (Crocker and Regens, 1985).

Clearly, the direct and indirect effects of acid rain in eastern North America cannot be ignored. The benefits of controlling those pollutants directly responsible for acid deposition are great and are likely to become even greater with time if they are not controlled. Accordingly, it is anticipated that the allocation of resources to the control task will increase.

ACID RAIN - THE CANADIAN PERSPECTIVE

Acid precipitation occurs when sulfur oxides and nitrogen oxides which are present in the atmosphere, undergo chemical conversions to sulfur trioxide and nitrogen dioxide. These gases subsequently dissolve in water droplets in the atmosphere to form sulfuric acid or nitric acid respectively and return to the earth in rain, fog or snow. The two gases do not, however, always contribute equally to the problem of acid precipitation. In the northeastern region of North America, approximately 70%-85% of the acidity is attributed to the presence of sulfur oxides. The primary sources of sulfur oxides in Canada are few in number. They include six copper-nickel smelters and one iron processing operation which together release 58% of total sulfur dioxide emissions while only 15% of total emissions are released by public utilities (Dowd, 1984). Due to the small number of sources, control is relatively easy to negotiate in Canada. However, in the United States a large number of utility plants is responsible for approximately 71% of the sulfur dioxide emissions and any program whose objective is to significantly reduce sulfur dioxide emissions must deal with a large number of individual entities across many states. Canada is particularly concerned with the difficulty of the task faced by American control authorities since it is estimated that eastern Canada receives 50% of its wet sulfate deposition from the northeastern United States. On the other hand, the United States receives only about 5% of its acid deposition from Canadian sources. Canadian concern over emission levels in the United States is further intensified by the fact that total sulfur dioxide emissions released by sources in the northeastern United States are five times greater than those released in eastern Canada, and given the general wind patterns, it is estimated that three to five times more sulfur flows north from the United States into Canada than flows from Canada to the United States (Dowd, 1984).

Furthermore, it is also important to recognize that the Canadian economy depends to a much larger extent upon forestry, fishing and tourism - activities which are all highly sensitive to the effects of acid rain. Approximately 8% of GNP is attributed to these sources of income. In light of these circumstances, it is not surprising to find that Canadians generally feel threatened by the current level of acid deposition in Canada, and voice concern over failure of American control authorities to reduce the level of those pollutants most responsible, namely sulfur oxides.

## SULFUR DIOXIDE EMISSION CONTROL POLICY IN THE UNITED STATES

Criteria pollutants such as sulfur dioxide are defined as those pollutants which are considered to be dangerous only in high concentrations. For this reason the EPA (Environmental Protection Agency of the United States) has established for each of these pollutants, ambient air quality standards which set legal ceilings on the allowable concentration levels for these pollutants averaged over the period of one year. For the case of sulfur dioxide both a primary and secondary standard have been set. The primary standard is referred to as the health threshhold since it defines a standard of safety such that no adverse health effects will occur to even the most sensitive member of the population. Such an approach presumes that a threshhold exists below which no adverse health effects will occur. In reality such a threshhold is probably close to zero, and certainly is lower than that established by the standard (Tietenberg, 1988, p.341). For the case of sulfur dioxide, the primary standard is designed to protect the population from symptoms of heart and lung disease as well as acute respiratory diseases. Additionally, a more stringent secondary standard has been established to address the problem of damage to plants and materials caused by acid rain. Once compliance with the secondary standard is achieved in a particular airshed, it is this standard which regulates the degree of control required by emitting sources. Noticeably the indirect effects of acid rain on human health are not directly addressed by the EPA.

State control agencies are held primarily responsible for ensuring that standards established by the EPA are met. Traditionally, the command and control approach has been used by the control authority in an effort to limit air polluting emissions and to maintain air quality standards as imposed by government. This approach distributes control responsibility among the sources of discharge by assigning separate emission standards, referred to as ceilings, for each point of discharge. Such standards are most simply set by allocating emission control equally among all sources. However, the problem with this approach is that it is not cost effective. Ideally, the standards should be set such that those sources whose emission control costs are relatively low will bear the major responsibility for reducing emissions. In this way the control solution will be achieved at minimum cost. However, if the responsibility is placed with the control authority for determining the standards for each individual source of emissions such that a least cost control allocation is achieved, access to a tremendous amount of cost information would be required. Specifically, information on all control technologies available to each source and the associated costs of employing these technologies must be made known to the control authority. In reality the control authority will likely hold only a fraction of the information required to do this job, and although it is highly likely that emitting sources will hold detailed information on costs of all possible control techniques available including the most cost effective, they will have little incentive to provide accurate cost information to the control authority. For example, by overstating emission control costs, sources may reduce the obligatory emission controls imposed upon them by the control authority. Clearly, any firm operating in the marketplace will have incentive to act in this manner in order to remain competitive with other sources.

Essentially, this is the fundamental problem with the command and control approach. Those who desire a cost effective control program have too little information and those with adequate information have no incentive to voluntarily seek a cost effective solution. Consequently, source emission standards have typically been set without consideration for cost burdens imposed on sources and a cost efficient control allocation has not been achieved. The relevant question for policymakers which naturally arises from this discussion is whether reform of the existing regulatory system of control is warranted. If the command and control approach provides a control solution which does not approximate the cost minimizing solution, the case for reform will be strong. Policymakers must, therefore, determine the degree to which costs under the traditional approach to control diverge from the least cost solution where control responsibility is primarily assigned to those sources with the lowest costs for controlling pollution levels. The extent of the divergence in costs will depend upon meteorology for the control area, the location of pollution sources, stack heights, and the variance in control costs between sources.

Indeed, the potential for large cost penalties associated with the regulatory approach has led researchers to examine alternative means of allocating control responsibility through the establishment of an emissions rights system. Such a system would involve the assignment of private ownership to the right to discharge pollutants into the air in such a way that the problem of overexploitation of the assimilative capacity of the environment is avoided. For example, the introduction of a system of transferable emission permits promises the potential for better air quality with a smaller commitment of resources to pollution control. Such an approach avoids the cost rigidities of the command and control approach by relying upon the incentives of the market to achieve a cost efficient position.

In an effort to move towards increasing reliance on market incentives to achieve ambient standards, the EPA has introduced an emissions trading program to encourage flexibility in the mix of control technologies while maintaining air quality standards. The basis of the program is the trading of emission reduction credits as provided by the offset, bubble and emissions banking policies which govern how these credits may be used. Under the program, any source which controls emissions beyond the level required by its legal obligations under the existing regulatory structure, may apply for certified emission credits in the event that the surplus reduction is permanent and quantifiable. Subsequently, these credits may be banked or used in the bubble or offset programs.

The offset program allows new sources to locate in nonattainment areas (areas which have failed to maintain the ambient standards imposed by the Clean Air Act) and for existing sources to expand. By purchasing sufficient emission reduction credits from existing sources, new and expanded industry may offset increases in pollution which would otherwise occur from increased production levels.

The bubble program allows existing sources of pollution to modify their emission standards imposed by the control authority. Specifically, the relaxation of the degree of control for one source is offset by a more stringent degree of control for another source of the same pollutant. Such substitutions may occur between plants or even between firms within the bubble area. In effect, multiple emission points are assumed to exist within an imaginary bubble and only the amount of pollution leaving the bubble is regulated. The idea of this program is to allow those sources within the bubble to meet an emission reduction goal using the most inexpensive control strategy while at the same time ensuring that air quality is not adversely affected. This is accomplished by allowing those sources with high control costs to exceed their emission standards if they are able to sufficiently reduce emissions from other sources within the bubble which have low control costs. Clearly, the increased flexibility in control options enjoyed by sources creates cost saving potential.

Indeed, the reforms offered by the EPA have been successful in introducing flexibility into the control problem, thereby reducing the cost burden for compliance of ambient standards. It has been estimated that federally approved bubbles have resulted in savings estimated at $300 million for the duration of the program up to 1986 while cost savings for state approved bubbles have been estimated at $135 million (Hahn and Hester, 1987). It would, therefore, appear that the emissions trading programs have allowed firms greater flexibility in meeting emission limits than under the pure regulatory system. However, these policies, though they represent improvements to the traditional regulatory approach, are only partial responses to the problem of minimum cost allocation. The bubble and offset programs restrict which sources may trade and what emission reductions may be traded and it is these restrictions which prevent the system from achieving the least cost control solution. In order to implement a full scale emission permit system with full transferability, the control authority would have to allow all sources to participate in trades and allow all emission reductions to be traded in the market. Only in this way can a cost effective control allocation be achieved.

In response to the inadequacy of the EPA reforms, the Bush administration has recently proposed the introduction of a transferable emission permit system which imposes few restrictions on trade. Under such a system those emitters with high marginal control costs will be able to purchase permits from emitters with relatively low marginal costs. In this way, those emitters incurring low costs of control will be held primarily responsible for achieving emission reductions and the system will move towards a costs efficient solution. However, it is important to note that under a transferable emission permit system, the equilibrium control allocation will achieve an aggregate emissions target at minimum cost as opposed to achieving an ambient standard at least cost. In other words, a legal ceiling on the allowable weight of emissions is set and control responsibility is allocated among emitters such that the smallest commitment of resources to control is used to achieve this ceiling. Other benefits of the transferable emission permit system are that it is relatively simple to administer, it is easy to monitor, and the contribution of each emitter to the policy target is easy to define.

The disadvantage of the proposed emission system, however, may be significant. For the case of nonuniformly mixed pollutants such as sulfur dioxide, air quality is determined not only by quantity of emissions released into the air, but also by the location of sources, specifically their proximity to one another and to sensitive receptor areas. Therefore, while the level of aggregate emissions is an important influence on air quality, other factors must be considered when the policy target is ultimately the maintenance of air quality levels at specific locations as opposed to total emission levels. For example, consideration must be given to the fact that the influence of any single emitter on the measure of air quality at a specific receptor area will depend upon the proximity of the emitter to the monitoring site, the topographical and flow characteristics of the environmental medium between the receptor site and the emitter (i.e. wind direction and velocity), level of other types of emissions with which the pollutant reacts, and upon the total level of emissions. The least cost solution for achieving ambient air quality standards will require that responsibility for reducing emissions lies primarily with those sources whose emissions have the greatest effect on air quality. In this way the cost of meeting the ambient standards can be minimized.

Indeed, the recent U.S. legislation which proposes the creation of a market in emission rights, may be criticized on the grounds that it fails to recognize the important relationship between source location and air quality at specific receptor sites. Furthermore, the tendency of the proposed transferable emission permit system to oversimplify these spatial complexities of the control problem may result in substantial cost penalties when the policy objective is to achieve air quality targets at minimum cost rather than aggregate emissions targets.

The following theoretical review and analysis focuses on the types of artificial markets in emission rights which may provide a solution to the problem of acid deposition in North America in light of the recent proposals by the Bush administration to introduce a market in sulfur dioxide emission rights. Emphasis is placed on the advantages of the simple emission permit system for achieving aggregate emission control targets. The extent of the cost penalties associated with using this type of system for achieving air quality standards for nonuniformly mixed pollutants is also examined in comparison with a more complex market system in pollution rights which addresses the spatial aspects of the control problem.

# CHAPTER 3

# A REVIEW OF THE THEORETICAL LITERATURE

## INTRODUCTION

The failure of the marketplace to recognize and internalize environmental costs of human activities may be attributed to the lack of property rights associated with environmental amentities such as clean air and water. For example, we cannot determine ownership of air resources on the basis of private ownership rights which have the properties of exclusivity and transferability, because the boundaries necessary to define these rights cannot be constructed. As a result of this difficulty, the right to use this resource as a means of waste disposal has been allocated among users at a price of zero, and inevitably an inefficient allocation has occurred.

Given that the problem of environmental abuse is attributed to the lack of well defined rights for the use of the assimilative capacity of the environment, a solution may lie in the establishment of correctly defined property rights. Indeed, in response to the failure of the market to efficiently allocate environmental assets, economists have developed the idea of creating markets which extend private ownership to the right to discharge pollutants. In the most general application of such a market system, those who wished to pollute and those who wished to preserve the environment would compete within a market framework for the saleable property rights associated with the limited capacity of the environment. This would require that a control authority issue permits for the right to emit pollutants in an amount which reflects the maximum number of emissions which the atmosphere (or water system) is able to assimilate. The acquisition of a right if used would entitle the owner to release a certain amount of pollution into the environment each period. On the other hand, by holding the right unused, the owner could prevent the same amount of pollution from occurring, thus preventing further degradation of our air or water resources. In a market equilibrium property rights would be allocated to those market participants who value the rights most highly and the level of pollution would be determined by the distribution of property rights among those wishing to pollute and those wishing to preserve environmental quality. The benefits of such a market system would lie in its ability to achieve an efficient level of pollution control at minimum cost, and to provide those market participants who are exposed to the negative effects of pollution created by profit seeking industry and who wish to sell their property rights, with a recourse in the form of financial compensation through the market.

Although the market system is believed to provide an optimal level of goods and services under conditions of perfect competition, it is highly unlikely that the system described above will provide a Pareto optimal level of pollution free resources. The reason for this market failure is the public nature of environmental resources which creates a situation where the owner of an unused right to pollute cannot exclude others who have not paid for the right, from sharing in the consumption of its benefits (i.e the benefits of clean air or water). Therefore, incentive does not exist for the self-interested individual to provide these resources since the full benefit realized by their provision cannot be captured by that individual. Clearly, the public goods nature of environmental improvements prevents any market in rights from achieving a desirable allocation of these most important resources since an insufficient purchase of rights by those wishing to prevent degradation would always occur. Accordingly, the efficiency criteria which requires that marginal costs of controlling pollution are equated with the marginal costs of damage of uncontrolled pollution, is difficult to achieve even in the unlikely case where market participants are fully knowledgeable of the costs of damage to the environment for increasing levels of pollution.

If instead of allowing those who wish to preserve the environment to participate in the market, a pollution control authority is established to act on their behalf, the efficiency criteria could be achieved. In other words, the control authority could assign the right to discharge for each pollution source such that the marginal control costs and marginal damage costs for each source were equalized. Clearly, this would be an enormous task which would require full knowledge of all cost and damage functions for each emitting source. Therefore, the criteria of efficiency has been replaced with the criteria of cost effectiveness and both theoretical and empirical work in this area has focused on the minimization of the cost of achieving externally determined air quality standards and aggregate emission targets. The problem of determining the optimal levels of air quality is thus replaced with the problem of providing a selected air quality or emission control level at minimum cost. Although such a methodology may be considered only second best, it can be shown to provide a quasi-Pareto optimum under certain conditions as discussed later in this chapter (Hamlen, 1975).

The following review of the theoretical literature examines the nature of the pollution control problem for achieving both aggregate emission target levels and ambient air quality targets at specific receptor areas. It is shown that the incentives provided under an emission licence system will lead the economy to a least cost control solution when the objective of the policy is to achieve a level of aggregate emissions control. Three alternative methodologies of varying complexity are examined in this regard. Montgomery (1972) focuses on the output decisions of each firm in response to emission constraints imposed by a control authority. For this case, the least cost solution minimizes the difference in profits between the optimal output solution where emissions are constrained and the unconstrained optimal output solution. The second methodology developed by Baumol and Oates (1975), shows that an emission licence or emission charge system achieves a specified quality of the environment at minimum cost for any given vector of outputs in the economy. The output adjustments of each firm in response to emission controls, explicitly dealt with in the Montgomery analysis are, therefore, ignored. Finally, Tietenberg (1985) approaches the control problem from the perspective of the firm who wishes to determine the optimal level of controlled emissions in isolation of all other production decisions.

Second, it is established that a system which assigns ownership to the right to pollute receptor sites (rather than the right to emit) achieves ambient air quality standards at minimum cost. However, due to the administrative complexity of this system, the desirability of using alternative systems to achieve ambient standards, including the simple emission permit system, the regulatory approach, and the zonal approach to permit trading, is examined.

## A DEFINITION OF THE POLLUTION CONTROL PROBLEM

Ideally, the question of pollution control should be examined in the context of a general equilibrium setting, particularly if distributional effects of abatement policy are important. Merrifield (1988), for example, examines the importance of capital flows and trade in determining the best abatement strategy for transnational pollutants such as sulfur dioxide. It is shown that distributional effects and terms of trade effects may occur along with changes in pollution flows, when various strategies of pollution control are employed. Due to the complexity of this type of analysis, however, the majority of analyses on pollution rights systems have relied on a partial equilibrium approach which ignores distributional effects of income and employment between regions and which focuses on the equilibrium distribution of market rights to pollute in the economy, the resulting ambient air quality levels at important receptor sites, and the total costs of pollution control.

The problem of cost minimization in a partial equilibrium setting is formally developed by Montgomery (1972) in his analysis of emission licences. The control problem is defined as follows. The region for which the pollution problem is examined contains a number of industrial sources of pollution which are assumed to be independent, profit-maximizing firms represented as the set $i = (1.......n)$. The economy of this region is deemed to be small relative to the entire economy so that any change in the level of output in the region will have no effect upon prices of inputs or outputs in the economy at large. Environmental air quality, in terms of a single pollutant, at receptors, j = (1.......m), is denoted as Q = ($q_1$..........$q_m$), and regional air quality standards are similarily denoted as Q* = ($q_1$*.........$q_m$*) where $q_j$ might represent annual average concentration of sulfur-dioxide. Furthermore, the rates of emission for all pollution sources are denoted as E = ($e_1$.........$e_n$) where $e_i$ represents quantity of emissions from firm, i. The theoretical relationship between these rates of emissions and average concentrations at the receptor sites can be calculated as E x D = Q where D represents an n x m matrix of transfer co-efficients which translate emissions into air quality by taking into account wind direction and velocity as well as such factors as stack height. For example, the co-efficient $d_{ij}$ would represent the concentration change at receptor, j, resulting from an increase in one emission by firm, i. Clearly, an underlying assumption of this model is that concentrations are a linear function of emissions discharged. This is perhaps not what one would ideally assume for reactive pollutants such as sulfur dioxide, but it is an assumption which is commonly used in the literature and generally thought to provide a reasonable approximation of the true relationship between pollutant concentration levels and levels of emissions discharged (Shannon, 1990). The assumption is also made that desirable air quality in terms of one pollutant is independent of desirable air quality of another pollutant. If quality is defined in terms of concentration levels of a pollutant at receptor sites, this is also an acceptable assumption.

Ideally, the imposed standards for air quality should be established so that the optimal level of pollution will exist. This requirement assumes that the value of damages generated by polluting industrial sources is known. However, for the case of environmental amenities, there does not exist a pricing mechanism which would clearly indicate such values. Therefore, in the absence of any market signals, a political process must be used to determine desirable levels of activity in the economy with the hope that such levels will approximate the optimal result.

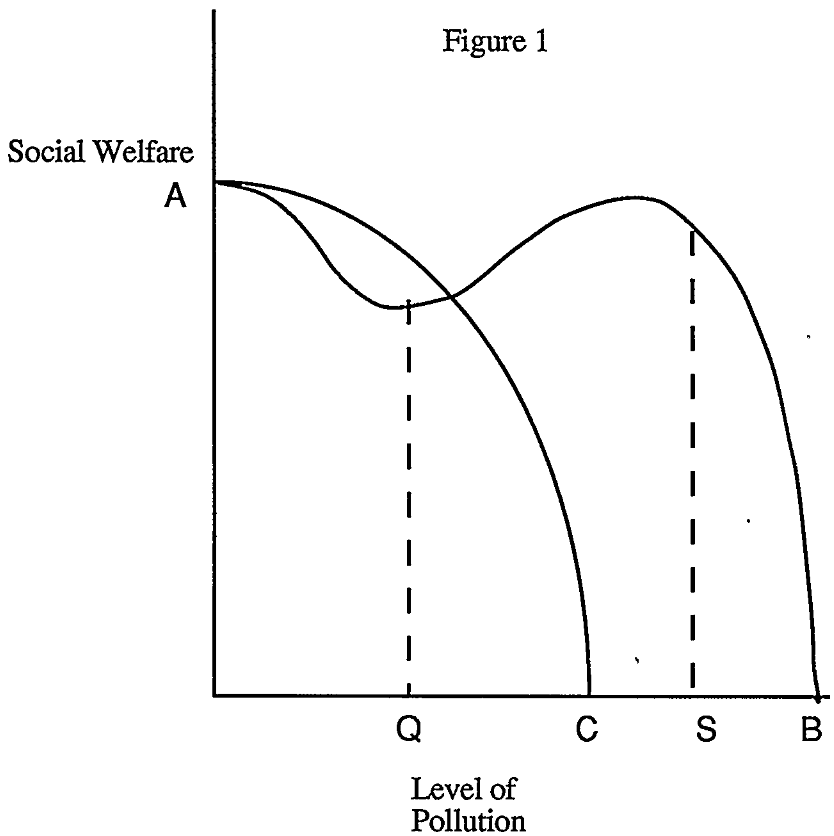
Even though the rationale for using imposed standards is based on ignorance of relevant information regarding the value of damage generated, the use of standards to increase social welfare will be effective when there is reason to believe that current levels of activity impose a high level of social cost and when these costs can be significantly decreased by reducing levels of pollution. If, for example, the relationship between the level of social welfare and the level of pollutants being emitted into the atmosphere as shown in Figure 1 can be represented by a curve such as AC which has a decreasing and steep slope, the implementation of imposed standards will lead to an increase in social welfare regardless of the position of the curve. However, if the relationship between welfare and pollution is not monotonically decreasing as demonstrated by curve AB, the imposition of a standard may actually decrease welfare as can be shown by a decrease in the level of pollution from S to Q. Furthermore, the efficient amount of pollution free resources is difficult to determine for this case since the satisfaction of the optimizing condition which requires that marginal costs of controlling pollution equal marginal benefits in terms of social welfare may exist for more than one level of pollution.

Second, it is necessary to consider whether the marginal benefits in terms of increases in social welfare associated with decreased levels of pollution exceed the marginal costs of achieving the reduction. If the social welfare function is fairly flat, the relatively small marginal benefits achieved by an imposed reduction standard may be exceeded by the additional marginal costs for controlling pollution.

Given these considerations, it can be stated that generally, the use of environmental standards for controlling pollution can be justified when we know that the social welfare function is monotonically decreasing with a relatively steep slope. This will hold true particularly when pollution levels have significant and unambiguous effects on quality of life. Satisfaction of these conditions, however, does not ensure that use of a standard will provide an optimal level of pollution. Rather, it merely ensures that net social welfare will increase by imposing the standard.

In the case of sulfur dioxide, it is feasible that such conditions exist, considering the potentially very significant effects to human health, fishing and forestry which result from acid bearing rain as discussed in the previous section. In other words, the marginal benefits of reducing sulfur dioxide concentration levels are likely to be high at present concentration levels. However, these benefits must be weighed against the control costs incurred to achieve these reduction levels.

Figure 1




Throughout the following theoretical review, the implicit assumption is made that these conditions exist. The problem of pollution control then becomes one of minimizing costs accruing to the polluter under the constraint that ambient air quality standards are met such that $E \times D \leq Q^*$.

Formally, the profit maximizing firm will attempt to minimize the following cost function:

(3.1) $Gi(y_{i1}....y_{ir}, e_i)$

which represents the minimum cost to the firm of producing R outputs, $y_{i1}.......y_{ir}$, as well as the related level of emissions, $e_i$, associated with these outputs. Additional assumptions are made that costs include both operating and annual capital costs and that $G_i$ is convex and twice differentiable. Accordingly, profit for each firm can be defined as follows:

(3.2) $\pi = \Sigma_r \; p_r y_{ir} \; - \; G(y_{i1}......y_{ir}, e_i)$

where $p_r$ represents the price of good, r. Further $(y_{i1}....y_{ir}, e_i)$ is defined to be those output and emission levels which maximize profits to the firm:

(3.3) $\Sigma_r \; p_r y_{ir} \; - \; G_i(y_{i1}....y_{ir}, e_i) = \text{Max} \; [\Sigma_r \; p_r y_{ir} - G_i(y_{i1}...y_{ir},e_i)]$

In the case where firms are required to achieve a specified level of emissions, ë, the level of output must be adjusted in order to maximize profits under such a constraint. This optimal level of output for a fixed level of emission is defined as $\ddot{y}_{ir}$ such that:

(3.4) $\Sigma_r \; p_r \ddot{y}_{ir} - G_i(\ddot{y}_{i1}.....\ddot{y}_{ir}, \ddot{e}_i) = \text{Max} \; [\Sigma_r \, p_r y_{ir} - G_i(y_{i1}.....y_{ir}, \ddot{e}_i)]$

Clearly then, the cost to the firm of adapting to an imposed emission level may be calculated as the difference between the maximum unconstrained profit and the maximum constrained profit:

(3.5) $F_i(e_i) = \Sigma_r p_r(y_{ir} - \ddot{y}_{ir}) - [G_i(y_{i1}....y_{ir}, e_i) - G_i(\ddot{y}_{i1}....\ddot{y}_{ir}, \ddot{e}_i)]$

This difference reflects both the change in income resulting from adjusted output and the change in costs of production when emissions are constrained. The cost of constraining emissions by one can be derived by differentiating $F_i(e_i)$ by $\ddot{e}_i$:

(3.6) $dF_i(e_i) = - \Sigma_r (p_r - \partial G_i/\partial \ddot{y}_{ir}) (d\ddot{y}_{ir}/d\ddot{e}_i) (d\ddot{e}_i) + (\partial G_i/\partial \ddot{e}_i)(d\ddot{e}_i)$

We assume that each profit maximizing firm will adjust output levels such that marginal revenue will equal marginal cost so that the following value will hold for each output 1....r:

(3.7) $p_r - \partial G_i/\partial \ddot{y}_{ir} = 0$

Therefore Equation (3.6) reduces to:

(3.8) $dF_i(e_i) = (\partial G_i/\partial \ddot{e}_i) (d\ddot{e}_i)$ or $dF_i(e_i)/d\ddot{e}_i = \partial G_i/\partial \ddot{e}_i$

In other words, the costs of constraining emissions will be totally reflected in the change in value of the cost function resulting from a change in emission level. Montgomery further provides proof that if $G_i(Y_{i1}....y_{ir}, e_i)$ is convex, then $F_i(e_i)$ is convex. One then can deduce that the conditions under which $\Sigma_i F_i(e_i)$ is minimized will be the same conditions under which total economic cost of emission control to all firms is minimized.

Therefore, the cost minimizing solution to the control problem may be addressed by determining the vector E** which is defined as that vector which provides air quality Q* at all receptors at least total cost to the region. Specifically, it is that vector which minimizes joint total cost:

(3.9) Min $\Sigma_i F_i(e_i)$ such that $E \geq 0$ and $E \times D \leq Q^*$

where $Q^* \geq 0$ and $d_{ij} \geq 0$ for all i,j.

The associated Lagrangian expression will be:

(3.10) Min $\Sigma_i F_i(e_i) + \Sigma_j \beta_j (\Sigma_i d_{ij}e_i - q_j^*)$

Accordingly the Kuhn Tucker conditions for a least cost solution will be:

(3.10a) $F_i'(e_i) + \Sigma_j \beta_j d_{ij} \geq 0$ $\quad$ $e_i [F_i'(e_i) + \Sigma_j \beta_j d_{ij}] = 0$ for all i

(3.10b) $q_j^* - \Sigma_i d_{ij}e_i \geq 0$ $\quad$ $\beta_j [q_j^* - \Sigma_i d_{ij}e_i] = 0$ for all j

Condition (3.10a) states that each firm will discharge emissions to the point where the benefits of an additional emission in terms of reductions in $F_i(e_i)$ will equal the costs, $\Sigma_j \beta_j d_{ij}$, which represent the value of the pollution resulting from an additional emission. The value of pollution at each receptor, $B_j$, reflects the control cost saved by allowing one additional unit of pollution when the constraint on the level of pollution is binding. In the case where $\Sigma_i F_i(e_i)$ is strictly convex, the vector E** which fulfills conditions (3.10a) and (3.10b) will be unique.

MARKETS FOR EMISSION LICENCES

Having identified the nature of the pollution control problem, the question must be addressed as to how the optimal cost minimizing solution defined by conditions (3.10a) and (3.10b) may be realistically achieved. Certainly, achievement of the least cost solution under the command and control approach would require that control authorities have access to a vast amount of cost information for every emitting source (unless the emitters were a very small and homogeneous group). However, since we cannot realistically assume that this would be the case, the implementation of an artificial market in emission rights remains as a viable alternative to be considered. Such a system could significantly reduce the amount of information the control authority would have to gather. It could also provide a mechanism to achieve an efficient allocation of environmental resources given imposed air quality constraints, and provide incentives for technological innovation in control processes.

The operation of the system requires that a control authority determine the desirable level of pollution in the atmosphere and, accordingly, issue an initial offering of licences to emitting sources such that pollution levels will remain equal to or below the desirable level. In order to determine the initial offering of licences which will ensure that those air quality levels defined by Q*, are achieved, these air quality targets must be redefined in terms of aggregate emissions. This will require that a direct relationship exist between air quality changes and changes in the quantity of emissions released by sources. Such a relationship can be easily defined only for the case of uniformly mixed pollutants. Because these pollutants are evenly distributed in the atmosphere, ambient concentration levels at receptor sites are dependent only on the total aggregate level of emissions and not on the location of the sources of discharge. Therefore a direct relationship between changes in the level of total emissions and changes in the air quality level for a region can be estimated. Essentially, this means that emission rights can be traded on a one for one basis among sources in the context of an emissions market system, without causing changes to air quality for the region. In terms of the previous analysis, this would suggest that only one transfer co-efficient, d, would be applicable in translating emissions at all sources, 1....n, into changes in the air quality level for the entire region. The control problem defined by Montgomery can, therefore, be simplified by eliminating all air quality constraints associated with receptor sites, j = 1....m, and imposing only one air quality constraint for the entire region. The definition of the least cost control solution previously defined by condition (3.10) can then be simplified as follows:

(3.10') $\text{Min} \quad \Sigma i\, F_i(e_i) + \beta\, (\Sigma i\, de_i - q^*)$

and accordingly the conditions for cost minimization would reduce to:

(3.10a') $F_i'(e_i) + \beta d \geq 0 \qquad e_i[F_i'(e_i) + \beta d] = 0 \qquad \text{for all } i$

(3.10b') $q^* - \Sigma i\, de_i \geq 0$ $\quad$ $ß[q^*-\Sigma i\, de_i] = 0$

Given that air quality targets, q* can be translated into an appropriate emissions target, (q*/d), the equilibrium market solution under an emissions licence system can achieve a least cost control allocation. Each source will be assigned an initial licence allocation which defines the allowable quantity of emissions the owner may release in a given period of time. Although licences are still defined in terms of allowable pollution changes in this analysis, they are easily translated into allowable emissions for all sources according to the same formula, $l_i/d$. Therefore, for all intents and purposes, they may be regarded as emission licences since each licence translates into the same number of allowable emissions regardless of which source acquires the licence. Specifically, the function $Å(d, l_i)$ defines the right to emit provided to source, i, by the holding of licences, $l_i$. Assuming an initial allocation of licences, $l_i^0$, each profit maximizing firm will attempt to minimize the following value where P* represents the equilibrium market price for licences:

(3.11) $F_i(e_i) + P^*(l_i - l_i^0)$ subject to the condition that $e_i \leq Å(d, l_i)$=li/d or $de_i - l_i \leq 0$

A market equilibrium will exist if and only if there exists $\mu^* \geq 0$ and $P^* \geq 0$ such that:

| | | | |
|---|---|---|---|
| (3.12a) | $\partial F_i'(e_i*) + \mu^*d \geq 0$ | $e_i* [\partial F_i'(e_i*) + \mu^*d ] = 0$ | for all i |
| (3.12b) | $P^* - \mu^* \geq 0$ | $l_i^* [P^* - \mu^*] = 0$ | for all i |
| (3.12c) | $l_i^* - de_i^* \geq 0$ | $\mu^* [l_i^* - de_i^*] = 0$ | for all i |

Here, $\mu$ represents the value of a licence, $l_i$, to source i when the constraint on licences is binding. Condition (3.12a) states that the cost minimizing firm will produce emissions to the point where the marginal benefit of additional emissions in terms of reductions in $F_i(e_i)$ is equal to the value $\mu^*d$ which represents the marginal costs of increased emissions in terms of the value of licences required to justify one additional emission.

Given that these conditions hold for a nonnegative price P* the following market clearing condition will hold:

(3.12d) $\Sigma i\ (l_i^* - l_i^0) \leq 0$  $P^*\ [\Sigma i\ (l_i^* - l_i^0)] = 0$

In other words, a set of prices will exist such that excess demand for licences will be nonpositive and such that excess supply of licences drives the price to zero.

Montgomery then defines the licence constrained joint cost minimum as that vector E** which minimizes the following expression:

(3.13) $\Sigma i\ Fi(ei)$ such that $ED \leq L^0$ and $E \geq 0$

where $L^0$ is a vector of licences initially issued by the control authority. There will exist a vector E** if and only if there exists $\mu^{**} \geq 0$ such that:

(3.14a) $F_i'(e_i^{**}) + \mu^{**}d \geq 0$  $e_i^{**}\ [F_i'(e_i^{**}) + \mu^{**}d] = 0$ for all i

(3.14b) $l^0 - \Sigma i\ de_i^{**} \geq 0$  $\mu^{**}\ [l^0 - \Sigma i\ de_i^{**}] = 0$

The question remains as to whether the market solution will achieve the licence constrained joint cost minimum. Montgomery provides proof that the conditions for a market equilibrium with $\Sigma i\ L_i^0 = L^0$, will satisfy the conditions for a licence constrained joint cost minimum when $\mu^{**} = P^*$. Appendix I provides details of proof for the case of nonuniformly mixed pollutants. The proof remains valid for the preceding analysis for uniformly mixed pollutants since equation (3.13) is merely a simplified version of equation (3.25) and, similarly, conditions (3.14a) and (3.14b) are simplifications of (3.25a) and (3.25b) for the one receptor case. Accordingly, the market exchange of licences can be relied upon to achieve a minimum total joint cost such that air quality is not less than that required by $L^0$.

Baumol and Oates (1975) have shown that an emission charge system will achieve a specified quality of the environment in terms of quantity of allowable emissions at minimum cost for any given vector of final outputs which the market selects. Again, because the objective is stated in terms of aggregate emissions, this analysis is most appropriately applied to the case of uniformly mixed pollutants. Although Baumol and Oates recognize that output levels in the economy will adjust in response to the introduction of emission charges or other restrictions on pollutant discharge, they claim that the vector of specified final outputs may be any vector of outputs including that which results from the independent decisions of each firm under a pollution control program. Accordingly, the assumption is made that regardless of the criteria used to determine output levels, the necessary adjustments will be made to provide those levels at minimum cost. The output adjustments of the firm in response to pollution controls, explicitly dealt with in the Montgomery analysis, are therefore ignored and the control problem becomes one of minimizing the cost of all inputs required to produce a specified vector of outputs:

(3.15) Min. $C = \sum k \sum i \, p_k r_{ki}$ subject to the constraint that output as determined by the production function is greater than or equal to the output requirement:

$f_i(r_{1i} \ldots r_{ni}, e_i) \geq y_i^*$ where

- $r_{ki}$ represents the quantity of input k used by plant i (i = 1...n);
- $e_i$ represents the quantity of waste discharge by source i;
- $y_i$ represents output level of plant i;
- $y_i = f_i(r_{1i} \ldots r_{ni}, e_i)$ represents the production function of plant i

(Note: $e_i$ is represented as an argument in the production function because the reduction of waste by way of recycling or disposal while maintaining an output level, will require additional inputs in the form of labor or capital.)

- $p_k$ represents the price of input k

- $e^*$ represents desired level of waste discharge

In contrast to the Montgomery analysis, a vector of given outputs is used to place a constraint on the system. The second constraint requires that total emissions must be less than or equal to total allowable emissions as determined by the control authority or in other words, $\Sigma i\ e_i \leq e^*$. Accordingly, the Lagrangian expression and Kuhn Tucker conditions for cost minimization of inputs for a given vector of outputs will be:

| | | | |
|---|---|---|---|
| (3.16) | Min $\quad \Sigma k \Sigma i\ p_k r_{ki} + \Sigma i\ \mu_i\ [y_i^* - f_i(r_{1i} \ldots r_{ni}, e_i)] + ß(\Sigma i\ e_i - e^*)$ | | |
| (3.16a) | $ß - \mu_i\ (\partial f_i/\partial e_i) \geq 0$ | $e_i[ß - \mu_i(\partial f_i/\partial e_i)] = 0$ | for all i |
| (3.16b) | $p_k - \mu_i\ (\partial f_i/\partial r_{ki}) \geq 0$ | $r_{ki}[p_k - \mu_i\ (\partial f_i/\partial r_{ki})] = 0$ | for all i |
| (3.16c) | $y_i^* - f_i(r_{1i} \ldots\ldots r_{ni}, e_i) \leq 0$ | $\mu_i\ [y_i^* - f_i(r_{1i} \ldots r_{ni}, e_i)] = 0$ | for all i |
| (3.16d) | $\Sigma i\ e_i - e^* \leq 0$ | $ß\ [\Sigma i\ e_i - e^*] = 0$ | |

where ß represents the marginal social benefit of a one unit decrease in the stringency of the emission standard (or the reduction in cost of control enjoyed by allowing one additional emission) and $\mu_i$ represents the marginal social benefit of an extra unit of output from the ith firm when the output constraint is binding (or the minimum cost increase when the output constraint is relaxed by one unit). Condition (3.16a) states that each firm, i, will control emissions to the point where the marginal benefit of additional emissions in terms of cost of control savings valued at ß, will be equal to or greater than the marginal costs of additional emissions in terms of output foregone when additional inputs are required for waste disposal or recycling in the production process.

Baumol and Oates then address the question of whether the cost minimizing actions of independent firms under an emission charge system will satisfy the conditions for cost minimization (Conditions 3.16a-d) of all outputs under the constraints imposed by the control program. This analysis can be easily translated for the case of an emission licensing program. For example we can examine the incentives existing for independent firms under a licensing system as follows:

(3.17) Min $C = T(e_i - e_i^0) + \Sigma k\, p_k r_{ki}$ such that $f_i(r_{1i}....r_{ni}, e_i) \geq y_i^*$

where $e_i^0$ represents initial allocation of licences and where T represents the price of emission licences, and C represents total costs of production and licence acquisition.

The first order conditions for the above cost minimization problem for each firm under the licence system will satisfy the Kuhn Tucker conditions (3.16a-d) required for minimization of input cost for all firms together, when the price of the licences, T, is equal to ß (the marginal social cost of an increase in the emission standard). The Kuhn Tucker condition $\Sigma e_i \leq e^*$ will be satisfied if each $e_i$ associated with a given set of prices is unique. This condition has no counterpart for the individual firm. Thus, an emission licence system may achieve the desired level of total emissions while at the same time satisfying the necessary conditions for the minimization of the program's cost to society.

Given that the market system produces a cost minimizing solution, it can further be shown that such a solution is indeed desirable in that it will yield a quasi-optimal Pareto solution as demonstrated by Hamlen (1975). Using a social welfare function defined in terms of monetary units, the problem of maximizing welfare of society subject to the constraint that air quality standards be met in terms of quantity of emissions released into the air, is addressed in Lagrangian form as follows:

(3.18) Max $\Sigma i\ \Omega_i U_i(x_i;e^*) + \Sigma j\, P_j\, [\Sigma i\, x_{ij}^* + \Sigma k\, y_{kj} - \Sigma i\, x_{ij}] + ß\, (e^* - \Sigma k\, G_k(y_k)) +$
$\Sigma k\, \mu_k\, F_k(y_k;e^*)$ where

- $U_i$ represents a concave utility function for individual i

- $x_i$ represents the m vector of commodities demanded by the ith individual

- $F_k$ represents the continuous and concave transformation function of the kth firm

- $y_k$ represents the m vector of inputs and outputs associated with the kth firm
- $x_{ij}*$ represents the inital endowment of commodity j held by individual, i
- $x_{ij}$ represents the consumption of commodity j by individual i
- $y_{kj}$ represents the quantity of the jth commodity provided by the kth firm
- $\Omega$ represents the reciprocal of the marginal utility of income for the ith individual
- $G(y_k)$ represents emissions resulting from production of yk
- e* represents constrained level of emissions

The solution lies in the maximization of the social welfare, $\Sigma i\ \Omega_i\ U_i(x_i;e^*)$, under the constraints that consumption does not exceed the availability of products and services in the economy, the production by each industry, y = 1...k, remains nonnegative, and finally that emissions do not exceed the level denoted by e*. Conditions for maximization require:

(3.18a) $\Omega_i\ (\partial U_i/\partial x_{ij}) - P_j \leq 0 \quad x_{ij}\ [\ \Omega_i\ (\partial U_i/\partial x_{ij}) - P_j] = 0$ for all i and all j

In words, this condition suggests that consumers will purchase quantities of product $x_{ij}$ such that marginal utility (in monetary terms) is equal to the cost of its purchase, $P_j$.

(3.18b) $P_j + \mu_k\ (\partial F_k/\partial y_{kj}) - ß\ (\partial G_k/\partial y_{kj}) \leq 0$ and

$y_{kj}\ [P_j + \mu_k\ (\partial F_k/\partial y_{kj}) - ß\ (\partial G_k/\partial y_{kj})] = 0$ for all k

Further, producers will produce as long as the benefits of producing additional units of $y_{kj}$ in terms of revenue, $P_j$, is greater than or equal to the costs of the additional unit in terms of foregone outputs by firm k, and in terms of the costs of controlling additional emissions, ß $G(y_k)$.

(3.18c) $\Sigma i\ x_{ij} + \Sigma k\ y_{kj} - \Sigma i\ x_{ij} \geq 0 \qquad P_j\ [\Sigma i\ x_{ij}* + \Sigma k\ y_{kj} - \Sigma i x_{ij}] = 0$ for all j

(3.18d) $F_k(y_k{:}e^*) \geq 0$ $\mu_k\,[F_k(y_k{:}e^*)] = 0$ for all k

(3.18e) $e^* - \Sigma k\, G_k(y_k) \geq 0$ $\beta[e^* - \Sigma k\, G_k(Y_k)] = 0$

Conditions (3.18a-e) establish the conditions for maximum utility for a given value of e*. The question which Hamlen then addresses is whether the conditions under which consumers and producers will operate under a market system in emission licences will satisfy conditions 18a-e.

The consumer's decision when permit charges or emission fees are introduced into the analysis becomes one of how to maximize $\Omega_i\, U_i(x_i;\, e^*)$ given that the level of pollution is a parameter beyond their control. Utility is therefore maximized with respect to all other market goods under the constraint that the level of pollution, e*, exists. If consumers act in this way, condition (3.18a) will be satisfied. In other words, each consumer will demand product $x_j$ to the point where the marginal benefits enjoyed by the consumption of one additional unit, $\Omega_i(\partial U_i/\partial x_{ij})$, are equal to the cost to the consumer of its purchase, $P_j$.

Producers, on the other hand, who would normally maximize profits (i.e. Max $\Sigma j\, P_j y_{kj}$) without regard for environmental costs, will seek to maximize the following when an emission fee system or an emission permit system is introduced:

(3.18f) Max $\Sigma j\, P_j\, y_{kj} - T\,[\,G_k(y_k)]$ such that $F_k(y_k;e^*) \geq 0$ for all k

Here, T, represents the value of the emission fee or price of emission licence. If the value T is equal to the value ß which represents the value of an emission in terms of costs of control avoided when the constraint on emissions is binding, then Condition (3.18b) will hold. Producers will provide good j to the point where the benefit received from one additional unit, $P_j$, is equal to the additional costs of producing one more unit in terms of emission fees to be paid, $T(\partial G_k/\partial y_{kj})$, and in terms of losses in total production of all other goods produced by firm k.

Given the satisfaction of conditions (3.18a) and (3.18b), it can be asserted that an emission fee system or emission licence system will achieve a quasi-Pareto optimum where all consumers maximize their utility for a given level of environmental quality. The term quasi is used in this instance to denote the fact that the level of pollution is beyond the control of consumers and producers. They simply maximize profits and utility for all market goods subject to the pollution control requirement.

Tietenberg (1985) further simplifies the control cost problem by examining all emission control decisions in isolation of other production decisions. He approaches the control problem from the perspective of the firm who wishes to determine optimal level of controlled emissions. In contrast to Montgomery's approach the issue of how the levels of output in the economy will be affected by the introduction of emission controls is ignored. Further, unlike Baumol and Oates, his approach deals only with the minimization of costs of pollution abatement and not with the minimization of costs of total output. The case where input decisions and control decisions are closely intertwined is not recognized. For example, the use of low sulfur coal may eliminate the need for high cost control technologies by utility plants. In such cases, the issue of pollution control cannot be separated from the broader issue of cost minimization of inputs. However, the model instead accepts that for a given level of output in the economy, an associated level of emissions will be produced. Firms will act to minimize costs of inputs required to produce these outputs, and they will also act to minimize the costs of controlling emissions such that imposed standards can be met[1]. Tietenberg deals only with the latter problem of controlling emissions at minimum cost as an issue independent of other cost issues.

---

1 In the case where input decisions and control decisions are related, the approach used by Tietenberg can be justified if control costs include additional input costs which serve to reduce emissions. For example, if reductions in

He defines the cost of control minimization problem for the case of uniformly mixed pollutants as the minimization of total abatement costs across all firms subject to the constraint that total emissions allow for air quality which is better or equal to the imposed standard:

(3.19) $\text{Min } \Sigma i\ C_i(r_i) + ß[a + d\ (\Sigma i\ \ (e_i - r_i)) - A]$

where $e_i$ = emission discharges without control policy and $r_i$ = controlled emissions for each firm i=1....n; A = allowable level of pollution; a = background pollution; and d = constant of proportionality or in other words the transfer co-efficient which translates changes in emissions from all sources into changes in air quality for the region. This problem gives rise to the following Kuhn Tucker condition:

(3.19a) $\partial C_i/\partial r_i - ßd \geq 0 \quad r_i\ [\ \partial C_i/\partial r_i - ßd\ ] = 0 \quad \text{for } i= 1....n$

In this context, ß represents the value of á one unit change in the pollution level of the region given that the constraint A is binding. This value represents the control cost saved if the constraint, A, were relaxed by one unit. Therefore, according to the above condition, the optimal reduction in emissions, $r_i$, will be that amount which equates the marginal cost (for each firm) of reducing one emission with the marginal benefit of improved air quality represented by ßd, the reduction in control costs associated with one additional emission if the constraint on A is binding. Given that all firms, 1...n, minimize costs according to this condition, the marginal cost of control in all firms will be equal to the value ßd. This further suggests that any firm with emission control costs on the first unit of emissions

---

emissions are achieved by using alternative energy sources, the increased costs of energy could be included as control costs.

greater than ßd, will be assigned no control responsibility at all, and in this case $r_i$ will be zero.

Tietenberg further asserts that the self-interest of industry to maximize profits can theoretically lead the market to the cost effective solution when an emission permit system is introduced to control uniformly mixed pollutants. The cost effective solution will occur when emission permits are transferred from those sources with low marginal control costs to those incurring high marginal control costs so that those firms which can most efficiently control emissions will be primarily responsible for doing so while those firms which are less efficient in controlling emissions will purchase permits and continue to discharge emissions subject to imposed air quality constraints. Indeed, incentive does exist under the permit system for sources with high costs of control to maintain or increase the level of discharge by purchasing the emission permits from sources with low control costs since the cost of purchasing permits is low relative to the costs of control. Similarly, incentive exists for firms with low costs of control to incur additional costs for controlling emissions so that they may collect revenue for the sale of their emission permits, the value of which should exceed the increased costs of control. When all such opportunities have been exhausted, the marginal costs of control will be equalized across all firms and the cost effective allocation will have been achieved.

Under this scenario, control authorities are required only to limit the set of transfers consistent with the attainment of air quality targets. Each participant then utilizes his available cost information in order to minimize control costs. Emission permits would be issued for each pollutant (specifying an allowable emission rate such as tons per hour) to the relevant sources of discharge according to the following formula for designation:

(3.20) $N = \sum i \, (e_i - r_i) = (A-a)/d$

where $e_i$ = the steady state emission discharges without emission control by source i. Given the assignment of N permits to the region under consideration, sources would then seek to acquire permits in such a way as to minimize their control costs. Each firm's cost minimization problem would be defined as follows:

(3.21) $\quad \text{Min } C_i(r_i) + P(e_i - r_i - q_i)$

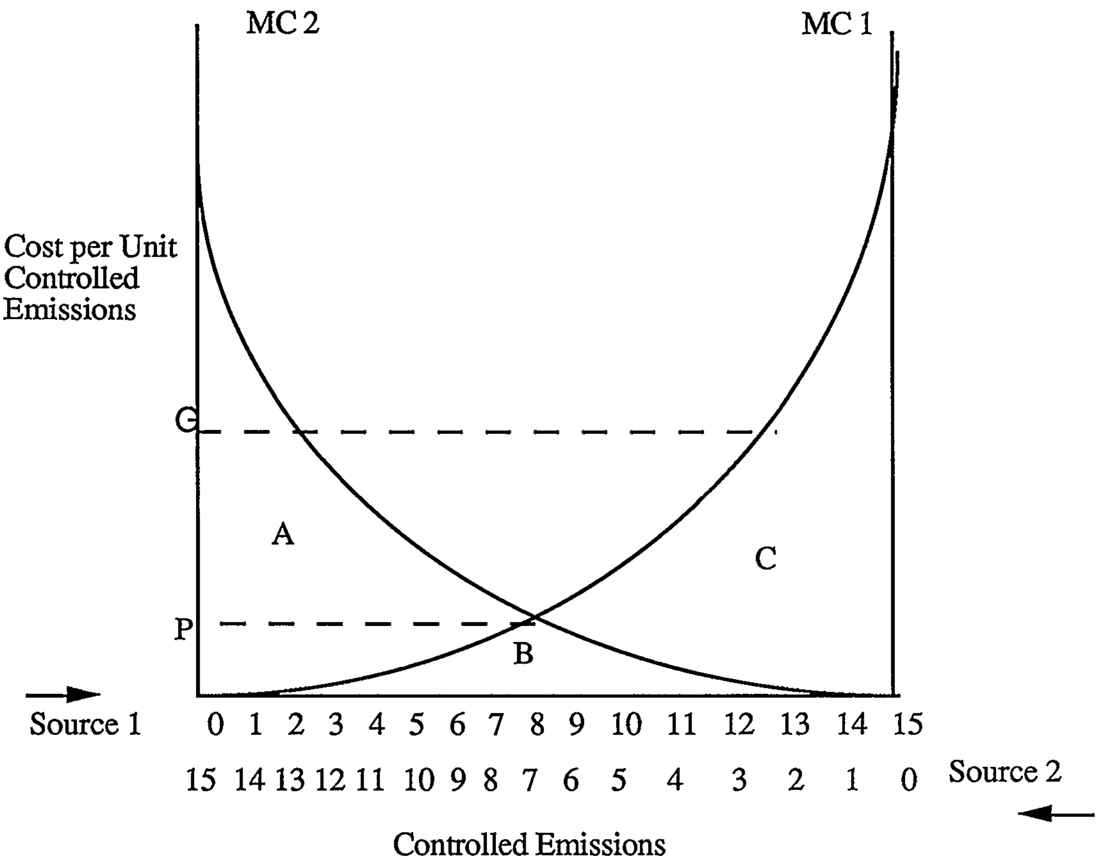
where P = price of the permit and $q_i$ = inital endowment of permits. Accordingly, the optimal emissions control condition will be:

(3.21a) $\quad \partial C_i(r_i)/\partial r_i - P \geq 0 \qquad r_i\,[\,\partial C_i(r_i)/\partial r_i - P\,] = 0$

In other words, firms will incur control costs to reduce emissions until a point is reached where the marginal cost to control one more emission is equal to the price of obtaining a permit to allow one further emission.

The question now arises as to whether this market solution is, indeed, the cost minimizing solution sought by the control authorities. By examining conditions (3.19a) and (3.21a) it is evident that the market will attain the cost minimizing solution if P, the price of permits equals, ßd, the cost of an additional emission in terms of the value of the resulting pollution. Tietenberg claims that the market equilibrium would indeed yield a value of P which is equal to ßd. Consider an example where only two sources of emissions exist. Figure 2 represents all possible allocations of control to attain a 15 unit reduction in emissions in the case where two firms together are initially emitting 30 units and where the level of total allowable emissions is 15. It is evident in this simple illustration that the equality between P and ßd would, indeed, hold. For example, it is clear that the cost minimizing solution is found where marginal costs are equated at value, P, and where total variable costs represented by Area B are minimized.

Figure 2

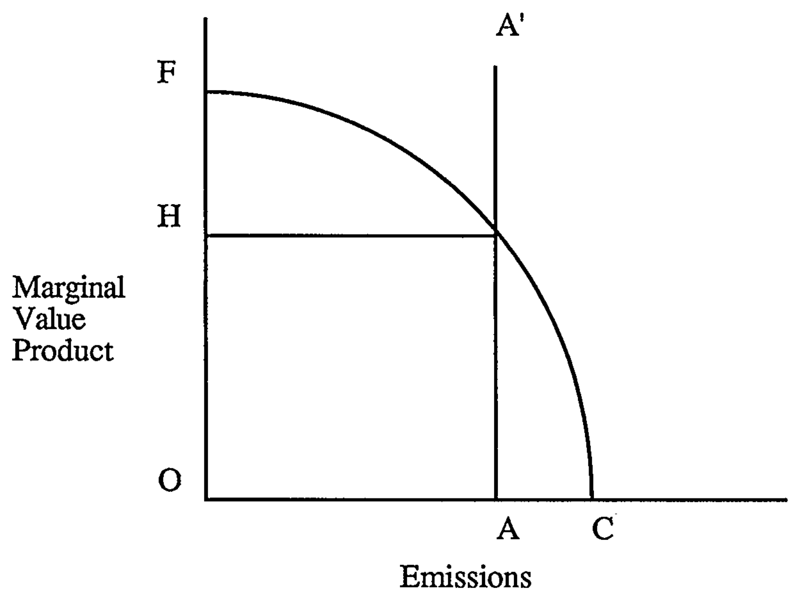



Similarly, the permit market solution would yield an equilibrium permit price with value, P, regardless of the initial permit allocation since only at this point would incentives for trading be eliminated. For example, if the initial allocation allowed Source 1 to emit only 3 units and required it to control 12 of its 15 emission units, then Source 2 would be required to control only 3 emissions. Both firms would have an incentive to trade as long as the marginal control cost of Source 1 was greater than that for Source 2. Specifically, Source 1 would reduce its control costs by purchasing an emission permit from Source 2 for a price less than G (and greater than marginal control costs of Source 2), while Source 2 would reduce its total emissions by one thereby increasing its control costs. Such a process would allow both sources to reduce total costs in terms of permit acquisition and emission control. Therefore, trading would likely occur until all such incentives were eliminated at the point where Source 2 would control 7 units and Source 1 would control 8. Thus, the market solution is synonymous with the cost minimizing solution. Given a system of transferable permits, the sources will efficiently decide on the distribution of control responsibility. Essentially, the reason for this is that trading incentives will exist for both sources until marginal costs are equated (the cost minimizing solution) at which point an equilibrium permit price will be established.

Tietenberg's analysis implicitly assumes that the marginal value product for emissions will be greater than or equal to the marginal cost of control (which equals permit prices) across all sources at the market equilibrium. In other words, it must be assumed that output in the economy has adjusted in order for this condition to hold. For example, consider Figure 3 where curve FC represents the marginal value product of increased levels of emissions and where AA' represents the imposed standard for quantity of emissions. At the maximum level of emissions allowed under the constraints of a pollution control program, the marginal value product of an emission is equal to OH. In the case where the equilibrium marginal cost of control for each source is equal to or less than OH, each source will control emissions according to condition (3.21a). However, if marginal costs of control at the market equilibrium solution exceed the value of the marginal value product, output would be adjusted downward so that emission reductions required for compliance to the imposed standard could be reduced and subsequently equilibrium value for marginal control costs (and permit prices) would be reduced to a level which does not exceed the marginal value product. Clearly, control decisions are not independent of output decisions. In some instances reducing output is the most inexpensive means of reducing emissions.

Such an analysis also explicitly assumes that the market in transferable discharge rights is a competitive one. However, if the emitting sources are few in number, they may conceivably charge higher prices for their permits in order to raise the costs of rivals in the same industry or to block the entry of new competitors. Clearly, any such action, while it may be effective in increasing profits and market shares, could move the market away from the least cost solution. Formal proof of this is provided by Misiolek and Elder (1989). However, the conditions for such manipulation are restrictive in that they require a very small number of emitters in the market and the absence of alternative locations from which the buyer could choose.

Figure 3




<u>MARKETS FOR POLLUTION LICENCES/THE AMBIENT MARKET SYSTEM</u>

The class of pollutants referred to as nonuniformly mixed assimilative pollutants, requires a more complex cost control analysis which recognizes the important relationship between location of polluting sources of discharge and achievement of pollution targets at specific receptor sites. Numerous air and water pollutants including sulfur dioxide and suspended particulates would fall under this classification. For such pollutants, concentration levels are sensitive not only to levels of emissions but to location and degree of clustering of the emitting sources. Specifically, highly clustered sources would more easily violate ambient quality standards due to high concentrations in a small volume. In order to deal most effectively with this class of pollutants, it is necessary to define a system in pollution rights rather than emission rights.

In response to the need for recognition of the importance of source location in attaining ambient air quality standards at sensitive receptor sites, Montgomery (1972) proposes that a market in pollution licences be established for each receptor site. He defines each licence $l_{ij}$ as the quantity of licences held by firm i which allows pollution at receptor point j. Each firm is required to hold a portfolio of licences, $L_i(l_{i1}...l_{im})$ which includes licences for all relevant receptor points. The quantity of emissions which the firm is allowed to emit according to these licences will be determined by the following function:

$å(d_i, l_i,) = \text{Min}_j \ l_{ij}/d_{ij}$

Therefore, firm i must control its emissions in order to comply with the following condition:

(3.22) $d_{ij}e_i \leq l_{ij}$ for $j=1....m$

In other words, the firm can produce emissions only to the point where the resulting pollution at every receptor point, j, remains below or equal to that which is allowed for by the licence portfolio.

A market equilibrium will exist for vector $L_i$* and E* which minimizes the costs of control and the costs of purchasing licences for each firm:

(3.23) $\text{Min } F_i(e_i) + \sum_j P_j^*(l_{ij} - l_{ij}^0) + \sum_j ß_{ij}^*(d_{ij}e_i - l_{ij})$

where $L_i^* \geq 0$, $E^* \geq 0$ and $P^* \geq 0$ and where $ß_{ij}$ represents the marginal benefit of a pollution licence for receptor j when the constraint on emissions and resulting pollution for firm i is binding. This value represents the control costs saved when an additional licence $l_{ij}$ is acquired.

Equilibrium will exist if vectors $(ß_{i1}^* \ldots ß_{im}^*) \geq 0$ for i=1...n and $(P1^* \ldots Pm^*) \geq 0$ exist and where the following conditions hold for all firms:

(3.23a) $F_i'(e_i^*) + \Sigma_j ß_{ij}^* d_{ij} \geq 0$ $\quad e_i^*[F_i'(e_i^*) + \Sigma_j ß_{ij}^* d_{ij}] = 0$

(3.23b) $P_j^* - ß_{ij}^* \geq 0$ $\quad l_{ij}^*[P_j^* - ß_{ij}^*] = 0$ $\quad$ for all j

(3.23c) $l_{ij}^* - d_{ij}e_i^* > 0$ $\quad ß_{ij}^*(l_{ij}^* - d_{ij}e_i^*) = 0$ $\quad$ for all j

Market equilibrium will also require that the following market clearing condition holds:

(3.24) $\Sigma i\,(l_{ij}^* - l_{ij}^0) \leq 0$ $\quad P_j^*\,[\Sigma i\,(l_{ij}^* - l_{ij}^0)] = 0$ $\quad$ for all j

Condition (3.23a) states that each firm will increase its level of emissions to the point where the marginal benefits, in terms of reductions in $F_i(e_i)$ are equal to the marginal costs of emissions in terms of the value of licences required to increase emissions by one unit.

Having derived the necessary and sufficient conditions for a market equilibrium, Montgomery then proceeds to examine the conditions for a least cost solution for pollution control under the constraint of a pollution licence system. He defines the constrained joint cost minimum level of emissions as that vector E** which minimizes total cost of emissions control across all industries:

(3.25) $\quad \text{Min } \Sigma i\, F_i(e_i)$

subject to the constraint that $E \geq 0$ and that pollution at each receptor point does not exceed that allotted by the licence system or in other words where $ED \leq L^0$ where $L^0$ represents the initial licence allocation. In other words, $l_j^0 - \Sigma_i d_{ij} e_i \geq 0$ for all j. The constrained solution for this problem requires that the following conditions hold:

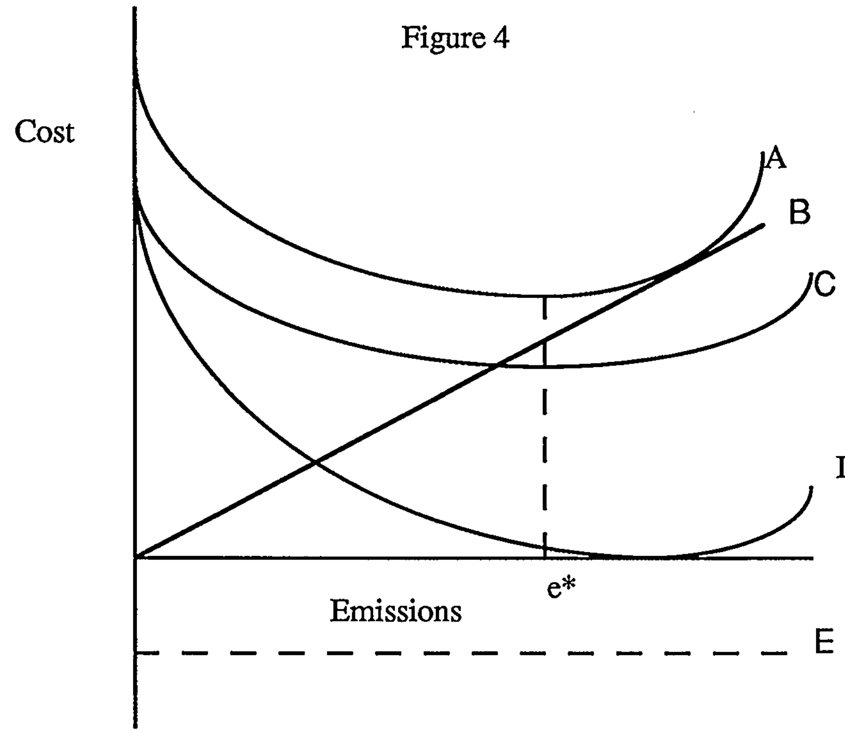
(3.25a) $F_i'(e_i^{**}) + \Sigma_j \beta_j^{**} d_{ij} \geq 0$ $\quad$ $e_i^{**}[F_i'(e_i^{**}) + \Sigma_j \beta_j^{**} d_{ij}] = 0$ for all i

(3.25b) $l_j^0 - \Sigma_i d_{ij} e_i^{**} \geq 0$ $\quad$ $\beta_j^{**} [l_j^0 - \Sigma_i d_{ij} e_i^{**}] = 0$ for all j

Naturally, the question which follows from this analysis is whether the solution provided by the market equilibrium with $\Sigma_i L_i^0 = L^0$, is equal to the licence constrained joint cost minimum. To show that this is indeed the case, Montgomery provides proof that any $e_i^*$ which satisfies the conditions for market equilibrium will satisfy those conditions required for a constrained joint cost minimum, when $\beta_j^{**} = P_j^*$. Refer to Appendix I for details of this proof. Accordingly, we can rely on the market exchange of licences to achieve a minimum total joint cost such that air quality at each receptor point j, is no less than that required by the licences issued.

An important advantage of this type of market system in pollution rights is that the equilibrium solution is independent of the initial allocation of licences if totals of each type of licence remain the same during redistribution . For each firm, emission rate, $e_i$, is associated with a cost of emission control, $F_i(e_i) + \Sigma_j P_j^* d_{ij} e_i$, shown as A in Figure 4. Equilibrium emissions, e*, will minimize this sum. Further, the initial allocation of licences, $l_j^0$ can be represented as a horizontal line, $\Sigma_j P_j l_{ij}^0$ (See E) because it is a lump sum subsidy which remains unchanged despite the level of emissions. As shown by C, the cost of emission control of firm i, net of the initial subsidy $\Sigma_j P_j l_{ij}^0$, is minimized at emission rate e*. The initial level of licences merely serves to shift the net cost of control curve A; it does not alter its shape. The problem of achieving air quality standards at each receptor point at minimum cost, given an arbitrary initial allocation of licences, is thus solved.

Figure 4




$A = F_i(e_i) + \Sigma j\ P_j\ d_{ij}\ ei$ $B = \Sigma j\ P_j\ d_{ij}\ e_i$

$C = F_i(e_i) + \Sigma j\ P_j\ d_{ij}\ e_i - \Sigma j\ P_j\ l_{ij}^0$ $D = F_i(e_i)$

$E = \Sigma j\ P_j\ l_{ij}^0$

Tietenberg (1975) again simplifies the control problem for the case of nonuniformly mixed assimilative pollutants by focusing on the actions of the market to minimize pollution control costs independently of other production decisions. For this analysis, air quality levels at each receptor site will depend upon the location of emitting sources as follows:

(3.26) $A_j = \Sigma i\ d_{ij}\ (e_i - r_i) + a_j$

where $A_j$ represents pollution concentration level at receptor j and $a_j$ represents background pollution at the jth receptor. The cost effective solution will minimize total costs of control subject to the constraint that air quality at all receptors, $A_j$, is below or equal to the desired concentration ceiling $A_j$:

(3.27) $\text{Min } \sum_i C_i(r_i) + \sum_j \beta_j \, (a_j + \sum_i d_{ij}(e_i - r_i) - A_j)$

Accordingly, the optimizing Kuhn Tucker condition will be as follows:

(3.27a) $\partial C_i(r_i)/\partial r_i - \sum_j d_{ij}\beta_j \geq 0 \qquad r_i[\partial C_i(r_i)/\partial r_i - \sum_j d_{ij}\beta_j] = 0 \qquad \text{for all } i$

Condition (3.27a) shows that the optimal condition will exist where each source equates its marginal cost of emission control with a weighted average of its marginal cost of concentration reduction ($\beta_j$) for every receptor, where the transfer co-efficients serve as weights. In other words, sources will equate marginal costs of controlling emissions to the marginal benefits of controlling additional emissions in terms of the value of the pollution reduced at all receptors, $\sum_j d_{ij} \beta_j$. The values for $\beta_j$ reflect the cost savings realized when the quality constraint for receptor j is relaxed by one unit. In the case of a nonbinding receptor, $\beta_j$ would equal zero since the pollutant concentration would lie below the ceiling and the constraint would not be binding. However, for all binding receptors the value for $\beta_j$ would be positive. For the one receptor case, the optimal solution exists where marginal concentration reduction costs are equalized across sources rather than marginal emission reduction costs (as for uniformly mixed pollutants). Each firm would operate according to the following optimal condition:

(3.28) $[\partial C_i(r_i)/\partial r_i] \, / \, d_{ij} = \beta_j$

where the left hand side term represents the marginal cost of concentration reduction at receptor, j. Examination of this condition suggests that for the case where two sources have identical marginal cost of control curves, the source with relatively high transfer co-efficients due to proximity to receptor sites will incur higher marginal emission control costs in a market equilibrium. Intuitively, this result is obvious in that sources located near receptor sites must control more emissions in order to reduce pollution levels by one unit at each site 1...j.

A complication arises in this type of analysis when the value for the transfer co-efficients change over time. For example, changes in seasons may affect not only the amount of desirable emissions, but also transfer co-efficients which respond to alterations in wind velocity and direction. Therefore, allocations of the optimal emission reduction responsibility must be adjusted accordingly.

Tietenberg asserts that a pollution rights system often referred to as an ambient permit system, could be initiated to yield a cost effective allocation of control responsibility. Under such a system, each firm would purchase licences from each receptor market so as to minimize the value of the following objective cost function:

(3.29) $\text{Min } C_i(r_i) + \Sigma_j P_j [d_{ij}(e_i - r_i) - q_{ij}]$

where $P_j$ represents price of the licence for the jth receptor and $q_{ij}$ represents pretrade concentration levels allowed to source i. In this case, the following condition defines the optimal control responsibility for each firm:

(3.29a) $\partial C_i(r_i)/\partial r_i - \Sigma_j P_j d_{ij} \geq 0 \quad r_i [\, \partial C_i(r_i)/\partial r_i - \Sigma_j P_j d_{ij} \,] = 0 \quad r_i \geq 0$

This condition states that sources will control emissions to the point where the marginal cost of controlling additional emissions is equal to the marginal cost of emitting additional emissions in terms of licence acquisition costs in the market equilibrium. Examination of conditions (3.27a) and (3.29a) suggests that the ambient permit system will yield an optimal allocation of responsibility if $P_j = \beta_j$. This condition would hold only if the control authority issues the appropriate number of licences such that required air quality could be achieved for each receptor.

Prices prevailing in each market should reflect the degree of difficulty of meeting the ambient standards at that receptor. For example, it follows that highly congested areas would sustain higher prices for licences to pollute relative to less congested areas, since the costs of reducing concentration levels for these areas would be relatively high given that emissions would have to be controlled to a greater extent. Similarly, the value of $\beta_j$ would be greater for these congested areas in that $\beta_j$ reflects the cost of reducing concentration levels by one unit given that the air quality constraint is binding for that area.

Clearly condition (3.29a) does not require that firms equate their marginal cost of controlling emissions. In fact, the marginal cost of controlling emissions among sources may differ quite drastically in the case where transfer co-efficients are significantly different. For example, sources with relatively large transfer co-efficients for highly congested receptor areas will be required to control their emissions to a greater extent than other sources, thereby incurring relatively high marginal costs of emission control. This variation in marginal emission control costs across sources stands in contrast to the least cost solution for uniformly mixed pollutants where these costs are equalized between all sources.

The advantage of the ambient system apart from its ability to achieve a cost minimizing solution, lies in its provision of the appropriate incentives to industrial pollution sources hoping to locate in the airshed. According to condition (3.29a) the system is likely to discourage sources from locating close to sensitive receptor sites. Kohn (1974) examines the implications of source location for the cost minimization problem which he defines as follows:

(3.30) Min. CX such that $UX = S$ and $EGX \leq q - b$ and $X \geq 0$

where X is an N x 1 vector representing activity levels under various pollution control methods. For example, $X_1$ may represent steel produced with precipitators while $X_2$ may represent steel produced with wet scrubbers as a means of controlling pollution. Further, C represents a 1 x N vector of unit costs of the jth control method. Vector S of dimension (M x 1) is a set of M production and consumption levels which are the sources of air pollution. Each element represents capacity constraints on the system. Matrix U of dimension M x N contains elements $u_{ij}$ where $u_{ij} = 1$ when the jth control method is defined for the ith pollution source and zero otherwise. Finally, the constraint $EGX \leq q - b$ constrains the level of pollution resulting from emissions (denoted as the P x N matrix E), at the relevant receptor point to the level of air quality associated with imposed standards denoted by the P x 1 matrix q, net of background pollution b. Here G represents an N x N matrix which converts pollutant levels for each control method j into pollutant levels at the one receptor point considered in this analysis. By applying data from the St. Louis Airshed in 1975, the least cost solution which minimizes the value CX was determined to be $33,150,000/annum.

The location of a single producer was then varied by altering the co-efficients associated with the control method used by the producer in the g matrix to reflect distances of 2, 4, 6, 8, 10, and infinity miles between the firm and the receptor site. As distance to the receptor was reduced, the optimal solution required that additional control methods be utilized by the firm and, accordingly, the firm's control costs increased substantially for that producer. Specifically, as the distance from the receptor decreased from 10 miles to 2 miles, the optimal least cost solution required that control costs for the firm increase almost eight fold from $128,000 per year to $954,000 per year. Furthermore, if the firm location was held fixed and the relevant gj co-efficients were adjusted to reflect changes in the assumptions regarding wind direction and frequency, control costs increased significantly.

Such analysis clearly illustrates the importance of spatial dimensions to the problem of optimal pollution control.

COMPLEXITIES OF THE SPATIAL DIMENSIONS

For the case of nonuniformly mixed assimilative pollutants, a cost efficient allocation of control responsibility must recognize the importance of source location. Although the pollution right system outlined above fulfills this objective, the practical application of such a system presents formidable obstacles which may prevent the successful operation of the program.

In the United States the law dictates that reasonable assurance must be given that violations of concentration ceilings at affected receptors will not occur as a consequence of the activities of any particular source. Realistically, this requires that sources must monitor approximately nine or ten sites in the typical airshed, and that a pollution permit system must be designed to manage concentrations for all these sites. Indeed, a separate market which defines pollution licences in terms of allowable concentration increases is required for each receptor location. Pollution sources are, therefore, faced with a rather difficult and complex challenge in that they must negotiate in a number of markets in order to legitimize their activities. For example, should a source wish to expand its productive capacity it must acquire pollution licences for all monitoring stations. The project could be jeopardized by a problem in negotiating in any one of these licence markets (perhaps due to noncompetitive prices existing in the case of few sellers). Furthermore, the source must conduct its negotiations among the various markets simultaneously as the demand for licences in one market would depend on prices of licences in all markets. The question remains as to whether sources could deal effectively and efficiently with the task imposed upon them by a system of pollution rights. Certainly, the complexity of their task is an inherent problem of this system and, indeed, a formidable one.

The second barrier which interferes with the operation of such a system has been introduced via legislation. In the United States, the Clean Air Act requires that for all areas which have not achieved ambient standards, reasonable further progress towards meeting these standards must be demonstrated annually where progress is defined in terms of emissions reductions rather than changes in air quality. Such a requirement prohibits strategies which might improve air quality by reducing concentration levels but which increase or maintain total emissions. Consequently, the most cost efficient means of achieving the standards may not be allowable under current legislation as in the case where attainment is most efficiently reached by relocating emitting sources rather than reducing emissions. Other means of improving air quality, which substitute for emission reduction are similarly ruled out. Specifically, dispersion techniques which diminish emissions at receptor sites, including use of tall stacks and intermittent controls which vary emissions with weather conditions, are not regarded as acceptable methods of seeking attainment. Put simply, the potential cost savings of the pollution right system lie in the smaller emission reductions required to meet the standards when location and dispersion are considered. The main disadvantage of the present legislation is that it foregoes the opportunity of realizing the minimum cost control position.

## ALTERNATIVES TO THE AMBIENT MARKET SYSTEM

### The Emission Permit System

Although the legal obstacles which deter the efficiency of the ambient market system (pollution licence system) can be resolved by legislative action, the administrative complexity of the system is not so easily resolved. Therefore, it is desirable to examine possible alternatives to the ambient permit system which impose relatively small efficiency costs. The first and least complex alternative is to use an emissions permit system which ignores the relevant spatial considerations. Indeed, this would appear to be a realistic compromise if the cost penalties of using this approach rather than the ambient market approach were acceptably small.

However, the empirical results of studies conducted by Atkinson and Lewis (1974), Atkinson (1983), and Seskin, Anderson and Reid (1983), indicate that the cost penalties in maintaining a specific level of air quality at all receptors are significant with the ratio of emission permit system control costs to ambient permit control costs ranging from 1.67 to 33.9.

Krupnick (1986) conducted a study of alternative policies for the control of nitrogen dioxide in the Baltimore Air Quality Control Region. Five different policies ranging from the least cost ambient permit system to the command and control approach were examined. It was found that in order to maintain an ambient standard of 250 ug/m3, control costs incurred would amount to $1.663 million for the least cost ambient permit system while the emission permit system (referred to as uniform fee) yielded costs of $14.423 million. Clearly, the substantial cost penalties in ignoring source location are undesirably high, suggesting that perhaps another alternative to the ambient permit system should be sought. For example, a policy alternative which utilized both the command and control approach and a market approach was found to substantially reduce cost penalties associated with a deviation from the least cost method. For the RACT/Least-cost option a RACT (Reasonably available control technology) was imposed on all sources of emissions. RACT in this case was defined to be any technology with marginal costs just below the point of sharply increasing costs. Then, if required, market incentives were used to induce further emission reductions. Total control costs for this method were estimated to be $2.2 million suggesting that a possible policy alternative to the ambient system may exist. Certainly, the RACT/Least-cost method is more desirable than the emissions permit system for this particular case. Futhermore, these empirical results indicate that an emission permit system may not be a desirable alternative to the ambient permit system.

Atkinson and Lewis (1974) examined the cost effectiveness of alternative air quality control strategies including the ambient least cost model, the least cost emission model and the SIP (State Implementation Plan) strategy utilized by the state in meeting the federally set ambient air quality standards for the St. Louis area. The SIP strategy resembled the command and control approach in that it determined the level of emission reduction for each plant according to such characteristics as plant size and source category, while ignoring the importance of other criteria regarding control costs and dispersion characteristics which are necessary to determine optimal control strategies.

Under the assumption that each unit of emission would have the same impact on ambient air quality regardless of source, the emission permit system minimized total control costs for the region subject to only one air quality constraint which represented the greatest required improvement in air quality at a particular receptor. On the other hand, the ambient least cost program minimized the total cost of control for all sources subject to nine air quality constraints (one for each receptor) and transfer co-efficients unique to each source were used to translate emissions from each source into air quality at each receptor.

The significant difference in costs between the least cost ambient program and least cost emission program served to emphasize the importance of including individual dispersion characteristics. Indeed, over a wide range of ambient air quality levels, the emissions program was at least twice as expensive as the ambient program in achieving the same quality level. However, the least cost emission program did enjoy a significant cost advantage over the SIP strategy with the ratio of SIP control costs to least cost emissions control costs as high as 6 to 1 dropping to 4 to 3 at the secondary required ambient quality levels.

Further examination of the results clarifies the reason for the large discrepancy in costs between the ambient and emissions based systems. The least cost ambient strategy removed only about one half of the particulates from the air required under the least cost emission strategy. While the ambient method improved air quality to the minimum extent required, the emissions method not only met the standard at the worst receptor but also significantly improved the air quality at most other receptors. The emission permit system, thus, imposed higher total control costs due to its requirement that greater emission reductions be achieved to maintain standards. The same result is obtained for the SIP strategy.

The implications of these results are certainly important to policy makers. For example, in the case where air quality rather than cost minimization is the primary consideration of the control authority, the emissions based program or SIP strategy is clearly more desirable. However, if costs are the primary consideration, it must be recognized that by simplifying the analysis to avoid the complications of spatial complexities, as in the least cost emission strategy, substantial cost penalties will be incurred. In order to avoid such cost penalties, an ambient permit system which imposes greater control requirements on sources having the largest impact on receptors, should be implemented. In this way fewer total emission reductions will be required.

Under an emission permit system, the costs of control are clearly expected to exceed those of the ambient permit system. Studies have also shown, however, that costs under the emission permit system or emission charge system may exceed control costs incurred under a command and control approach for the case of nonuniformly mixed pollutants. Certainly, this result is surprising given that the latter approach does not consider control cost information for all sources when allocating control responsibility. Further, this result suggests that control strategies which rely on market incentives, such as the emission permit system, are not necessarily more cost effective than strategies which rely on the arbitrary assignment of control. The implications of studies which provide this surprising result are of great interest in light of the fact that emission permit programs for sulfur dioxide, a nonuniformly mixed pollutant, are being proposed by the Bush administration in 1990 in order to alleviate the problem of acid deposition.

The study by Krupnick (1986) noted earlier, for example, establishes that control costs required to meet ambient standards under an emission permit system may substantially exceed costs under a command and control approach in meeting those same standards. The command and control approach which required that a reasonably available control technology (RACT) be imposed upon all sources, achieved the required ambient standard at a cost of \$9.911 million. Although this amount deviated substantially from the \$1.663 million in control costs for the least cost ambient system, it was exceeded by the \$14.423 million in control costs incurred under the emission permit system. Clearly, these results suggest not only that an emissions permit system may be an undesirable alternative to the ambient permit system, but also that it may be one of the least desirable alternatives.

Russell (1986) provides a formal analysis of the cost minimization problem with respect to a uniform emission charge approach (which is comparable to the emission permit system where marginal costs of control are equated across all sources) and a command and control approach which requires a uniform percentage reduction of emissions across all sources. His analysis serves to show that under certain conditions a regulatory command and control approach may incur lower total control costs than a uniform emission charge system.

The model considers the case where only two sources of pollution exist and only one monitoring point exists for which ambient standards are defined and monitored. The notation used is defined as follows:

$X_i$ = original generation of the pollutant at source i

$R_i$ = the reduction in pollutant loading obtained by treatment at i

$X_i$-$R_i$ = discharge of the pollutant from i

$a_iR_i$ = the marginal cost of discharge reduction at source i when reduction level being achieved is $R_i$. Where "a" is assumed to be positive, marginal costs increase at a constant rate.

$\Omega_i$ = the dispersion co-efficient which translates discharge from source i into ambient concentration at the receptor point.

S = the standard to be attained at the monitoring point.

When an equal percentage emission reduction is required under a command and control approach, the condition will hold that $R_1/X_1 = R_2/X_2$. The cost minimization problem will in this case be defined as follows:

(3.31) $$\text{Min } L = [(a_1/2)R_1^2 + (a_2/2)R_2^2] - \mu_1[\Omega_1(X_1 - R_1) + \Omega_2(X_2 - R_2) - S] - \mu_2[R_1/X_1 - R_2/X_2]$$

In other words, total costs of control represented by the first term of equation (3.31), are minimized subject to the condition that air quality standards are met and subject to the condition that equal percentage emission reduction is attained. Accordingly, the Kuhn Tucker conditions will be:

(3.31a) $a_1R_1 + \mu_1\Omega_1 - \mu_2/X_1 \geq 0$ $\qquad R_1[a_1R_1 + \mu_1\Omega_1 - \mu_2/X_1] = 0$

(3.31b) $a_2R_2 + \mu_1\Omega_2 + \mu_2/X_2 \geq 0$ $\qquad R_2[a_2R_2 + \mu_1\Omega_2 + \mu_2/X_2] = 0$

(3.31c) $\Omega_1(X_1\text{-}R_1)+\Omega_2(X_2\text{-}R_2)\text{-}S \leq 0$ $\qquad \mu_1[\Omega_1(X_1\text{-}R_1) + \Omega_2(X_2\text{-}R_2)\text{-}S]=0$

(3.31d) $R_1/X_1 - R_2/X_2 = 0$

In the case where uniform emission charges are implemented, the marginal costs of control across all sources will be equated such that $a_1R_1 = a_2R_2$, assuming optimal response by emission sources. Accordingly, the cost minimizing problem will be defined as follows:

(3.32) $\text{Min } L = [(a_1/2)R_1^2 + (a_2/2)R_2^2] - \mu_1[\Omega_1(X_1 - R_1) + \Omega_2(X_2 - R_2) - S] - \mu_3[a_1R_1\text{-}a_2R_2]$

The cost minimizing solution for this problem will require that the following first order conditions be satisfied:

(3.32a) $a_1R_1 + \mu_1\Omega_1 - \mu_3a_1 \geq 0$ $\qquad R_1[a_1R_1 + \mu_1\Omega_1 - \mu_3a_1]=0$

(3.32b) $a_2R_2 + \mu_1\Omega_2 + \mu_3a_2 \geq 0$ $\qquad R_2[a_2R_2 + \mu_1\Omega_2 + \mu_3a_2] = 0$

(3.32c) $\Omega_1(X_1\text{-}R_1) + \Omega_2(X_2\text{-}R_2) - S \leq 0$ $\qquad \mu_1[\Omega_1(X_1\text{-}R_1) + \Omega_2(X_2\text{-}R_2) - S] = 0$

(3.32d) $a_1R_1 - a_2R_2 = 0$

Russell then proceeds to solve for the optimal values of $R_1$ and $R_2$ for each control strategy in terms of the problem parameters $a_i$, $X_i$, $\Omega_i$, and S. These values are then used to define total control costs for each strategy by substituting values of $R_1$ and $R_2$ into the first term of equations (3.31) and (3.32). In order to determine how total costs for each strategy will rank, the difference between total costs of control under the command and control strategy (C & C) and those costs under the emission charge system (ECS) is examined. In order to determine the sign of this difference, the following relationships are defined:

$X_1 = kX_2 \qquad a_1 = na_2 \qquad \Omega_1 = m\Omega_2$

It was found that the sign of the difference will depend on the relative characteristics of the sources represented by n and m. In the case where $n > 1$, $m > 1$ and where $m > \sqrt{n}$, total control costs under the emission charge system will exceed those under the command and control strategy. In other words, when marginal costs for source 1 are greater than those for source 2 (i.e. $n > 1$) and where emissions from source 1 have a greater effect on the monitoring site (i.e. $m > 1$), then the emission charge system will be more expensive than the uniform percentage reduction unless the difference in effects on environmental quality is sufficiently small to overbalance the difference in marginal costs (i.e. $m < \sqrt{n}$).

Intuitively, the reason for this is clear. Under the uniform emission charge system, each source will control emissions to the point where marginal cost of control is equal to the emission charge or price of emission permit. Given this condition for cost minimization, it is clear that sources with high marginal costs of control will control less than those sources with relatively low marginal control costs. If these high cost of control sources are located closer to receptor sites than the low cost of control sources, there is greater risk that violations in air quality standards will occur. Consequently, a large safety net in terms of required emission reductions must be established and the associated cost penalties imposed on the system may be significant. The conclusion of this analysis is that the uniform emission charge approach or emission permit system, even though it relies on market incentives, will not necessarily be a desirable alternative to any approach which entirely disregards the variances in costs of control between sources.

In addition to the cost disadvantage of using the emission permit system as an alternative to the ambient permit system, the emission permit system may experience difficulties over time in maintaining desirable levels of concentration. For example, given that the authority is able to maintain ambient standards in the current period, future reallocation of emission permits may result in an increase in emissions from sources located close to the receptors. This situation may subsequently lead to a violation of the ambient standards. Clearly, the design of the emission permit system does not incorporate any mechanism to prevent such violations through time since only total emissions are restricted and there exists no correlation between total level of emissions and air quality at a specific receptor.

Furthermore, the emission permit system possesses yet another drawback in that it sends incorrect signals to firms hoping to locate in a particular airshed. Because the price of emission permits will not vary with location of the source, potential polluters are not discouraged from locating their operations close to receptor sites, and therefore, again it is clear that an inadequate protection of ambient standards is given by this permit system.

<u>The Zonal Permit System</u>

In order to alleviate the concerns in using an emission permit system in maintaining ambient standards, a zonal approach to control has been suggested. Under this approach, a control region may be divided into a number of zones each of which is assigned a baseline control responsibility. Emission permits may be traded within each zone; however, trading between zones is prohibited. Such a system, by taking source location into consideration, restricts trading to sources which are located in the same proximate area and which are assumed to have similar transfer co-efficients (under the strong assumptions that sources are clustered together and stack heights are similar). Accordingly, any emission trades should not produce large alterations in concentrations at the receptor sites. Essentially, by prohibiting trade between nonproximate sources, the zonal permit system serves to alleviate the need for overcontrol of distant sources as experienced under the emission permit system. Furthermore, in theory it would appear that the zonal system would reduce the vulnerability of the system to hot spots (areas where concentration levels are above the ambient standard) since nonproximate sources do not engage in trade.

An inherent problem with the zonal approach lies in the conflict between optimum zone size for cost savings and optimum zone size for maximum protection against hot spots. The smaller the zonal boundaries, the greater are the restrictions in trading and, therefore, the smaller the potential for cost savings. On the other hand, the smaller the size of the zones, the greater is the protection afforded against hot spot areas. Given this inherent conflict, it is not surprising that the task of the control authority to decide upon zonal boundaries is a difficult one.

Similarly, the task of allotting total emission reductions among zones is a difficult one. Theoretically, there exists an allocation which minimizes control costs across all zones; however the control authority would require cost information from every source in order to establish such an allocation. If such information were not available, cost penalties would inevitably be associated with the establishment of an inappropriate standard for total emission reduction and with the misallocation of control responsibility between zones. Furthermore, even if the authority were able to establish the cost minimizing solution, the dynamics of the economy would require that changes in the zonal assignments be implemented over time to accommodate changing circumstances.

Such concerns regarding the administrative allocation of control responsibility to zones addresses one source of cost penalty imposed by the zonal approach. The other source involves the costs imposed by utilizing emission reduction trades within zones as opposed to concentration reductions. Tietenberg (1985) reports several unpublished studies in which the full information zonal solutions are evaluated . In other words, assuming full information on the part of the authority, the cost effectiveness of solutions as the number of zones is increased within an airshed is examined. As expected, when the number of zones is increased within a region, state or within an airshed, the cost penalty of the system is reduced significantly. For example the Roach et al (1981) study sited by Tietenberg (1985) reveals that the control costs for the entire Four Corners region is 3 to 4 times higher than when separate zones are established for each airshed of the region. As the number of zones increases the solution moves toward the cost effective ambient permit system solution in which the reductions are targeted on those sources which most significantly affect receptor sites.

However, as the number of zones is increased and the size of the zones decreases, the greater are the trading restrictions, and given the limited information of authorities in the real world to evaluate allocation of responsibility between zones, this can be an important consequence. Indeed, studies simulating limited information zonal systems in which rules of thumb are used to determine allocation of emission control across zones (Tietenberg, 1985, p.76), suggest that zonal solutions do impose high cost penalties due to trade restrictions. Further these cost penalties can be reduced only by increasing trade opportunities. However, such trade opportunities decrease as the number of zones is increased.

Montgomery (1972) suggests that ambient air quality standards may be achieved under an emissions licence system which allows for trading of all licences subject to the rule that resulting pollution is equal to or below that amount of pollution which would have occurred if those sources from which the licences were purchased had emitted to the maximum amount allocated by the permits. He distinguishes emission rights by location such that $l_k$ represents the quantity of licences to emit at location k and where $l_{ik}$ is the quantity of licences held by source i, which allow emissions at location k. If we define each location k=1...r as a zone, this type of analysis may be interpreted as a type of zonal system. Accordingly, all sources within each zone, k, would be designated identical transfer co-efficients, $d_{kj}$, for every receptor site, j=1...m. Transfer co-efficients would differ only between sources associated with different emission zones. Within each zone, k, trading of emissions would be allowed between sources on a one to one basis, and trading of emission licences between zones would be allowed, but only to the point where the resulting pollution was equal to or less than that amount of pollution which would have occurred if those sources from which the rights were purchased had emitted to the maximum amount allocated by the licences. Therefore, trading would be allowed between any two sources of emissions subject to this rule, and cost penalties normally associated with trade restrictions of the zonal system might be avoided.

Market equilibrium under this type of system would be established where $Li^* \geq 0$, $E^* \geq 0$ and $P^* \geq 0$ exist such that the following expression is minimized for each source:

(3.33) $\text{Min} \quad F_i(e_i) + \Sigma k \, P_k \, (l_{ik} - l_{ik}{}^0)$ subject to the constraints:

(3.34) $\Sigma k \, d_{kj} l_{ik} - d_{ij} e_i \geq 0$ for $j=1....m$

(3.35) $e \geq 0$ and $l_{ik} \geq 0$

(3.36) $\Sigma i \, (l_{ik}{}^* - l_{ik}{}^0) \leq 0$ $\qquad P_k{}^* \, [\, \Sigma i \, (l_{ik}{}^* - l_{ik}{}^0) \,] = 0$ $\quad$ for all k

In other words, each source will seek to minimize the costs of control and licence acquisition subject to the constraint that emissions discharged by each source will be allowed only to the point where the resulting pollution is less than or equal to the level of pollution which would have occurred had each emission allowed by licence $l_{ik}$ been discharged by a source associated with zone k. The solution for market equilibrium will require that the following conditions be met:

(3.33a) $(\beta_{i1}{}^* .... \beta_{im}{}^*) \geq 0$ $\qquad (p_1{}^* .... P_n{}^*) \geq 0$

(3.33b) $F_i'(e_i{}^*) + \Sigma j \, \beta_{ij}{}^* d_{ij} \geq 0$ $\qquad e_i{}^* \, [F_i'(e_i{}^*) + \Sigma j \, \beta_{ij}{}^* d_{ij}] = 0$ $\qquad$ for all i

(3.33c) $P_k{}^* - \Sigma j \, \beta_{ij}{}^* d_{kj} \geq 0$ $\qquad l_{ik}{}^* \, [P_k{}^* - \Sigma j \, \beta_{ij}{}^* d_{kj}] = 0$ $\qquad$ for all k

(3.33d) $\Sigma k\ d_{kj}l_{ik}^* - d_{ij}e_i^* \geq 0$ $\quad$ $\beta_{ij}^* [\Sigma k\ d_{kj}l_{ik}^* - d_{ij}e_i^*] = 0$ $\quad$ for all j

(3.33e) $\Sigma i\ (l_{ik}^* - l_{ik}^0) \leq 0$ $\quad$ $P_k\ [\Sigma i\ (l_{ik}^* - l_{ik}^0)] = 0$ $\quad$ for all k

According to Condition (3.33b), emissions will be controlled by each source only to the point where the marginal benefit of an additional emission in terms of reductions in $F_i(e_i)$ is equal to the cost of licence acquisition required to justify an additional unit of emissions, $\Sigma j\ \beta_{ij}^* d_{ij}$. Furthermore, according to condition (3.33c), sources will purchase emission licences, $l_{ik}$, for k = 1....r, to the point where marginal costs of licence acquisition, $P_k$, are equal to marginal benefits of licence acquisition in terms of costs saved by not controlling pollution (which would have resulted had licence not been purchased) at the equilibrium as represented by the value $\Sigma j\ \beta_{ij}^* d_{kj}$.

The value of such an approach lies in its ability to reduce cost penalties normally associated with zonal systems which restrict trade of emissions between zones. Indeed, in the case where source location is an important influence on air quality, such a system may serve as an ideal compromise between the complex ambient permit system and the oversimplified emission permit system. However, it should be noted that the cost penalites associated with trades within each zone remain a cause of concern, given the assumption that every source within a zone will have an identical transfer co-efficient.

## SUMMARY OF THEORETICAL REVIEW

In summary, a system in emission rights is an effective control approach for achieving aggregate emission targets. As shown previously, the market incentives provided by this system will lead the economy to a least cost control solution. However, for the case of nonuniformly mixed pollutants, where a direct relationship does not exist between the level of aggregate emissions and air quality, the achievement of ambient air quality standards is a more appropriate control objective. Furthermore, it is only through an ambient permit system in pollution rights that such an objective can be achieved at least cost. Realistically, the implementation of a system in pollution rights may be so complex, however, as to offset the control cost reduction benefits and for this reason alternative systems in control should be considered in meeting air quality goals.

The cost penalties associated with using the emission permit system as an alternative approach appear to be substantial for the cases examined in this review. Indeed, the failure of the emission permit system to recognize the spatial dynamics of the control problem for nonuniformly mixed pollutants, requires that quantity of controlled emissions be increased significantly in order to ensure the adherence of imposed standards. Although this result is not entirely unexpected, it is surprising to find that cases may exist where the regulatory approach to control is more cost efficient than the emission permit system in achieving ambient standards. Clearly, the notion that any system which relies on market incentives is more likely to yield a desirable allocation of resources in the economy cannot be accepted without question. Given the recent proposals by the Bush administration to implement a system in sulfur dioxide emission rights, these theoretical results are particularly interesting and certainly would suggest that careful consideration of the spatial complexities of the control problem be examined. Although little research has been done in this area, the zonal approach to emission control may prove most useful in the future in that this type of system recognizes the importance of emitting source location, yet is significantly less complex than the full ambient system in terms of the tasks required of both the control authority and of the market participants.

# CHAPTER 4

# A DEFINITION OF THE SULFUR DIOXIDE CONTROL PROBLEM

## THE REFORM OF U.S. CONTROL POLICY

Recent legislation proposed by the Bush administration provides for a 10 million ton reduction in sulfur dioxide emissions from 1980 levels by the year 2000 in order to alleviate the acid precipitation problem. It is estimated that nine million tons of this reduction would be associated with the reduction in emission rates for electric utilities while a reduction of only one million tons would come from nonutility sources.

In the first phase of the program, all fossil fuel electric utility plants with capacity of 100 megawatts and over will be issued emission permits which will allow them to emit at a rate of 2.5 lbs. per million BTU output. By the year 1995, these utility plants will be required to reduce their emission rates to this required level or alternatively purchase permits from sources within the state in order to legitimize emission levels which exceed this standard. All permits will be fully transferable only between sources within the state in this phase of the program.

In the second phase of the program, all utility plants with capacity of 75 megawatts and over will be issued permits which allow for emission rates of only 1.2 lbs. per million BTU; these plants will be required to comply with this emission standard by the year 2000, or alternatively purchase emission permits for all emissions which exceed this standard. In this phase of the program, emission allowances will be fully transferable across state lines. Therefore, opportuntities for plants to engage in trade will be much greater and it is expected that greater control cost savings will be realized. Furthermore, new plants may be established by acquiring offsetting emission allowances from utility plants located in any state, which have either been shut down or which are earning excess emission credits.

The following analysis addresses two issues which arise in regards to the proposed legislation. The first issue addresses the concern that the full transferability of the emission allowances between states may prevent the anticipated improvement in air quality from being realized. Specifically, if under an emission permit system, the emitting sources which purchase the greatest number of emission allowances are located very close to sensitive receptor areas, the benefits of the program may be less than hoped if air quality levels do not improve significantly in these areas. For example, if the economic incentives provided under the emission trading program are such that the coal burning midwest utilities purchase emission allowances from utilities located in the southern United States, they will continue to bombard the northeastern area of the United States and the southeastern area of Canada with acid bearing rains. In response to this criticism, advocates of the program maintain that the absolute size of the required reductions will ensure that air quality levels improve at every receptor to some extent. In order to determine whether this is, indeed, the case an analysis of the distribution of emission permits across all states in a market equilibrium must be conducted, and the impacts of this distribution on sensitive receptor areas determined.

A second issue addresses the question of cost effectiveness. Specifically, are the cost savings realized under an emission permit system which allows for the trading of emission rights across all states substantial enough to justify the costs of implementing the system? And, furthermore, can air quality levels which are achieved under the proposed system be achieved by alternative control systems at lower cost? Certainly, it is in the interests of the public and of the government to implement a control program which will provide the greatest benefits for the least cost since any increases in emission control costs incurred by utility companies will inevitably involve future rate increases to the public.

In response to these concerns the following economic analysis examines the cost effectiveness of alternative market systems for controlling sulfur dioxide, as well as the influence of each system on pollution levels at specific receptor sites which are known for their sensitivity to the effects of acid deposition. A market system in emission rights which allows for the trading of emission rights only between sources within a state, is first examined. This system, which is analogous to the approach recommended in the first phase of the proposed legislation, is essentially a simple zonal system in which emission trading is allowed within each zone (state) but prohibited between zones. It requires that a market in emission rights be established for each state so as to allow utility plants to engage in the trading of emission permits in order to minimize costs of achieving aggregate state emission control targets. However, in terms of achieving one aggregate emission control target for all states together, this approach is not likely to provide a least cost allocation of control due to the restrictions on transferability of rights across state lines. Therefore, a system which allows for the unrestricted transfer of rights between all sources in all states is also examined. This approach is analogous to the emissions market system proposed in the second phase of the legislation. It is anticipated that sources will enjoy greater flexibility in their control options under this approach and, therefore, a more cost efficient allocation of control will be achieved. The following analysis provides a comparison of these two systems based on total cost of achieving aggregate emission control levels across all states as well as the impact of each on receptor sites in terms of sulfur dioxide reduction levels.

Furthermore, a comparison of the costs of achieving target levels of sulfur dioxide at specific receptor sites using an emission permit system versus a more complex and efficient system of control which recognizes the important relationship between source location and air quality levels is made. Hence, the following analysis also examines the cost effectiveness of using an emission right system to control air quality levels at specific receptor sites, and investigates whether an ambient market system of pollution rights could be more effective in achieving those same target levels.

Ideally, data on control costs at the plant level should be used in the analyses. However, since data is not available at this level, the analyses are conducted using state level data. Specifically, the analyses will require information on control costs and emission levels for each state in the eastern United States as well as estimates for the transfer co-efficients which translate emissions from each state into sulfur dioxide concentration levels at sensitive receptor sites.

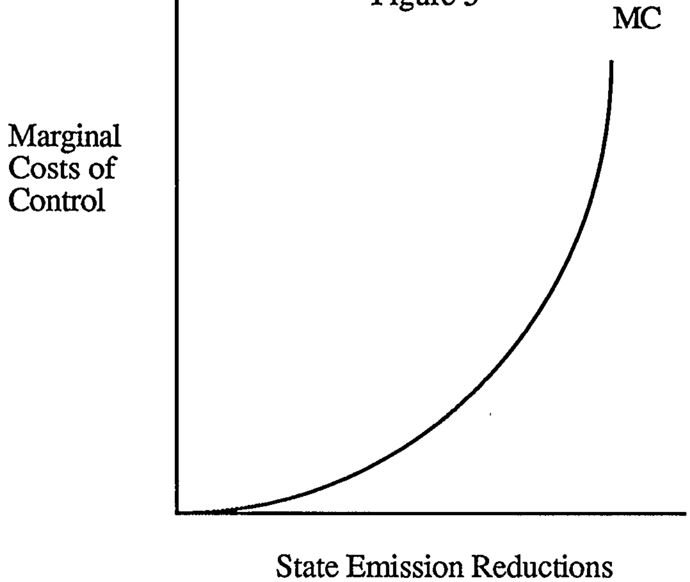
## COSTS OF CONTROL

### Methodology

Using a simplified version of the Utility Control Strategy Model (UCS) developed at Carnegie Melon University, Cushey (1986) has developed algorithms which represent the cost of reducing sulfur dioxide ($S0_2$) emissions at the state level. The model estimations were based on a compliance date of 1995 and, accordingly, all control strategy decisions were assumed to be made in 1992 in order to allow for a three year planning period for installing new control devices.

Given the assumption that those plants which utilize sulfur dioxide control devices cannot significantly reduce their emission rate further, the model simulated only those coal fired power plants existing in 1986 which had no devices for controlling sulfur dioxide emissions. By analyzing site specific data for each utility plant including such characteristics as quantity of coal burned, furnace design, emission standards, and scheduled retirement date etc., the available control strategies for each plant were compared for their cost effectiveness. Specifically, strategies involving coal switching, installation of control devices, a combination of switching and control devices, and no action were evaluated. Alternative control strategies for all plants within each state were then ranked according to their cost effectiveness measured in dollars per ton of sulfur dioxide removed. From such a ranking the marginal cost of control curve for the entire set of plants in a state could be constructed. For example all points on the marginal cost curve of Figure 5 will represent the set of plant specific abatement strategies which minimize total overall cost for the associated level of emission reduction. Therefore, for each level of reduction, the plants with the lowest costs of control assume responsibility for reducing emissions. The lower portions of the curve represent least cost strategies involving only coal switching and cleaning while the higher portions of the curve represent control strategies involving increasing amounts of scrubber equipment.

Figure 5




Cost of sulfur dioxide control was defined as the annual additional cost for a plant to meet an imposed reduction requirement in 1985 dollars. Such costs included the capital costs for new pollution control equipment or modifications to existing equipment amortized over the remaining life of the plant as well as operational costs for adjustments in the cost of fuel when alternative coal supplies were used.

<u>Assumptions Underlying Costs of Control</u>

Assumptions regarding technological advancements, economic forecasting and regulatory constraints which underly the UCS model will be examined individually:

a) <u>Technological Advancements</u>

The model used by Cushey (1986) examined two alternative scenarios regarding level of technology for pollution control. The first scenario reflected the assumption that the existing level of pollution control equipment was available throughout the entire time frame of the analysis. The advanced technology scenario assumed that an optimistic yet feasible forecast of pollution control technology would be made commercially available for retrofit applications by the year 1992. For the purposes of the present analysis, the latter scenario will be used. Accordingly, the control options available to utility plants by 1992, will consist of the following:

Coal Switching - Under the UCS model, coal is classified into 11 categories according to content of sulfur. These coals are assumed to be produced in 35 supply regions throughout the United States as defined by the model. Each utility plant is assigned to one of 66 demand nodules, each of which selects a least cost coal for all 11 sulfur content categories. A further complication is introduced by allowing available supplies to consist of both washed and unwashed coals so that washed coals compete directly with unwashed coals. Physical coal cleaning removes sulfur from the coal before combustion, typically by 10% - 30% for medium and high sulfur coals. Costs incurred by utility plants for coal input will therefore include those costs associated with mining, transportation, as well as physical coal cleaning if applicable.

Suspended Particulate Control - When the option of switching to a low sulfur coal is exercised, additional modifications for particulate control will be required since the resistivity of the particulates decreases as the sulfur content in the coal decreases and the efficiency of TSP (Total Suspended Particulates) control to remove particles decreases. For approximately 75% of uncontrolled coal fired utility plants, cold side electrostatic precipitators (ESP) are used for particulate control. Use of lower sulfur content coal may require that the collector area size of these devices be increased in order to provide adequate control of particulates. However, a less expensive alternative is to upgrade the existing ESP by injecting additives into the flue gas. These additives decrease the resistivity of particulates so that increases in the collector area size are unnecessary. For the purposes of this analysis, marginal costs for control of sulfur dioxide include capital costs in the order of $6.25 /KW for ESP upgrade options for switching to a lower sulfur coal.

FGD Devices - The highest levels of sulfur dioxide reduction are presently achieved by flue gas desulfurization processes (FGD). The wet FGD systems which use lime or limestone as a reagent are the most prevalent accounting for more than 80% of the control systems in use in 1985. A typical system of this sort will achieve 90% sulfur removal. Cost and performance of the wet FGD retrofit is determined on an individual basis for each plant.

Lime Spray Dryers - Although the use of lime spray dryers as an alternative to the wet FGD systems has not occurred to a great extent for retrofit applications, the technology remains a promising one. The process which employs lime spray dryers is similar to that for the wet FGD except that a dry reagent is used in order to reduce waste handling requirements and to minimize problems of plugging and scaling. Although the cost of this new technology is approximately two thirds the cost of a wet FGD device, the potential cost savings may be offset by increased TSP costs. Because lime spray dryers are placed upstream of particulate control devices, the sulfur content of the flue gas is reduced and subsequently the resistivity of the particulates increases before the flue gas reaches the TSP control device. The cost advantage is further offset by the reduction in the capacity of the technology to remove sulfur dioxide from the flue gas. For the purposes of this analysis, it is estimated that 70% reduction in sulfur dioxide will be achieved by the lime spray dryer.

Limestone Injection Multistage Burners (LIMB) - Limestone injection multistage is a relatively new technology which can be implemented at a cost of approximately one third of that for wet FGD devices. However, because LIMB removes sulfur dioxide during combustion, the sulfur content of the flue gas is reduced before it reaches TSP control devices and consequently the problem of increasing particulate control must again be addressed. Furthermore, only 50% of sulfur dioxide is removed form the flue gas.

TSP control for Lime Spray Dryers & LIMB - Clearly, the disadvantage of using either lime spray dryers or LIMB is the increased level of particulates released into the atmosphere. It is most efficent for utility plants to upgrade their cold side ESP to increase particulate control, rather than introduce relatively expensive baghouse collectors. Upgrading would involve the use of additives, prechargers and gas conditioners. It may also require that the size of the collector areas be increased in some cases. Estimated cost for upgrading cold side ESP devices is assumed to be $18/KW.

b. Economic Conditions

Interest Rate - The total cost of controlling increased levels of emissions will undoubtedly be influenced by the real interest rate levels which are assumed to exist over the life of each plant. For example, low interest rate levels will provide the incentive for plants to outlay large capital investments to acquire scrubber technologies while high interest rates will encourage coal switching as a means of controlling emissions. Indeed, studies conducted with the UCS model have shown that the proportion of coal switching to scrubber technology optimally selected as a means of controlling sulfur dioxide can be significantly altered by changes in the assumed real rate of interest.

The reason for the decreased reliance of plants on scrubber technology under a high interest rate scenario, is that the scrubber capital costs are amortized over a long period of time and, therefore, a greater proportion of total control costs will be attributed to interest payments under a high interest rate scenario, particularly in the case where amortization periods and plant life are long.

For the purposes of the following economic analysis, it is assumed that real interest rates remain at 3.7% since this assumption underlies the total control cost estimations for each state calculated by the UCS model.

Coal Prices - The real escalation rate of coal prices will also affect each plant's optimal control strategy if coal switching is assumed to be an available alternative for emissions control. The state control cost estimations provided by the UCS model were based on the assumption that real coal prices do not increase through time. In other words a 0% real escalation rate was assumed in order to reflect stability in the coal market. Therefore, real prices for coals with high sulfur content would not escalate at a different rate than real prices for coal with low sulfur content.

Government Regulation - The assumption was made in estimating control costs under the UCS model that state governments would not act to limit the control options of utility plants to retrofit scrubbers only. In other words, states would allow utilities to switch to out-of-state sources of coal supply, even though domestic coal industries which provided employment and income to the region could be threatened. On the basis of this assumption, utility plants were allowed to acquire the sources of coal which minimized costs of production and control of emissions for each given level of reduction. This clearly had an influence on calculations of total cost for controlling sulfur dioxide emissions. Generally speaking, as the number of control strategies available to utility plants increased, the total cost of controlling emissions decreased. Indeed, Cushey (1986) found that restrictions on the availability of alternative coal sources did impose substantial increases in sulfur dioxide control costs.

Given that pollution control programs are bound to become more constraining to a growing industrial sector in the United States in the future, and given the importance which the public now places upon environmental protection, the assumption underlying the model is perhaps not an unreasonable one.

## The Cost Algorithm

Based on the above assumptions, the UCS model was used to estimate total costs for controlling alternative levels of sulfur dioxide emissions for each state. In order to describe the relationship between sulfur dioxide reduction and total control costs which resulted, a nonlinear polynomial of the following form was estimated for all states:

$$Y = a_0 + a_1X + a_2X^b$$

where Y represented the costs for control in millions of \$1985; X represented millions of tons of sulfur dioxide reduced; $a_0$, $a_1$ and $a_2$ represented estimated co-efficients for each state; and b represented a parameter which varied across all states.

This particular form of algorithm was chosen so as to introduce only those elements which represent the relationship between costs and reductions when coal switching dominates as a control method and when scrubber technology dominates as the control method. At lower levels of reduction when coal switching remains the dominant control option, the relationship between total costs and level of reduction can be approximated by a linear relationship which is represented in the algorithm by the term, $a_1X$. Similarily, the term $a_2X^b$ was introduced into the algorithm to reflect the changing relationship between costs and reduction levels as the transformation was made from coal switching as the primary means of control to scrubber technology as the dominating control method.

The co-efficients $a_0$, $a_1$ and $a_2$ for each state were estimated by Cushey using multiple regression analysis while b was estimated through a process of trial and error (i.e. b = 0,1,2...). A value of b was accepted when resulting standard residuals were between -2 and +2. This value was found to vary from state to state. This may be explained by the fact that the rate of transformation between control methods is determined by specific state characteristics for coal supply as well as plant characteristics such as age and size. For example, one important characteristic which significantly influenced the value of b was the conformity of coal choice among all noncontrolled coal fired power plants for a given state. Specifically, if the estimated value of b was low, then generally it was found that most plants within the state used coal of a similar sulfur content as well as similar control strategies. As the level of required emissions increased, plants would switch gradually from coal switching to scrubber technology and, accordingly, the transformation rate was found to be low. A relatively high estimate of b suggested that little conformity in the use of coal existed. Small increases in the level of control required radical changes in control strategies, and accordingly the increase in costs of control occurred rapidly to reflect a quick transformation of the dominant control strategy. For example, the relatively low b value (b=2) for Missouri reflected a situation where the majority of plants burned high sulfur coals and all low reduction requirements were achieved by coal switching. On the other hand, because Illinois's coal usage was bimodal with a large percentage of plants utilizing coal low in sulfur content and an equally large percentage of plants utilizing coal high in sulfur content, a relatively high value of 14 was assigned to b.

### Regions of Consideration

Only those 25 eastern states listed in Appendix II were examined for effects of sulfur dioxide control. Of the 31 eastern states, Connecticut, Maine, Rhode Island and Vermont were excluded from the following analysis since these states would have no uncontrolled coal fired utility plants in the year 1995 according to the UCS model assumptions for plant expectancy. Furthermore, Louisiana and Massachusetts were excluded since each of these states would produce only negligible amounts of sulfur dioxide emissions (i.e. less than 20 Ktons in 1995).

## STATE EMISSION LEVELS FOR SULFUR DIOXIDE

For the purpose of the following analyses on alternative market systems for controlling sulfur dioxide, the level of state emissions assumed to exist in the year 1995 from all uncontrolled coal fired utility plants will be those levels provided by Cushey (1986) using a simplified version of the UCS Model. These values are listed in Appendix II. The sulfur dioxide emission levels calculated by the UCS model were determined according to individual plant emission rates and assumed capacity factors of 65% for each plant. Such an approach was used by Cushey in order to avoid making broad assumptions regarding the nature of future demand for energy output of each plant - a task which would require the introduction of highly uncertain parameters.

However, in order to determine state emission control targets under the intrastate trading model in Chapter 5, a knowledge of state emission levels before and after a standard of 1.20 lbs. sulfur dioxide per million BTU's is assigned to individual plants will be required. This will further require a knowledge of emission rates and capacity levels on an individual plant basis. Because this information is not provided by Cushey's model, the 1985 NAPAP Annual Emissions Inventory Version 2 will be used as an alternative data source to calculate state emission levels before and after control is imposed, as well as state reduction targets which are represented by the difference of these values.[2] The state reduction targets provided by the NAPAP data will be used as approximations of those state emission control targets which would be calculated under the Cushey model.

## TRANSFER CO-EFFICIENTS

The transfer co-efficients used in the following analysis will be those provided by Argonne National Laboratories.[3] Calculations for the source receptor matrices were made by the Advanced Statistical Trajectory Regional Air Pollution Model (ASTRAP), whereby transfer co-efficients were estimated according to meteorological data on wind direction and velocity as well as on precipitation fields. For detailed information on the matrices used to translate emissions from each state into air quality levels at sensitive receptor sites and on the location of the receptor sites, please refer to Appendix III and IV respectively. Also, Shannon (1981) provides a detailed explanation of the workings of the ASTRAP model.

---

2 NAPAP sulfur dioxide emission levels are based on actual fuel usage of utility plants in 1985.

3 Transfer co-efficients reflect the average change in sulfur dioxide levels at each receptor site in Kgrams per hectare for each million tons of SO2 emissions from each state.

# CHAPTER 5

# EMPIRICAL ANALYSIS

## INTRODUCTION

The following analysis examines three different market approaches for controlling sulfur dioxide emissions in the coal fired utility sector in the eastern United States. Ideally, it would be desirable to compare the costs of control imposed under these market approaches to pollution control with the costs imposed by a regulatory command and control approach. However, the lack of control cost information on an individual plant basis precludes a study of this kind. Therefore, a comparative analysis is conducted for the three market approaches only, based on their ability to minimize control costs across all sources in the 25 eastern states as well as their ability to improve air quality at 25 sensitive receptor areas located in both Canada and the United States.

## INTRASTATE EMISSIONS TRADING MARKET

### Background

The first control policy examined will be one which implements a market in emission rights within each of the 25 eastern states listed in Appendix II. This approach is comparable to that of the first phase of the proposed U.S. emissions trading program in which trading of emission rights is allowed within states but prohibited between states. The implementation of the system will require that state control authorities issue emission permits to each of the major sources of sulfur dioxide emissions such that compliance with a state emission target can be achieved. Upon receipt of an initial allocation of permits, these sources can then engage in the trading of emission rights so as to minimize their costs of control and permit acquisition. Given that the unrestricted transferability of emission rights between sources within each state is allowed, a least cost allocation of control for each state will be achieved.

For the purposes of this analysis, the target of the control policy will be based on the objectives of the proposed legislation which requires that all utility plants with capacities of 75 megawatts and over, recognize a minimum standard of control of 1.20 lbs. $SO_2$ per million BTU. It is expected that full compliance with this standard will result in a reduction of approximately nine million tons of sulfur dioxide in the utility sector. If such a standard were imposed under a purely regulatory approach, all sources with capacities greater than 75 megawatts would be required to meet the 1.20 lb. standard regardless of the cost burden imposed upon them and, therefore, the potential for a cost efficient allocation of control responsibility would be virtually nonexistent under this approach as discussed previously. Alternatively, the implementation of a market in emission rights which allows for full transferability of rights between sources within a state, would require that aggregate state emissions be controlled to the same extent as the regulatory approach; however, sources would be allowed greater flexibility in the control strategies used to meet these emissions targets. For example, sources would be assigned an emissions allowance which recognizes the maximum emission rate of 1.20 lbs. $SO_2$/MBTU for each source. Based on these allowances, sources would then be allowed to engage in the trading of emission rights in order to minimize the costs of the control policy. Under the incentives provided by the market, those sources capable of controlling additional emissions at least cost would be motivated to sell emission rights and assume responsibility for the imposed controls while those sources with high marginal control costs would be motivated to purchase emission rights and continue to pollute. Accordingly, it is anticipated that a more cost efficient distribution of control responsibility would be realized within each state. Given that no barriers to trade exist, trading will continue until the marginal costs of control are equated across all sources within each state as expressed mathmatically by the following condition:

(5.1) $\partial C_i(r_i)/\partial r_i - P \geq 0 \qquad r_i\,[\partial C_i(r_i)/\partial r_i - P] = 0 \quad \text{for all } i$

where $C_i$ represents costs of control[4], $r_i$ represents the quantity of emissions controlled, and P represents equilibrium permit price. At this point no further incentives for trade will exist since a cost efficient allocation of control will have been achieved. Marginal control costs of all sources within the state will be equal to the value of the equilibrium permit price, P, for that state and the value, P, will reflect the degree of difficulty experienced by state sources, in terms of cost of control required to meet the emissions target imposed on the individual state. For example, if the imposed standard (i.e. 1.2 lbs. $SO_2$ per MBTU) required that a state reduce its aggregate emissions by 500 Ktons of sulfur dioxide, the equilibrium permit price, P, would represent the cost of control which could be saved if this target were reduced by one Kton in the case where permits are defined in terms of Ktons.

Of course, the potential for a cost efficient control allocation for all states together would be prohibited by this approach due to the restrictions on transferability of rights across states. Generally, it can be stated that the greater the variance in equilibrium permit prices across states, the greater will be the potential for realizing cost savings through trade across states, and accordingly, the greater will be the costs imposed by any policy which restricts trading in this way.

Intrastate Emissions Trading Model

The control cost algorithms provided by Cushey (1986) are used to estimate the costs of reducing sulfur dioxide emissions for all uncontrolled coal fired utility plants at a state level. For each specified level of emissions control, the cost algorithms provide a

---

4 $C_i$ may represent direct control costs only, costs of producing a fixed output, or costs in terms of lost net revenues when an emissions control program is implemented. Control costs provided by Cushey's model include direct costs of installing scrubber equipment as well as costs incurred from fuel switching when a fixed output is produced. Changes in other input costs are not considered.

value for total control costs which is representative of the set of plant specific abatement strategies that minimizes control costs for the entire state.

However, because the algorithms provided by Cushey are valid only between certain ranges of emission control for each state (approximately 30% to 90% emissions reductions), these equations accurately represent only the middle portion of the true total cost curve. The absence of the latter part of the curve reflects the fact that efficiency reductions of greater than 90% are not feasible given the assumptions of the model regarding available control technologies. In effect, the control curve becomes vertical at the point where the range of validity ends. On the other hand, the domination of coal switching at lower levels of reduction between 0% and 30%, suggests that costs, for the most part, linearly increase with the level of reduction. Therefore, a linear relationship between costs and reductions can be used to describe the initial portion of the curve, which may be represented by a line extending from the origin to the point on the cost curve where the range of validity for the algorithm begins. Given that there are no fixed costs associated with coal switching as a control option, the assumption that the curve passes through the origin appears reasonable. A listing of the cost algorithms for both the lower and middle portions of the total cost curves for each state is provided in Table 1. Emission reductions beyond the upper limit of the middle range are so costly that they are assumed to be infeasible.

These cost algorithms determine the least cost means of achieving aggregate state emission targets. According to theory, this would require that those plants with the lowest marginal control costs assume responsibility for achieving state emission targets. This allocation of control responsibility may be achieved in a competitive setting through a market approach which allows for complete flexibility in the control strategies available to all emitting sources within a state. In short, it is achievable through a marketable emission rights system which allows full transferability of emission rights among sources within each state (but which prohibits trades between sources of different states). Therefore, the

TABLE 1

LINEAR AND NONLINEAR COST ALGORITHMS FOR INTRASTATE MODEL

| STATE | ALGORITHM<br>X = millions of tons $SO_2$<br>Y = Control costs in $ 1985 millions | RANGE*<br>(million tons $SO_2$) |
|---|---|---|
| Alabama | $Y = 150.0069 (X)$ | .000 - .190 |
| | $Y = 175.78 - 1578.30(X) + 4227.10(X^2)$ | .190 - .508 |
| Arkansas | $Y = 9.8333(X)$ | .000 - .012 |
| | $Y = -46.19 + 3859.60(X)$ | .012 - .025 |
| Delaware | $Y = 161.6(X)$ | .000 - .030 |
| | $Y = -59.04 + 2129.60(X)$ | .030 - .067 |
| Florida | $Y = 121.60873(X)$ | .000 - .142 |
| | $Y = 16.78 - 16.40(X) + 6929(X^4)$ | .142 - .423 |
| Georgia | $Y = 227.98901(X)$ | .000 - .243 |
| | $Y = -21.92 + 311.39(X) + 1951.60(X^5)$ | .243 - .698 |
| Illinois | $Y = .5565138(X)$ | .000 - .418 |
| | $Y = -227.82 + 545.58(X) + 28.40(X^{14})$ | .418 -1.191 |
| Indiana | $Y = 109.06603(X)$ | .000 - .546 |
| | $Y = 21.97 + 49.59(X) + 118.19(X^4)$ | .546 - 1.650 |
| Iowa | $Y = 50.531163(X)$ | .000 - .215 |
| | $Y = 1080.20 - 10130(X) + 23983(X^2)$ | .215 - .296 |
| Kentucky | $Y = 56.78998(X)$ | .000 - .358 |
| | $Y = -9.03 + 20.91(X) + 476.76(X^3)$ | .358 - 1.068 |
| Maryland | $Y = 142.73515(X)$ | .000 - .068 |
| | $Y = 38.11 - 1038.07(X) + 9123(X^2)$ | .068 - .195 |

Table 1 Continued

| | | |
|---|---|---|
| Michigan | $Y = 128.972(X)$ | .000 - .195 |
| | $Y = -84.42 + 552.67(X) + 6380.5(X^5)$ | .195 - .582 |
| Minnesota | $Y = 324.330(X)$ | .000 - .062 |
| | $Y = 32.79 - 241.20(X) + 2481009(X^5)$ | .062 - .148 |
| Mississippi | $Y = 91.6997(X)$ | .000 - .038 |
| | $Y = 5.57 - 62.76(X) + 3779615(X^5)$ | .038 - .108 |
| Missouri | $Y = 42.287648(X)$ | .000 - .591 |
| | $Y = 172.55 - 642.30(X) + 664.34(X^2)$ | .591 - 1.323 |
| N. Hampshire | $Y = 516.08(X)$ | .000 - .034 |
| | $Y = -35.50 + 1560.20(X)$ | .034 - .045 |
| N. Jersey | $Y = 31.308(X)$ | .000 - .048 |
| | $Y = -80.51 + 1708.60(X)$ | .048 - .106 |
| New York | $Y = 161.247(X)$ | .000 - .070 |
| | $Y = 98.83 - 2578.30(X) + 18967(X^2)$ | .070 - .186 |
| N. Carolina | $Y = 700.1446(X)$ | .000 - .145 |
| | $Y = 22.99 + 368.20(X) + 8247(X^3)$ | .145 - .403 |
| Ohio | $Y = 1.746086(X)$ | .000 - .964 |
| | $Y = -231.93 + 236.41(X) + 7.12(X^6)$ | .964 - 2.155 |
| Pennsylvania | $Y = 223.194(X)$ | .000 - .344 |
| | $Y = 30.53 + 112.60(X) + 536.61(X^4)$ | .344 - 1.022 |
| S. Carolina | $Y = 280.6485(X)$ | .000 - .070 |
| | $Y = 112.38 - 2805(X) + 21146(X9)$ | .070 - .161 |
| Tennessee | $Y = 1.38175(X)$ | .000 - .340 |
| | $Y = -208.45 + 614.38(X) + 503.93(X^9)$ | .340 - .936 |

Table 1 Continued

| | | |
|---|---|---|
| Virginia | $Y = 560.280(X)$ | .000 - .051 |
| | $Y = 93.93 - 2654.20(X) + 26916(X^2)$ | .051 - .150 |
| W. Virginia | $Y = 188.192(X)$ | .000 - .325 |
| | $Y = -81.41 + 432.19(X) + 582.17(X^5)$ | .325 - .911 |
| Wisconsin | $Y = 70.37(X)$ | .000 - .200 |
| | $Y = 110.09 - 980.60(X) + 2502.60(X^2)$ | .200 - .536 |

* For each state the first range represents 0% to 30% emission reduction, and the second range represents 30% to 90% reduction. Reductions greater than 90% are assumed infeasible.

algorithms presented in Table 1 may be used to calculate the control costs for achieving specified targets for each state under the intrastate trading model and, subsequently, the total costs of the program in pollution control for all 25 states together may be calculated by totalling these costs across all states.

However, state control targets must first be established. In order to estimate the emission control target levels for the individual states based on the requirement that all sources with capacity of 75 megawatts and over, meet a minimum standard of 1.20 lbs. $SO_2$ per MBTU, an alternative data source must be used since Cushey's analysis does not provide $SO_2$ emission rates and capacity levels on a plant basis. The NAPAP 1985 Emissions Inventory (Version II), on the other hand, provides information on emission rates and capacity factors for all uncontrolled coal fired utility plants with capacity of 75 megawatts and over. The reduction levels estimated using this data source will be used as rough approximations of those reductions which would be calculated under Cushey's model given his assumptions regarding input prices, availability of input supplies, and plant capacity levels. However, in order to do this, it is necessary to make the assumption that the factors which influenced the actual decisions of utility plants in 1985 with respect to both emission rates and capacity levels are consistent with those affecting the modelled decisions in Cushey's analysis. Specifically, it will be assumed that the values of the economic parameters (i.e. the relative costs of inputs such as coal) assumed in deriving the cost algorithms for each state reflect those actually experienced in 1985 when the emissions inventory was taken by NAPAP, and that plants have correct and complete knowledge of costs and availabilities of production inputs required to make optimal decisions (as is assumed in Cushey's model).

For example, it will be assumed that no discrepancy exists between the level of relative coal prices assumed in Cushey's model (where coal type is specified according to sulfur content) and the actual relative coal prices existing in 1985, since any such discrepancy could result in a plant actually using coal of a different sulfur content than that assumed by Cushey's model. In that case, the rate of emission for the plant could differ from that calculated by the model. However, given Cushey's assumption that real coal prices for all coal types do not escalate through time, the difference between real coal prices experienced in 1985 and the 1995 real coal prices forecast by the model should be limited.

It is also expected that state capacities for the uncontrolled utility sector provided by NAPAP will be comparable to those of Cushey's in 1995 for two reasons. First, Cushey's model reflects the fact that no additions to the inventory of uncontrolled plants will be allowed in any state in the years 1985-1995 due to regulation of the industry. Therefore, it is anticipated that the inventories of uncontrolled utility plants for the two data sources will coincide very closely. Secondly, in compliance with Cushey's assumption that all plants operate at 65% capacity, the plant capacities for the NAPAP inventory will be adjusted accordingly.

To the extent that the factors affecting plant emission rates and state capacity levels are consistent between the two data sources, the estimates of the reduction targets provided by the NAPAP data will approximate those reductions which would have been established under Cusheys' model if the relevant data were available. For the purpose of this analysis, however, state emission reduction targets determined according to the NAPAP data will be viewed as rough approximations only.

The aggregate emission control targets for each state are provided by totalling the level of increased control required of all plants in each state by imposing the standard. Specifically, using the capacity factors and emission rates provided by NAPAP, a comparison is made between plant emissions based on uncontrolled actual rates of discharge and 65% plant capacity and plant emissions based on an imposed rate of discharge of 1.20 lbs. sulfur dioxide per MBTU and plant capacity of 65%. The aggregate difference in these values for each state represents the state target level of control.

Control Allocations for the Intrastate Trading Model

Table 2 lists emission control targets for each state which have been derived in the above manner. As anticipated, Pennsylvania, Tennessee, Illinois, Missouri, Ohio, Indiana, West Virginia and Georgia are among those states which require the greatest level of control. Indeed, these states have the country's highest annual sulfur dioxide emissions and are, therefore, prime targets for any program which implements acid rain control requirements. The high levels of control assigned to these states reflect both the large number of coal fired utility plants per state and the high emission rates associated with these plants. In the case of Missouri and Georgia, high levels of control primarily reflect the relatively high emission rates associated with their utility plants. On the other hand, the high levels of control assigned to Ohio and Illinois reflect the unusually large numbers of utility plants. Those states which have been assigned relatively low levels of control include Delaware, Mississippi, Arkansas, Virginia and Michigan. The low levels of control allocated to Delaware and Mississippi reflect the fact that there are relatively few coal fired utility plants located in these states. Plants in Michigan and Virginia are assigned low levels of control primarily because low emission rates are associated with their plants.

Control Costs for the Intrastate Trading Model

The total costs of control for the specified state targets have been calculated using the cost algorithms of Table 1. These values are listed in Table 2 along with emission control targets for each state. Not surprisingly, substantial control costs are associated with Pennsylvania, Tennessee, Illinois, Indiana, Missouri, Ohio, Georgia and West Virginia. Because Georgia is required to control 76% of its total emissions its marginal costs of control are extremely high. These high marginal costs are responsible for the relatively large total cost commitment for control. High control costs associated with Ohio and Indiana reflect both the high levels of reductions required (71% and 65% respectively) and the relatively high marginal costs associated with these levels of

TABLE 2

CONTROL ALLOCATION UNDER THE INTRASTATE TRADING MODEL

| State | Control (Million Tons) | Percentage Reduction | Total Costs ($Million 1985) | Marginal Costs ($Million 1985) |
|---|---|---|---|---|
| Alabama | 0.227668 | 40% | $35.553 | $346.450 |
| Arkansas | (.066374) | ------ | 0.000 | 9.833 |
| Delaware | 0.010018 | 14% | 1.618 | 161.600 |
| Florida | 0.257638 | 55% | 43.083 | 457.579 |
| Georgia | 0.592886 | 76% | 305.669 | 1,517.108 |
| Illinois | 0.754109 | 56% | 184.153 | 555.721 |
| Indiana | 1.179398 | 65% | 309.132 | 825.162 |
| Iowa | .0920640 | 27% | 4.652 | 50.531 |
| Kentucky | 0.418484 | 35% | 34.661 | 271.393 |
| Maryland | 0.109048 | 51% | 33.396 | 951.619 |
| Michigan | 0.007887 | 01% | 1.017 | 128.972 |
| Minnesota | 0.075863 | 46% | 20.725 | 169.683 |
| Mississippi | 0.039054 | 32% | 3.462 | -18.797 |
| Missouri | 0.859496 | 58% | 111.265 | 499.695 |
| New Hampshire | 0.031833 | 63% | 14.165 | 516.080 |
| New Jersey | 0.041739 | 35% | 1.306 | 31.308 |
| New York | 0.101354 | 49% | 32.349 | 1,266.462 |
| N. Carolina | 0.071309 | 16% | 49.926 | 700.144 |
| Ohio | 1.706571 | 71% | 347.404 | 854.786 |
| Pennsylvania | 0.623070 | 55% | 181.561 | 631.793 |
| S. Carolina | 0.082183 | 46% | 24.677 | 670.683 |
| Tennessee | 0.561778 | 54% | 139.503 | 659.371 |
| Virgina | 0.019375 | 11% | 52.608 | 560.280 |
| W. Virginia | 0.505839 | 49% | 156.488 | 622.766 |
| Wisconsin | 0.265223 | 44% | 026.053 | 346.894 |
| | 8.567513 | | $2114.426 | |

reduction. Alternatively, low levels of control and low marginal costs of control characterize those states which are required to expend little for their control requirements. These include Delaware, Arkansas, Michigan, and New Jersey with emission reductions of 14%, 0%, 1%, and 35% respectively. In total, the costs of controlling the 8.567513 million tons of sulfur dioxide across all twenty-five states is estimated to be $2,114.426 million (in 1985 dollars) under the intrastate market for emission rights.

Table 2 provides the marginal costs of control for each state when all markets have achieved equilibrium. These costs were calculated by taking the derivative of the total cost algorithms at the point where the emission targets for each state are met. Alternatively, these values could be viewed as the state equilibrium market price for emission rights. Clearly, the range of these values across all states is so broad as to suspect that substantial costs savings could be realized by introducing interstate trading.

## Environmental Impacts under the Intrastate Trading Model

The impact of state reduction levels on areas in both the United States and Canada which are particularly sensitive to increased acidity is equally as important to examine as are the costs of controlling emissions. Changes in state emission levels may be translated into changes in air quality at receptor sites by using a transfer co-efficient matrix. For the purposes of this analysis, transfer co-efficients provided by The Argonne National Laboratory will be used to translate sulfur dioxide reductions for each state into changes in sulfur dioxide levels at the twenty-five receptor areas listed in Appendix IV. The matrix takes into account various meteorological conditions including wind velocity and direction as well as precipitation fields in order to estimate the direct impact of emissions generated from various sources on a specific site. Appendix III provides details on the transfer co-efficients used for this analysis. The co-efficients relate changes in emission levels to changes in sulfur dioxide levels which would result in both wet and dry acid deposition at receptor sites. Due to the uncertainty associated with the values for the transfer co-efficients, the changes in air quality will be viewed as rough approximations only.

Assuming the reduction targets assigned to each state under the intrastate trading model are achieved, the total changes in air quality for each receptor site may be calculated simply by multiplying the emission reductions for each state (in millions of tons) by the relevant transfer co-efficient for a receptor site and summing across all states. Table 3 provides approximations of air quality improvements for each receptor site (in Kgrams of sulfur dioxide per hectare) which could be realized, if full compliance with the state emission targets was achieved. Although it remains highly uncertain as to what constitutes a significant increase or decrease in sulfur dioxide levels in sensitive areas, there appears to be some consensus that levels of sulfur dioxide in the area of 10.5 Kgrams per hectare to 13.4 kgrams of $SO_2$ per hectare are significant (Shannon, 1990). Under the assumption that the damage function for $SO_2$ concentration levels is linear, changes of this magnitude may also be viewed as significant. Of the 25 receptors considered, 14 could potentially realize a change of this order under the intrastate trading approach. However, of these 14, only Longwoods, Ontario, north of Lake Erie is Canadian. Though it experiences a significant decrease in the sulfur dioxide level in the order of 16.518 Kgrams $SO_2$ per hectare, the impact of the control program on other Canadian receptors is minimal with reductions ranging from 2.5 Kgrams $SO_2$ per hectare to 7.68 Kgrams $SO_2$ per hectare. Generally, it is estimated that significant impacts will be felt at receptors located in New York, Pennsylvania, West Virginia, Virginia, Ohio, Tennessee, North Carolina and Washington, D.C., while other receptors located in Georgia, Wisconsin, Minnesota, New Hampshire and Colorado as well as those Canadian receptors located in Ontario, Quebec and Nova Scotia (with the exception of Longwoods, Ontario) would experience minimal impact. Indeed, these results are not surprising in light of the fact that the most substantial emission reductions occur in Indiana and Ohio. However, considering that Canada receives 50% of its wet sulfate deposition from the United States, it is clearly disappointing

TABLE 3

AIR QUALITY IMPROVEMENTS UNDER INTRASTATE MODEL

| Receptor * | $SO_2$ Reductions (in Kgrams/Hectare) |
|---|---|
| Zanesville, Ohio | 49.443208 |
| Penn State, Pennsylvania | 41.844811 |
| Kane Exp. Forest, Pennsylvania | 33.841126 |
| Babcock State Park, West Virginia | 25.112212 |
| Shenandoah National Park, Virginia | 24.805595 |
| Tunkhannock, Pennsylvania | 24.733085 |
| Washington, D.C. | 23.845538 |
| Oak Ridge, Tennessee | 23.776400 |
| Horton's Station, Virginia | 17.624820 |
| Longwoods, Ontario | 16.518532 |
| Coweeta, N. Carolina | 15.5330200 |
| Clingman's Peak, N. Carolina | 15.304802 |
| Great Smokie Mountains, Tennessee | 14.102788 |
| Big Moose Lake, N.Y. | 10.571082 |
| Dorset, Ontario | 7.683648 |
| Hubbard Brook, New Hampshire | 7.265989 |
| Whiteface Mountain, New York | 7.0720294 |
| Uvalda, Georgia | 6.919537 |
| Fernberg, Minnesota | 6.470815 |
| Chalk River, Ontario | 5.601415 |
| Trout Lake, Wisconsin | 4.764556 |
| Algoma, Ontario | 3.578712 |
| Montmorency, Quebec | 2.677350 |
| Kejimkujik, Nova Scotia | 2.514678 |
| Yampa, Colorado | .058969 |

* Canadian receptor sites are underlined

to find that under a program which imposes emission reductions in the order of 51% (i.e. reductions of 8.567 million tons out of a possible 16.495 million tons in the 25 states considered), Canadian receptors, with the exception of one, will not experience a significant reduction in the level of sulfate deposition.

Although the potential for improvement in air quality for Canadian receptors under the intrastate trading model appears to be limited, the size of the changes which are realized should be considered in light of the fact that the U.S. utility sector is only one source of existing sulfur dioxide concentration levels in Canada. While American receptor sites receive 95% of sulfate deposition from sources in the United States, American sources are responsible for only 50% of Canada's sulfate deposition. Therefore, it would be anticipated that any program to control emissions in the United States would have a less significant impact on Canadian receptors in absolute terms. However, in terms of percentage reductions of sulfur dioxide from American sources, the Canadian receptors do enjoy substantial improvements in the range of 41% to 54%:

| | |
|---|---|
| Montmorency, Quebec | 48% |
| Algoma, Ontario | 44% |
| Kejimkujik, Nova Scotia | 51% |
| Longwoods, Ontario | 41% |
| Dorset, Ontario | 47% |
| Chalk River, Ontario | 54% |

On average a reduction of 45% in sulfur dioxide levels for all six sites results from the intrastate trading program.

One further issue of importance concerns the levels of sulfur dioxide concentrations which remain after the intrastate control policy is implemented. Specifically, do the remaining levels constitute a significant threat to the receptor areas considered in this analysis? Table 4 provides a listing of sulfur dioxide concentration levels which are generated from uncontrolled U.S. coal fired utility plants after controls are imposed. Twelve out of the twenty-five receptors still experience levels above 10.5 Kgrams $SO_2$/hectare. Of the Canadian receptors, only Longwoods, Ontario, continues to receive significant levels from American sources (23.184 Kgrams per hectare annually). However, this is not to say that the total level of sulfur dioxide concentrations at Canadian receptor sites will not remain at dangerous levels after U.S. control is enforced, considering that Canadian emitting sources which are equally responsible for levels of acid deposition will continue to bombard these areas at present levels. Eleven out of nineteen American receptors remain threatened by levels of emissions generated after control. The high levels associated with Zanesville (31.94 Kgrams/hectare), Penn State (32.79 Kgrams/hectare), Tunkhannock (31.28 Kgrams/hectare), Kane Exp. Forest (25.99 Kgrams/hectare), Washington (23.55 Kgrams/hectare), Shenandoah Natl. Park (22.13 Kgrams/hectare) and Babcock State Park (21.07 Kgrams/hectare) are of particular concern.

## INTERSTATE EMISSIONS TRADING MARKET

### Background

Clearly, the potential exists for the intrastate trading model examined above to reduce the costs of control required to achieve aggregate emission reduction targets for each state from those required to achieve the same targets under a purely regulatory approach. In theory, further costs savings could be realized if the flexibility of plants to pursue control strategies was broadened even further by allowing trade of emission rights across state lines. Rather than creating twenty-five separate markets in emission rights (intrastate model), only one market would be required to facilitate trading among all twenty-five states and the control problem would be simplified to allotting control responsibility across all plants in all states such that one reduction target for all states in aggregate was achieved at least cost. Therefore, each state would not be required to achieve a specified level of

TABLE 4

INTRASTATE TRADING MODEL

| | $SO_2$ LEVELS (Kgrams/hect.) before control | % REDUCTION $SO_2$ | BALANCE $SO_2$ (Kgrams/hect.) |
|---|---|---|---|
| Penn State, Pennsylvania | 74.635 | 56% | 32.791 |
| Zanesville, Ohio | 81.387 | 60% | 31.944 |
| Tunkhannock, Pennsylvania | 56.015 | 44% | 31.282 |
| Kane Exp. Forest, Pennsylvania | 59.835 | 56% | 25.994 |
| Washington, D.C. | 47.404 | 50% | 23.559 |
| Longwoods, Ontario | 39.702 | 41% | 23.184 |
| Shenandoah National Park, Virginia | 46.935 | 52% | 22.130 |
| Babcock State Park, West Virginia | 46.184 | 54% | 21.072 |
| Oak Ridge, Tennessee | 43.712 | 54% | 19.936 |
| Clingman's Peak, North Carolina | 33.658 | 45% | 18.354 |
| Horton's Station, Virginia | 35.231 | 50% | 17.607 |
| Great Smokie Mountains, Tennessee | 25.755 | 54% | 11.653 |
| Big Moose Lake, New York | 20.225 | 52% | 9.654 |
| Coweeta, North Carolina | 24.255 | 64% | 8.722 |
| Dorset, Ontario | 16.285 | 47% | 8.602 |
| Hubbard Brook, New Hampshire | 13.917 | 52% | 6.652 |
| Whiteface Mountain, New York | 13.551 | 52% | 6.479 |
| Fernberg, Minnesota | 12.394 | 52% | 5.924 |
| Trout Lake, Wisconsin | 9.901 | 48% | 5.137 |
| Chalk River, Ontario | 10.299 | 54% | 4.698 |
| Algoma, Ontario | 8.004 | 44% | 4.426 |
| Uvalda, Georgia | 11.309 | 61% | 4.390 |
| Montmorency, Quebec | 5.488 | 48% | 2.811 |
| Kejimkujik, Nova Scotia | 4.859 | 51% | 2.345 |
| Yampa, Colorado | .09 | 64% | .032 |

emission reduction; rather all plants in each state would participate in a program to achieve one emissions target for all states combined.

The intrastate emissions trading model does not have the capability of achieving such an objective at least cost due to the restrictions it imposes on the transferability of emission rights. The least cost control allocation for all 25 states together under the intrastate trading approach would be achieved only in the remote case in which the marginal costs of emission control for each state were equal when all twenty-five markets were in equilibrium. Given that this situation does not exist, there is a potential for cost savings using an alternative market approach which allows for full transferability of rights across all states. The question remains, however, as to the size of these potential cost savings.

According to theory, the minimization of control costs across all states will require that plants in all states operate within one market for emission rights according to the cost minimizing condition (5.1) stipulated in the intrastate trading model. However, in this case, the range of opportunities to engage in trade will be much broader and the potential for control cost reductions will be much greater. Again plants will engage in trading of emission licenses so as to minimize the sum of the costs of emission control and the costs of permit acquisition. Incentives for trade will exist until the marginal costs of control across all plants in all states are equalized. Only one equilibrium price for permits will be established and this value will reflect the degree of difficulty which the market experiences in achieving the emission reduction target. In a perfectly competitive market, the marginal costs of control for all market participants will be equal to the value of this equilibrium permit price as per condition (5.1). This solution represents the least cost allocation of control responsibility across all sources.

In order to conduct a cost analysis of a market approach which provides total flexibility in the control options for all sources, as described above, control cost information at a plant level would normally be used. However, given that cost information is available only on a state wide basis, the form of the interstate model must be modified to reflect the trading of emission rights between states rather than between sources. In other words, the states themselves will be viewed as the individual market participants and the control problem will be one of allocating emission reductions across individual states rather than across individual sources. Sources will be allowed to trade internally (within state) so as to minimize the costs of control and permit acquisition, and to the extent that cost reductions can further be realized through interstate trading, the state will act as the means of exchange for permits. In this way all potential cost savings can be achieved including those savings which could be realized through the direct trading of emission rights between sources of different states. Essentially, the state acts to extend the trading opportunities of individual sources beyond state borders.

Under this approach to interstate emissions trading, states themselves will act to minimize their aggregate control cost commitments by participating in the market according to the following cost minimizing condition:

$$(5.2) \quad \partial C_i(r_i)/\partial r_i - P \geq 0 \qquad r_i\,[\partial C_i(r_i)/\partial r_i - P\,] = 0 \quad \text{for all } i$$

In this case the value of $\partial C_i/\partial r_i$ represents the marginal costs of control for the state rather than the individual source. This value may be calculated by taking the derivative of the total cost function for that state. Trading incentives between states will exist until a market equilibrium is established at which point emission reduction levels for each state will have adjusted so that marginal costs of control across all states will be equal to the equilibrium price for emission permits. Because the marginal control cost curves for each state represent least cost strategies for each level of control, this in turn will require that individual sources in every state adjust their level of control such that marginal control costs for every source are also equal to the equilibrium price for permits. Otherwise incentive would exist for sources within each state and for states themselves to continue to engage in trade to reduce overall control costs.

The resulting allocation of control responsibility will represent the least cost solution for achieving one aggregate control target for the entire region of 25 states, and the equilibrium price, P, will represent the degree of difficulty which all states and all sources experience in achieving this target. The decrease in total commitment of resources to emission control resulting from trade will reflect the cost savings realized by allocating more control responsibility to those states which can control additional emissions for the least cost given a specific least cost assignment of control to the individual sources within each state. Accordingly, the reduction in costs will also reflect changes in the control levels adopted by individual sources as would be expected in a full interstate trading model.

## The Interstate Emissions Trading Model

In order to address this question of potential cost saving under an interstate trading model, the total cost algorithms provided by Cushey (1986) are used in the framework of a linear programming model to determine the savings potential for achieving one emissions reduction target for the 25 states together.[5]

The objective of the program is to minimize the sum of the control costs across 25 states under the constraint that total emissions reductions equal the level achieved in the intrastate trading model, specifically 8.567513 million tons of sulfur dioxide. Accordingly, the objective function is represented by a sum of the cost algorithms for each state:[6]

(1) $F=a_{01}+a_{11}X1+a_{21}X_1^{b1}+\ldots a_{0,25}+a_{1,25}X25+a_{2,25}X_{25}^{b25}$

---

5 The linear programming computer model referred to as Mathmatical Programming System (MPS), will be used for the interstate and ambient trading models.

6 For the purposes of outlining a general model, it will be assumed that the cost algorithms provided by Cushey (1986) represent all levels of emission reduction including reductions of 0% to 30%.

where $a_{0i}$, $a_{1i}$, and $a_{2i}$ represent co-efficients in the cost algorithm for state i; $b_i$ represents the parameter b in the cost algorithm for state i; and $X_i$ represents the level of emissions control for state, i, in millions of tons of sulfur dioxide. The constraints required by the model are formulated as follows:

(2) $X_1 + X_2 + X_3 \dots . X_{25} = 8.567513$

(3) $X_1 \leq W_1, X_2 \leq W_2, \dots\dots\dots X_{25} \leq W_{25}$

The constraints listed in (3) restrict the levels of reductions for all 25 states to those which are feasible given state emission levels and technological limitations. In other words, only approximately 90% reductions in emission levels are allowed for each state and the values for $W_i$ represent the maximum values for emission reductions indicated by the ranges provided in Table 1.

Clearly, the problem with this approach is that the objective function is not linear in the parameters $X_1 \dots X_{25}$. Therefore, all state cost algorithms must be linearized in order to utilize a linear programming system. For the purposes of the present analysis, total cost curves for each state will be divided into three portions. The inital portion of the curve will represent the linear segment in which coal switching remains the dominant control strategy. This, in fact, is the portion of the curve which remains outside the valid range of the cost algorithms as discussed previously. The nonlinear portion of the curve which is represented by the cost algorithms, however, must be transformed into linear sections in order to be incorporated into the objective function. For each state, this portion of the curve is divided into two segments of equal length. Regressions of total costs on emission levels are then run for each individual segment in order to obtain linear approximations of the cost algorithms.[7] Table 5 presents all linear equations obtained

---

7 Regressions for each linear segment were based on 10 observations in the 60% to 90% reduction range.

TABLE 5

LINEARIZATION OF COST ALGORITHMS

| STATE | REGRESSION | RANGE (in million tons of $SO_2$) | $R^2$ | T STAT |
|---|---|---|---|---|
| Alabama | -120.24 + 700.17(X) | .190-.3490 | .93 | 11.5 |
| | -588.86 + 2042.6(X) | .349-.5080 | .99 | 32.7 |
| Arkansas | -46.19 + 3859.6(X) | .0120-.025 | N/A | N/A * |
| Florida | -25.845 + 268.18(X) | .142-.2825 | .92 | 10.4 |
| | -251.93 + 1067.8(X) | .2825-.423 | .97 | 19.4 |
| Delaware | -59.04 + 2129.60(X) | .030-.0670 | N/A | N/A * |
| Georgia | -70.227 + 491.69(X) | .243-.4705 | .98 | 24.7 |
| | -567.80 + 1508.1(X) | .4705-.698 | .97 | 17.8 |
| Illinois | -229.12 + 548.10(X) | .418-.8045 | 1.0 | 784 |
| | -850.66 + 1247.2(X) | .8045-1.19 | .89 | 08.8 |
| Indiana | -142.25 + 333.0(X) | .546-1.098 | .95 | 13.1 |
| | -1248.3 + 1310.5(X) | 1.098-1.65 | .97 | 18.8 |
| Iowa | -240.42 + 1142(X) | .215-.2555 | .94 | 12.7 |
| | -733.61 + 3075.3(X) | .2555-.296 | .99 | 33.3 |
| Kentucky | -151.40 + 441.51(X) | .358-.7130 | .97 | 17.4 |
| | -675.48 + 1165.4(X) | .713-1.068 | .98 | 27.6 |
| Maryland | -48.457 + 776.41(X) | .068-.1315 | .95 | 14.5 |
| | -200.13 + 1933.3(X) | .1315-.195 | .99 | 35.3 |

Table 5 Continued

| STATE | REGRESSION | RANGE | $R^2$ | T STAT |
|---|---|---|---|---|
| Michigan | -142.54 + 819.18(X) | .195-.3885 | .98 | 26.9 |
| | -789.46 + 2416.5(X) | .3885-.582 | .97 | 17.8 |
| Minnesota | -9.0083 + 412.70(X) | .062-.105 | .84 | 06.8 |
| | -293.15 + 3044.9(X) | .105-.148 | .96 | 14.9 |
| Mississippi | -2.8759 + 140.01(X) | .038-.073 | .81 | 06.2 |
| | -88.051 + 1263.6(X) | .073-.108 | .95 | 13.5 |
| Missouri | -216.31 + 385.80(X) | .591-.957 | .96 | 17.0 |
| | -681.58 + 872.09(X) | .957-1.323 | .99 | 38.5 |
| New Hampshire | -35.50 + 1560.2(X) | .034-.045 | N/A | N/A * |
| New Jersey | -80.51 + 1708.60(X) | .048-.106 | N/A | N/A * |
| New York | -79.782 + 1168.5(X) | .070-.128 | .93 | 11.3 |
| | -360.90 + 3368.6(X) | .128-.186 | .99 | 32.6 |
| N. Carolina | -124.66 + 1476.4(X) | .145-.274 | .98 | 23.7 |
| | -609.81 + 3224.1(X) | .274-.403 | .99 | 32.1 |
| Ohio | -388.38 + 391.07(X) | .964-1.559 | .98 | 24.4 |
| | -1753.5 + 1237.7(X) | 1.559-2.15 | .96 | 17.0 |
| Pennsylvania | -82.893 + 425.45(X) | .344-.683 | .96 | 15.5 |
| | -823.76 + 1479(X) | .683-1.022 | .97 | 19.8 |
| S. Carolina | -65.152 + 1117.6(X) | .070-1.155 | .94 | 12.4 |
| | -287.37 + 3041.6(X) | 1.155-.161 | .99 | 33.9 |

Table 5 Continued

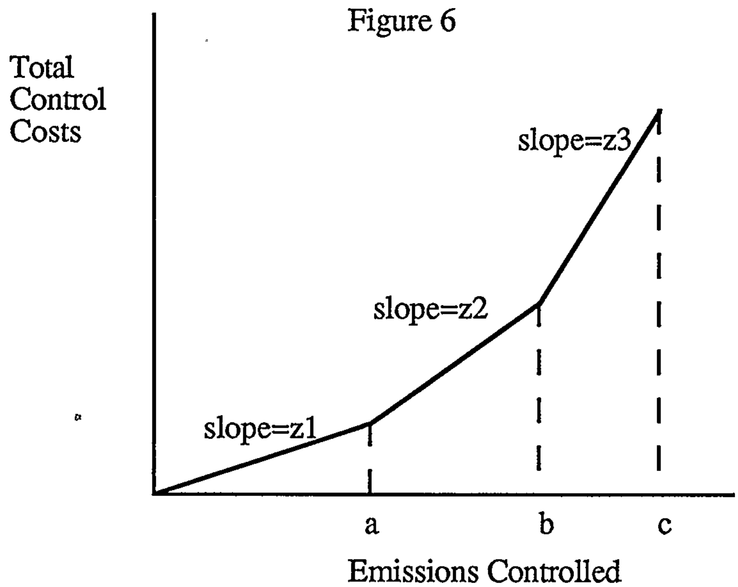
| STATE | REGRESSION | RANGE | $R^2$ | T STAT |
|---|---|---|---|---|
| Tennessee | -218.56 + 639.45(X) | .340-.638 | .99 | 133 |
| | -772.14 + 1446.6(X) | .638-.936 | .95 | 13.2 |
| Virginia | -54.808 + 1437.0(X) | .051-.101 | .93 | 11.4 |
| | -326.66 + 4128.6(X) | .101-.151 | .99 | 32.9 |
| W. Virginia | -139.66 + 595.99(X) | .325-.618 | .99 | 33.7 |
| | -706.79 + 1478.7(X) | .618-.911 | .97 | 20.3 |
| Wisconsin | -84.696 + 440.88(X) | .200-.368 | .93 | 11.2 |
| | -394.14 + 1281.8(X) | .368-.526 | .99 | 32.7 |

* Cost algorithms provided by Cushey (1986) estimate linear relationship between costs and reduction levels. Therefore, linearization of algorithms is not required.

through this methodology. The high $R^2$ values as well as the high values for the t-statistic associated with the emission reduction variable, X, suggest that these equations will serve as reasonable approximations of the true curve and that further segmentation of the cost curves is unnecessary.[8]

Accordingly, the analysis of the interstate trading model will employ three linear equations to represent the relationship between total control costs and the levels of emission control for each state, rather than the nonlinear cost algorithms provided by Cushey. Figure 6 illustrates the nature of the total cost curves resulting. Each linear segment on the total cost curve is associated with a constant marginal cost of control. For example, as shown in Figure 6, the emission reductions from o to a, are associated with constant marginal costs equal to $Z_1$ which is represented by the slope of the cost curve from o to a. Similarly marginal costs for reductions between a and b will be constant at a value of $Z_2$ and emission reduction levels between b and c will be associated with constant marginal costs of $Z_3$.

Figure 6




---

8 Regressions estimated provide good fits in terms of $R^2$ values. The Y values at end points of intervals were not constrained to coincide. However, they are relatively close in all cases.

For the purposes of defining an objective function which is linear in all parameters, three emission reduction variables will be defined for each state as opposed to using only one emission reduction variable as in the intrastate model. Each of these three variables will be associated with one of the three linear segments forming the total cost curves for each state. Accordingly, each variable will be associated with a different marginal cost represented by the slope of the associated linear segment. Table 6 provides a listing of marginal costs associated with each of the three emission reduction variables for each state and the ranges to which they apply.

In the case of the example shown in Figure 6 , this will mean that a variable $X_1$ will represent all reduction levels between 0 and a for state 1, variable $X_2$ will represent all reduction levels between a and b for state 1, and variable $X_3$ will represent all reduction levels between b and c. Each of these variables is associated with constant marginal costs of control, $Z_1$, $Z_2$, $Z_3$ respectively. In the most simple case, the model for minimization of costs of control for one state only will be formulated as follows:

(1) $\text{Min } F = Z_1X_1 + Z_2X_2 + Z_3X_3$ subject to

(2) $X_1 \leq W_1$ (3) $X_2 \leq W_2$ (4) $X_3 \leq W_3$

(5) $X_1 + X_2 + X_3 = R$

The purpose of constraints (2)-(4) is to limit the level of reductions for each variable according to the length of the linear segment associated with it. For example, according to Figure 6, W1 = a, W2 = b-a and W3 = c-b. Clearly, the purpose of constraint (5) is to to impose a minimum level of emission reduction.

Accordingly, the problem of minimizing costs of control across all 25 states is represented as follows:

TABLE 6

EMISSION REDUCTION VARIABLE

| STATE VARIABLE | MARGINAL COSTS ($millions 1985) | RANGE (million tons) |
|---|---|---|
| Alabama1 | 150.0069 | .0000 - .1900 |
| Alabama2 | 700.1700 | .1900 - .3490 |
| Alabama3 | 2042.6000 | .3490 - .5080 |
| Arkansas1 | 9.8333 | .0000 - .0120 |
| Arkansas2 | 3859.6000 | .0120 - .0185 |
| Arkansas3 | 3859.6000 | .0185 - .0250 |
| Delaware1 | 161.6000 | .0000 - .0300 |
| Delaware2 | 2129.6000 | .0300 - .0485 |
| Delaware3 | 2129.6000 | .0485 - .0670 |
| Florida1 | 121.6087 | .0000 - .1420 |
| Florida2 | 268.1800 | .1420 - .2825 |
| Florida3 | 1067.8000 | .2825 - .4230 |
| Georgia1 | 227.9890 | .0000 - .2430 |
| Georgia2 | 491.6900 | .2430 - .4705 |
| Georgia3 | 1508.1000 | .4705 - .6980 |
| Illinois1 | .5564 | .0000 - .3580 |
| Illinois2 | 548.1000 | .4180 - .8045 |
| Illinois3 | 1247.2000 | .8045 - 1.190 |
| Indiana1 | 109.0660 | .0000 - .5460 |
| Indiana2 | 333.0000 | .5460 - 1.098 |
| Indiana3 | 1310.5000 | 1.098 - 1.650 |
| Iowa1 | 50.5311 | .0000 - .2150 |
| Iowa2 | 1142.0000 | .2150 - .2555 |
| Iowa3 | 3075.3000 | .2555 - .2960 |
| Kentucky1 | 56.7899 | .0000 - .3580 |
| Kentucky2 | 441.5100 | .3580 - .7130 |
| Kentucky3 | 1165.4000 | .7130 - 1.068 |
| Maryland1 | 142.7351 | .0000 - .0680 |
| Maryland2 | 776.4100 | .0680 - .1315 |
| Maryland3 | 1933.3000 | .1315 - .1950 |
| Michigan1 | 128.9720 | .0000 - .1950 |
| Michigan2 | 819.1800 | .1950 - .3885 |
| Michigan3 | 2416.5000 | .3885 - .5820 |

Table 6 Continued

| STATE VARIABLE | MARGINAL COSTS | RANGE |
|---|---|---|
| Minnesota1 | 324.3300 | .0000 - .0620 |
| Minnesota2 | 412.7000 | .0620 - .1050 |
| Minnesota3 | 3044.9000 | .1050 - .4800 |
| Mississippi1 | 91.6997 | .0000 - .0380 |
| Mississippi2 | 140.0100 | .0380 - .0730 |
| Mississippi3 | 1263.6000 | .0730 - .1080 |
| Missouri1 | 42.2876 | .0000 - .5910 |
| Missouri2 | 385.8000 | .5910 - .9570 |
| Missouri3 | 872.0900 | .9570 - 1.323 |
| New Hampshire1 | 516.0800 | .0000 - .0340 |
| New Hampshire2 | 1560.2000 | .0340 - .0395 |
| New Hampshire3 | 1560.2000 | .0395 - .0450 |
| New Jersey1 | 31.3080 | .0000 - .0480 |
| New Jersey2 | 1708.6000 | .0480 - .0770 |
| New Jersey3 | 1708.6000 | .0770 - .1060 |
| New York1 | 161.2470 | .0000 - .0700 |
| New York2 | 1168.5000 | .0700 - .1280 |
| New York3 | 3368.6000 | .1280 - .1860 |
| N. Carolina1 | 700.1446 | .0000 - .1450 |
| N. Carolina2 | 1476.4000 | .1450 - .2740 |
| N. Carolina3 | 3224.1000 | .2740 - .4030 |
| Ohio1 | 1.7460 | .0000 - .9640 |
| Ohio2 | 391.0700 | .9640 - 1.559 |
| Ohio3 | 1237.7000 | 1.559 - 2.150 |
| Pennsylvania1 | 223.1940 | .0000 - .3440 |
| Pennsylvania2 | 425.4500 | .3440 - .6830 |
| Pennsylvania3 | 1479.0000 | .6830 - 1.022 |
| S. Carolina1 | 280.6485 | .0000 - .0700 |
| S. Carolina2 | 1117.6000 | .0700 - 1.155 |
| S. Carolina3 | 3041.6000 | 1.155 - 1.610 |
| Tennessee1 | 1.3817 | .0000 - .3400 |
| Tennessee2 | 639.4500 | .3400 - .6380 |
| Tennessee3 | 1446.6000 | .6380 - .9360 |
| Virginia1 | 560.2800 | .0000 - .0510 |
| Virginia2 | 1437.0000 | .0510 - .1010 |
| Virginia3 | 4128.6000 | .1010 - .1510 |

Table 6 Continued

| STATE VARIABLE | MARGINAL COSTS | RANGE |
|---|---|---|
| W. Virginia1 | 188.1920 | .0000 - .3250 |
| W. Virginia2 | 595.9900 | .3250 - .6180 |
| W. Virginia3 | 1478.7000 | .6180 - .9110 |
| Wisconsin1 | 70.3700 | .0000 - .2000 |
| Wisconsin2 | 440.8800 | .2000 - .3680 |
| Wisconsin3 | 1281.8000 | .3680 - .5260 |

(1) $\text{Min } F = Z_{11}X_{11} + Z_{12}X_{12} + Z_{13}X_{13} + Z_{21}X_{21} + Z_{22}X_{22} +$

$$Z_{23}X_{23}\ldots\ldots\ldots Z_{25,1}X_{25,1} + Z_{25,2}X_{25} + Z_{25,3}X_{25,3}$$

subject to

(2) $X_{ij} \leq W_{ij}$ for all i and j

(3) $\Sigma X_{ij} = R$

where $Z_{ij}$ = constant marginal costs for variable j in state i, and $X_{ij}$ = emission reduction levels for variable j in state i.

Control Allocation for the Interstate Trading Model

The market equilibrium solution to the interstate emission trading model, defined above, will yield the least cost control allocation for achieving an 8.567513 million ton reduction in sulfur dioxide. Theoretically, this market solution should represent the allocation of control whereby the marginal costs of control for each state are equated across all states. However, due to the linear representation of the cost curves, increasing levels of reductions for each state are not associated with constantly increasing marginal control costs. Rather, increasing reduction levels are characterized by constant marginal costs over wide ranges and, in fact, only three values for marginal control costs are provided for each state under the methodology described in the previous section. Given these limitations, states cannot necessarily operate according to condition (5.2) which requires that they equate marginal costs of control with the equilibrium permit price. Rather, states will increase their level of control until marginal costs are below or equal to the equilibrium price. Therefore, the cost minimizing allocation of control will be such that control responsibility is assigned to those ranges of reduction in each state which are associated with the lowest marginal costs until the aggregate control target is achieved. At the point where the last unit of control is assigned, the marginal control costs for the associated emission reduction variable will be at a maximum and the marginal costs incurred by each state, according to the optimal control allocation, will be below or equal to this value. Table 7 provides details on the marginal costs of control associated with reduction levels for each state in the optimal solution. It can be seen clearly from this table, that marginal control costs incurred by each state in the optimal solution are below or equal to $548 million (1985 dollars) per million tons of sulfur dioxide. State levels of reduction which are associated with marginal costs above this value are not represented in the optimal control allocation.

Essentially, this value represents the degree of difficulty which the market experiences in achieving the emission control target. Alternatively, the significance of this value lies in the fact that it represents the shadow price for emission rights, or in other words, the unit worth of the emission rights according to the optimal solution provided by the linear programming model. Specifically, if the constraint on emissions rights was relaxed by one unit, the value of the total costs of control would decrease according to this value. In the linear program developed for the interstate emissions trading model, the shadow price reflects the marginal costs incurred by Illinois in the range of .418 million tons sulfur dioxide reduction and .8045 million tons sulfur dioxide reduction. If the aggregate emission control target for the program were relaxed by one unit, Illinois, with the highest level of marginal costs in the optimal solution, would reduce its level of control by one unit and the value of the objective cost function would decrease by $548 million (1985 dollars).

Table 7 also illustrates that the state control allocations are such that, once again, Ohio, Missouri, Illinois, Pennsylvania, Indiana and Georgia are responsible for relatively large reduction levels. Substantial control is also assigned to the state of Kentucky. A further comparison of the levels of control required of each state under the intrastate model and the present model, shows that additional levels of control are required under the interstate model for the states of Minnesota, Michigan, Iowa, Delaware, Florida, Arkansas, Kentucky, Missouri, Wisconsin, Pennsylvania, New Jersey, Mississippi and New

TABLE 7

CONTROL ALLOCATIONS UNDER THE INTERSTATE TRADING MODEL

| State | Control (Million tons) | Percentage Reduction | Total Costs ($million 1985) | Marginal Costs ($million 1985) |
|---|---|---|---|---|
| Alabama | .1900 | 34% | 28.5013 | 150.0069 |
| Arkansas | .0120 | 43% | .1179 | 9.8333 |
| Delaware | .0300 | 42% | 4.8480 | 161.6000 |
| Florida | .2825 | 61% | 54.9477 | 268.1800 |
| Georgia | .4705 | 61% | 167.2608 | 491.6900 |
| Illinois | .6610 | 50% | 133.4279 | 548.1000 |
| Indiana | 1.0980 | 61% | 243.3660 | 333.0000 |
| Iowa | .2150 | 65% | 10.8642 | 50.5311 |
| Kentucky | .7130 | 60% | 177.0668 | 441.5100 |
| Maryland | .0680 | 32% | 9.7059 | 142.7351 |
| Michigan | .1950 | 30% | 25.1495 | 128.9720 |
| Minnesota | .1050 | 65% | 37.8545 | 412.7000 |
| Mississippi | .0730 | 61% | 8.3849 | 140.0100 |
| Missouri | .9570 | 65% | 166.1948 | 385.8000 |
| New Hampshire | .0340 | 68% | 17.5467 | 516.0800 |
| New Jersey | .0480 | 41% | 1.5027 | 31.3080 |
| New York | .0700 | 34% | 11.2872 | 161.2470 |
| North Carolina | Nil | ----- | Nil | 700.1446 |
| Ohio | 1.5595 | 65% | 234.5654 | 391.0700 |
| Pennsylvania | .6830 | 60% | 221.0062 | 425.4500 |
| South Carolina | .0700 | 39% | 19.6453 | 280.6485 |
| Tennessee | .3400 | 33% | .4697 | 1.3817 |
| Virginia | Nil | ----- | Nil | 560.2800 |
| West Virginia | .3250 | 32% | 61.1624 | 188.1920 |
| Wisconsin | .3680 | 62% | 88.1418 | 440.8800 |
| Totals | 8.5675 | | $1723.0176 | |

Hampshire. In order to understand why these relative changes in state reduction levels occur when moving from the intrastate model to a model which allows for trading between states, it is necessary to examine the marginal control costs associated with each state before interstate trading is introduced.

However, if any cost comparisons between the previous intrastate trading model and the present interstate model are to be made, it will be necessary to re-evaluate the intrastate model in terms of the linearized version of the cost algorithms in order to maintain consistency. Table 8 provides the cost estimates of the total control costs as well as the marginal control costs for the intrastate trading model when a linearized version of the cost algorithms is used, and when the state reduction targets calculated previously for the intrastate model are achieved. Examination of these marginal costs reveals that for all states which are allocated additional control responsibility under the interstate trading model, the marginal control costs are below $548 million in the intrastate trading solution. Similarly, all states with marginal costs higher than this value, are allocated less control responsibility when interstate trading is introduced. Intuitively, the reason for this is clear. If the equilibrium price for permits represents the difficulty, in terms of control costs, which the market experiences in meeting an emissions target, the equilibrium permit price will be equal to $548 million, the cost of controlling the last unit of emission to achieve the target[9]. For states which incur marginal control costs above this value, incentive will exist to buy emission rights and increase their level of emissions. Alternatively, incentive will exist for those states whose marginal control costs are below the equilibrium price, to sell emission rights and increase their level of control. Thus the reason for the adjustments in state emission control levels under the interstate model is clear.

Control Costs for the Interstate Trading Model

---

9 The value $548 Million represents only an approximation of the equilibrium price since marginal cost curves are represented by step functions.

TABLE 8

INTRASTATE TRADING MODEL COSTS WITH LINEARIZED COST ALGORITHMS

| STATE | TOTAL COSTS (in $millions 1985) | MARGINAL COSTS (in $millions 1985) |
|---|---|---|
| Alabama | $ 54.8753 | $ 700.1700 |
| Arkansas | 0.0000 | 9.8333 |
| Delaware | 1.6189 | 161.6000 |
| Florida | 48.2802 | 268.1800 |
| Georgia | 351.8311 | 1508.1000 |
| Illinois | 184.4539 | 548.1000 |
| Indiana | 350.0381 | 1310.5000 |
| Iowa | 4.6521 | 50.5311 |
| Kentucky | 47.0351 | 441.5100 |
| Maryland | 41.5760 | 776.4100 |
| Michigan | 1.0172 | 128.9720 |
| Minnesota | 25.8297 | 412.7000 |
| Mississippi | 3.6321 | 140.0100 |
| Missouri | 128.5777 | 385.8000 |
| New Jersey | 1.3067 | 31.3080 |
| New Hampshire | 16.4283 | 516.0800 |
| New York | 47.9244 | 1168.5000 |
| North Carolina | 49.9266 | 700.1446 |
| Ohio | 416.5951 | 1237.7000 |
| Pennsylvania | 195.5090 | 425.4500 |
| South Carolina | 33.2611 | 1117.6000 |
| Tennessee | 142.2857 | 639.4500 |
| Virginia | 10.8554 | 560.2800 |
| West Virginia | 168.9406 | 595.9900 |
| Wisconsin | 42.8295 | 440.8800 |
| | | |
| Total Costs | $2369.2798 | |

In terms of total control costs, those states which are assigned the greatest control responsibility incur the greatest costs under the interstate model (See Table 7). These include Indiana ($243 million), Ohio ($234 million), Pennsylvania ($221 million), Kentucky ($177 million), Georgia ($167 million), Missouri ($166 million) and Illinois ($133 million). The fact that these states emit high levels of sulfur dioxide may partly explain why they are assigned primary responsibility for controlling emissions. However, in a model which allocates control according to cost efficiency, this not a sufficient condition for such an allocation. Those states identified as the primary controllers, also are characterized by relatively flat total control cost curves. In other words, over a wide range of reductions, marginal control costs remain relatively low, and consequently in the least cost control allocation, these states are assigned substantial control levels. Total costs for these states remain high relative to other states since increased costs resulting from the increased level of control responsibility outweigh the fact that relatively low costs of control are incurred to achieve these levels.

Under the interstate model, the total costs of control across all states are valued at $1,723 million (in 1985 dollars). With total control costs estimated at $2,369 for the intrastate model using linearized cost algorithms, a potential savings of $646 million dollars (a 27% cost reduction) may be realized by moving to a market approach which encourages the trading of rights between states. Considering that any increases in operating costs in the electric utility sector resulting from pollution control requirements are likely to be passed onto consumers in the form of rate increases, a $646 million cost saving represents a significant incentive for governments to develop more flexible control approaches. Furthermore, if we accept that the control of pollution is a necessary objective for society to pursue, it is clearly in the interests of both industry and consumers to promote a program in pollution control which will provide the greatest benefit for the least cost. The introduction of an interstate market in emission rights provides a step in this direction.

Environmental Impacts Under the Interstate Trading Model

Table 9 provides estimates of the air quality improvements for each of the 25 receptor sites in Canada and the United States which would result from the optimal control allocation under the interstate trading model. These results do not deviate substantially from those obtained from the intrastate model. Using the level of 10.5 Kgrams sulfur dioxide per hectare as a benchmark to define significant levels of sulfur dioxide concentrations, it was found that 13 of the 25 receptor sites would experience changes of this order under the interstate model. All 13 of these receptors showing marked improvements coincide with those receptors experiencing significant improvements under the intrastate trading model. In fact, of the 14 receptor sites realizing significant changes under the intrastate model, only Big Moose Lake, New York, with an improvement of 10.458 Kgrams $SO_2$/hectare (relative to concentration levels without control of emissions) does not meet the standard.

From the Canadian perspective, these results are once again disappointing in that only one Canadian receptor site would experience significant changes in air quality. Specifically, Longwoods, Ontario, would enjoy an improvement in the order of 19.755 Kgrams $SO_2$/hectare, an increase of 3.236 Kgrams over concentration reductions experienced under the intrastate trading model. Other Canadian receptors, enjoy improvements in the order of 2.438 Kgrams $SO_2$/hectare for Kejimkujik, Nova Scotia, to 8.435 Kgrams $SO_2$/hectare for Dorset, Ontario.

Again, it must be recognized that the potential for improvement in air quality for Canadian receptors is limited given the absolute quantities of sulfur dioxide which are transported into Canada from the United States before control is imposed. In terms of percentage reductions, Canadian receptors again fair quite well, enjoying reductions in the order of 49% to 58% from emission reductions of American sources:

TABLE 9

AIR QUALITY IMPROVEMENTS UNDER INTERSTATE MODEL

| RECEPTOR * | $SO_2$ REDUCTIONS (in Kgrams/Hectare) |
|---|---|
| Zanesville, Ohio | 47.175 |
| Penn State, Pennsylvania | 40.976 |
| Kane Exp. Forest, Pennsylvania | 33.230 |
| Tunkhannock, Pennsylvania | 24.454 |
| Babcock State Park, West Virginia | 22.756 |
| Shenandoah National Park, Virginia | 21.599 |
| Washington, D.C. | 19.912 |
| <u>Longwoods, Ontario</u> | <u>19.755</u> |
| Oak Ridge, Tennessee | 19.242 |
| Horton's Station, Virginia | 15.622 |
| Coweeta, North Carolina | 12.790 |
| Great Smokie Mountains, Tennessee | 12.601 |
| Clingman's Peak, North Carolina | 12.175 |
| Big Moose Lake, New York | 10.458 |
| <u>Dorset, Ontario</u> | <u>8.435</u> |
| Hubbard Brook, New Hampshire | 7.241 |
| Whiteface Mountain, New York | 7.028 |
| Uvalda, Georgia | 6.161 |
| Trout Lake, Wisconsin | 6.067 |
| <u>Chalk River, Ontario</u> | <u>6.008</u> |
| Fernberg, Minnesota | 5.132 |
| <u>Algoma, Ontario</u> | <u>4.337</u> |
| <u>Montmorency, Quebec</u> | <u>2.694</u> |
| <u>Kejimkujik, Nova Scotia</u> | <u>2.438</u> |
| Yampa, Colorado | .054 |

* Canadian receptors are underlined

| | |
|---|---|
| Montmorency, Quebec | 49% |
| Algoma, Ontario | 54% |
| Kejimkujik, Nova Scotia | 50% |
| Longwoods, Ontario | 51% |
| Chalk River, Ontario | 58% |
| Dorset, Ontario | 51% |

On average, the 48% improvement in air quality levels experienced in Canada is considerable, given that the level of control for American utility sources is increased by 51%.

Table 10 lists additional changes in air quality provided by interstate trading relative to the intrastate approach for all receptor sites considered in this analysis. It is interesting to note that while the Canadian receptors generally enjoy greater air quality improvement when interstate trading is introduced, 18 out of 19 receptors in the United States experience smaller air quality improvements. This result may be attributed to substantial decreases in the levels of control assigned to Tennessee, Ohio, Georgia, and West Virginia all of which exert substantial influence on the U.S. receptors as indicated by the transfer co-efficient matrix. Further examination of the state transfer co-efficients for all Canadian receptor sites suggests that improvements are most likely attributed to increased levels of control for Wisconsin (102,777 tons $SO_2$ reduction), Michigan (187,113 tons $SO_2$ reduction) and Pennsylvania (59,930 tons $SO_2$ reduction).

In terms of sulfur dioxide concentration levels remaining after the interstate control policy is implemented, thirteen out of twenty-five receptors remain threatened by levels of emissions from the coal fired utility sector in the United States as shown in Table 11. Again, Longwoods, Ontario receiving 19.947 Kgrams/hectare is the only Canadian receptor which continues to receive significant levels of sulfur dioxide from these sources (as defined by the 10.5 kgrams/hectare standard). However, concern remains for the

TABLE 10

ADDITIONAL AIR QUALITY IMPROVEMENTS OF INTERSTATE TRADING MODEL RELATIVE TO INTRASTATE TRADING MODEL

| RECEPTOR | $SO_2$ REDUCTION * (In Kgrams/Hectare) |
|---|---|
| Big Moose Lake, New York | -.113082 |
| Zanesville, Ohio | -2.268208 |
| Montmorency, Quebec | .016649 |
| Algoma, Ontario | .758287 |
| Kejimkujik, Nova Scotia | -.076678 |
| Longwoods, Ontario | 3.236468 |
| Trout Lake, Wisconsin | 1.302443 |
| Fernberg, Minnesota | -1.338815 |
| Great Smokie Mountains, Tennessee | -1.501788 |
| Shenandoah National Park, Virginia | -3.206595 |
| Penn State, Pennsylvania | -.868811 |
| Uvalda, Georgia | -.758537 |
| Dorset, Ontario | .751352 |
| Babcock State Park, West Virginia | -2.356212 |
| Hubbard Brook, New Hampshire | -.024989 |
| Clingman's Peak, North Carolina | -3.129802 |
| Horton's Station, Virginia | -2.002820 |
| Kane Exp. Forest, Pennsylvania | -.611126 |
| Chalk River, Ontario | .406585 |
| Tunkhannock, Pennsylvania | -.279085 |
| Oak Ridge, Tennessee | -4.534400 |
| Washington, D.C. | -3.933538 |
| Yampa, Colorado | -.004069 |
| Whiteface Mountain, New York | -.044029 |
| Coweeta, North Carolina | -2.743020 |

* Negative values represent decreases in air quality under the interstate trading model relative to the intrastate trading model.

TABLE 11

INTERSTATE TRADING MODEL

| RECEPTOR * | $SO_2$ LEVELS (Kgrams/hect.) before control | % REDUCTION $SO_2$ | BALANCE $SO_2$ (Kgrams/hect.) |
|---|---|---|---|
| Zanesville, Ohio | 81.387 | 57% | 34.212 |
| Penn State, Pennsylvania | 74.635 | 54% | 33.659 |
| Tunkhannock, Pennsylvania | 56.015 | 43% | 31.561 |
| Washington, D.C. | 47.404 | 42% | 27.492 |
| Kane Exp. Forest, Pennsylvania | 59.835 | 55% | 26.605 |
| Shenandoah National Park, Virginia | 46.935 | 46% | 25.336 |
| Oak Ridge, Tennessee | 43.712 | 44% | 24.470 |
| Babcock State Park, West Virginia | 46.184 | 49% | 23.428 |
| Clingman's Peak, North Carolina | 33.658 | 36% | 21.483 |
| Longwoods, Ontario | 39.702 | 51% | 19.947 |
| Horton's Station, Virginia | 35.231 | 44% | 19.609 |
| Great Smokie Mountains, Tennessee | 25.755 | 48% | 13.154 |
| Coweeta, North Carolina | 24.255 | 52% | 11.465 |
| Big Moose Lake, New York | 20.225 | 51% | 9.767 |
| Dorset, Ontario | 16.285 | 51% | 7.850 |
| Fernberg, Minnesota | 12.394 | 41% | 7.262 |
| Hubbard Brook, New Hampshire | 13.917 | 52% | 6.676 |
| Whiteface Mountain, New York | 13.551 | 51% | 6.523 |
| Uvalda, Georgia | 11.309 | 54% | 5.148 |
| Chalk River, Ontario | 10.299 | 58% | 4.291 |
| Trout Lake, Wisconsin | 9.901 | 61% | 3.834 |
| Algoma, Ontario | 8.004 | 54% | 3.667 |
| Montmorency, Quebec | 5.488 | 49% | 2.794 |
| Kejimkujik, Nova Scotia | 4.859 | 50% | 2.421 |
| Yampa, Colorado | .090 | 60% | .036 |

* Canadian Receptors are underlined.

majority of American receptors, particularly Zanesville (34.212 Kgrams/hectare), Penn State (33.659 Kgrams/hectare), Shenandoah National Park (25.336 Kgrams/hectare), Babcock State Park (23.428 Kgrams/hectare), Kane Exp. Forest (26.605 Kgrams/hectare), Tunkhannock (31.561 Kgrams/hectare), and Washington (27.492 Kgrams/hectare).

## AMBIENT MARKET SYSTEM

### Background

While the previous analyses have focused on the use of market systems to achieve aggregate emissions targets, the nature of the pollutant considered would suggest that perhaps a more appropriate policy target would be the achievement of air quality standards at each of the 25 sensitive receptor sites considered. In other words, if the ultimate objective of the sulfur dioxide control program is to alleviate the damage caused by acid bearing precipitation in sensitive areas of the United States and Canada, the control of concentration levels in these areas should be the focus of concern. However, because the quantity of sulfur dioxide emissions released into the air is not directly related to changes in air quality at these sensitive areas, the achievement of aggregate emissions targets may be unsuccessful in achieving the desired levels of air quality improvement. In the case of nonuniformly mixed pollutants such as sulfur dioxide, any control policy which seeks to directly limit concentration levels at important receptor sites, must take into consideration the level of aggregate emissions as well as the location and degree of clustering of the emitting sources. Ideally, those sources whose emissions have the greatest effect on air quality should assume primary responsibility for reducing emissions.

In the two market approaches examined previously, the importance of considering source location in achieving air quality targets is ignored. Aggregate emission targets are established in the hope that the resulting changes in sulfur dioxide concentration levels in regions of the country particularly sensitive to the effects of acid precipitation, are significant. Indeed, because the size of the emission reduction targets established are so substantial, improvement in air quality occurs at all 25 receptors examined. The question remains, however, as to whether the resulting air quality improvements at each receptor can be achieved with less commitment of resources to abatement control.

As discussed in the theory portion of this paper, only a system in pollution rights is capable of providing a least cost control allocation when the policy target is the achievement of air quality standards as opposed to aggregate emissions reduction targets. Substantial cost penalites may be associated with the use of a simple market system in emission rights (relative to an ambient market system) when the objectives of the policy are defined in this way. In response to this concern, the following analysis will examine the costs of achieving the air quality improvements achieved under the interstate emissions trading model when a system in pollution rights is implemented.

According to theory, sources participating in a market for pollution rights will operate according to the following condition:

$$(5.3)\quad \partial C_i(r_i)/\partial r_i - \Sigma_j\, d_{ij}\, P_j \geq 0 \quad r_i\, [\partial C_i(r_i)/\partial r_i - \Sigma_j\, d_{ij}\, P_j\, ] = 0$$

In other words, sources will increase their level of control to the point where marginal control costs are equal to a weighted average of the permit price for all receptors where the transfer co-efficient serves as the appropriate weight. This will require that sources participate in all receptor markets for which the value of their transfer co-efficient is greater than zero. Intuitively, this condition means that sources will continue to increase their level of emission control until the marginal cost of controlling an additional emission is equal to the cost of acquiring the pollution rights required to emit an additional unit of emissions. In a market equilibrium where all sources are operating according to this condition, the resulting control allocation will represent the least cost allocation for achieving air quality targets. Furthermore, an equilibrium price for pollution rights, Pj, will be established in each receptor market, the value of which will reflect the difficulty, in terms of control costs, which the market experiences in meeting the target for each receptor j.

In order to evaluate the cost effectiveness of a pollution rights system which allows complete flexibility in the control strategies available to all sources in meeting air quality targets at various receptor sites, cost information on a state level must once again be used. The states themselves will be viewed as the market participants in a type of zonal market system which is based on the premise that each state will constitute an individual zone and each zone will be assigned an initial allocation of pollution rights such that required air quality levels at all important receptor sites will be maintained. Each pollution right will be distinguished according to receptor site, and will entitle the designated state to increase its level of emissions to the point where the pollution concentration level at the specified receptor increases by one unit. Therefore, once an inital allocation of pollution rights has been assigned to each state, the state control authorities must determine the allowable level of emissions such that the resulting pollution concentration levels at every receptor remain below or equal to that allowed by the pollution licences.

Specifically, if $l_{ij}$ represents a pollution licence for state, i, to pollute at receptor, j; $d_{ij}$ represents the transfer co-efficient which translates emission levels from state, i, into pollution concentrations at receptor, j; and $e_i$ represents emissions from state i, then the emission targets consistent with the initial allocation of licences for the state may be calculated according to the following condition:

(5.4) Emissions = Min j $l_{ij}/d_{ij}$ or alternatively $d_{ij}e_i \leq l_{ij}$ for all j.

Once emission targets for each state have been established in this manner, individual sources within each state will be allowed to compete for ownership of the designated emission rights. In other words, for the purposes of this model, it will be assumed that a market in emission rights is established for each of the 25 states considered.

Sources within each state will engage freely in the trading of rights (as in the interstate model) so as to achieve a cost effective allocation of control for achieving the state emission targets determined by condition (5.4). These least cost solutions for each state will be represented once again by the linearized cost algorithms in Table 5.

In summary, states are assigned an inital allocation of pollution rights which may be traded in the context of an interstate pollution rights market; the allocation of pollution rights is subsequently translated into emission control targets for each state, and the cost algorithms of Table 5 are used to calculate total costs for achieving these emission targets. This approach is similar to the zonal approach formulated by Montgomery (1972) in which emissions trading is allowed on a one for one basis between sources of each zone given the assumption that all sources within each zone have identical transfer co-efficients. Trades between zones, however, are only allowed subject to the rule that the resulting pollution levels remain below or equal to those levels which would have occurred had no trade been executed.

The basic intent of the following analysis will be to examine the potential for achieving control cost reductions through the reallocation of pollution rights between states. If each state is allowed to freely engage in the trade of pollution rights in the context of an interstate market for pollution rights, a cost efficient allocation of pollution control will be achieved. This will require that each state engage in trade so as to minimize its costs of controlling emissions and acquiring pollution licenses according to the following condition:

(5.5) $\partial C_i(r_i)/\partial r_i - \Sigma_j\, d_{ij}\, P_j \geq 0 \quad r_i\, [\, \partial C_i(r_i)/\partial r_i - \Sigma_j\, d_{ij}\, P_j\, ] = 0$

where $P_j$ represents the equilibrium price of pollution licences for receptor, j. In this case marginal costs of control, $\partial C_i(r_i)/\partial r_i$, represent the state marginal costs of control associated with each of the three state reduction variables (See Table 6). Simply, this condition implies that states will control emissions to the point where marginal costs of controlling one additional emission are equal to the cost of emitting one additional emission in terms of licence acquisition expenditures. In a market equilibrium, where all states operate according to this condition, the resulting allocation of emission control will reflect the least cost allocation for achieving desired air quality levels. Though the analysis is conducted on a state basis due to data limitations, all trading opportunities for individual sources to reduce costs of achieving air quality standards will be recognized by the model given the limiting assumption that all sources within each state have identical transfer co-efficients. Therefore, the following analysis is representative of a full ambient market approach which allows for complete flexibility in the control options available to every source in every state.

<u>The Ambient Market Model</u>

The following analysis examines whether the costs of achieving those air quality improvements realized under the interstate trading model, can be substantially reduced when instead of constraining aggregate emission control levels across all states, the proximity of state emission sources to sensitive receptor areas is taken into account. Once again, the linear programming system, MPS, is used to evaluate the cost saving potential of the model outlined in the previous section.

Essentially the problem is one of minimizing the cost of emission control across all 25 states subject to the constraints that air quality improvements are greater than or equal to those improvements experienced under the interstate trading model. Accordingly, the linear program is formulated as follows:

(1) $\text{Min } F = Z_{11}X_{11} + Z_{12}X_{12} + Z_{13}X_{13} \ldots Z_{25,1}X_{25,1} + Z_{25,2}X_{25,2} + Z_{25,3}X_{25,3}$

subject to

(2)-(26) $D_{11}(X_{11}) + D_{11}(X_{12}) + D_{11}(X_{13})$............$D_{25,1}(X_{25,1})$ + $D_{25,1}(X_{25,2}) + D_{25,1}(X_{25,3}) \geq a_k$ for all receptors, k = 1...25

(27) $X_{ij} \leq W_{ij}$ for all i and all j

where $X_{ij}$ represents emission reduction variable j for state, i; $Z_{ij}$ represents marginal cost of emission reduction variable j for state i; $D_{ik}$ represents the transfer co-efficient for state i, receptor, k; and $a_k$ represents the required reduction in sulfur dioxide concentration levels at receptor, k as defined by the changes shown in Table 9 which were generated by the interstate model.

The objective function remains the same as that for the interstate trading model. The linearized version of the cost algorithms are used once again to represent total control costs for each state, and accordingly, the three emission reduction variables are defined for each state. However, because the policy target is the achievement of air quality improvements rather than the achievement of aggregate emission control levels, the constraints are defined in terms of reductions in sulfur dioxide concentration levels at each of the 25 receptor sites rather than in terms of the aggregate emissions control level. The values for $a_k$, k=1...25, represent the levels of reduction in sulfur dioxide for each receptor, k, which are achieved under the interstate emissions trading model. These values provide the minimum requirements for air quality improvement in the model. On the other hand, the quantity of controlled emissions across all states will remain unconstrained, and it is expected that air quality levels will be achieved at less cost than under the interstate trading model simply because the level of control required is expected to be less given the consideration to the importance of source location (or in this case state location) in addition to marginal control costs.

Control Allocation for the Ambient Market Model

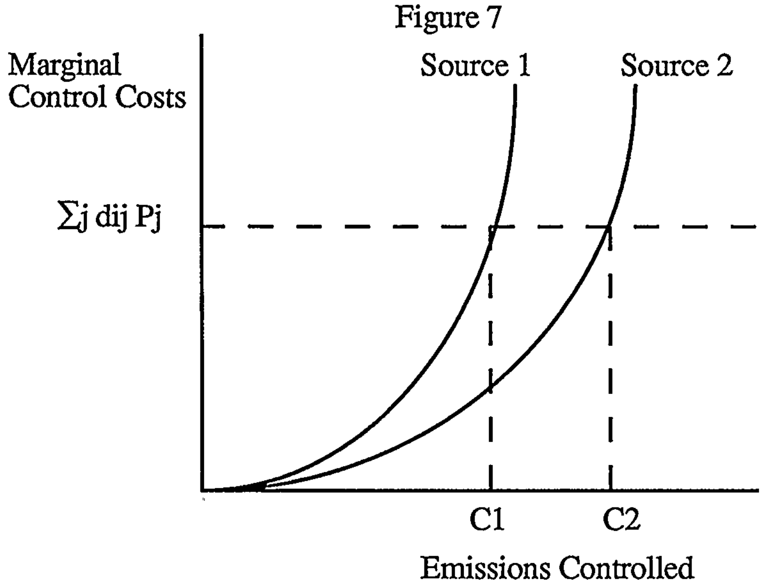
The optimal solution provided by the linear program detailed above, should reflect the cost minimizing solution provided by a state market in pollution rights where the minimum requirements for air quality improvements represented by $a_k$, k=1...25, reflect the quantity of pollution rights initially allocated across states. According to theory, this least cost allocation will be established where each state controls emissions according to the following condition:

(5.6) $\partial C_i/\partial r_i - \Sigma_j\, d_{ij}\, P_j \geq 0 \quad r_i\, [\, \partial C_i/\partial r_i - \Sigma_j\, d_{ij}\, P_j\, ] = 0$

where $P_j$ represents the value of a pollution right for receptor j in a market equilibrium, or alternatively the shadow price for pollution rights as determined by the linear programming model. Further examination of this condition reveals the general conditions under which high or low levels of control responsibility may be assigned. The first condition holds that because sources will optimize by equating marginal costs of control with the cost of licence acquisition required for each additional unit of emission, a higher level of control will be assigned to those sources with relatively low marginal costs at all reduction levels in the case where the set of transfer co-efficients is assumed identical for all sources. This condition is illustrated in Figure 7 where two sources are considered, each with the same value for $\Sigma_j\, d_{ij}\, P_j$, (the costs of licence acquisition for each additional emission). Source 2 with relatively low marginal control costs will be assigned a level of control at C2 while Source 1 with relatively high marginal control costs will be assigned a control responsibility of C1.

The second condition considers how differences in the value of the transfer co-efficients may influence control responsibility in the simple case where marginal costs are assumed to be equal for all sources. Specifically, for those sources which have relatively high values for transfer co-efficients, $d_{ij}$, particularly for those associated with highly congested receptors with high values for $P_j$, a higher level of control responsibility will be assigned. In other words, the higher the values for $d_{ij}$, for j=1...25, generally, the higher will be the cost of emitting one additional unit in terms of pollution right acquisition costs. Since cost efficient sources will increase control to the point where marginal costs equal the value $\Sigma_j\ d_{ij}\ P_j$, those sources with higher values for $\Sigma_j\ d_{ij}\ P_j$, will increase control to higher levels. This condition is illustrated in Figure 8 where the level of efficient control increases for this source as alternative values of $\Sigma_j\ d_{ij}\ P_j$ are considered.

Figure 7




It is important to mention, however, that because the linearized versions of the cost curves are used in this analysis, increasing levels of reductions for each state will be associated with constant marginal costs over wide ranges, rather than with continuously increasing marginal costs. Therefore, every state may not be able to equate marginal control costs with the value $\Sigma_j\ d_{ij}P_j$ as required by condition (5.6). Instead, each state will increase its level of control to the point where the marginal costs of control are less than or equal to the cost of emitting an additional unit of emissions in terms of licence acquisition for all relevant receptors.

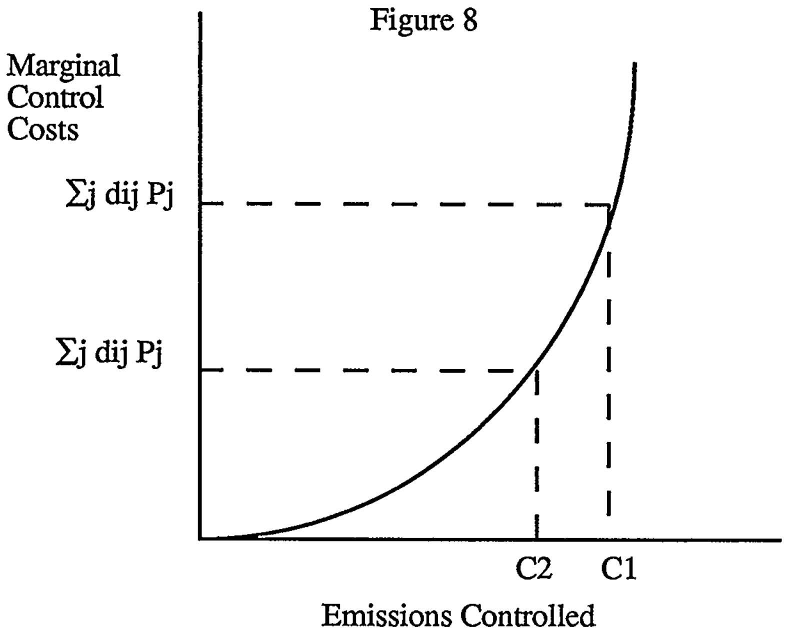



Table 12 provides the efficient allocations for control responsibility for the linear program representing the ambient market approach. Once again, Indiana, Missouri, Ohio, Kentucky and Pennsylvania are assigned high levels of responsibility. On the other hand, Arkansas, Delaware and Virginia are assigned no control responsibility whatsoever. A comparison of all control allocations with those under the interstate emissions trading model shows that Alabama, Michigan, North Carolina, Tennessee, Wisconsin, West Virginia and Ohio are assigned a higher level of control under the ambient approach while Arkansas, Delaware Minnesota, Mississippi, New Hampshire, Missouri and Illinois are assigned less responsibility.

Examination of the factors influencing control allocation according to condition (5.6), for those states with relatively high levels of control and those with little or no control may provide some insight as to why this allocation is assigned. For example, Ohio, with the highest level of control responsibility, is characterized by low marginal

TABLE 12
CONTROL ALLOCATION UNDER AMBIENT MARKET

| STATE | Control (Million tons) | Percentage Reduction | Marginal Cost ($million 1985) | Total Cost ($million 1985) |
|---|---|---|---|---|
| Alabama | .2796 | 50% | 700.1700 | 91.2401 |
| Arkansas | 0.0000 | ----- | 9.8333 | 0.0000 |
| Delaware | 0.0000 | ----- | 161.6000 | 0.0000 |
| Florida | .2825 | 61% | 268.1800 | 54.9477 |
| Georgia | .4705 | 61% | 491.6900 | 167.2608 |
| Illinois | .4245 | 32% | 548.1000 | 3.8230 |
| Indiana | 1.0980 | 61% | 333.0000 | 243.3660 |
| Iowa | .2150 | 65% | 50.5311 | 10.8641 |
| Kentucky | .7130 | 60% | 441.5100 | 177.0668 |
| Maryland | .0680 | 32% | 142.7351 | 9.7059 |
| Michigan | .2823 | 44% | 819.1800 | 96.7113 |
| Minnesota | .0793 | 49% | 412.7000 | 27.2689 |
| Mississippi | .0380 | 32% | 91.6997 | 3.4845 |
| Missouri | .5910 | 40% | 42.2876 | 24.9919 |
| New Hampshire | .0333 | 67% | 516.0800 | 17.1920 |
| New Jersey | .0480 | 41% | 31.3080 | 1.5027 |
| New York | .0700 | 34% | 161.2470 | 11.2872 |
| North Carolina | .0026 | 01% | 700.1446 | 1.8240 |
| Ohio | 1.5748 | 66% | 1237.7000 | 253.5994 |
| Pennsylvania | .6830 | 60% | 425.4500 | 221.0062 |
| South Carolina | .0700 | 39% | 280.6485 | 19.6453 |
| Tennessee | .3777 | 36% | 639.4500 | 24.6005 |
| Virginia | 0.0000 | ----- | 560.2800 | 0.0000 |
| West Virginia | .3626 | 36% | 595.9900 | 83.6212 |
| Wisconsin | .4364 | 74% | 1281.8000 | 175.8429 |

Total Control Costs: $1720.8524

control costs at all levels of reduction relative to other states. (See Table 6 for marginal costs associated with each emission reduction variable for each state.) Secondly, Ohio's cost of licence acquisition for each additional unit of emission in a market equilibrium (i.e. $\Sigma j\ d_{ij}P_j$), is relatively high. In order to determine this value for Ohio, the shadow prices for all binding receptors provided by the linear program and presented in Table 13, are used as approximations for each $P_j$.[10] For non-binding receptors, the equilibrium permit price or alternatively, the value of the pollution rights in the optimal solution, is assumed to be zero. Accordingly, the value $\Sigma j\ d_{ij}\ P_j$ for Ohio is calculated as follows:

| | | |
|---|---|---|
| Zanesville, OH | 18.352 (48.093)= | $ 882.60 |
| Algoma, ONT | .251(223.943)= | 56.20 |
| Trout Lake, WI | .084(39.174)= | 3.29 |
| Fernberg, MN | .028(21.682)= | .60 |
| Great Smokie Mtns, TN | .503(93.477)= | 47.00 |
| Uvalda, GA | .112(46.495)= | 5.20 |
| Hubbard Brook, NH | 1.256(41.286)= | 51.85 |
| Clingman's Peak, NC | .726(.082)= | .05 |
| Horton's Station, VA | 3.072(9.683)= | 29.74 |
| Yampa, CO | 0.000(15,442)= | 0.00 |
| Whiteface Mtn, NY | 1.508 (106.827)= | 161.09 |
| Total Cost of Licence Acquisition: | | $1237.62 |

This relatively high value for $\Sigma j\ d_{ij}\ P_j$ is primarily attributed to the high value for the transfer co-efficient associated with Zanesville, Ohio (d = 18.352). For each

10 Shadow prices represent approximate values for pollution rights at each receptor since marginal control costs are represented by step functions when the linearized version of the cost algorithms is used.

TABLE 13
SHADOW PRICES FOR BINDING RECEPTORS UNDER AMBIENT MARKET MODEL

| RECEPTOR | SHADOW PRICE ($million 1985) |
|---|---|
| Yampa, Colorado | $15,442.000 |
| Algoma, Ontario | 223.943 |
| Whiteface Mountain, New York | 106.827 |
| Great Smokie Mountains, Tennessee | 93.477 |
| Zanesville, Ohio | 48.093 |
| Uvalda, Georgia | 46.495 |
| Hubbard Brook, New Hampshire | 41.286 |
| Trout Lake, Wisconsin | 39.174 |
| Fernberg, Minnesota | 21.682 |
| Horton's Station, Virginia | 9.683 |
| Clingman's Peak, North Carolina | .082 |

additional unit of emissions (i.e. one million emissions) by the state of Ohio, the cost of licence acquisition for this receptor is equal to $882.607 (in millions of $1985), and therefore, strong incentive exists for the state to control emissions, particularly given its low marginal control costs at all levels of reduction. In fact, Ohio is one of the few states for which control at the highest levels of reduction (75% - 90%) in a market equilibrium is more cost efficient than purchasing pollution licences for additional emissions.

Relative to Ohio, Indiana has both higher marginal control costs for most levels of reduction (although costs are low relative to other states), as well as higher costs for licence acquisition estimated at $1310.49 million ($1985):

| | | |
|---|---|---|
| Zanesville, OH | 4.32(48.093)= | $ 207.761 |
| Algoma, ONT | .559(223.943)= | 125.184 |
| Trout Lake, WI | .254(39.174)= | 9.950 |
| Fernberg, MN | .051(21.612)= | 1.105 |
| Great Smokie Mtns., TN | 1.524(93.477)= | 142.458 |
| Uvalda, GA | .305(46.495)= | 14.180 |
| Hubbard Brook, NH | .507(41.286)= | 20.932 |
| Clingman's Peak, NC | 1.32(.082)= | .108 |
| Horton's Station, VA | 1.726(9.683)= | 16.712 |
| Yampa, CO | .05(15,442)= | 772.100 |
| Whiteface Mtn, NY | 0(106.827)= | 000.000 |
| | | $1310.490 |

In this case, the relatively high licencing costs reflect the fact that Indiana must purchase pollution rights from the receptor at Yampa, Colorado. The value for these rights as indicated by the shadow price of $15,442 million ($1985), substantially exceeds the values for any other receptor. High values for transfer co-efficients associated with Zanesville, Great Smokie Mountains, Clingman's Peak and Horton's Station also contribute to the high costs of licence acquisition. The fact that Indiana has the second highest level of control under the ambient market approach, therefore, again reflects relatively low marginal costs of control as well as high costs of licence acquisition particularly for Yampa, Colorado.

On the other hand the relatively high allocation of control responsibility to Missouri primarily reflects its low marginal control costs particularly at low levels of reduction (See Table 6). The state's cost of licence acquisition for each additional unit of emissions remains moderately low at $381.712 million ($1985), since state emissions do not have an unusually large effect on receptors as indicated by the average size of the transfer co-efficients associated with these receptors (See Appendix III).

In contrast to the low marginal control costs and high costs of licence acquisition characterizing states with high levels of control responsibility, it is expected that those states with little or no control will generally be characterized by high marginal costs, low transfer co-efficients or a combination of both. Virgina, for example, with a control allocation of zero, has high marginal costs relative to its costs of licence acquisition. The cost of its expenditures on licence acquisition for each additional unit of emissions, remains relatively low due to the fact that its transfer co-efficients for six out of the eleven binding receptors is zero, and therefore licence purchases are not required for these areas. In total an additional unit of emission will cost $321.983 million ($1985) in terms of licence acquisition in the market equilibrium. However, marginal control costs even at the lowest reduction levels is valued at $560.28 million ($1985) which exceeds the costs of licence acquisition. Therefore, there exists no incentive for Virginia to control any emissions since it is more cost efficient to purchase licences. Similarly, Delaware with high marginal control costs, particularly for reductions in the midrange or high range of control, is assigned no control responsibility. This may also be attributed to the zero values for transfer co-efficients associated with eight out of the eleven binding receptors which ultimately translate into low costs of licence acquisition. The most simple case is perhaps illustrated by the state of Arkansas for which all transfer co-efficients are assigned a value of zero. Clearly, Arkansas will have no incentive to control emissions since it is not required to purchase any pollution licences regardless of its level of total emissions.

As a general observation it would appear that low marginal control costs and high values for transfer co-efficients translate into high levels of control, and vice versa. Ultimately, it is the interplay of these two conditions for each state which will determine their optimal control allocation. Allocations will also take into account whether high values of transfer co-efficients are associated with receptors which are highly congested and therefore, exhibit high values for pollution rights (or alternatively high costs of controlling pollution in the optimum) or whether these are associated with less congested receptors for which the value of pollution rights is relatively low. These factors, clearly will affect the costs of licence acquisition, and accordingly will affect the control allocation for each state.

Costs of Control under the Ambient Market Model

Total control costs for each state under the ambient market approach are presented in Table 12. As anticipated those states with the highest levels of control are associated with high total costs of control, namely, Indiana, Kentucky, Ohio, and Pennsylvania.

However, the low total costs of control associated with Missouri ($24.9919 million in 1985 dollars) with a level of control at .5910 million tons relative to the high total control costs for Wisconsin ($175.8429 million in 1985 dollars) with a level of control of .4364 million tons perhaps requires some explanation. Examination of the transfer co-efficients for Wisconsin reveals that for each additional unit of emission by this state, substantial impacts will result at Zanesville, Algoma, Trout Lake, and Fernberg. This factor ultimately translates into a high cost of licence acquisition for the state, which subsequently translates into a relatively high level of control responsibility. Missouri, on the other hand, is assigned a substantial portion of control responsibility, not necessarily due to its environmental impacts, but rather because of its unusually low marginal costs of control. Therefore, in the case of these two states, the high allocation of control is attributed primarily to different factors which ultimately translate differently into total control costs. For Wisconsin, control at reduction levels associated with relatively high marginal costs is assigned due to the high costs of licence acquisition to increase emissions. Total costs are, therefore, high. However, for Missouri, marginal control costs remain low along with costs of licence acquisition in a market equilibrium, and therefore, total control costs remain relatively low.

In total, the cost of achieving the required sulfur dioxide concentration reductions at each of the 25 receptors considered, is estimated at $1720 million (in $1985). This represents a cost saving of $3 million (in $1985) over the interstate emissions trading approach. In terms of the costs which would be required to organize, implement, and operate a more complex system of this type, this cost saving is not substantial.

Shadow Prices for Binding Receptors

The shadow prices associated with each of the binding receptors presented in Table 13 represent the approximate value of the pollution rights for each receptor. Alternatively, these values represent the difficulty which the emitting sources experience in achieving pollution reduction levels, in terms of costs of control at the optimal allocation. The extremely high value for Yampa, Colorado reflects the fact that only emission reductions from the state of Indiana will improve air quality levels. Furthermore, because the transfer co-efficient which translates emissions from Indiana into sulfur dioxide levels at Yampa is valued at only .05 Kgrams per million tons of sulfur dioxide emitted, very substantial reductions for the state of Indiana would be required in order to reduce sulfur dioxide levels by one Kgram. Similarly, the very low transfer co-efficients which translate emission levels into changes in sulfur dioxide levels for Algoma, Ontario, explain the relatively high shadow price for pollution rights for this receptor. Generally, low transfer co-efficients require high levels of control by states in order to achieve significiant changes in air quality, and to the extent that these required levels of reduction are associated with high marginal costs, the value of pollution rights for the associated receptor will be high. Furthermore, the fewer the number of states which affect air quality at a specific receptor, the greater is the likelihood that high marginal costs will be associated with control requirements for achieving air quality improvements in a market equilibrium. If only a small number of states can effect air quality changes for a receptor, the levels of reduction required of these states may be high and the marginal costs associated with these high control levels may also be high given the assumption that marginal costs rise with the level of control. Accordingly, the high shadow prices will reflect the high degree of difficulty for achieving air quality improvements.

On the other hand, for the case of receptors assigned low shadow prices for pollution rights, generally high transfer co-efficients are associated with those states which affect air quality and, generally, low marginal costs are associated with the levels of control required by these states to achieve a one unit improvement in air quality at the market equilibrium. Furthermore, the greater the number of states over which control responsibility can be spread, the greater is the likelihood that control costs will remain low. For example, the low shadow price assigned to Clingman's Peak can be explained by the fact that 18 out of 25 states positively affect air quality through emission reductions and of these 18 states, 9 have high values for the transfer co-efficient associated with this receptor. For the 11 binding receptors listed in Table 13, the interaction between marginal costs and size of transfer co-efficients for all states will determine the values for the shadow prices for pollution rights for a given air quality target.

Environmental Impacts under the Ambient Market Model

In terms of the level of sulfur dioxide reduction levels achieved by the ambient market approach, there is very little change from those levels achieved under the interstate emissions trading model. Receptor sites for which air quality targets are not binding in the optimal solution do, however, experience some additional improvement over the interstate model. These improvements to air quality are listed in Table 14. Five Canadian receptors enjoy additional improvements in air quality. Relatively minor additional improvements are also experienced by nine other receptors located in the United States.

TABLE 14
ADDITIONAL AIR QUALITY IMPROVEMENTS UNDER
AMBIENT MARKET MODEL
(RELATIVE TO INTERSTATE TRADING MODEL)

| RECEPTOR | $SO_2$ REDUCTIONS (in million tons/hectare) |
|---|---|
| Big Moose Lake, New York | .10079912 |
| Montmorency, Quebec | .00996530 |
| Kejimkujik, Nova Scotia | .00000193 |
| Longwoods, Ontario | .87260284 |
| Shenandoah National Park, Virginia | .29026543 |
| Penn State, Pennsylvania | .33942570 |
| Dorset, Ontario | .16368917 |
| Babcock State Park, West Virginia | .06759330 |
| Kane Exp. Forest, Pennsylvania | .29019153 |
| Chalk River, Ontario | .00556856 |
| Tunkhannock, Pennsylvania | .11043274 |
| Oak Ridge, Tennessee | .50066727 |
| Washington, D.C. | .18621387 |
| Coweeta, North Carolina | .15112048 |

# CHAPTER 6

# CONCLUSIONS

## VIABILITY OF AN INTERSTATE EMISSIONS TRADING MARKET

One of the basic intents in conducting the empirical analysis detailed in Chapter 5, is to determine the cost effectiveness of implementing a system in marketable emission permits as a viable alternative to the traditional regulatory approach to environmental management which currently predominates U.S. control policy. Ideally, a comparison between costs associated with controlling emissions under a purely regulatory approach should be made with those incurred under an emission trading market approach. However, given that data limitations preclude an analysis of this sort, the intrastate trading model is used as a basis for evaluating the cost effectiveness of the interstate emission trading model which is comparable to that proposed in Phase II of current U.S. legislation.

The intrastate trading model defined in Chapter 5 achieves the same state control targets as a purely regulatory approach which requires that all sources (75 megawatts and over) meet an imposed standard of 1.20 lbs. $SO_2$/MBTU. However, the benefits of an approach which allows for the trading of emission rights between sources within a state is that it achieves state emission control targets with the least commitment of resources to emission control. Clearly, then the costs of control incurred to achieve those same state control targets under a regulatory approach will be equal to or, more likely, greater than those incurred under an intrastate market in emission rights. Therefore, comparision of control costs incurred under the interstate trading model defined in Chapter 5 and those incurred under the intrastate trading model will define the minimum cost savings achievable by moving from a purely regulatory approach to pollution control to an emission trading system which allows for the full transferability of rights between all sources of all states. It is , however, highly likely that the cost savings attainable by implementing such a system in place of a regulatory structure will be significantly greater than the minimum.

The analysis provided in Chapter 5 indicates that a $646 million ($1985) cost saving may be realized by moving from a restricted market approach which confines trade to sources within a state to a market approach which broadens trading opportunities beyond state borders. This represents a 27% cost reduction from the intrastate trading model. Clearly, this cost advantage of increased flexibility in control options available to sources in the context of an interstate emission market is substantial, and considering that the cost advantage of such a system over a regulatory policy is bound to be even greater, the implementation of an interstate emissions trading program certainly warrants consideration.

However, it must be recognized that the estimated potential cost savings of $646 million ($1985) is based on the assumption that a pure interstate market in emission rights is established. In other words, no distinctions between sources on the basis of age, ownership, type of industry etc. are made. All sources are assumed to participate equally in the program and the allocation of emission control among sources is determined solely by the market. Furthermore, approval of control methods or distribution of permits by the control authority is not required. Indeed, the role of the control authority under a pure market system is only to establish emission targets, issue permits such that these targets can be achieved, and finally to enforce compliance of sources with permit allowances. To the extent that an emissions trading market actually implemented in the United States does not reflect the characteristics of a pure market system, cost advantages of this approach to pollution control may be lessened.

Specifically, if an emissions trading program is introduced to supplement, rather than replace, an existing regulatory structure, the restrictions on trading of emission rights imposed by the regulatory structure will serve to reduce the flexibility in control strategies enjoyed by emitting sources, thereby reducing potential cost saving opportunities. For example, if the American control authorities continue to enforce stringent standards upon new emitting sources, cost saving opportunities for trade will be limited.

Furthermore, even in the case where a market system in emission rights with few or no restrictions on trade between sources is implemented in the United States, the fact that a regulatory structure has been in place for over a decade may also have a significant impact on costs savings realized. Because the control policy has in the past focused on the use of particular control technologies to maintain air quality standards, existing sources have incurred sunk costs in control equipment which restrict their ability to adjust emission control strategies in order to realize cost savings. Indeed, this circumstance serves as one example of how actual systems in emission trading may differ significantly from the theoretical systems advanced by economists as promising alternatives to the regulation of industry.

Another concern regarding the practicality of markets in emission rights is whether a competitive smooth functioning market can be established. The assumption underlying the market models presented in Chapter 5 is that a well functioning market exists in which a large number of buyers and sellers actually engage in the trading of permits such that a market permit price is established at the long run equilibrium. However, this ideal may be difficult to achieve in the actual application of market systems. If few sources of emissions account for a high proportion of emissions traded in the market, strategic behavior, specifically price manipulation, may occur thereby preventing a least cost allocation of permits. Furthermore, potential also exists for severe price fluctuations in the case where trades occur too infrequently. Such fluctuations tend to undermine the ability of sources to make efficient decisions regarding their control strategies. Concerns in this regard, however, may be unjustified in light of the fact that there exist hundreds of coal fired utility plants in the 25 eastern states considered in this analysis.

Given that the assumptions underlying the market models may not reflect real world circumstances, the cost savings estimated for the interstate trading model versus the more restrictive intrastate model, should be viewed as approximations only. Nevertheless, they are substantial enough to justify consideration of this market approach as a viable alternative to the regulation of industry.

VIABILITY OF THE AMBIENT MARKET SYSTEM

A second objective of this thesis is to establish whether a more complex market system in pollution rights can achieve those air quality improvements achieved under an interstate emission trading market, at much less cost. It is anticipated that under an ambient market approach, those sources which have the greatest impact on sensitive receptor areas will be assigned primary control responsibility, and achievement of air quality control targets will, therefore, require that less aggregate emissions be controlled. Accordingly, it is anticipated that aggregate control costs will be lower.

However, a comparison of control costs estimated for the interstate market model and the ambient market model, indicate that only a $3 million ($1985) saving would be realized by moving to a market system which recognizes the spatial complexities of the control problem. In view of the fact that such a system is extremely complex to implement and enforce, it is likely that control cost savings in the amount of $3 million will be more than offset by increased costs for design, administration and enforcement of the program. It also remains questionable whether market participants, in this case the states themselves, would be capable of accomplishing the complex task of negotiating pollution rights such that a least cost allocation is achieved. Furthermore, the high degree of uncertainty associated with the transfer co-efficients, raises the question as to whether the air quality improvements achieved under the alternative market approaches are, in fact, comparable.

In light of these considerations, a $3 million cost saving to emitting sources under the ambient market approach appears to be inconsequential, and certainly does not indicate that the implementation of a market in pollution rights warrants consideration.

ENVIRONMENTAL IMPACTS

The third objective of this thesis is to determine whether the increased flexibilities in control strategies available to emitting sources under an interstate emissions trading market, will result in a distribution of control responsibility across all states such that air quality levels at sensitive receptor sites are adversely affected. Again, the intrastate trading model is used as a basis of comparision for determining how sulfur dioxide concentration levels change when an interstate market in emission rights is implemented in place of a regulatory approach to control. This comparison is justified since the air quality improvements realized under the intrastate model as presented in Table 3, actually represent those improvements which would be realized under a purely regulatory control policy which imposes a standard of 1.20 lbs. $SO_2$/MBTU, on all sources with capacity of 75 megawatts or greater (given that transfer co-efficients are assigned to individual states rather than individual sources).

The results detailed in Chapter 5 indicate that air quality improvements achieved under the interstate emissions market do not differ substantially from those experienced under a purely regulatory control policy (as provided by the intrastate model analysis). While Canadian receptors, with the exception of Kejimkujik, Nova Scotia, realize small improvements in the order of .016649 Kgrams/hectare to .758287 Kgrams/hectare, American receptor sites generally experience sulfur dioxide concentration increases in the order of .004069 Kgrams/hectare to 4.5344 Kgrams/hectare. While these air quality differences are relatively small, concern may arise over the fact that those sites which experience increases in the level of sulfur dioxide are specifically those sites which continue to receive significant levels of sulfur dioxide from utility plants even after the control policies are implemented. The increase of 4.5 Kgrams/hectare in Oak Ridge, Tennessee is of particular concern given that sulfur dioxide levels of 19.936 Kgrams/hectare are experienced before interstate trading is introduced (under the intrastate trading program).

However, from a Canadian perspective, concerns that air quality will be adversely affected by the distribution of emission permits when the trading of emission rights between states is allowed are not justified. Air quality levels, for the most part, improve by the introduction of interstate trading. On the other hand, all American receptor sites but one experience small increases in sulfur dioxide concentration levels under the interstate market program. However, relative to concentration levels when no controls are imposed, the interstate market provides substantial concentration reductions in the order of 36% to 60% for American receptors while Canadian receptors enjoy reductions ranging from 49% to 58%. Considering the potential benefits of the interstate trading market in terms of cost savings, the dismissal of this market approach on the grounds that small air quality improvements must be sacrificed (relative to the intrastate trading model) does not appear justified.

The analyses presented in this paper also provide some insight as to whether sulfur dioxide concentration levels in sensitive regions will remain at potentially dangerous levels after controls have been implemented. When interstate trading is introduced, 12 out of 19 American receptors continue to receive sulfur dioxide emissions of 10.5 Kgrams/hectare or greater. This clearly indicates a need for further action if the acid deposition problem is to be addressed effectively. However, the Canadian case is more difficult to determine since this analysis has been confined to changes in air quality resulting from control of American sources only. While it does not appear that American sources will be responsible for concentration levels at Canadian receptor areas above 10.5 Kgrams/hectare (with the exception of Longwoods, Ontario), these areas may be threatened by total sulfur dioxide levels originating from sources in both Canada and the United States. In the case of Longwoods, Ontario, however, it is clear that emission levels of American utility plants remain threateningly high.

APPLICATION OF MARKET SYSTEMS IN CANADA

The results obtained from this study indicate that marketable permit systems in emission rights can provide a cost effective alternative to regulation for achieving environmental policy objectives. However, the application of a market approach for controlling sulfur dioxide in Canada may not be practical, considering that the primary emitting sources are so few in number. As noted earlier in this paper, only six copper nickel smelters and one iron processing operation are responsible for approximately 58% of total sulfur dioxide emissions. Clearly, any market in emission rights would be too thin to facilitate adequate trading levels and a smoothly functioning competitive market would not be established. Therefore, the likelihood of achieving a cost efficient allocation of sulfur dioxide control through a market approach would be low in Canada. However, the potential for Canadian sources to enter the U.S. emissions trading market may warrant future consideration.

Furthermore, markets in emission rights in Canada should be considered for other control problems, namely the control of greenhouse gases. Recently, Canada has agreed to achieve a level of carbon dioxide emissions equal to 1988 levels by the year 2000. Given that carbon dioxide is a uniformly mixed pollutant, the control task is easily applied to a market approach in emission rights since the spatial considerations of the control problem can be ignored. The cost savings found in this study indicate that the feasibility of the carbon dioxide application is worth further investigation.

# BIBLIOGRAPHY

## JOURNAL ARTICLES

Atkinson, Scott E. and T. H. Tietenberg. "Approaches for Reaching Ambient Standards in Non-Attainment Areas: Financial Burden and Efficiency Considerations." Land Economics, 60 (1984), 148-159.

Atkinson, Scott E. "Marketable Pollution Permits and Acid Rain Externalities." Canadian Journal of Economics, 16 (1983), 704-722.

Atkinson, Scott E. and Donald H. Lewis. "A Cost Effectiveness Analysis of Alternative Air Quality Control Strategies." Journal of Environmental Economics and Management, 1 (1974), 237-250.

Atkinson, Scott E. and T. H. Tietenberg. "The Empirical Properties of Two Classes of Designs for Transferable Discharge Permit Markets." Journal of Environmental Economics and Management, 9 (1982), 101-121.

Cowling, Ellis B. "Acid Precipitation in Historical Perspective." Environmental Science and Technology, 16 (1982), 110A-121A.

Crocker, Thomas D. and James L. Regens. "Acid Deposition Control." Environmental Science and Technology, 19 (1985), 112-115.

Cushey, Mark A. and Edward S. Rubin. "Simplified Models of U.S. Acid Rain Control Costs." APCA Journal, 38 (1988), 1523-1527.

David, M., W. Eheart, E. Joeres and E. David. "Marketable Permits for the Control of Phosphorus Effluent Into Lake Michigan." Water Resources Research, 16 (1980), 263-270.

Dowd, A. " Acid Rain Perspectives." Environmental Science and Technology, 18 (1984), 341A-344A.

Downing, Paul B. and Lawrence J. White. "Innovation in Pollution Control." Journal of Environmental Economics and Management, 13 (1986), 18-29.

Hahn, R. W. "Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders." Journal of Economic Perspectives, 3 (1989), 95-114.

Hahn, Robert W. and Gordon L. Hester. "Where Did All the Markets Go? An Analysis of EPA's Emissions Trading Program." Yale Journal on Regulation, 6 (1989), 109-153.

Hamlen, William A. "The Quasi-optimal Price of Undepletable Externalities." The Bell Journal of Economics, (1975), 324-334.

Kohn, Robert E. "Industrial Location and Air Pollution Abatement." Journal of Regional Science, 14 (1974), 55-63.

Krupnick, Alan J., Wallace E. Oates and Eric Van De Verg. "On Marketable Air Pollution Permits: The Case for a System of Pollution Offsets." Journal of Environmental Economics and Management, 10 (1983), 233-247.

Krupnick, Alan J. "Costs of Alternative Policies for the Control of Nitrogen Dioxide in Baltimore." Journal of Environmental Economics and Management, 13 (1986), 189-197.

McDonald, Michael E. "Acid Deposition and Drinking Water." Environmental Science and Technology, 19 (1985), 772-776.

McGartland, Albert M. and Wallace E. Oates. "Marketable Permits for the Prevention of Environmental Deterioration." Journal of Environmental Economics and Management, 12 (1985), 207-228.

Mendelsohn, Robert. "Regulating Heterogeneous Emissions." Journal of Environmental Economics and Management, 13 (1986), 301-312.

Merrifield, John D. "The Impact of Selected Abatement Strategies on Transnational Pollution, the Terms of Trade, and Factor Rewards: A General Equilibrium Approach." Journal of Environmental Economics and Management, 15 (1988), 259-284.

Misiolek, Walter S. and Harold W. Elder. "Exclusionary Manipulation of Markets for Pollution Rights." Journal of Environmental Economics and Management, 16 (1989), 156-166.

Montgomery, W. David. "Markets in Licenses and Efficient Pollution Control Programs." Journal of Economic Theory, 5 (1972), 395-418.

Morrison, Michael B. and Edward S. Rubin. "A Linear Programming Model for Acid Rain Policy Analysis." APCA Journal, 35 (1985), 1137-1148.

Riordan, Courtney, George Hidy and James Galloway. "Jekyll Island Meeting Report." Environmental Science and Technology, 19 (1985), 904-907.

Rubin, Edward S. Mark A. Cushey, Ronald J. Marnicio, Cary N. Bloyd, and James F. Skea. "Controlling Acid Deposition: The Role of FGD." Environmental Science and Technology, 20 (1986), 960-969.

Russell, Clifford S. "A Note on the Efficiency Ranking of Two Second Best Policy Instruments for Pollution Control." Journal of Environmental Economics and Management, 13 (1986), 13-17.

Seskin, Eugene P., Robert J. Anderson, Jr., and Robert O. Reid. "An Empirical Analysis of Economic Strategies for Controlling Air Pollution." Journal of Environmental Economics and Management, 10 (1983), 112 - 124.

Shannon, Jack D. "A Model of Regional Long Term Average Sulfur Atmospheric Pollution, Surface Removal, and Net Horizontal Flux." Atmospheric Environment, 15 (1981), 689-701.

Streets, David G., Barry M. Lesht, Jack D. Shannon, and Thomas D. Veselka. "Climatological Variability Effect on Strategies to Reduce Acid Deposition." Environmental Science and Technology, 19 (1985), 887-893.

Tietenberg, Thomas H. "Transferable Discharge Permits and the Control of Stationary Source Air Pollution: A Survey and Synthesis." Land Economics, 56 (1980), 391-415.

Tietenberg, Thomas H. "Air Pollution Control." Public Policy, 22 (1974), 275-292.

BOOKS AND PUBLICATIONS

Anderson, Frederick R., Allen V. Kneese, Phillip D. Reed, Russell B. Stevenson, and Serge Taylor. Environmental Improvement Through Economic Incentives. Baltimore: The Johns Hopkins University Press, 1977.

Baumol, William J. and Wallace E. Oates. The Theory of Environmental Policy. Englewood Cliffs, New Jersey: Prentice Hall, Inc., 1975.

Hite, James C., Hugh H. Macaulay, James M. Stepp, and Bruce Yandle, Jr. The Economics of Environmental Quality. Washington, D.C.: American Enterprise Institute for Public Policy Research, 1972.

Hahn, Robert W. "Designing Markets in Transferable Property Rights - A Practitioner's Guide." Buying a Better Environment, ed. Erhard F. Joeres and Martin H. David. University of Wisconsin Press, 1983.

Hahn, Robert W. and Roger G. Noll. "Designing a Market for Tradable Emissions Permits." Reform of Environmental Regulation, ed. Wesley A. Magat. Cambridge, Mass.: Ballinger, 1982. pp. 119-146.

Kneese, Allen V., Robert U.Ayres and Ralph C. d'Arge. Economics and the Environment. Washington, D.C.: Resources for the Future, Inc., 1970.

MacKintosh, Douglas R. The Economics of Airborne Emissions, The Case for an Air Rights Market. London, England: Praeger Publishers, 1973.

ReVelle, Penelope and Charles ReVelle. The Environment Issues and Choices for Society, 2nd ed. Boston: Willard Grant Press, 1984.

Roberts, Marc J. "Some Problems of Implementing marketable Pollution Rights Schemes: The Case of the Clean Air Act." Reform of Environmental Regulation, ed. Wesley A. Magat. Cambridge, Mass.: Ballinger, 1982. pp. 93-117.

Tietenberg, Tom. Environmental and Natural Resource Economics, 2nd Edition. Glenview, Illinois: Scott, Foresman and Company, 1988.

Tietenberg, Tom. Emissions Trading. Washington, D.C.: Resources for the Future, 1985.

UNPUBLISHED MATERIAL

Argonne National Laboratories. Transfer Co-efficient Matrix from Advanced Statistical Trajectory Regional Air Pollution Model, 1985.

Cooley, J.M. "Aquatic Effects: Water Quality and Fisheries." Proceedings of the APCA Conference, Acid Deposition, Known and Unknowns: The Canadian Perspective, Montreal, April 7-8, 1981.

Cushey, Mark Aaron. "Simplified Models of Sulfur Dioxide Control Costs for the Electric Utility Sector", Masters Thesis, Department of Civil Engineering, Carnegie Mellon University, Pittsburgh, PA, 1986.

Hahn, Robert W. and Gordon L. Hester. "Where Did All the Markets Go? An Analysis of EPA's Emissions Trading Program." School of Urban and Public Affairs, Carnegie Mellon University, Pittsburgh, PA, 1987.

The 1985 NAPAP Emissions Inventory (Version II): Development of the National Utility Reference File. Prepared for The National Acid Precipitation Assessment Program, EPA-60017-89-013a, 1989.

Shannon, Jack D. Oral Communication. Argonne National Laboratory. Argonne, Illinois, 1990.

# APPENDIX I

MONTGOMERY PROOF: The conditions for market equilibrium under a pollution rights system will satsify those conditions required for a constrained joint cost minimum when $ß_j^{**} = P_j^*$.

Proof of Equation (3.25a):

By equation (3.23b), either $ß_{ij}^* = P_j$ or $l_{ij}^* = 0$ and by Equation (3.23c) $l_{ij}^* \geq d_{ij}e_i^*$. Further when $P_j^*$ does not equal $ß_{ij}^*$, then $l_{ij}^* = 0$, and from Equation (3.23c) either $e_i^* = 0$ or $d_{ij} = 0$. When $d_{ij} = 0$, $P_j^*d_{ij} = ß_{ij}^*d_{ij} = 0$. Accordingly, $e_i^*[F_i'(e_i^*) + \Sigma j\ P_j^*d_{ij}] = 0$ holds regardless of whether $P_j^* = ß_{ij}^*$. From equation (3.23b) $ß_{ij}^* \leq P_j^*$, so $\Sigma j\ ß_{ij}^*\ d_{ij} \leq \Sigma j\ P_j^*\ d_{ij}$, and from Equation (3.23a), $F_i'(e_i^*) + \Sigma j\ ß_{ij}^*\ d_{ij} \geq 0$. Therefore one can deduce that $F_i'(e_i^*) + \Sigma j\ P_j^*\ d_{ij} \geq 0$. Therefore, $e_i^*$ and $P_j^*$ satisfy condition (3.25a) for a constrained joint cost minimum.

Proof of Equation (3.25b)

Given that $\Sigma i\ l_{ij}^0 = l_j^0$, according to Equation (3.24) $l_j^0 = \Sigma i\ l_{ij}^0 \geq \Sigma i\ l_{ij}^*$. By equation (3.23c) $l_{ij}^* - d_{ij}e_i^* \geq 0$, therefore $\Sigma i\ l_{ij}^* - \Sigma i\ d_{ij}e_i \geq 0$. Further by the market clearing condition we know that $l_j^0 \geq \Sigma i\ l_{ij}^*$ so that $l_j^0 - \Sigma i\ d_{ij}e_i^* \geq 0$ thus satisfying the inequality of (3.25b). Then by simple substitution of $l_j^0$ for $\Sigma i\ l_{ij}0$, Equation (3.24) gives us $\Sigma j\ P_j^*[l_j^0 - \Sigma i\ l_{ij}^*] = 0$. When $l_{ij}^* = d_{ij}ei^*$ for all i and all j, then $\Sigma j\ P_j^*[l_j^0 - \Sigma d_{ij}e_i^*] = 0$. If $l_{ij}^* - d_{ij}e_i^* > 0$ for some i and j then by Equation (3.23c) $ß^* = 0$. If $P_j^*$ does not equal zero, equation (3.23b) suggests that $l_{ij}^* = 0$ since $(P_j^* - ß_{ij}^*)$ does not equal zero for that i and j, so that $e^*$ must be negative (since $d_{ij} \geq 0$ for every i and j). Therefore because $e^*$ cannot realistically be a negative number, the circumstances must be such that $l_{ij}^* = d_{ij}e_i^*$ or $P_j^* = 0$. Therefore $P^*$ and $e^*$ satisfy equality condition of (3.25b):

$P_j^*[\Sigma i\ d_{ij}e_i^* - l_j^0] = 0$

# APPENDIX II

## STATES CONSIDERED FOR CONTROL ALLOCATIONS

| STATE | 1995 EMISSION LEVELS BEFORE CONTROL (in Ktons) |
|---|---|
| Alabama | 563 |
| Arkansas | 28 |
| Delaware | 72 |
| Florida | 464 |
| Georgia | 774 |
| Illinois | 1326 |
| Indiana | 1814 |
| Iowa | 329 |
| Kentucky | 1184 |
| Maryland | 213 |
| Michigan | 646 |
| Minnesota | 162 |
| Mississippi | 119 |
| Missouri | 1467 |
| New Hampshire | 50 |
| New Jersey | 117 |
| New York | 203 |
| North Carolina | 446 |
| Ohio | 2393 |
| Pennsylvania | 1134 |
| South Carolina | 178 |
| Tennesee | 1041 |
| Virginia | 165 |
| West Virginia | 1014 |
| Wisconsin | 593 |
| TOTAL | 16,495 |

APPENDIX III
TRANSFER CO-EFFICIENT MATRIX
Kgrams Sulfur Dioxide per Hectare at Receptor Sites Per Million Emissions by State Sources

| RECEPTOR | Kentucky | Ohio | Missouri | Illinois | W. Virg. | Wisconsin | Virginia | S Carolina | Tenn. | Penn. | N. York | N. Hamp. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIG MOOSE LK. | .893 | 2.095 | .365 | .742 | 1.869 | 1.058 | .717 | .000 | .642 | 3.146 | 7.156 | 0.000 |
| ZANESVILLE | 6.888 | 18.352 | 1.369 | 2.40 | 5.917 | 1.323 | 1.075 | .327 | 3.209 | 1.049 | .183 | 0.000 |
| MONTMOR. | .255 | .503 | .091 | .285 | .467 | .529 | .000 | .000 | .128 | .607 | 1.101 | 0.000 |
| ALGOMA | .255 | .251 | .547 | .913 | .156 | 3.175 | .000 | .000 | .128 | .110 | .091 | 0.000 |
| KEJIMKUJIK | .128 | .447 | .091 | .171 | .467 | .265 | .358 | .000 | .128 | .773 | 1.284 | 0.000 |
| LONGWOODS | 2.296 | 3.659 | 1.095 | 2.225 | 1.246 | 2.646 | .358 | .000 | 1.412 | 1.049 | .367 | 0.000 |
| TROUT LAKE | .128 | .084 | .821 | .742 | .000 | 8.730 | .000 | .000 | .128 | .055 | 0.000 | 0.000 |
| FERNBERG | .000 | .028 | .274 | .228 | .000 | 1.323 | .000 | .000 | 8.472 | .000 | 0.000 | 0.000 |
| GT. SMOKIES | 2.551 | .503 | .912 | .970 | .467 | .265 | .717 | 2.295 | 1.669 | .166 | 0.000 | 0.000 |
| SHENANDOAH | 2.423 | 5.056 | .639 | 1.027 | 11.838 | .529 | 12.545 | 1.639 | 1.412 | 3.587 | .367 | 0.000 |
| PENN STATE | 2.423 | 8.101 | .730 | 1.198 | 10.125 | 1.058 | 2.151 | .327 | .770 | 25.552 | 1.468 | 0.000 |
| UVALDA | .383 | .112 | .274 | .285 | .000 | .000 | .000 | 2.295 | .642 | .055 | 0.000 | 0.000 |
| DORSET | .893 | 1.480 | .547 | 1.027 | .779 | 1.852 | .358 | .000 | .642 | .993 | 1.193 | 0.000 |
| BABCOCK ST. | 4.846 | 5.418 | .912 | 1.426 | 8.099 | .529 | 7.168 | 1.311 | 3.337 | .827 | .091 | 0.000 |
| HUBBARD | .637 | 1.256 | .273 | .456 | 1.246 | .529 | .716 | .327 | .256 | 2.262 | 4.220 | 12.500 |
| CLINGMAN'S | 2.168 | .726 | .821 | .912 | .623 | .264 | 1.433 | 3.606 | 4.364 | .220 | 0.000 | 0.000 |
| HORTON'S ST. | 3.188 | 3.072 | .729 | 1.083 | 3.271 | .529 | 13.978 | 2.295 | 3.080 | .717 | .091 | 0.000 |
| KANE EXP. | 2.423 | 8.743 | .821 | 1.426 | 6.074 | 1.322 | 1.433 | .327 | 1.412 | 13.300 | 1.926 | 0.000 |
| CHALK RIVER | .637 | 1.089 | .364 | .741 | .623 | 1.322 | .000 | .000 | .385 | .883 | 1.284 | 0.000 |
| TUNKHANNOCK | 1.530 | 4.162 | .547 | .912 | 4.984 | 1.058 | 2.150 | .327 | .898 | 14.790 | 5.688 | 0.000 |
| OAK RIDGE | 3.571 | .530 | 1.094 | 1.197 | .467 | .264 | .716 | 1.639 | 18.741 | .165 | 0.000 | 0.000 |
| WASHINGTON | 1.658 | 3.882 | .456 | .912 | 8.566 | .529 | 17.204 | 1.639 | 1.283 | 5.077 | .642 | 0.000 |
| YAMPA | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | 0.000 | 0.000 |
| WHITEFACE | .765 | 1.508 | .364 | .570 | 1.401 | .793 | .358 | .000 | .385 | 2.262 | 4.495 | 0.000 |
| COWEETA | 1.658 | .363 | .729 | .798 | .311 | .000 | .716 | 2.622 | 4.749 | .165 | 0.000 | 0.000 |

# APPENDIX III
## TRANSFER CO-EFFICIENT MATRIX
Kgrams Sulfur Dioxide per Hectare at Receptor Sites Per Million Emissions by State Sources

| RECEPTOR | N. Jers. | Miss. | N. Car. | Minn. | Maryld | Mich | Indiana | Georgia | Iowa | Delaware | Florida | Alabama | Arkansas |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIG MOOSE LK. | 1.579 | 0.000 | .448 | 0.000 | 1.316 | 2.500 | .813 | .215 | .627 | .940 | .000 | .212 | .000 |
| ZANESVILLE | 0.000 | .778 | 1.121 | 0.000 | .658 | 3.000 | 4.320 | 1.074 | 1.250 | 0.000 | .172 | 1.272 | 0.000 |
| MONTMORENCY | .526 | 0.000 | 0.000 | 0.000 | .329 | .500 | .254 | .107 | .313 | .313 | 0.000 | 1.06 | 0.000 |
| ALGOMA | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 2.000 | .559 | 0.000 | 1.250 | 0.000 | 0.000 | .106 | 0.000 |
| KEJIMKUJIK | 1.579 | 0.000 | .224 | 0.000 | .658 | .500 | .203 | .107 | 0.000 | .940 | 0.000 | .106 | 0.000 |
| LONGWOODS | 0.000 | 4.280 | .224 | 0.000 | .329 | 18.000 | 2.641 | .215 | 1.567 | .3131 | 0.000 | .530 | 0.000 |
| TROUT LAKE | 0.000 | 0.000 | 0.000 | 5.000 | 0.000 | 0.000 | .254 | 0.000 | 2.194 | 0.000 | 0.000 | 0.000 | 0.000 |
| FERNBERG | 0.000 | 0.000 | 0.000 | 10.000 | 0.000 | 0.000 | .051 | 0.000 | .940 | 0.000 | 0.000 | 0.000 | 0.000 |
| GREAT SMOKIE | 0.000 | .389 | 5.381 | 0.000 | 0.000 | 0.000 | 1.524 | 9.237 | .627 | 0.000 | .862 | 5.090 | 0.000 |
| SHENANDOAH | .526 | .389 | 4.932 | 0.000 | 6.579 | 1.000 | 1.473 | 1.719 | .627 | .940 | .345 | 1.060 | 0.000 |
| PENN STATE | 1.053 | .389 | 1.569 | 0.000 | 4.934 | 3.000 | 1.676 | .859 | .627 | 1.254 | .172 | .742 | 0.000 |
| UVALDA | 0.000 | 1.167 | .448 | 0.000 | 0.000 | 0.000 | .305 | 5.800 | 0.000 | 0.000 | 4.655 | 2.015 | 0.000 |
| DORSET | 0.000 | 0.000 | .224 | 0.000 | .329 | 4.500 | 1.067 | .107 | .940 | .313 | 0.000 | .212 | 0.000 |
| BABCOCK | 0.000 | .778 | 4.260 | 0.000 | .986 | .500 | 2.234 | 2.470 | .626 | .313 | .344 | 1.802 | 0.000 |
| HUBBARD | 2.631 | 0.000 | .448 | 0.000 | 1.315 | 1.500 | .507 | .214 | .313 | 1.25 | 0.000 | .106 | 0.000 |
| CLINGMAN'S | 0.000 | 1.556 | 22.197 | 0.000 | .328 | 0.000 | 1.320 | 7.089 | .626 | 0.000 | .862 | 3.287 | 0.000 |
| HORTON'S ST. | 0.000 | .778 | 8.071 | 0.000 | .986 | .500 | 1.726 | 3.007 | .626 | .313 | .517 | 1.908 | 0.000 |
| KANE EXP. | 1.052 | .389 | .896 | 0.000 | 1.973 | 4.500 | 1.980 | .644 | .940 | .626 | .172 | .636 | 0.000 |
| CHALK RIVER | 0.000 | 0.000 | 0.000 | 0.000 | .328 | 2.500 | .711 | .107 | .626 | .313 | 0.000 | .106 | 0.000 |
| TUNKHANNOCK | 2.631 | .389 | .121 | 0.000 | 4.605 | 2.500 | 1.168 | .644 | .626 | 2.821 | .172 | .530 | 0.000 |
| OAK RIDGE | 0.000 | 1.945 | 2.466 | 0.000 | 0.000 | 0.000 | 2.031 | 7.196 | .626 | 0.000 | .862 | 5.514 | 0.000 |
| WASHINGTON | .526 | .389 | 4.260 | 0.000 | 46.710 | 1.500 | 0.000 | 1.288 | .626 | 3.134 | .344 | .742 | 0.000 |
| YAMPA | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | .050 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| WHITEFACE | 1.052 | 0.000 | .224 | 0.000 | 1.315 | 1.500 | 0.000 | .214 | .313 | .940 | 0.000 | .212 | 0.000 |
| COWEETA | 0.000 | 1.945 | 4.484 | 0.000 | 0.000 | 0.000 | 0.000 | 13.426 | .313 | 0.000 | 1.034 | 5.196 | 0.000 |

# APPENDIX IV

## RECEPTOR SITES

Big Moose Lake, New York
Zanesville, Ohio
Montmorency, Quebec
Algoma, Ontario
Kejimkujik, Nova Scotia
Longwoods, Ontario
Trout Lake, Wisconsin
Fernberg, Minnesota
Great Smokie Mountains, Tennessee
Shenandoah National Park, Virginia
Penn State, Pennsylvania
Uvalda, Georgia
Dorset, Ontario
Babcock State Park, West Virginia
Hubbard Brook, New Hampshire
Clingman's Peak, North Carolina
Horton's Station, Virginia
Kane Exp. Forest, Pennsylvania
Chalk River, Ontario
Tunkhannock, Pennsylvania
Oak Ridge, Tennessee
Washington, D.C.
Yampa, Colorado
Whiteface Mountain, New York
Coweeta, North Carolina