THE ECONOMICS OF AIR POLLUTION

THE ECONOMICS OF AIR POLLUTION, WITH SPECIAL REFERENCE TO THE CONTROL OF SULPHUR-OXIDES EMISSIONS IN CANADA

by

GIUSEPPE LEPORE

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF ECONOMICS
McGILL UNIVERSITY
MONTREAL

APRIL, 1974

ABSTRACT

This study attempts to demonstrate a number of propositions regarding the economics of air pollution and its control. First, it presents a synthesis and an appraisal of the economic nature of air pollution and its control. Second, based on that analysis, it evaluates alternative control policies. One type of policy, the use of emission taxes, is seen as being particularly appropriate to achieve predetermined standards of air quality. The economics of levying a tax on emissions of sulfur oxides are worked out. Finally, the study attempts to estimate, within a range, the level of emission taxes necessary to achieve given reductions of sulfur oxides in Canada.

SOMMAIRE

Cette étude essaye d'établir certains principes économiques concernant le contrôle de la pollution de l'air. Elle s'efforce d'abord de fournir une synthèse analytique de la nature économique de la pollution de l'air et des moyens de la contrôler. Puis, sur les bases de cette analyse, elle évalue plusieurs systèmes de contrôle. L'un de ces systèmes, l'utilisation de taxes d'emission, semble être particulierement efficace pour atteindre un niveau, fixé à l'avance, de qualité de l'air. Les principes économiques d'imposition d'une taxe sur les emissions d'oxydes de soufre sont étudiés. Finalment, cette étude essaye d'évaluer, dans une certaine mesure, le niveau des taxes d'emission nécessaires pour atteindre des reductions données d'oxydes de soufre au Canada.

ACKNOWLEDGEMENTS

I wish to express my gratitude to Professor M.A. Loutfi for the help and guidance which he generously gave in his role as supervisor of this thesis. I am also indebted to Professor C. Green for his assistance and encouragement in the first (frustrating) stages of the project, as well as for reading and commenting on the work. Thanks are also due to Professor E.F. Beach for reading the dissertation and for his many helpful comments and suggestions.

I am indebted to many of my friends and colleagues for helping me in a variety of ways. Among these, I must single out Keith Brewer and Dennison Moore.

I appreciate the financial assistance provided by the Arts Division Research Grant of the Royal Military College of Canada in support of this project.

Finally, I am grateful to Mrs. Gerda Pennock for her excellent typing performance and for the patience she displayed in the effort.

TABLE OF CONTENTS

CHAPTER PAGE

CHAPTER PAGE

LIST OF FIGURES

LIST OF TABLES

TABLE		PAGE

TABLE | PAGE

LIST OF TABLES IN APPENDICES

TABLE		PAGE

CHAPTER I

INTRODUCTION

The problem of environmental pollution is not new. Air pollution, for example, was common in England during the Industrial Revolution. However, it has received extensive attention, both by people in general and by the scientific community, only in recent years. Economists have been pleasantly surprised to find out that their tools are quite adequate to enable them to provide a diagnosis of the causes of the problem and to suggest some appropriate solutions. This is not to say that they all agree, whether in regard to analysis or policy. The considerable literature on the subject which has been spawned in the last few years contains many lively debates. Nor is it true that everything there is to say on the subject has been said - quite the contrary. Among other things, most of the literature is fragmented and deals with specific aspects in a rather piecemeal fashion. It is difficult to find a coherent and complete statement of the economic aspects of pollution, except at a very elementary level. Nevertheless, it seems that the fundamental lines along which future analytical developments will occur and empirical research will be undertaken have been established.

One area in which economists, especially of the academic variety, have achieved relatively little is in providing quantitative estimates of the effects predicted by their theorizing. All too often, they conclude their papers and articles by stating that, unfortunately, lack of data prevents them from providing such estimates. While, no doubt, this is true in many cases, it is not so of others. The truth is that sometimes the data is not available in the form in which the economist would prefer it and is not found in sources with which he is familiar. Economists have not been the only ones who have concerned themselves with the problem of pollution. So have, among others, engineers, consulting firms, and government agencies. These have produced a substantial amount of data which does not yet circulate widely among economists. It is uncommon, for example, to pick up a current issue of some journal of applied engineering and technology and not find in it some paper dealing with pollution control. More often than not, these papers contain quantitative estimates of control effectiveness and control costs. But the data is usually presented in a manner unfamiliar (and, sometimes, frustrating) to the economist. Costs of control, for example, are seldom given in terms of cost per unit of output; they are given even more infrequently in terms of cost per unit of pollutant abated; most frequently, they are lump-sum investment and operating costs. The task of the economist is to transform the data provided to him into a form more suitable for his purposes. As some of the empirical research in this study will show, the transformation is not always straight-forward.

It must be said, also, that engineers, technologists, and consultants frequently treat the economic aspects of the processes they are considering in a manner which leaves much to be desired. Often they dismiss out of hand a given feasible technology with the curt statement that it is "uneconomical". What they mean, or should mean, is that the technological process in question is uneconomical under the present set of economic incentives. If this set of incentives were changed, as a result of economic policy, say, that technological process could become quite economical.

There is great need, therefore, for more intellectual interaction between economists and the people who can supply the information he needs. This study attempts to bridge a small part of the existing gap. The empirical research undertaken in Chapter VI has involved a fairly extensive search for the data produced by the aforementioned people. That data was used to estimate control costs in a manner which enables the economist to predict (within a range) the effects of one of the policies of environmental control which he advocates most frequently, namely, an emissions tax (or effluent charge).

To be more specific, this study attempts to achieve the following objectives.

The first objective is to provide a synthesis and a critical appraisal of the economic analysis of environmental pollution and of the solutions which have emerged from such analysis. The emphasis is on the allocative aspects of the problem. The analysis of these allocative aspects has taken a number of different, though not mutually exclusive, "approaches." These are discussed in Chapter II. The first three sections discuss the approaches which are found in the literature.

The fourth suggests an alternative one which seems well suited to the analysis of the problem of air pollution. The merits and shortcomings of this approach compared to those found in the literature are discussed. In particular, the discussion shows the difficulty of attaining in practice the optimal results indicated by the analysis. What can be more easily attained is the admittedly second-best result of using the market to achieve some predetermined acceptable standards. Emission taxes would perform as prices which would efficiently reduce emissions to the acceptable level. The rest of the study proceeds on the assumption that this is the goal to be attained, without making any pronouncements as to what the standards should be.

Chapter III examines the distributive aspects of pollution and pollution control. This is an often neglected aspect of the analysis. Unfortunately, here too the discussion of this aspect is limited mostly to an exposition of the ideas found in the scant literature. It would have been interesting, among other things, to provide empirical estimates of the distribution of the incidence of an emission tax and of the benefits of the resulting pollution abatement. This, however, can be the subject of a study in itself.

The second objective is to provide an empirical estimate of the order of magnitude of the emission tax required to achieve given levels of abatement of one type of pollutants, sulfur oxides. Since, as shown in Chapters V and VI, the tax would reduce emissions up to the point where the marginal cost of abatement would equal the amount of the tax, the marginal cost of abatement should be estimated. Because of the complexities and difficulties involved, however, what actually is estimated is a range of costs.

The procedure used is as follows. Chapters IV and V set the stage for the calculations undertaken in Chapter VI. Chapter IV attempts to provide an overview of the dimensions of the problem of sulfur oxides emissions in Canada. It shows, among other things, that because most important sources of emissions of sulfur oxides are not important sources of emissions of other pollutants, it is legitimate to study the control of sulfur oxides separately from those of other pollutants. Chapter V attempts to provide an overview of the technology of control of sulfur oxides. The economics of implementing each type of technology are also worked out. In particular, it is shown how and to what point an emission tax would prompt the emitter of sulfur oxides to implement a given technology. Chapter VI provides a detailed inventory of the costs of controlling sulfur oxides from thirteen major sources by the available techniques. Step-function marginal cost curves are postulated. Moreover, since it cannot be assumed that any given technique will be universally applied, a range of marginal cost rather than a single curve is estimated. This range shows either the maximum and minimum amounts of reduction of emissions to be expected from the imposition of a given tax or, alternatively, the range within which lies the tax necessary to attain some specified level of emissions control. This range, for selected tax levels, is summarized in Table 6-69. Chapter VII reiterates the broad outlines of the issues developed in the dissertation, and suggests some areas where the work done here could be improved and extended.

Finally, the study contains six appendices where data which are used in Chapter VI are either calculated (based on stated assumptions) or shown.

CHAPTER II

THE ECONOMIC NATURE OF AIR POLLUTION: ALLOCATIVE ASPECTS

This chapter examines the allocative aspects of the economic nature of air pollution. The analysis can be carried out using a number of distinct, but not mutually exclusive, "approaches." Here these are explored at some length.

1. The Externality Approach

The framework which economists have most frequently used and are currently using in analyzing the problem of environmental pollution is that which embodies the concept of externalities. Unfortunately, this concept is one of the most elusive in economic theory. The reason, as E.J. Mishan points out, is that

> the original clarity of the externality concept has become blurred in consequence of the term being used over the years as a convenient peg on which to hang a variety of economic phenomena which might be used to justify intervention in the private enterprise sector of the economy.[1]

It is necessary, therefore, to review the meaning of the concept and to assess the suitability of the prescriptions derived from its application to the control of pollution.

---

1 E.J. Mishan, "The Postwar Literature on Externalities: An Interpretative Essay," Journal of Economic Literature, IX (March, 1971), p. 6.

General Vs Partial Equilibrium Models of Externalities

The first distinction which must be made is between the analysis of externalities in a general equilibrium framework and that in a partial equilibrium setting. Most of the analytical literature on externalities is of the latter type. It is only recently that attempts have been made to develop the former.

A - General Equilibrium Models

One of the main theoretical contributions which considers externalities in a general equilibrium framework is undoubtedly that of Ayres and Kneese.[1] These authors examine the generation of externalities arising from the production of wastes of all kinds from all economic activity. They make three important observations:

(i) the pervasiveness of this type of externality is very great; indeed, externalities are a normal, inevitable result of most economic activity.

(ii) the waste-assimilation capacities of the various components of the environment are to some extent substitutes; so, that one cannot validly speak of air, water, or soil pollution independently.

(iii) economic activity only changes the chemical and physical characteristics of materials but not their mass (or weight).

---

1 R.V. Ayres and A.V. Kneese, "Production, Consumption, and Externalities," American Economic Review, LIX (June, 1969), pp. 282-297.

The model developed by Ayres and Kneese embodies the physical principle of conservation of mass and evolves the idea of materials balance; it purports to analyze simultaneously all of the externalities generated in the course of the transformation of materials into different forms by economic activity. Materials taken from the environment become consumer or capital goods, but eventually will have to be returned to the environment as residuals; some wastes are generated in the production process itself. This puts emphasis on the limitations of the total capacity of the environment to assimilate these residuals and on the desirability of recycling some of them.

Analytically, Ayres and Kneese attempt to incorporate this flow of materials into a Walras-Cassel type of general equilibrium model. The flow of residuals is not accounted for by the traditional Walras-Cassel model because residuals usually go unpriced and, hence, do not enter the market.

The Ayres and Kneese's model has been criticized at length by Victor, who brings out a number of inconsistencies and shortcomings,[1] though some of these have been obviated

---

1 P. Victor, Pollution: Economy and Environment, (London: George Allen and Unwin, 1972), pp. 25-35. For instance, Victor points out that, because the model is static, it cannot deal with the dynamic problem of how present waste generation affects the future capacity of the environment to assimilate wastes.

in later formulations of the model.[1] The important point we wish to make here is that a practical application of the model, the pricing (positive or negative) of all inputs and residuals, would require an enormous quantity of information which is not yet available and is not likely to be available for some time.

Attempts to develop general equilibrium type of models amenable to practical application have been made by Leontief[2] and Victor.[3] Leontief puts his input-output machinery to use to demonstrate, by the inclusion in a normal input-output table of an anti-pollution industry and of "pollution coefficients," how to estimate the impact on prices of given pollution-control policies. Useful as it is and will be, the Leontief model falls far short of being a truly general equilibrium model comparable to that of Ayres and Kneese; Leontief ignores the balance of materials. Moreover, limited as it is, there is as yet no published table which estimates a comprehensive set of pollution coefficients.[4]

---

1 A.V. Kneese and R.C. D'Arge, "Pervasive External Costs and the Response of Society," in U.S. Congress, Joint Economic Committee, The Analysis and Evaluation of Public Expenditure: The PBB System, Vol. 1, (Washington: U.S. Government Printing Office, 1969), pp. 87-115. A.V. Kneese, R.V. Ayres, and R.C. D'Arge, Economics and the Environment, (Washington: Resources for the Future, 1970).

2 W. Leontief, "Environmental Repercussions and the Economic Structure: An Input-Output Approach," Review of Economics and Statistics, LII (August, 1970), pp. 262-271.

3 Victor, op.cit.

4 Victor, ibid., reports that, at a conference in Geneva in April, 1971, Professor Leontief revealed some preliminary results of an application of his model to a matrix of five air pollutants and ninety U.S. sectors.

Victor extends the commodity-by-industry model used by the Canadian Dominion Bureau of Statistics to include "ecologic" commodities and inputs, as distinguished from the "economic" commodities and inputs which are part of the published DBS input-output table. He estimates the flows of four types of water inputs and twenty-seven types of water, air, and land outputs for the year 1961; therefrom, he estimates "impact tables" which show the material flows resulting from supplying final users with a dollar's worth of each of forty economic commodities. Worthy though it is and indicative of the usefulness of further research in this area, Victor's effort cannot be taken as a comprehensive and fully adequate application of the materials balance model. Again, the main problem is the paucity of data. Until the required data is available, we can expect the practical usefulness of general equilibrium models which incorporate external effects to be rather limited. Partial equilibrium models, though they have their own limitations, may be more useful in tackling particular problems.

Throughout the remainder of this study, a partial equilibrium framework is assumed. Therefore, such things as the public good character of pollution control, the question of property rights, the distributive aspects of pollution and of its control, and so forth, will be discussed in a partial equilibrium setting, even though these problems would also arise in a general equilibrium framework. Moreover, air pollution will be discussed as separate from other pollution problems, even though it must be recognized that in some cases there are tradeoffs between different types of pollution.

B - Partial Equilibrium Models

The tradition of analyzing externalities within a partial equilibrium framework originated with Marshall. The rather narrow type of external economies (diseconomies) with which he was concerned are economies (diseconomies) external to the firm but internal to the industry; they accrue to the firm as a result of the expansion (contraction) of a decreasing cost industry.

More important, from our point of view, was the use of the concept made by Pigou. He was concerned with the possibility that, even in a competitive economy, the marginal social net product would diverge from the marginal private net product because of the presence of externalities. As he put it,

> the essence of the matter is that one person, A, in the course of rendering some service for which payment is made to a second person, B, incidentally also renders services or disservices to other persons (not producers of like services), of such a sort that payment cannot be exacted from the benefited parties or compensation enforced on behalf of the injured parties.[1]

Pigou's proposed solution was a system of output taxes and subsidies which would force externality-generating economic units to internalize the social costs and benefits arising from the externalities incidental to their economic activity. This would insure the attainment of a social optimum as well as of a private optimum.

---

1 A.C. Pigou, The Economics of Welfare, 4th edition, (London: Macmillan & Co., 1950), p. 183.

Until recently, departures from the social optimum resulting from competition were believed to be fairly rare exceptions.[1] Concern with environmental pollution has convinced economists that, on the contrary, the generation of externalities accompanies much economic activity. This has prompted a substantial number of contributions to economic literature which, on the one hand, have tended to clarify the meaning of the concept and its implications and, on the other, to demonstrate how complex those implications are.

(a) Definitions and Classification of Externalities

Stated in the most general terms, an externality is said to exist when the economic activity of one economic unit (firm or consumer) affects another economic unit in such a way that the effect is not accounted for by the market. This latter proviso is necessary because, in fact, all economic activity by one unit affects other economic units one way or another. But, in cases where these effects are reflected in prices and costs, the operation of the competitive market will insure optimal outputs (in a Pareto sense). It is only when these effects are not captured in the market that meaningful externalities exist. Mishan suggests that the former effects be referred to as "indirect" effects, that is, effects exerted through prices

1 The main types of divergencies were thought to arise from the indivisibility of some investment. See, for example, T. Scitovsky, "Two Concepts of External Economies," Journal of Political Economy, LXII (April, 1954), pp. 143-151.

and costs in an interdependent system, and the latter as "direct" effects.[1] An externality would then be said to exist only when direct effects occur.

In the light of this proposition, the distinction which often has been made in the literature, since it was introduced by Viner,[2] between pecuniary and technological externalities strikes Mishan as "extravagant"[3] and the use of the former term as "gratuitous."[4] If industry A expands and thereby bids up factor prices used also in industry B, the externality thereby imposed on B is of a pecuniary type. But clearly these externalities represent simply an extention to the industry of the Marshallian brand of externalities and are fully accounted for by the market. These externalities do not give rise to misallocation of resources, though they may have distributive implications. In a purely competitive economy, they involve intramarginal transfers of rents among specialized factors, though the gains of one group are offset by the losses of another group.[5]

---

1 Mishan, "The Postwar Literature on Externalities...," pp. 2-3.

2 J. Viner, "Cost Curves and Supply Curves," Zeitschrift fur National Okonomie, III (September, 1931), pp. 23-46. Reprinted in American Economics Association, Readings in Price Theory, (New York: Blakiston, 1953).

3 Mishan, op.cit., p. 6.

4 Ibid., p. 4.

5 W.J. Baumol, Welfare Economics and the Theory of the State, 2nd edition, (London: Bell & Sons, 1969), p. 72.

On the other hand, genuine externalities having allocative significance occur when the actions of an economic unit affect directly other economic units and, yet, the former cannot be or is not forced to take these effects into account. More precisely, the production function or utility function of one party is affected by the level of activity of the other party, the effect going either unpaid for or uncompensated.[1] This latter proviso is important for it suggests that interdependence alone (whether "direct" or "indirect") is not sufficient to indicate the presence of externalities having allocative significance: the interdependence must be accompanied by lack of compensation.[2] This, as we shall see, has relevance for public policy; for, if the parties in question can somehow agree on compensation, even in cases of direct interaction, no misallocation of resources exists and no public intervention is justified (on allocative grounds); if they cannot, there is a *prima facie* case for public intervention.

---

1 Mathematically, taking the consumption-on-consumption type of externalities, this interdependence could be stated as $U_X = U_X(x_1, x_2, \ldots, x_n, y_k)$, where U_X represents the utility of individual X and $x_1, x_2, \ldots, x_n$ his level of consumption of goods, 1, 2,...,n, and y_k represents the level of consumption of good k by individual Y. By substituting, where appropriate, "firms" for "individuals" and "production function" for "utility function," production-on-production and production-on-consumption externalities are similarly defined.

2 On this, see Baumol, *op.cit.*, pp. 24-27.

The test of compensation (or failure of compensation) is implicit in the distinction made by Buchanan and Stubblebine between "Pareto-relevant" and "Pareto-irrelevant" externalities.[1] This distinction was meant principally to differentiate between "normal" interaction (in a Walrasion sense) among economic agents and genuine externalities. According to these authors,

> An externality is defined to be Pareto-relevant when the extent of the activity may be modified in such a way that the externally affected party, A, can be made better off without the active party, B, being made worse off. That is to say, "gains from trade" characterize the Pareto-relevant externality, trade that takes the form of some change in the activity of B as his part of the bargain.[2]

Elimination of Pareto-relevant externalities would result in the attainment of a Pareto equilibrium. Yet, at this equilibrium, some interaction in the form of Pareto-irrelevant externalities would still be present.[3] The significance of this point, Buchanan and Stubblebine conclude, is that

---

1 J.M. Buchanan and W.C. Stubblebine, "Externality," Economica, XXIX (November, 1962), pp. 371-384.

2 Ibid., p. 374. Buchanan and Stubblebine also define "potentially" Pareto-relevant and irrelevant externalities. According to them, a potentially Pareto-relevant externality exists "...when the activity, to the extent that it is actually performed, generates any desire on the part of the externally benefited (damaged) party to modify the behavior of the party empowered to take action through trade, persuasion, compromise, agreement, convention, collective action, etc." (pp. 373-374). While this distinction may be, strictly speaking, logical it does seem hair-splitting and redundant.

3 Ibid., p. 375.

> there is not a prima facie case for intervention in all cases where an externality is observed to exist. The internal benefits from carrying out the activity, net of costs, may be greater than the external damage that is imposed on other parties.[1]

One may agree with this, but also argue that, where Pareto-relevant externalities are observed, that is, when the external damage imposed on other parties is assessed to exceed net internal benefits, the market, as it is set up, must have failed. When private action, through bargaining, agreement, and so on fails to eliminate Pareto-relevant externalities, then there is a prima facie case for public or collective action.[2]

Another important definitional distinction is that between "separable" and "non-separable" externalities introduced by Davis and Whinston.[3] These authors adopt as their analytical framework two firms in a competitive industry and choose to discuss externalities in terms of cost functions rather than production functions. According to their definition, a separable externality exists when a change in the level of activity of, say, firm A will cause a shift, upward or downward, of the average and total cost curves of firm B, but not its

1 Ibid., p. 381.

2 As seen below, Buchanan and Stubblebine also claim that the Pigovian tax-subsidy remedy is inadequate.

3 O.A. Davis and A. Whinston, "Externalities, Welfare and the Theory of Games," Journal of Political Economy, LXX (June, 1962), pp. 241-262.

marginal cost curve. The effect is purely intramarginal and there is no effect on the optimal level of B's output, though it has on its profits (and investment decisions). Aside from the latter effects, A's decisions have no effect on B's decisions. A non-separable externality, on the other hand, exists when the marginal cost of one of the firms is affected by the level of activity of the other. In such a case, the marginal cost of the affected firm is determined not only by the level of its own output, but by the level of output of the other firm as well. Consequently, there may be no clearly determinate optimal output. Supposing that A imposes a non-separable externality on B, for example, it becomes impossible for B to determine its optimal level of output without knowing what A's level of output will be. The existence of such externalities, according to Davis and Whinston, results in a situation such that "...even in what is usually considered the certain world of competitive price theory,...decisions must be made under uncertainty."[1] There is no way to determine optimal outputs by _a priori_ methods.

Externalities have also been classified as "reciprocal" and "non-reciprocal." A non-reciprocal externality of any of the types discussed above is unidirectional; for example, B's production, cost, or utility function is affected by A's activity.

---

1 _Ibid_., p. 255. Davis and Whinston draw attention to the similarity between this situation and that arising in duopoly theory.

A reciprocal externality, on the other hand, exists if not only B is affected by A's activity, but, at the same time, A is affected by B's activity, though not necessarily to the same extent or in the same manner. When motorist A, for example, drives his vehicle on a congested highway, he imposes an external diseconomy on B, but so does motorist B on A. Needless to say, reciprocal externalities need not be restricted to two parties, but can take place between any number. Even in the two party case, however, neither A nor B can individually determine their optimum levels of output or consumption without knowledge of the other party's level of output or consumption. This is true *a fortiori* for the n-party case.

(b) Corrective Prescriptions

Following Pigou, received doctrine has offered a relatively simple corrective prescription for externalities: a tax-subsidy scheme. If the production or consumption of a good generates an external diseconomy, an excise tax equal to the value of the marginal external diseconomy at the optimal output or consumption would reduce output or consumption to the optimal level. Similarly, an excise subsidy equal to the value of a marginal external economy at the optimal level of output or consumption would expand output or consumption to the optimal level.

The effects of a tax-subsidy scheme on the output of an externality-generating, perfectly-competitive firm producing good X is shown in Figure 2-1. When allowed to disregard the

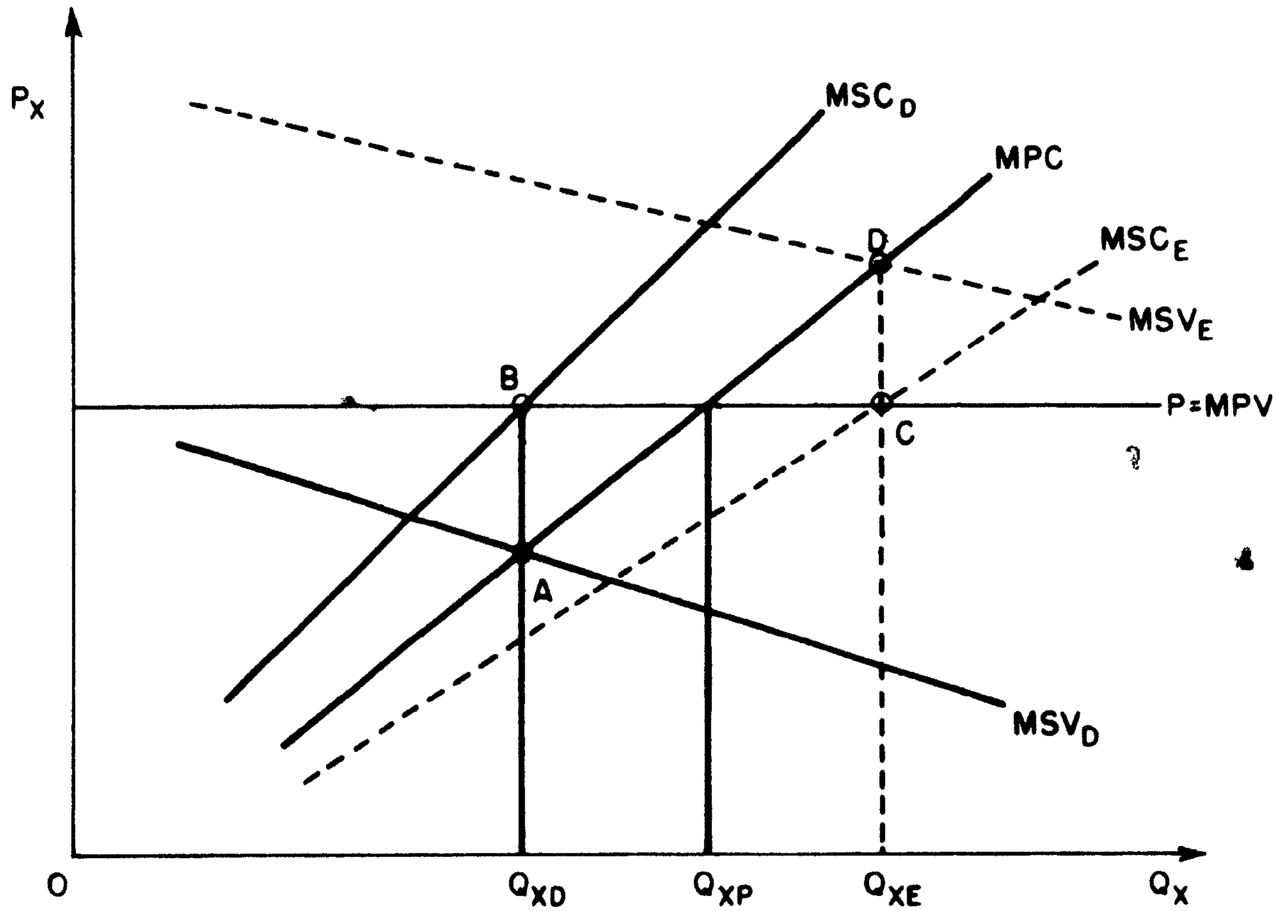

Figure 2-1 · Effect of a Tax or Subsidy on the Output of an Externality-Generating Firm.

externality, the firm produces and sells an output Q_{XP}, where its marginal "private" cost (MPC) is equal to the marginal private value (MPV) of a unit of the good. If the production of X generates an external diseconomy, however, we could say either that the marginal social value (MSV_D) of the good is lower than its MPV or that its marginal social cost (MSC_D) is higher than its MPC. This is shown in Figure 2-1 by solid lines. In either cases, a tax AB = MPV - MSV_D = MSC_D - MPC will induce the firm to reduce its output to the optimal level Q_{XD}. If, on the other hand, the production of X generates an external economy, it can be said either that its marginal social value (MSV_E) exceeds its MPV or that its marginal social cost (MSC_E) is lower than its MPC as shown by broken lines in Figure 2-1. In either case, an excise subsidy CD = MPC - MSC_E = MSV_E - MPV would induce the firm to expand output to the optimal level Q_{XE}. It must be emphasized that the tax or subsidy must be equal to the divergence between private and social cost or private and social value <u>at the optimal level of output</u>.

Now, this apparently simple and logical solution has been criticized, qualified, and rejected by a number of economists on a variety of grounds. In examining these objections, we shall proceed as follows. First, we shall examine qualifications arising from the attempts to define and classify externalities discussed above. Later on, we shall see how this solution fares in the larger framework of market failure and in comparison with alternative solutions, such as those arising from definitions, changes, and clarifications of property rights and liability.

There seems to be two inferences from the distinction between Pareto-relevant and Pareto-irrelevant externalities. The first is that any corrective action resulting in the attainment of a social optimum would eliminate only Pareto-relevant externalities. But this is exactly the goal which should be achieved; only ignorance of basic economics would prompt one to suggest that <u>all</u> external effects should be eliminated. The point has been made very well by Turvey:

> We should never aim to get rid of all external effects of one activity upon another, since the net gain from doing so would be negative. A world with no traffic congestion at all, never any noise, no overhead power lines and not a trace of smoke is a nice thought, but irrelevant to action. Thus the question is not one of abolishing adverse unfavorable effects, but is one of reducing them in some cases where investigation shows that on balance such a reduction is worth-while.[1]

In other words, in terms of society as a whole, the removal of Pareto-irrelevant externalities would be uneconomical because the cost of removing the marginal unit would exceed the benefits of such removal. This can be demonstrated by a simple diagram (Figure 2-2). The most efficient level of control, from the social point of view is where the marginal cost of control is equal to the marginal benefit of control; in the diagram this level is OC (i.e., OC units of pollutants should not be allowed to be emitted). The marginal and total benefit of pollution control is the marginal and total damage avoided because of pollution control.[2] The total damage avoided

---

1 R. Turvey, "The Side Effects of Resource Use," in H. Jarret, ed., Environmental Quality in a Growing Economy, (Baltimore: Resources for the Future, 1966), p. 49.

2 The fact that the marginal benefit (or marginal damage avoided) curve slopes downward to the right reflects (assumed) diminishang marginal utility of pollution control.

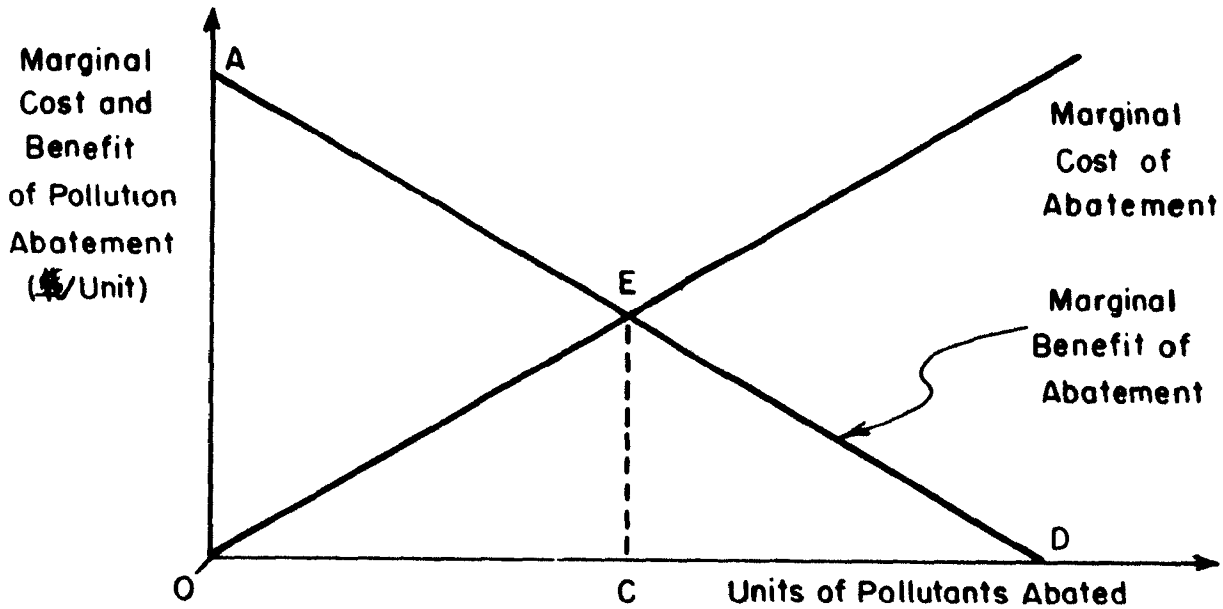

Figure 2-2: Optimal Pollution Abatement

by removing all emissions would be OAD. At the socially optimum level of control the total damage avoided is OAEC. This is the monetary value of the Pareto-relevant externality. Therefore, CED is the monetary value of the Pareto-irrelevant external diseconomy. This should not be eliminated because the marginal cost of doing so exceeds the marginal benefit. Incidentally, at the optimal level of control, since the total cost of removing the Pareto-relevant external diseconomy is OCE, the net gain to society is OAE. This is the maximum possible gain society can realize from the control of this external diseconomy.

The second inference, according to Buchanan and Stubblebine, is that

> full Pareto equilibrium can never be attained via the imposition of unilaterally imposed taxes and subsidies until all marginal externalities are eliminated. If a tax-subsidy method, rather than 'trade', is to be introduced, it should be bilateral taxes (subsidies). [1]

The reason that traditional theory has concluded that unilateral taxes (subsidies) can achieve the optimum, according to Buchanan and Stubblebine, is that all of the attention has been concentrated on the originator of the externality but not on the recipient. Yet, his position is also important. He must be made to take into account (in his output or consumption decisions) the costs imposed "internally" on the originating party through corrective measures. Otherwise, though the "Pigovian" solution is attained, Pareto optimum is not. This can be shown by a diagram (Figure 2-3). The horizontal axis measures the level of activity of party B. This activity imposes an external diseconomy on party A. The vertical axis measures the (positive and negative) marginal utilities of the two parties as a function of the level of B's activity. These marginal utility functions are MU_A and MU_B. If B is allowed to disregard the externality, he will maximize his utility by carrying out the activity up to level M (assuming the cost of carrying it out to be zero). If, on the other hand, he has to pay a tax equal to the marginal external disutility he imposes

1 Buchanan and Stubblebine, op.cit., p. 383.

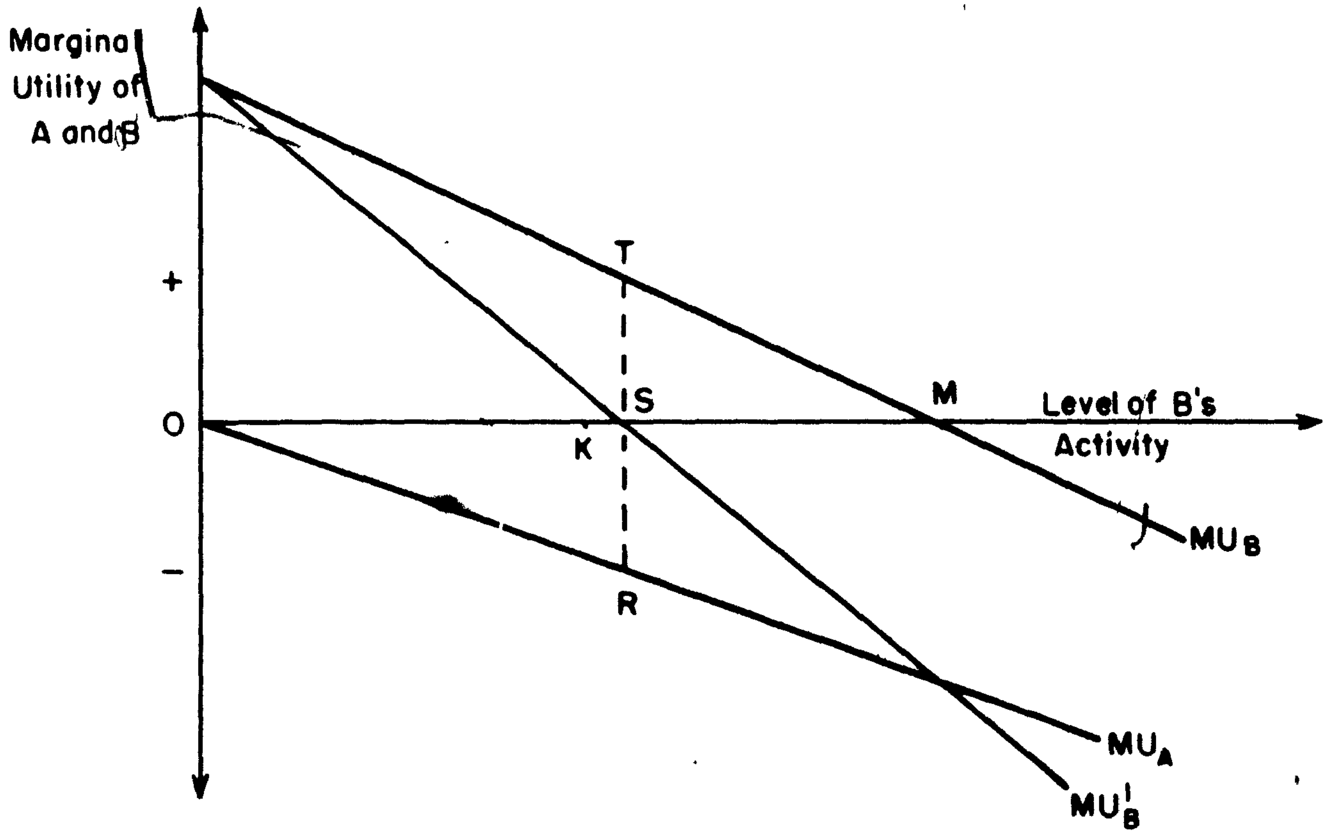

Figure 2-3 : The Pigovian Solution and Pareto Optimum.

on A, he will consider his (after tax) marginal utility to be MU_B' and will maximize his utility by carrying out the activity at the lower level S (where ST = SR). This is the social "Pigovian" optimum. But, and this is Buchanan and Stubblebine's point, at level of activity S, the marginal disutility of the activity to A is greater than the marginal utility (net of tax) to B (in the diagram the latter is zero). Hence, if possible, A would have an incentive to bargain with B to induce the latter to reduce his level of activity even further, say to K. This would clearly be to the advantage of at least one of the parties. Hence, S, though a "Pigovian" optimum, is not a Pareto optimum. As mentioned, Buchanan and Stubblebine believe that, in order to achieve this truly Pareto optimum, the externality recipient must be made aware of the costs imposed "internally" by the tax on the party whose activity generates the externality. This can be done either by imposing bilateral taxes (subsidies) or by having the externally affected party actually compensate the acting party for modifying his behavior.

Though Buchanan and Stubblebine's conclusions are formally correct, they, on reflection, do not seem meaningful. For, if bargaining between the parties is possible, there is no necessity for using taxation in the first place. On the other hand, if bargaining is not possible, the "Pigovian" optimum achieved by the imposition of a unilateral tax (subsidy) is also a Pareto optimum. As discussed above and below, the latter situation is more in accordance with a meaningful concept of externality. In particular, it is the situation explicitly assumed by Pigou.[1]

In the same vein, Davis and Whinston point out that, even in the case where externalities are separable, it will be difficult for the policymakers to calculate (even approximately) the taxes and subsidies which will result in optimal levels of output.[2] This is especially true in a world where there are many firms, individuals, and types of externalities.

---

1 Pigou, op.cit., p. 183 ff.

2 Davis and Whinston, op.cit.

Air pollution sources and recipients, for example, may be large in numbers and generate simultaneously other externalities such as congestion, accidents, and so on, so that the calculation of optimal taxes and subsidies would be very difficult, even if externalities were separable.

When externalities are of the non-separable type, however, it will be impossible to determine the optimal taxes and subsidies even at the conceptual level. Because the optimal level of output of one firm depends on that of the other, there is no unique equilibrium solution. Since policy-makers cannot predict these optimal outputs even in principle, they will be unable to devise the proper taxes and subsidies. Davis and Whinston suggest that a more practical solution would be to allow mergers among the parties affecting each other. The existence of non-separable externalities would provide the motivation for such mergers. The mergers would go on until some "natural decision-making unit" which internalized all of the externalities would be achieved.

In order for Davis and Whinston's analysis to be valid, however, externalities must be not only non-separable but also reciprocal.[1] When externalities are unidirectional even if non-separable, government intervention may be required, especially if the damaged group is large and dispersed. Whether

---

1 "Our results here hold for the case of reciprocal, non-separable externalities. If the externalities are not reciprocal in any sense...then our analysis does not hold." Ibid., p. 257, footnote 31.

a system of output taxes and subsidies is the best type of government intervention is an open but somewhat different question.

Even in the case of non-separable, reciprocal externalities, merger is not always feasible in practice, as Davis and Whinston admit. The costs of merging and bargaining, or the difficulty of bringing the parties together may prevent mergers from taking place. Moreover, as Davis and Whinston recognize, their "natural decision-making unit" may be so large that its achievement would cause a change in the market structure; yet, their analysis only holds if the market is assumed to remain competitive even after all of the mergers required to internalize the externalities have taken place. Whether the market structure will change or not, they rightly point out, is an empirical question.[1] A further limitation of the merger solution is that, by its very nature, it must be confined to production units. One cannot see households "merge" (as distinct from possible bargaining for compensation), even though households (or individuals) are certainly important sources of externalities.

For completeness, let us mention the impracticability of the output taxes-subsidies solution in the case of reciprocal externalities (whether or not they fall into the other categories). It should be obvious why there is no determinate set of optimal taxes and subsidies in the case of reciprocal externalities.

---

1 An analogous question is whether a competitive market existed in the first place.

Since optimal outputs cannot be determined because of interdependence, neither can optimal taxes and subsidies.

A point worth making with respect to reciprocal externalities is that they occur most frequently in cases involving the exploitation of so-called common property resources. These are resources whose supply is scarce but whose use is nevertheless free. Examples are fishing grounds, roads, and air.[1] Because the use of common property resources is free, the effect of an increase in its use is not felt by the individual user, it is felt by others. This leads to overexploitation of the resources. Thus fishing grounds are depleted by overfishing, roads become congested, and air is polluted. Therefore, the social cost of the activities exceeds their private cost. This suggests an alternative theoretical approach to deal with externalities, that is to create a market for the common property resource by charging a price for its use. This price would raise the cost of private use to equality with its social cost and, thereby, reduce the total

---

1 See, for example, H. Scott Gordon, "The Economic Theory of Common Property Resource: The Fishery," Journal of Political Economy, LXII (April, 1954), pp. 124-142. and J. Rothenberg, "The Economics of Congestion and Pollution: An Integrated View," American Economic Review, Papers and Proceedings, LXI (May, 1970), pp. 114-121. Rothenberg prefers to call the common property resource a "public good." To him, moreover, "pure congestion" consists of purely symmetrical reciprocal externalities, while "pure pollution" consists of purely unidirectional externalities; "customary" congestion and pollution consist of a mixture of the two.

intensity of its use. A model which attempts to establish the theoretically optimal price of common property resource use in the case of air is developed below.[1]

(c) Relative Efficiency of Different Types of Taxes and Subsidies

Aside from the appropriateness of the tax-subsidy solution as such, in the light of the qualifications of the concept of externality discussed, there is the question of the relative efficiency of alternative types of taxes and subsidies. From Pigou onward, the analysis of externalities has implied or stated that the appropriate corrective taxes (subsidies) would be taxes (subsidies) on the output or consumption of the externality-generating economic units. This followed from the presumption that when production or consumption of some good generates external diseconomies, there must be an overproduction or overconsumption of the good. Recently, however, the efficiency of these taxes has been questioned.[2]

1 A detailed model dealing with the management of the water resources of the Delaware Estuary using this approach was developed by Russell and Spofford as reported by A. Kneese, "Environmental Pollution: Economics and Policy," American Economic Review, Papers and Proceedings, LXII (May, 1971), pp. 153-166.

2 Hereafter, for simplicity, the discussion will be carried out in terms of taxes only, though in the case of external economies the same remarks, mutatis mutandis, apply to subsidies. Also, the discussion will emphasize production externalities but the discussion applies as well to consumption externalities.

More precisely, it has been shown that other types of taxes, in certain circumstances, are more efficient than output taxes. Or, put differently, there is disagreement as to what exactly should be taxed.[1] In the context of environmental pollution, possible alternatives to output taxes are: input, emission (or effluent), and damage taxes.

Plott, for example, has shown that, if an external diseconomy can be attributed to the use of some externality-producing input, such as the combustion of a fuel, an output tax may worsen the situation.[2] Even though the tax will reduce the output produced, more of the externality-generating input may be used, hence, increasing the external diseconomy. In this case, the tax which would lead to the optimal result is one imposed on the externality-generating input.

Plott's analysis, it is generally conceded, is essentially correct as far as the short-run is concerned. But, as Fraser has shown, it does not take into account the long-run adjustment.[3]

---

1 For a discussion of some of the issues, see R.O. Zerbe, "Theoretical Efficiency in Pollution Control," Western Economic Journal, VIII (December, 1970), pp. 364-376.

2 C.R. Plott, "Externalities and Corrective Taxes," Economica, XXXIII (February, 1966), pp. 84-87. Plott formulates the problem in terms of joint products. The externality (eg. smoke) is a joint product of the output of the firm. Therefore, he recognizes that the tax could be put directly on the joint product - i.e., an emission tax.

3 R.D. Fraser, "Externalities and Corrective Taxes: A Comment," Canadian Journal of Economics, I (May, 1968), pp. 473-475.

Plott's analysis is valid in the long-run only under rather restrictive assumptions with respect to relative changes in factor prices caused by the imposition of the output tax. Fraser shows that, if one assumes constant relative factor prices and that producers have similar production functions (which he does not regard as particularly restrictive assumptions), an output tax will always lead to a reduction in the use of the "offending" input. Basset and Borcherding have also argued that, in the long-run, an output tax would cause a reduction in the amount of externality produced.[1]

It is notable that none of these writers purported to prove that, even in the long run, an output tax is superior to an input tax under the circumstances indicated. One can safely state, then, that, in the case where an external diseconomy can be traced to the use of a specific input, there is a *prima facie* case for imposing an input tax rather than an output tax.

The drawback of the input tax (shared by the output tax) is that it offers no incentive to adopt innovations which reduce the quantities of pollutants emitted with a given input mix, or, per unit of output. Suppose, for example, that it is the common practice throughout a competitive industry to use as one of the inputs a fuel which results in the emission of obnoxious pollutants. A tax on the use of this fuel would be

1 L.R. Bassett and T.E. Borcherding, "Externalities and Output Taxes," *Southern Economic Journal*, XXXVI (April, 1970), pp. 462-464.

effective in inducing some firms in this industry to switch to some "cleaner", but more expensive fuel, while other firms would continue to use the "dirtier" fuel and pay the tax and reduce their output until their marginal cost-*cum*-tax equals their marginal revenue. Now, this is an improvement over the initial situation. Moreover, at least in the short run, this solution would be superior to that which would force all firms to reduce emissions through a reduction in output, as would occur if an output tax were imposed. But it would be even better if firms were given the additional incentive to use the "dirtier" fuel and install devices which prevented the pollutants from being discharged into the environment. Some firms might find that this would be, for them, a cheaper alternative to the other two. The input tax, as such, offers no such incentive. The firms that did install such devices would have to pay as much tax as those that did not do so. It is possible, however, that in some cases, this drawback can be obviated or minimized. This can be done if an administratively simple way could be found to refund the input tax to those firms which would either install devices to capture pollutants before they were discharged into the environment or achieved the same result by modifying their production process. In this case, there would be no essential difference between an input tax and an emission tax. In fact, if there is a simple linear relationship between the use of the externality-producing input and the level of emissions, the input tax-*cum*-refund would be really only a convenient method of administering an emission tax.

The only tax which would directly provide all of the incentives required to produce a social optimum would be a tax levied against the damage caused by the external diseconomy. More precisely, a tax function equivalent to the marginal damage function, if this were known, would establish this result. Firms would produce only the output which is socially optimum (except as far as distortions due to imperfections in market structure are concerned); they would produce this output at minimum cost; and the cost would reflect the damage which firms still inflict upon others (as Pareto-relevant external diseconomies). In addition, this tax would provide an incentive for polluters to install devices which would reduce emissions and, ultimately, to introduce innovations in processes which generate smaller quantities of waste.

The problem with a damage tax is that it is very difficult to obtain quantitative estimates of damage cost functions. The relationship between levels of emissions of air pollutants, for example, and damage levels to materials, crops, human health, and so on are still very scanty.[1] In addition, a large share of damage costs are subjective costs which individuals may find difficult to estimate, even if they were willing to reveal their exact magnitude. As will be shown below, there are reasons why they have an incentive to exagerate or understate these costs.

---

1 Some of the attempts which have been made to assess damage from air pollution are reviewed in Chapters III and IV.

Moreover, there is the probabilistic character of the damages.[1] Pollutant concentrations vary in time. For example, carbon monoxide and sulfur dioxide concentrations in urban areas vary during different hours of the day and different periods of the year. To get accurate estimates of pollution damage functions, therefore, the damage that could result with each level of concentration must be correlated with the frequency (or, at least, the probability) of the occurence of each pollutant concentration. In this way, the _expected_ damage cost functions could be estimated. But, obviously, this greatly complicates already extremely difficult calculations.

The type of tax that has been most frequently advocated as a substitute for the damage tax is an emission tax (also known as effluent charge or fee). The amount of the tax would be a function of the quantities of specified pollutants discharged into the environment. This type of tax would be equivalent to the damage tax if there were linearity between pollutant concentrations and damage.[2] Linearity would exist if each additional unit of pollutant emitted resulted in equal increments of damage. Obviously, this cannot be known _a priori_; nevertheless, linearity can be assumed as a first approximation.

---

1 This aspect is discussed in A.V. Kneese and B.T. Bower, _Managing Water Quality: Economics, Technology, Institutions_, (Baltimore: Johns Hopkins Press, 1968), pp. 116-120.

2 See, _Ibid_., pp. 109-112.

There is one instance where the emissions of a major pollutant can be easily predicted by the amount of an input used. These are emissions of sulfur oxides from the combustion of fuels. Basically, all of the sulfur contained in fuels is emitted in the atmosphere in the form of sulfur oxides unless it is removed from the combustion gases. It is a relatively easy and inexpensive task to measure the sulfur recovered. So that an administratively convenient method of implementing a tax on emissions of sulfur oxides would be to tax the sulfur content of fuels and give tax rebates for the sulfur recovered.

One last point must be made clear. This is what we may call the regional aspect of air pollution control. It is unlikely that the emission of pollutants from a given source will result in the same amount of damage independently of the location where this occurs. It follows that a uniform tax, except the damage tax, would lead to results inferior to those where the level of the tax takes account of the location. Ideally, the tax should be correlated to the damage each source is liable to impose upon others. This, however, again because of measurement difficulties, is out of the question. There is nothing, however, which says that a tax should be uniform throughout the country.[1] It is a relatively simple matter to

1 No attempt is made here to discuss questions of jurisdiction between various levels of government. Some of the issues are discussed in D. Alheritiere, "Les Problemes Constitutionels de la Lutte Contre la Pollution de l'Espace Atmospherique au Canada," The Canadian Bar Review, L (December, 1972), pp. 561-579.

designate regions where different tax rates would apply. One would expect, for example, that tax rates would be highest in and around heavily populated urban areas where given concentrations of pollutants can do most damage.

(d) Market Structure

The use of corrective taxes (of whatever kind) has been questioned from another point of view, namely, the market structure of the externality generating industry. As shown by Buchanan,

> only when the industry generating the external diseconomy is competitively organized can the corrective tax be unambiguously hailed as welfare-improving, even in the presence of the other required conditions. Under monopolistic organization, the corrective tax may well lead to a reduction of welfare rather than an increase.[1]

Buchanan's reasoning is that, if the output of the monopolistically organized industry is already smaller than the socially optimum due to monopolistic restrictions, a corrective tax aimed at reducing its output may reduce welfare. This result will obtain when the reduction in welfare caused by the additional reduction in output is greater than the increase in welfare which results from the reduction in the external diseconomy.

Buchanan's conclusion seems inescapable. Nor can the existence in the economy of non-perfectly competitive industries

---

1 J.M. Buchanan, "External Diseconomies, Corrective Taxes and Market Structure," American Economic Review, LIX (March, 1969), p. 175.

which generate externalities be doubted. Hence, the use of corrective taxes in the presence of these market imperfections can only lead to second best results.

Two points can be made, however. The first is that the possible adverse welfare effects can be minimized by the use of appropriate corrective taxes. By this I mean that an emission tax would minimize the possible loss in welfare arising from the reduction in output caused by the tax relative to an output tax. This can be shown by Figure 2-4. This diagram represents an industry monopolistically organized which generates an external diseconomy equal (in monetary terms) to the distance MN. D is the demand curve for its product and MR its marginal revenue curve. A constant marginal cost (MC) is assumed. When no tax whatsoever is imposed on the industry, it will produce quantity Q and the product will be sold at price P. If an output tax T equal to the external diseconomy MN is imposed, the marginal cost-_cum_-tax will rise to MC_T, the industry will produce output Q_T, and sell it at price P_T. The net loss in welfare is equal to the area ABCD.[1] Suppose, however, that the cost of reducing the diseconomy by the same extent through the installation of anti-pollution equipment is less than the output tax. The output tax would not induce the monopolist to reduce the externality in this cheaper manner because, in addition to the cost of the anti-pollution equipment he would have to purchase, install, and maintain, he would still have to pay the tax on the output that he does sell. An emission tax, on the other

1 See, _Ibid_.

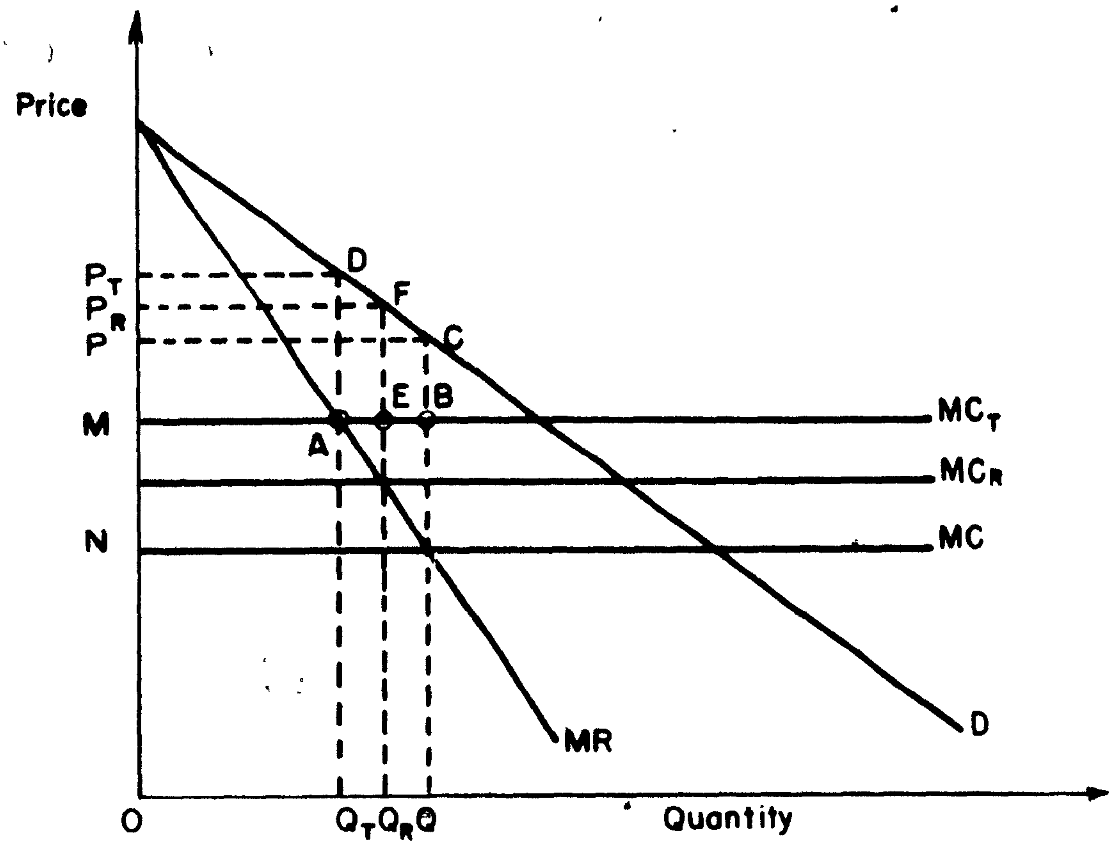

Figure 2-4 : Effects of Output and Emission Taxes on Monopolistic Firms.

hand, would encourage him to install the equipment. Suppose, for example, that the cost of reducing the externality in this manner is $R < T$. Then, MC would rise only to MC_R, the output would be Q_R, it would be sold at price P_R, and the loss in welfare would be only EBCF. Clearly, this is a situation to be preferred to the previous one and again establishes the principle that, whatever an output tax can do, an emission tax can do better.

The second point which can be made with respect to the inefficiencies created by the existence of imperfections in market structure is that it is not legitimate to use the existence of these inefficiencies solely as an argument against the use of corrective taxes.[1] The same argument could be made against any method of controlling externalities. If resource allocation is not optimal due to the existence of market structure imperfections, any reallocation, brought about by any method, will be second best.

2. The Market Failure Approach

The pervasiveness of externalities and their manifestation as environmental pollution can be and has been analyzed in terms of another concept: that of market failure. This concept includes externalities but encompasses several other interrelated aspects. Arrow, for example, states that "the problem of externalities is...a special case of a more general phenomenon, the failure of markets..." though "Not all examples of market failure can fruitfully be described as externalities."[2]

In the textbook type of economy, given certain conditions such as perfect competition in all markets and, specifically,

---

1 On this point, see J.T. Wenders, "Profit Maximization, Pollution Abatement, and Corrective Taxes," Journal of Economic Issues, VI (September, 1972), pp. 137-140.

2 K.J. Arrow, "The Organization of Economic Activity: Issues Pertinent to the Choice of Market Versus Nonmarket Allocation," in United States Congress, Joint Economic Committee, The Analysis and Evaluation of Public Expenditures: The PPB System. (Washington: U.S. Government Printing Office, 1969), p. 59.

the absence of external economies or diseconomies, the unfettered working of the market results in a Pareto optimum allocation of economic resources.[1] If in the actual economy some of the assumptions upon which this more or less idealized system do not obtain, this optimum allocation of resources will not be realized and the market is said to "fail." The existence of excessive pollution can be regarded as evidence that the market has failed to achieve the Pareto optimum. It is useful, then, to review briefly how the market fails and the aspects of market failure relevant to environmental pollution.

(a) Classification

Bator offers a useful classification of market failures. He suggests five modes (or types) of market failure and three, not mutually exclusive, causes.[2]

The absence of a set of prices or shadow prices which will equate the set of marginal conditions necessary to maximize social welfare will cause the market to fail by "existence." The possibility that the price system may lead profit maximizing producers into minimum or local maximum profit positions instead of overall maxima will cause the market to fail by "signal."[3]

1 A good statement of the necessary conditions can be found in F.M. Bator, "The Simple Analytics of Welfare Maximization," American Economic Review, XLVII (March, 1957), pp. 22-59.

2 F.M. Bator, "The Anatomy of Market Failure," Quarterly Journal of Economics, LXXII (August, 1958), pp. 351-379.

3 That is, it will give false price information to profit maximizing producers. This will lead to sub-optimal decisions.

The case where the set of prices allows only negative profits for producers of some socially desirable products will cause failure by "incentive." Imperfections in market structures will cause market-determined prices not to correspond to those leading to a Pareto optimum and the market will fail by "structure." Finally, arbitary legal or institutional imperfections may prevent prices from being assigned or preclude the appropriation of some gains through the market process, thereby causing the market to fail by "enforcement."

The three causes of market failure, according to Bator, consist of the presence of (1) ownership externalities, (2) technical externalities, and (3) public goods externalities. These are viewed as polar, but not mutually exclusive categories.

Ownership externalities exist when a factor owner is unable to charge for its services. This is referred to as the problem of non-appropriability (or non-exclusion). The result is failure by enforcement. Technical externalities arise because indivisibilities or increasing returns to scale exist. In the former case production can occur at a local profit maximum and the market will fail by signal. In the latter case, if marginal cost pricing is practiced, price may equal marginal cost below average cost. The result is that producers will be taking losses and the market will fail by incentive. Increasing returns, furthermore, can be incompatible with perfect competition, in which case the market will fail by structure. Public good externalities may be said to be present when the consumption of a good by one individual leads to no subtraction from any other individual's consumption of that good.[1] When this is the case, no set of market prices which will yield a social optimum will exist. Since the same consumption items enter the preference functions of more than one individual, there is no reason to ration the allocation of public goods and, hence,no positive price will allocate public goods efficiently. In such cases, the market, even when perfectly competitive, can be said to fail by existence, and will not achieve a social welfare optimum. Moreover, each individual acting in his self-interest will find it advantageous to understate his desire for public goods; hence, market forces will lead to a less than optimum provision of public goods.

This classification does touch on most of the problems connected with the pervasive existence of externalities in general and of environmental pollution in particular. *Inter alia*, it points to the "public good" character of pollution control and to the role of property rights in resource allocation or, in more general terms, the interconnections of economics and the law. These issues will be discussed more fully below.

One can argue, however, that Bator, by ascribing all causes of market failure to some type of externality, is overextending the concept of externality, thereby reducing its

---

1 Bator uses Samuelson's definition of public goods. See P.A. Samuelson, "The Pure Theory of Public Expenditure," *Review of Economics and Statistics*, XXXVI (November, 1954), pp. 387-389, and "Diagrammatic Exposition of a Theory of Public Expenditure," *Review of Economics and Statistics*, XXXVII (November, 1955), pp. 347-356.

analytical potency and its usefulness for policy. There is little reason for including under the concept of externality such things as problems of discontinuity and improper curvature and it is questionable whether the concept should include problems of indivisibility and returns to scale.[1] Baumol, for example, states that "by making the definition of externality broad, we can be led to the conclusion that anything which is wrong with the market mechanism is necessarily an externality."[2] This practice would greatly reduce the usefulness of the concept, especially as a guide to public policy.

Bator also downplays the importance of non-appropriability which, on the contrary, at least with respect to environmental problems, seems to be of crucial importance. Arrow, for example, suggests that the main causes of market failure are the inability to exclude (or non-appropriability) and the lack of information necessary to allow market transactions to take place.[3] The inability of the market to take account of external effects can be ascribed precisely to the fact that scarce resources are non-appropriable, that is, exclusion from their use cannot be enforced (and, as we shall see, to the fact that property rights to their use have not been clearly defined). Head, also, has

1 See, for example, Mishan, "Reflections on Recent Developments in the Concept of External Effects," The Canadian Journal of Economics and Political Science, XXXI (February, 1965), pp. 1-34.

2 Baumol, op.cit., p. 24.

3 Arrow, op.cit., p. 59.

advanced the view that exclusion difficulties and externalities refer essentially to the same phenomena.[1] After defining externalities in terms of interactions between production functions and/or utility functions of different individuals (firms), he attributes their existence to a "divorce of scarcity from effective ownership" such that it is

> impossible for private firms and individuals, through ordinary private pricing, to appropriate the full social benefits (or to be charged the full social costs) arising from their production and/or consumption of certain goods. [2]

(b) Public Good Aspects of Pollution Control

The "public good" character of pollution as well as of pollution control is evident. If the general level of air pollution is reduced in a city, all of the inhabitants will benefit, whether they contributed to the defrayment of the cost incurred in taking measures which resulted in the reduction of pollution or not. Therefore, any individual acting purely in his interest, if asked, say, to reveal his desire for pollution control with the proviso that he would have to contribute accordingly, will find it advantageous to understate his desire for pollution control. This is generally known as the "free rider" problem. The result is that no

---

1 J.G. Head, "Public Goods and Public Policy," Public Finance, XVII (1962), pp. 197-220.

2 Ibid., pp. 203-204.

corrective action will be taken. Each receptor and each emitter has an incentive to do nothing, hoping that others will do everything. The very universality of this incentive will insure that nothing will be done solely by market forces. Similarly, pollution itself may be considered an excessive use of common property resources such as air, water, and so on; hence, it may be called a "public bad." Here the use of the resource by one individual will decrease its supply to all. But, because the use of the resource cannot be appropriated by the market, excessive use cannot be prevented by the play of market forces alone.

It is also clear that there is some relationship between external effects and public goods, and that this relationship is inherent in the economic nature of pollution and its control. The nature of this relationship, however, is difficult to formulate. As Mishan puts it, "the nature of the suspected relationship between public goods and external effects has remained elusive."[1]

A related characteristic of externalities which has received attention is their identification with joint supply. Joint supply has been a recognized feature of public goods.[2] When a good is supplied for one consumer, it must be supplied to others. Thus, according to Buchanan, externalities are

---

1 Mishan, "The Postwar Literature on Externalities.." p. 9.

2 See, for example, W.H. Oakland, "Joint Goods," <u>Economica</u>, XXXVI (August, 1969), pp. 253-268.

merely a special category of joint supply arising when "an individual's act of consuming or producing a good or service is, at the same time, *jointly* supplying at least one other person with a good (or a 'bad')."[1] This is not intended to mean, however, that all joint products generate externalities. Buchanan believes that this approach has the advantage of concentrating on the "optimal externality mix" when the technological proportions between the components of the joint products are not fixed and on the derivation of the conditions necessary to attain this optimal mix. What this approach does is to integrate two aspects which are usually treated as being distinct, namely, the difficulties arising from conventional public good joint supply which limit the decision-maker's ability to adjust the quantity available to him, and those arising from conventional externalities involving interdependence of utility or production functions. The significance of this approach, according to Buchanan, is that it shows that there is an incentive for trade in externalities. This trade will tend towards the satisfaction of the optimal conditions "if the interacting groups are critically small."[2] If the groups are large, the free rider problem will arise, and the mix will not be optimal, though there may be possibility of "political trade." Unfortunately, as far as air pollution externalities are concerned, this is likely to be an acute problem since, very often, the groups involved are

---

1 J.M. Buchanan, "Joint Supply, Externality, and Optimality," *Economica*, XXXIII (November, 1966), p. 408.

2 *Ibid*., p. 415.

large, both as regards emitters and receptors.

An attempt to integrate joint supply, public goods, and external effects has also been made by Mishan.[1] He distinguishes between four situations, namely private goods with and without external effects, and public goods with and without external effects. He then examines the optimal social marginal conditions for production of jointly produced private and public goods with or without external effects.

While this classification helps in clarifying the effect of externalities on the degree of "publicness" of public goods, the effort must be seen, as Mishan states elsewhere, as "primarily an exercise in taxonomy."[2]

One further aspect of the relationship between public goods and external effects, with special reference to pollution control, deserves attention. Buchanan has shown that the usual conclusion of public goods theory that individuals have an incentive to be free riders is modified if these individuals are given the possibility to trade the opportunity to be free riders in exchange for some private goods.[3] That is, if the marginal rates of substitution of their preference patterns warrant it, they may be willing to trade their ability to costlessly use some public good such as air (i.e., to pollute)

---

1 E.J. Mishan, "The Relationship Between Joint Products, Collective Goods, and External Effects," Journal of Political Economy, (May/June, 1969), pp. 329-348.

2 Mishan, "The Postwar Literature on Externalities..." p. 9.

3 J.M. Buchanan, "A Behavioral Theory of Pollution," Western Economic Journal, VI (December, 1968), pp. 347-358.

in exchange for some private good, so that "depollution" clubs are formed. A possible way to achieve some level of depollution is for club members to bribe some potential polluters not to pollute. These clubs may engage in some degree of depollution activity even though they can expect that some individuals will elect to remain free riders and even generate some additional pollution, as long as the latter do not behave "anti-socially" and systematically cancel the efforts of those who initiate improvements.[1] Presumably, the net result would be some amount of "depollution." However, though Buchanan believes that "the model does have specific and direct relevance to many examples of congestion and/or pollution," he admits that it may have little relevance to problems arising from classic public good situations and, moreover, that the size of the total interacting group is important since "in critically large groups, the possibility of 'enlightened' behavior patterns may be remote."[2] Unfortunately, as mentioned, in most instances of air pollution problems, it is the case that large and diffuse groups are involved. So that reliance on voluntary initiative through the formation of clubs is hardly to be expected.[3]

---

1 _Ibid_., p. 354.

2 _Ibid_., p. 353, footnote 5.

3 The same difficulty, namely, the likelihood that most real problems involve large groups, limits the applicability of cooperation predicted from games situations, such as described by the so-called "prisoner's dilemma." These games are placed in small-group settings. See, for example, J.M. Buchanan, "Cooperation and Conflict in Public Good Interaction," _Western Economic Journal_, V (March, 1967), pp. 109-121.

(c) The Role of Property Rights

As discussed, the theory of externalities and the theory of market failure has provided the rationale for advocating public intervention in the economy. Following the Pigovian tradition, at least with respect to the problems at hand here, the intervention most frequently advocated has been the imposition of a system of taxes and subsidies of some kind which would bring social costs in line with social benefits. As early as 1924, however, Frank Knight took a different view and laid the foundations of another school of thought.[1] To Knight, most instances of Pigovian divergences between private and social costs were merely instances of wasteful uses of scarce resources. Such wasteful exploitation was the result of shortcomings or absence of appropriate ownership of these scarce resources. If congestion resulted on a road, for example, it was because the road was publicly owned (and, hence, not owned by anybody in particular). The solution according to him, was to place the road under private ownership so that an appropriate price for its use would be charged (i.e., a price equal to the value of the marginal product of the resource) and, given competitive markets, the resulting use would be optimal.

Knight's analysis is entirely valid, though it does not prove the Pigovian analysis wrong. As Mishan puts it,

---

1 F.H. Knight, "Some Fallacies in the Interpretation of Social Cost," Quarterly Journal of Economics, XXXVII (August, 1924), pp. 582-606. Reprinted in American Economic Association, Readings in Welfare Economics, (Homewood: Irwin; 1969), pp. 213-227.

"Pigou's external diseconomies approach is not shown incorrect by Knight's analysis, which, of course, is itself entirely correct."[1] Therefore, the two approaches must be considered alternative ones, at least potentially. In particular instances, the role and structure of property rights is crucial to the relative suitability of the two approaches.

We have also seen that one of the possible consequences of the existence of external effects and of public goods is to provide incentives to private parties to bargain in such a way as to achieve or approach the social optimum. We discussed some of the difficulties in the way of such bargaining, especially the fact that external effects related to environmental pollution are likely to affect large groups. We want to discuss these aspects more fully now and, since the role of property rights again has some bearing on the possible solution, discuss the influence of property rights on these issues.

The general idea is that a more clear delineation of property rights both facilitates private bargaining which internalizes externalities and will arise when such bargaining is made desirable by the existence of external effects. The clearer demarcation of property rights would change the structure of incentives and penalties, remove uncertainty, and promote a more efficient allocation of resources. As Desmetz puts it,

---

1 Mishan, "The Concept of External Effects..." p. 18.

"A primary function of property rights is that of guiding incentives to achieve a greater internalization of externalities."[1] and, in many cases,

> it is the prohibition of a property rights adjustment, the prohibition of the establishment of an ownership title that can thenceforth be exchanged, that precludes the internalization of external costs and benefits.[2]

The implication is that the assignment of rights of ownership or use to resources such as air, water, etc., would result in internalization of external costs and benefits and would prevent their overuse. Desmetz, for example, draws the conclusion that the "overhunting" connected with the fur trade in Canada was due to a lack of land rights among the Indians.[3] So, as Knight had done before, he ascribes the "overuse" of "communally owned" resources to the characteristics of a type of ownership which fails to correlate the private cost of use with the extent of that use. Distribute private ownership rights to the resource and internalization of external effects will follow. Any exceptions would be due to difficulties of exclusion.[4] Moreover, it is claimed, the resulting optimal "mix of output

---

1 H. Desmetz, "Toward a Theory of Property Rights," American Economic Review, LVII (May, 1967), p. 348.

2 Ibid., p. 349.

3 Ibid., pp. 351-353.

4 Ibid., p. 357.

will be independent of the distribution of property rights among persons except insofar as changes in the distribution of wealth affect demand patterns."[1]

On the other hand, property rights will arise when a gain can be realized by those affected by externalities through the internalization of benefits and costs. Once they realize that gains may be obtained from restricting individual use of the resource, the parties involved will enter into some agreement which re-defines user's rights, provided the costs of agreement will not exceed the gains.

The delineation of property rights often is the result of changes in technology and productivity. Desmetz, for example, states that

> Increased internalization, in the main, results from changes in economic values, changes which stem from the development of new technology and the opening of new markets, changes to which old property rights are poorly attuned.[2]

In the case of environmental pollution, these changes may consist of a shift in the status of a resource from very abundant to scarce, the introduction of polluting technology in place of non-polluting technology, changes in individual valuation of the amenities provided by the environment, and so on.

---

1 H. Desmetz, "Some Aspects of Property Rights," Journal of Law and Economics, IX (October, 1966), p. 62.

2 Desmetz, "Toward a Theory of Property Rights," p. 350.

The same conclusions can be reached from examining the mirror image of property rights, namely, liability for external effects.

Much of the literature on the subject has been spawned by an article by Coase who purported to demonstrate three related propositions.[1] Let us, therefore, examine his theses, in particular what has come to be known as the Coase Theorem.

(1) The nature of external effects is symmetrical; therefore, contrary to what Coase sees as the usual practice, considerations of social policy should not be directed only at controlling the actions of the party whose activity generates external effects. As he puts it,

> The traditional approach has tended to obscure the nature of the choice that has to be made. The question is commonly thought of as one in which A inflicts harm on B and what has to be decided is: how should we restrain A? But this is wrong. We are dealing with a problem of a reciprocal nature. To avoid the harm to B would inflict harm on A. The real question that has to be decided is: should A be allowed to harm B or should B be allowed to harm A? The problem is to avoid the most serious harm.[2]

It would be difficult to take exception with this position itself, except perhaps on distributive grounds. The

---

1 R.H. Coase, "The Problem of Social Cost," Journal of Law and Economics, III (October, 1960), pp. 1-44. Reprinted in W. Breit and H.M. Hochman, eds., Readings in Microeconomics, (New York: Holt, Rinehart and Winston, 1968), pp. 423-456.

2 Ibid., p. 424.

proposition can be interpreted as saying that, at any time, a given structure of property rights must be established and it is in the interest of the community to establish that structure which minimizes social harm or maximizes social welfare. If social harm is minimized by giving A the right to impose external diseconomies on B and let B adjust as he may, let it be so (aside from distributive objections). If, on the other hand, total social damage can be minimized by making A liable for the external diseconomies imposed on B (i.e. by denying A the right to impose external diseconomies on B), let it be so also, and let A make whatever adjustments he deems appropriate. It may be cheaper, for example, for a polluter to install devices which reduce emissions than for receptors to bear the costs or move away from the pollution source. In this case, liability should rest with the polluter. On the other hand, the contrary may be true. It may be cheaper for those harmed to adjust than for the polluter; in the extreme case the latter may be driven out of business. Coase shows this by the use of a numerical illustration of an external diseconomy involving damage to farm crops by smoke from a railroad. It might prove less costly for farmers to grow crops farther away from the railroad than to subsidize (or tax) the railway to curtail its operations. In such cases, the polluter should retain the right to pollute.

This argument is entirely correct. Liability, or property rights, should be assigned in such a way that the adjustment would have to be made by the party for whom it is cheaper to do so. In fact, it is a standard condition for achieving Pareto optimum that social welfare could not be increased by shifting the uses to which factors of production can be put. This condition implies the above rule concerning the assignment of liability. And, it is important to stress that it is entirely an empirical question as to which party would find it cheaper to adjust.

(2) Once the structure of property rights has been determined according to the criterion discussed in (1), it would be in the interest of the parties involved to initiate bargaining which would achieve a socially optimal level of external effects. Coase illustrates this with a number of law cases. His point is that the Pigovian tax-subsidy solution would not be optimum if there are cheaper alternative ways to eliminate or reduce damages from Pareto-relevant external diseconomies. The market, in his view, is such an alternative. The market can take account of external effects through transactions between the parties affected once legal rights have been clearly established. Under competitive conditions and assuming zero transactions costs, the settlements would result in an efficient solution to the externality problem.

We noted, in our discussion of the nature of externalities, that other theorists have arrived at the same conclusion.[1] The remarks made there apply to this second of Coase's propositions as well. The voluntary monetary settlement which would achieve a social optimum could be reached only if all of these

1 For example, Buchanan and Stubblebine, op.cit., and Davis and Whinston, op.cit.

necessary conditions are satisfied:

(i) bargaining is confined to the marginal unit of externality.

(ii) each party can measure the benefits he will derive from inducing the other party to modify his behavior.

(iii) the number of parties involved is small so as to avoid the possibility of free riders.

On theoretical grounds, Calabresi has stated that Coase's proposition is a kind of Say's Law of welfare economics.[1] The reason is that

> "...if one assumes rationality, no transaction costs, and no legal impediments to bargaining, all misallocations of resources would be fully cured in the market by bargains. Far from being surprising, this statement is tautological...."[2]

Classic definitions boil down to "mean that there is misallocation when a situation can be improved by bargains" so that bargains, under ideal conditions, would occur ex hypothesis.[3] In other words, the proposition that externalities could be internalized by bargaining is true by definition, and not a deduction.[4] Whether bargaining will occur or not depends on the existence of transaction costs, the structure of property

---

1 G. Calabresi, "Transaction Costs, Resource Allocation and Liability Rules - A Comment," Journal of Law and Economics, XI (1968), pp. 67-73.

2 Ibid., p. 68.

3 Ibid.

4 In fact, this is precisely how Buchanan and Stubblebine define Pareto-relevant externalities.

rights, and the psychological circumstances related to particular situations.

The primary implication, as Calabresi sees it, is that the best means by which externalities should be internalized is an empirical rather than a theoretical question.

> The question then becomes: Is this (approximately optimal allocation of resources in the presence of external effects) accomplished most accurately and most cheaply by structural rules (like anti-trust laws), by liability rules, by taxation and governmental spending, by letting the market have free play or by some combination of these? This question depends in large part on the relative cost of reaching the corrective result by each of these means...and the relative chances of reaching a widely wrong result depending on the method used.... The resolution of these two problems and their interplay is the problem of accomplishing optimal resource allocations.[1]

This approach seems to provide an escape route from having to decide *a priori* between the validity of the Pigovian solution or the solution which would rely on private initiative, the latter being facilitated by changes or clarifications of the structure of property rights. Both approaches are valid, but which one should be used in specific instances depends on the circumstances, such as relative costs, administrative feasibility, feasibility of exclusion, and so forth. Each case would be assessed individually, as long as the general criteria of minimizing cost or of maximizing net benefits are applied.

---

1 *Ibid.*, p. 69.

On the other hand, this again would place the policymaker in a world of second best solutions.

(3) The third proposition which Coase purported to demonstrate is that, assuming no transaction costs, the same allocation (or reallocation) of resources would occur, irrespective of which party were assigned property rights to communal resources, or liability for external diseconomies. Thus, it would not matter, in the absence of transaction costs, whether liability for pollution were placed on emitters or on those damaged by pollution; in either cases, the parties involved would negotiate a monetary settlement which would lead to the same internalization of the Pareto-relevant external diseconomy, pollution. This proposition has been reiterated by Kneese and Bower,[1] Turvey,[2] and seems to be accepted by Desmetz.[3]

The argument can be illustrated diagrammatically (Figure 2-5). Assume there is one emitter and one receptor. OE is the marginal cost of withholding pollutants. Its slope reflects the usual characteristic that it increases as more

---

1 A.V. Kneese and B.T. Bower, Managing Water Quality: Economics, Technology, and Institutions. (Baltimore: Johns Hopkins Press, 1968), pp. 98-109.

2 R. Turvey, "On Divergencies Between Social Cost and Private Cost," Economica, XXX (August, 1963), pp. 309-312.

3 Desmetz, "Toward a Theory of Property Rights."

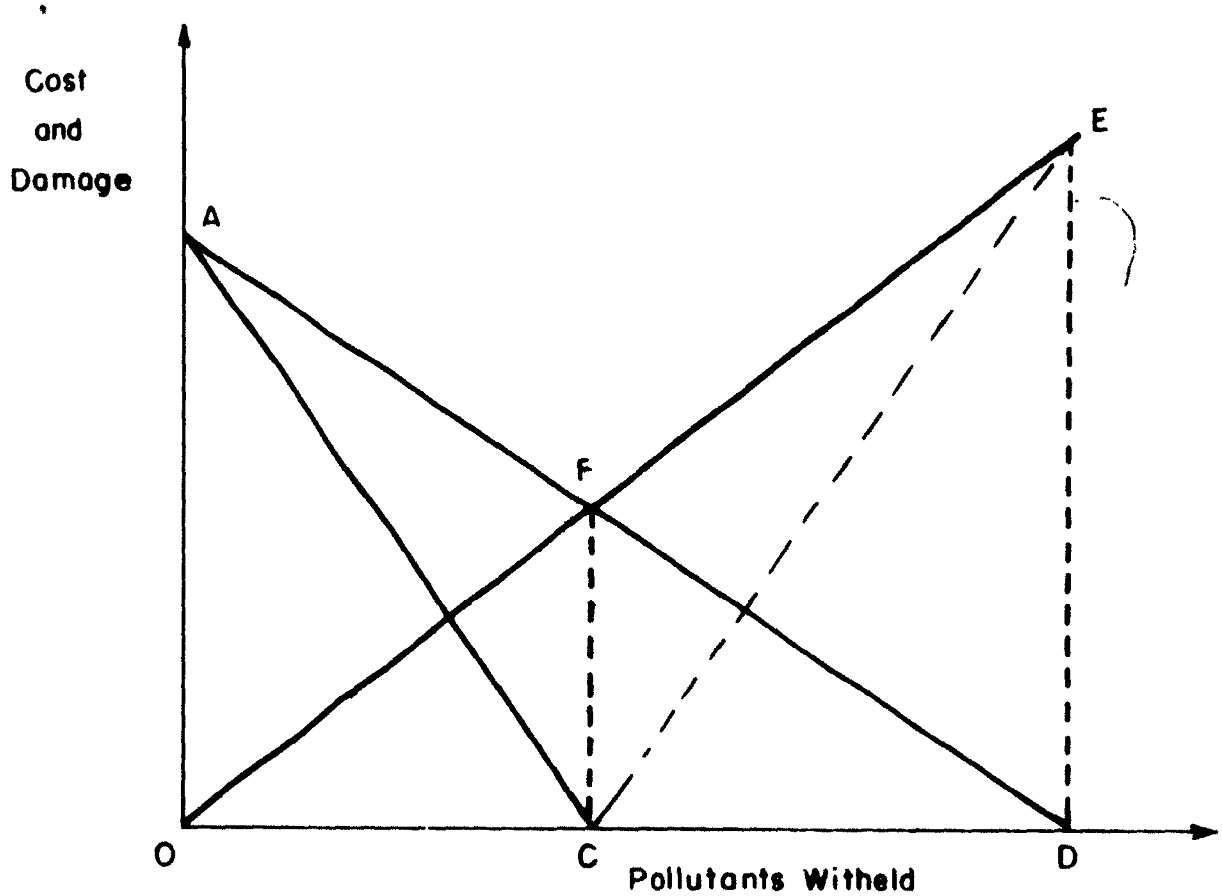

Figure 2-5 : Pollution Abatement through Bargaining.

pollutants are withheld. AD shows the incremental damages avoided by withholding pollutants and exhibits the usual assumption of diminishing marginal utility of pollution control to the receptor. At point D enough pollutants are withheld that no incremental damages occur.

Initially, when no rights have been assigned, the emitter would not withhold any pollutants and the total damage would be the area under AD, that is, area OAD. Suppose now that the receptor can exact compensation for damages by the emitter (i.e., the right of damaging other parties is denied to the emitter by the law). Assume, for simplicity, that the emitter would have to pay an amount exactly equal to the marginal damage inflicted on the receptor. The emitter could reduce his waste discharges to zero by withholding an amount OD. If he tried to withhold this quantity, however, he would find that, for each unit of pollutant withheld, the marginal cost of withholding this unit would exceed the damage avoided (which he would have to pay for if he did not avoid it). Hence, he would continue to discharge that unit of pollutant. This is true up to point C.[1] At any point between O and C, the opposite is true. Therefore, his "net gain" function (i.e. the difference between the cost of withholding a unit of pollutant and the value of the damage that unit, if emitted, would represent and for which the emitter would be liable) becomes AC. Therefore, the optimal solution is to reduce emissions by an amount OC. At the optimal level of emissions CD, total damage is CFD and total cost is OFC. Hence, total social net gain is OAF.

Alternatively, suppose that the law gives to the emitter the right of inflicting damage on the receptor and that, therefore, the latter must bribe the emitter not to discharge pollutants. Assume he would have to pay exactly the marginal cost of withholding pollutants. In this case starting from O,

---

1 The same optimum point of pollution discharge could be obtained by the same type of reasoning, by measuring "pollutants emitted" instead of "pollutants withheld" on the abscissa of Figure 2-5. In that case, the marginal cost curve of reducing pollution would be downward sloping and the marginal damage curve of additional pollution would be upward sloping.

the receptor would find that, for each unit of pollutants withheld, the marginal damage exceeds the marginal cost until point C is reached, after which the opposite is true, Hence, after compensation, the marginal cost of control to the emitter is CE and the optimal level of pollution control is OC. Again OAF is the net social benefit.[1] Note, however, that as expected, in the previous case the net social benefit accrues to receptors, while in the latter case it accrues to emitters.

Such argument is deceptively simple. Mishan, for instance, has demonstrated that the optimal outcome of bargaining would depend on the initial state of the law. That is, the outcome would be different depending on who initially were granted property rights or were assigned liability.[2] Adapting Hicksian terminology, he looks at the familiar situation of comparing the compensating-variation and equivalent-variation measures of a change in existing law (or, policy), instead, in terms of compensating-variation and equivalent-variation measures under alternative initial states of the law.[3] The

---

1 Note that the bargaining would achieve the efficient solution postulated by Figure 2-2 above.

2 Mishan, "The Postwar Literature on Externalities..." pp. 18-24. Also, his "Pareto Optimality and the Law," Oxford Economic Papers, XIX (November, 1967), pp. 247-280.

3 The compensating variation is the difference between the maximum sum an individual would be willing to pay for acquiring a good (or, avoiding a 'bad') and the going price. The equivalent variation is the difference between the minimum amount the individual must receive to induce him not to acquire the good (or, put up with the 'bad') and the going price.

initial alternatives are: a "permissive" law L which is tolerant of externalities, that is, it gives firms and individuals the right to impose external effects on others, and a "prohibitive" law $\bar{L}$ which does not permit such externalities.

Mishan considers the situation of an airline, A, which imposes noise on people who act as a group, B. The situation is reproduced in the following table:

Existing Law	A	B	Total (A + B)
L	-\$55 m	\$40 m	-\$15 m
$\bar{L}$	\$45 m	-\$70 m	-\$25 m

Source: Mishan, "The Postwar Literature..." p. 19.

Positive signs indicate maximum amounts which individuals or groups are willing to pay to acquire a good (or, avoid a 'bad'); negative signs indicate minimum amounts they will accept to forego a good (or, put up with a 'bad'). So that there is a possible Pareto-improvement if the algebraic sum of a contemplated change is positive, and a Pareto-loss if the sum is negative. Now, it is obvious that, in the example, the existing state of the law is Pareto optimal no matter what the law is. In other words, no change in the law would be warranted, no matter what the law is initially. Therefore, the optimal outcome depends on what is the initial state of the law. Mishan goes on to show that, even assuming costless bargaining, the outcome of such bargaining would be different under initial states of the law.[1]

(d) Transaction Costs

Aside from the point made by Mishan, it must be recognized that, in practice, bargaining will rarely be costless. Hence, the question of neutrality of property rights under costless bargaining is largely academic. So, let us examine the effects of transaction costs on the matter.

"Transaction" costs actually include (i) the costs of reaching an agreement, and (ii) the costs of enforcing and policing the agreement.

One consequence of the existence of transaction costs is that, even when all other conditions are favourable, some agreements will not be reached. In principle, failure to reach agreements will occur whenever the transaction costs exceed the benefits from the agreement. That this is the case may explain in part the persistence of external effects. McKean, for example, states that

> One reason external effects exist is that the cost of defining, exchanging, and policing rights to benefits or rights not to be afflicted with damages, sometimes exceed the gains to private groups 'internalizing' those effects.[2]

Coase also emphasized that failure to achieve the results he predicted was to be ascribed often to the costs of reaching and maintaining agreements.[3]

---

1 Mishan, "The Postwar Literature...," pp. 20-21.

2 R.N. McKean, Public Spending, (New York: McGraw-Hill, 1968), p. 65.

3 Coase, "The Problem of Social Cost."

With reference to air pollution, one unfortunate thing is that transaction costs are likely to be very large due to the fact that large groups are usually involved, especially as regards receptors. Though no proof has been offered, Mishan, among others, believes that these costs will rise exponentially with the size of the bargaining group.[1]

The difficulty of reaching agreement in the presence of transaction costs is reinforced when exclusion from the benefits to be derived from the agreement is not possible. Since transaction costs include the cost of maintaining the agreement, when exclusion is not possible, those who remain free riders will be able to enjoy the same benefits as those who pay, without incurring the cost. Therefore, the incentive not to participate in any agreement will be much greater than in the case where transaction costs are zero. This makes successful bargaining much more unlikely. Again, we have seen that this is a common feature of pollution abatement.

The conclusion which has often been derived from the consideration of these difficulties is that government should intervene directly, instead of relying on market forces as expressed through bargaining. Possible forms which this intervention can take are the implementation of tax-subsidy schemes, the creation of control agencies, and explicit legislation.

Such conclusion often disregards the fact that government intervention is not costless either. In some cases, this

1 Mishan, "Pareto Optimality and the Law."

might simply involve the shifting of transaction costs from private parties to the government. In these cases, if the existence of these costs did not justify the reaching of an agreement on grounds that the cost exceed the expected benefits, it is difficult to see how a government-enforced agreement can be justified. In general, when transaction costs are positive, it is necessary to ask whether government can correct external effects at less cost than can the market or, indeed, whether such correction is warranted, given costs and benefits. This was one of Coase's points. The mistaken notion that government intervention is always warranted when a market failure is observed occurs often because economists tend to use what Desmetz calls the "nirvana approach."[1] That is, they compare the actual performance of the market and compare it to an ideal market and, unsurprisingly, they deduce that the former is inefficient. The correct approach, according to Desmetz, is to use a "comparative institution" approach which would attempt

> to assess which alternative real institutional arrangement seems best able to cope with the economic problem; practitioners of this approach may use an ideal norm to provide standards from which divergences are assessed for all practical alternatives of interest and select as efficient that alternative which seems most likely to minimize the divergence.[2]

---

1 H. Desmetz, "Information and Efficiency: Another Viewpoint," Journal of Law and Economics, XII (April, 1969), pp. 1-22.

2 Ibid., p. 1.

One possible reason why state intervention may not be optimal is that, if the intervention takes the form of the creation of a control agency, such agency, once in place, might not be interested in maximizing social net benefits. De Alessi, for example, has shown that rational bureaucrats bent on maximizing their own utility, have an incentive to favour projects which they prefer, including projects which may enhance their own prestige.[1] Even assuming that the state agency is interested solely in maximizing social welfare, moreover, there is no *a priori* reasons why its establishment should be a less costly alternative. In addition to the costs of taking and enforcing its decisions, the agency, or the state in general, must incur costs of obtaining the information upon which its decisions must be based. In order to make "good" decisions in terms of some objective functions and given means, a public body must have information about consumer preferences and about alternatives open to producers. The operation of the market provides this information at a very low cost, enabling producers to maximize profits and consumers to maximize utility. When inefficiencies in the market are present, the social choice is between the inefficient decisions reached by the market and decisions reached by public bodies. The latter, on the one

1 L. De Alessi, "Implications of Property Rights for Government Investment Choices," *American Economic Review*, LIX (March, 1969), pp. 13-24. See also W. Niskanan, "Non-Market Decision Making: The Peculiar Economics of Bureaucracy," *American Economic Review*, LVIII (May, 1968), pp. 293-305.

hand, attempt to eliminate the inefficiencies generated by the market and, on the other, may create their own inefficiencies because their decisions are based on incomplete, expensively acquired information. A priori insistence on the latter course of action, according to McKean and Minasian, is to achieve "Pareto optimality regardless of cost."[1]

The decisions of a public body could be inefficient even if it were perfectly responsive to the dictates of the parties affected, if these dictates are expressed as a one-man-one-vote majority (that is, if the information is sought through majority voting). Voting will not necessarily generate decisions which maximize net benefits. Suppose, for example, that a majority of citizens wanted a greater amount of pollution control than the minority wants. As expressed by voting, more pollution control would be undertaken, even if the minority were willing to pay more for the right to continue some pollution than the majority were willing to pay for its abatement. In terms of net benefits, the voting decision would be inefficient.

The costs of obtaining information will be larger and the information obtained less reliable when exclusion to the benefits derived from decision is not possible. For, in those instances, individuals will have an incentive to conceal or give misleading information. As Desmets puts it,

1 R.N. McKean and J.R. Minasian, "On Achieving Pareto Optimality Regardless of Cost," Western Economic Journal, VII (December, 1969), pp. 14-23.

> If the government should merely question those who alleged that they will be harmed by the activity, it will be in their interest to exagerate the harmful effects so that they can increase the probability that the activity will be prohibited. Those who allege that they will be harmed if the activity is prohibited have an incentive to exagerate the benefits they will derive from the activity. Assessing these benefits and costs by simple-minded questionnaires or by relying on the publicity of complaints will lead to the decision being based on inaccurate information, although this is a fair description of the way in which the political calculus sometimes operates.[1]

One way to decrease the costs of information is to require compensation actually to be paid by those who gain from a policy change to those who lose.

The rationale for this is as follows. According to the Pareto criterion, a change from the status quo is to be considered an improvement if it makes at least one person better off without making anybody worse off. This would be achieved if the gainers were to compensate the losers and still be better off. Now, since this would be quite a restrictive criterion for economic policy, in the "New Welfare Economics" a weaker criterion of potential compensation was devised; use of this weaker criterion makes possible the acceptance of policies which do leave some individuals worse off.

The criterion of potential compensation has been rejected by Buchanan on grounds that it assumes omniscience on the part

---

1 H. Desmetz, "Some Aspects of Property Rights," Journal of Law and Economics, (October, 1966), p. 69.

of the economist as an observer, especially of the preference functions of individuals, where in fact he has no such omniscience.[1] As he puts it,

> But quite clearly if the political economist is presumed to be ignorant of individual preference fields, his predictions (as embodied in suggested policy changes) can only be supported or refuted if full compensation is, in fact, paid.[2]

This, he argues, need not create a bias towards the status quo, as some economists have maintained because, if the suggested policy change makes everybody better off, this will include those who must make the compensation. Moreover, as the examples of charity and the support for progressive taxation indicate, it is quite possible that individuals may be willing to reduce their own income in order to support a policy change of which they approve, provided there is horizontal equity, that is, provided all individuals in similar circumstances can be induced to do likewise.

The government, by requiring gainers to actually compensate losers, would elicit more accurate information. The individual who would gain from a policy change and, therefore, favor such a change, would have no incentive to overstate

---

1 J.M. Buchanan, "Positive Economics, Welfare Economics, and Political Economy," in his Fiscal Theory and Political Economy, (Chapel Hill: University of North Carolina Press, 1960), pp. 105-124.

2 Ibid., p. 111.

the gains since otherwise he would be required to contribute a larger amount in order to compensate the losers. A loser, on the other hand, would have no incentive (or, if he does have an incentive, it will be smaller) to overstate the expected losses because, if he were to demand a compensation greater than the gains accruing to the givers, no policy change would take place.

This, of course, presupposes that individuals are capable of assessing damages and benefits. With respect to environmental pollution, where there are considerable subjective benefits and costs, this may not be the case.

(e) Asymmetry in Transaction Costs

One aspect of transaction costs has implications regarding who should be assigned property rights to benefits or liability for external diseconomy. In the discussion of this issue above, symmetry was assumed with respect to transaction costs incurred (or bargaining power) by opposing groups. Often, however, no such symmetry exists. Kneese, for example, states that

> parties involved in an environmental pollution situation are usually anything but "separate but equal" insofar as organization, power, and information are concerned. The typical situation is one in which one or more sources of pollution, usually associated with a well-organised economic interest, affect a large and diffuse group of parties where individual interests are hit relatively little.[1]

---

1 A.V. Kneese, "Environmental Pollution: Economics and Policy," American Economic Review, Papers and Proceedings, XLI (May, 1971), p. 154.

The clear implication is that liability should rest with the polluter.

Mishan also makes a case for assigning liability to the polluter.[1] Advancing the aforementioned argument that transaction costs will rise exponentially with the size of the group, he concludes that transaction costs will be larger if the larger group initiates bargaining than if the smaller group does so. Since in most situations involving environmental pollution the number of receptors is likely to be larger than the number of emitters, the assignment of liability to emitters would result in lower overall bargaining costs. Under a law which puts liability on receptors, an individual taking the initiative for bargaining must exert considerable effort and incur the risk of substantial personal costs in order to achieve a solution which will reward the individual with relatively low personal benefits. Under a law which put the liability on the polluter, business executives, without incurring substantial personal risks, can more easily organize into a group which can carry out negotiations with the damaged parties.

Similarly, Olson shows that, in many instances, groups will not organize because the costs of organizing exceed the expected benefits; or, if groups do organize, they will not attain optimal quantities of a good in which individual members have a common interest (such as pollution abatement) because the individual rewards are small.[2] The difficulties are far

1 Mishan, "Pareto Optimality and the Law," and "The Postwar Literature..."

2 M. Olson, The Logic of Collective Action, (Cambridge: Harvard University Press, 1965), pp. 5-65.

greater for larger groups than for smaller ones.

While these arguments seem convincing, in some cases clearly they are not true. For example, in the important instance of air pollution by motor vehicles the groups involved are both very large, if not equally so. It is difficult, therefore, to make general statements, on allocative grounds, about the superiority of one structure of property rights or liability over another.

One alternative would be to invest in some public agency the authority to assign liability to different parties in different circumstances. But, as we have seen, this involves costs and difficulties of its own.

In conclusion, bargaining solutions, when the inevitable transaction costs are taken into account, may not only be impracticable but also inefficient, even in principle, because no general rules about liability can be derived.

Earlier we saw that equally serious difficulties and inefficiencies are involved in tax-subsidy schemes.

So what is the appropriate solution? Clearly, second best solutions will have to do. Solutions must be tailored to individual situations based on empirical assessments of different control strategies.

3. The Benefit-Cost Approach

Frequently, environmental pollution problems and proposed solutions are evaluated by using benefit-cost analysis. Let us, therefore, examine its relevance to air pollution problems.

As its name indicates, benefit-cost analysis is concerned with a comparison of benefits and costs of publicly financed investment projects, whether the investment be in physical assets or in human resources. As such, it can also be used to rank projects, determine their optimum size, their product mix, capital intensity, and other aspects. In simplest terms, a project is considered justified if the discounted stream of benefits over the life of the project exceeds costs (or, alternatively stated, if the benefit-cost ratio exceeds unity).

While the principle of this decision rule is fairly simple and reasonable, its application raises many difficulties.[1] The main problems have hinged on the methods of measurement of costs and especially benefits, the appropriate rate of discount, the constraints surrounding projects, and on the issue of whether other objectives, such as income redistribution, should be considered "secondary" or on a par with economic efficiency.[2]

---

1 A summary is to be found in A.R. Prest and R. Turvey, "Cost-Benefit Analysis: A Survey," Economic Journal, LXXV (December, 1965), pp. 683-735.

2 See, for example, A. Maas, "Benefit-Cost Analysis: Its Relevance to Public Investment Decisions," Quarterly Journal of Economics, LXXX (May, 1966), pp. 208-226.

Our point here is that, though benefit-cost analysis has been used extensively with respect to the development of water resources and the abatement of water pollution, its usefulness with respect to air pollution control is rather limited. This is because, by its very nature, benefit-cost analysis is concerned with public investment. That is, its primary application has been to justify projects undertaken or financed directly by the government. This is because the benefits and costs to which the analysis refers include both social and private costs and benefits. As Pearce puts it

> The immediate distinction between a cost-benefit appraisal of expenditure policies and an appraisal in terms of private returns is...that CBA (cost-benefit analysis) attempts to allow for all the gains and losses as viewed from the standpoint of society.[1]

Thus the government may want to assess all social costs and benefits before deciding that the building of a dam or a water purification plant is justified.

Now, with some exceptions, the nature of air pollution is such that it cannot be controlled through public projects. The air over urban areas cannot be conveyed to a plant to be purified. So that, though the analysis of the previous indicates that government intervention is required to ensure air pollution abatement, one cannot expect this intervention to take the form

---

1 D.W. Pearce, Cost-Benefit Analysis, (London: Macmillan, 1971), p. 9.

of government financed projects. The exceptions which come to mind are the construction of municipal refuse incinerators and the abatement of emissions from public utilities. Important as they may be, these account only for a minor fraction of total air pollution emissions. In any case, abatement from these sources can be incorporated in some more general control approach. Much more promising forms of government intervention are the previously discussed tax-subsidy schemes or the promotion of private action through the demarcation of property rights and liability.

A more promising variation of benefit-cost analysis amenable of application to air pollution problems is the so-called "cost-effectiveness" analysis. This procedure, an offshoot of the evaluation of military programs in the United States, can be used to explore the relative costs of alternative means of achieving some given objective. It could be used, for example, to estimate the costs of achieving given levels of pollution control by alternative strategies. Ernst and Ernst, for instance, have made cost-effectiveness studies for a small number of metropolitan areas in the United States.[1]

1 See, for example, Ernst and Ernst, <u>A Cost-Effectiveness Study of Air Pollution Abatement in the National Capital Area</u>. (Washington, D.C.: Ernst & Ernst, 1969). In this particular study, the objective was the achievement of given levels of sulfur dioxide and suspended particulates from 99 major stationary sources. The strategies evaluated were: (1) a least-cost combination of emission control from all sources; (2) restricting fossil fuel combustion to at most one per cent sulfur content by weight; and (3) a "universal abatement" approach - i.e., to require all sources to undertake prescribed successive control measures.

This approach, however, requires the availability of two essential sets of data:

(i) a model which simulates average concentrations of given pollutants in the area under study; and

(ii) a source-by-source inventory of the emission of given pollutants in those areas.

Unfortunately, these sets of data exist for only a handful of urban areas (all situated in the United States, to the knowledge of the author) and even these are not generally accessible. Therefore, until such data becomes available in Canada, the potential of this approach must be left unrealized.

4. The Common-Property Resource Pricing Approach

One alternative approach to the problem of air pollution is to focus on the fact that air or, at least, clean air, is a scarce good or resource which, at the moment is not treated as such. Economists have been in the habit of citing air as the classic example of a good which, though extremely useful, is free because there is more of it available than could possibly be sold at any positive price. This might have been an accurate description of the situation during most of mankind's history. In the last few decades, however, especially in the last few years, it has become increasingly evident that this description is no longer a true reflection of reality in the modern industrialized world. Air has been put to uses which were largely or wholly non-existent before. Besides the traditional uses, such as supporting life, air is being used as a medium in which to discharge gaseous and particulate wastes arising both from consumption and production processes. Many of these processes have been introduced or have become widespread comparatively recently. The growth of cities, the intensification of industrialization, and the generalized use of motor vehicles, among other things, are examples of sources of demand for air use which are of a relatively recent origin.

It is quite probable, then, that air has become a scarce good or resource which, among other things, should command a positive price. This price, as in the case of other scarce economic goods, would be the economically appropriate instrument for allocating this scarce good or resource, air, efficiently.[1]

Yet, society still permits its individual members to use air for whatever purpose they please without requiring them to pay a price commensurate with this use. Some of the reasons why this is so were discussed in the previous sections. What interests us now is to discuss what would happen if, somehow, the deficiencies inherent in the market and legal systems were overcome, and a true market for air could be established. More precisely, how could a price for air be calculated? What would be the economic consequences of charging such a price to air users?

On the theoretical level, the answer to the first question is deceptively simple: by the interplay of demand and supply.[2] Demand for and supply of air differ from the demand for and the supply of ordinary goods in some important aspects, however.

In order to see the way in which this is true, it is necessary to discuss more fully the economic uses of air. Air has two basic economic dimensions. The first is to support life, to provide well-being and amenity, and to preserve property.

---

1 The discussion below is not meant to be a general discussion of resource pricing, but only of how such prices can be applied to the control of air pollution.

2 Demand and supply would be expressed as rates of use per period of time at various prices. We deal at this point with total demand and supply schedules, that is the sum of the supply and demand schedules for all the individual economic units in the economy.

Air's role in supporting life is obvious. Well-being and amenity include the subjective satisfaction of breathing "pure" air as contrasted with being forced to breathe "polluted" air; or the satisfaction of being able to enjoy an unobstructed view as contrasted with being forced to see things through a haze of smog. It also includes more objective entities such as the incidence (or avoidance) of diseases, especially respiratory diseases. Preserving property includes such things as keeping one's clothes clean, preventing the erosion of buildings (or allowing the erosion to take place more slowly), and so on. We can summarize these functions of air, for lack of a better word, as the <u>sustenance</u> use of air. The other economic function of air is its use as a medium in which to dispose gaseous and particulate wastes arising either from consumption activities (e.g., house heating, automobile driving), or from production activities (e.g., factory smoke, truck driving). We can call this the <u>waste-disposal</u> use of air.

Keeping in mind the distinction between these two basic uses of air, we can see that the demand for air consists of two components. The peculiar aspect of the demand for air is that the total demand is not simply the algebraic sum of the two components. This is because the air demanded for each of the two uses need not be of the same quality. The demand for air for sustenance purposes might in fact be called the demand for "clear air." In contrast, the quality of the air demanded for waste-disposal purposes practically does not matter. A manufacturer, for instance, does not really care about the quality of the air into which he discharges his own wastes, though he might care on other grounds (e.g., because polluted air increases his maintenance costs). In fact, it is possible to argue that corresponding to each of the uses of air, there are two demand schedules for air; that these are actually demand schedules for different commodities; and that they should be kept separate. On the other hand, they cannot be kept separate because increased use of air for waste-disposal purposes decreases the quantity of clean air available for sustenance purposes.[1] Hence, the two components of the demand for air are interrelated and must be considered simultaneously.

Consider now the supply of air. The volume of air over a given area, in the sense of the mixture of gases which compose it, is given. That is, it is beyond man's power to alter it significantly. The original mixture of gases (i.e., before it is put to any use) constitute the supply of clean air and it is perfectly inelastic with respect to price. Now, if air were used exclusively for sustenance purposes, the amount available would exceed the quantity demanded at any positive price. That is, it is unlikely that, by itself, the demand for air for sustenance purposes would intersect the supply of air for that purpese at a positive price if air were not used for waste-disposal

1 Perhaps it would be more accurate to say that an increased use of air for waste-disposal purposes decreases the quality of air available for sustenance. The quantity of clean air available is meant henceforth to be an index of quality.

purposes. This is precisely what economists meant when they stated that air was a free good. The supply of air for waste-disposal purposes, on the other hand, is given by air's capacity to contain and disperse wastes. Since this capacity is relatively great (provided we did not have to worry about what happens to the quality of air), the supply of air for this purpose would also exceed the quantity demanded at any positive price. That is, taken by themselves, the demand for and the supply of air for waste-disposal purposes are unlikely to intersect at a positive price. Yet, when the two uses of air are considered simultaneously, as they must be, it is quite probable that a positive price is warranted. This results from the fact that the use of air for waste-disposal purposes at a rate higher than some critical rate will decrease the quantity of clean air (or the quality of air) available for sustenance purposes and, in this sense, decrease the supply of air for this purpose. This creates the element of scarcity necessary for any good or resource to command a positive price.

How could we incorporate these considerations into a model from which relatively meaningful conclusions could be drawn? This is attempted in Figure 2-6. In this diagram, the abscissa measures rates of air use and the ordinate measures price per rate of use. S_AS_A is the total supply of air in the sense of the volume of air over a given area available at a given moment; it is perfectly inelastic with respect to price because man is powerless to alter this volume. D_WD_W is the demand for air for waste-disposal purposes. It slopes downward

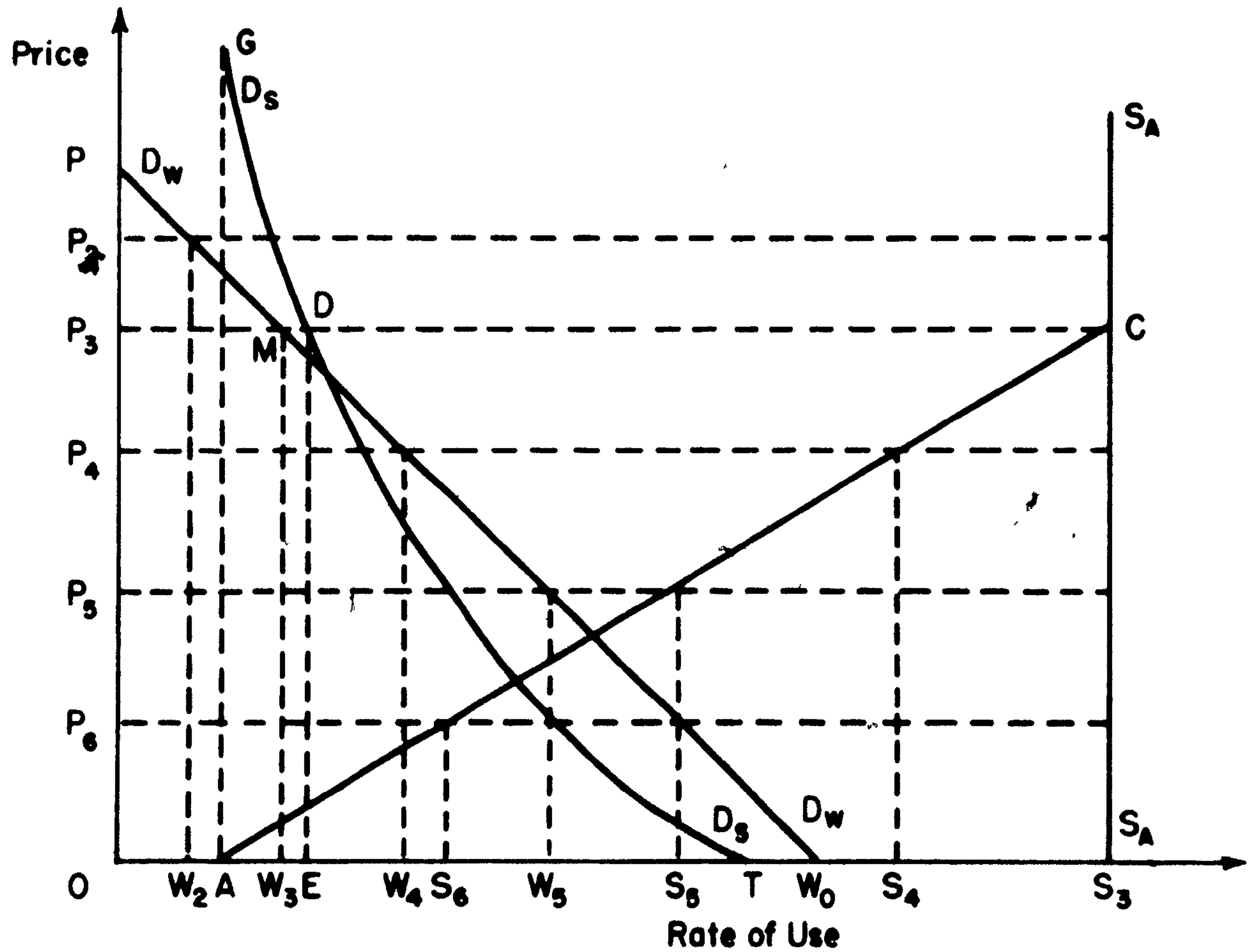

Figure2-6 · The Market for Air Use

to the right, indicating that at higher prices less air would be used for these purposes.[1] A price OP would be considered so prohibitively high that no economic unit would be willing to use air to disperse wastes. If no payment for waste discharge were required, air would be used for this purpose at the rate OWo,

---

1 D_WD_W has been drawn as a straight line. There is no particular reason for this: D_WD_W could have any curvature, as long as it slopes downward to the right and does not intersect S_AS_A at any positive price.

a rate smaller than the available supply of air. D_sD_s is the demand for air for sustenance purposes. It slopes downward to the right and it is probably very steep at high prices since, at these prices, air would be demanded for such essential uses as breathing. At low prices, the demand is likely to be less steep because air is demanded for such comparatively low priority uses as aesthetic pleasure. It is unlikely that D_sD_s would intersect S_AS_A at any positive price. That indicates that, if air were used solely for sustenance purposes, the amount available would exceed the amound demanded even when no payment for its use would be required.[1]

If air were used for either sustenance purposes only or for waste-disposal purposes only, then, no positive price for the use of air would be warranted. When air is used for both purposes simultaneously, as it is the case, however, the situation is different. Air has the property that it can renew itself in the sense that, given time, air currents and winds will disperse and dilute the pollutants discharged into it. How fast this self-cleaning will take place depends on the geographical and meteorological conditions prevailing in the area under consideration. It is possible, then, to use air for waste-disposal purposes to some extent and yet leave the supply of clean air (or, in other words, air quality) unaffected. That is, there is a given rate

---

1 D_sD_s has been drawn as intersecting D_wD_w. There is no particular reason for this, and it is possible to satisfy oneself that all the conclusions derived below would obtain even if D_sD_s were situated to the right of D_wD_w throughout the whole range of prices.

of use of air for waste-disposal purposes that leaves the original quality of air unaltered. If air were used for waste-disposal purposes at some rate greater than this critical rate, the quality of air available for sustenance purposes will decrease and, in that sense, its supply diminishes.

Referring to Figure 2-6, suppose that the maximum rate at which air could be used for waste-disposal purposes without affecting the original air quality is OW_3. A greater rate of use would exceed the airshed capacity to disperse wastes and would cause a deterioration of air quality. A rate of use of OW_4, for instance, would diminish air quality (say, by an amount measured by S_3S_4) and, in that sense, diminish the supply of air available for sustenance purposes by that amount. A rate of use of air for waste-disposal purposes of OW_5 would reduce the quality of air available for sustenance purposes even further, (say, by S_3S_5). Infinitesimally small increases in the rate of use of air for waste-disposal purposes above the rate OW_3, then, generate the curve CA which is the supply curve of clean air (always in terms of an index of quality), given the rate of air use for waste-disposal purposes.[1]

We are now in a position to draw some conclusions from the model. We saw that if air were used for either sustenance purposes only or for waste-disposal purposes only, no payment for the use of air would be warranted. Such a payment would indeed be warranted, however, when air is used for both purposes

1 There is no particular reason why CA should be a straight line.

simultaneously. Suppose, for the sake of discussion, that society imposed a price for the use of air for waste-disposal purposes. If this price were, say, OP_2 (Figure 2-6), air would be used for waste-disposal purposes at a rate OW_2. This rate of use would not be sufficient to affect the original purity of the air available for sustenance purposes. The same result would be obtained by imposing any price $P > OP_3$. At prices $P < OP_3$, however, air would be used at rates which would generate the supply of air for sustenance purposes CA. Now, presumably, the concern about air pollution is a concern about the quality of air available for sustenance purposes. We are not interested in the waste-disposal aspect of air use per se; we are interested in it because of its effects on the other use.

With this in mind, we may try to answer the following question: what would be the optimum price for air use? It would not make much sense to impose a price higher than OP_3, since the same air quality could be obtained by charging some lower price. What about OP_3? I suppose this would be the price which the no-matter-cost conservationist would advocate since, at this price, the original quality of air would be preserved. It is this the optimal price, however?

I think that, at this point, it is useful to distinguish between two possible alternatives. These are (a) both types of users of air pay the same user price and (b) only users of air for waste-disposal purposes will pay.[1]

1 It is possible to postulate other alternatives, but I do not believe that they are interesting or significant.

Consider alternative (a) first. Let us initially compare the situation prevailing today, that is allowing air to be used for both purposes at zero price, and that in which society imposed a user price of OP_3 on both types of users. In the case where air is used free, air is used for waste-disposal purposes at a rate OWo. As a result, air quality available for sustenance purposes is OA. If D_WD_W and D_SD_S indicate the monetary valuations which users of air attach to the use of air for waste-disposal and sustenance purposes respectively, we can measure the social surplus accruing to each type of user as the area under each demand curve (minus the amount he would have to pay).[1] At zero price, then, the social surplus accruing to the users of air for waste-disposal purposes would be OP_1Wo. At zero price also, the users of air for sustenance purposes would be content with an air quality level of OT. This would give them a social surplus equivalent to the whole area under D_SD_S. But as a result of use of air for waste-disposal purposes at a rate OW_O, air quality, we saw, deteriorates to OA. This means that the users of air for sustenance purposes are deprived of a share of social surplus equivalent to AGT. Compare this with the situation in which society imposes a uniform price OP_3. At this price, the loss in surplus to users of waste-disposal purposes is OP_3MWo. At this price, the level of air quality available to sustenance users is OS_3. Their monetary valuation of air

---

1 This social surplus is identical with consumer surplus when air is used in conjunction with consumption activities and is a rent when air is used in conjunction with production activities.

quality is represented by D_sD_s. Hence, they would gain, compared with the former situation, an amount of social surplus AGT. But they would have to pay an amount OP_3DE. Hence, their net gain (or loss) would be the algebraic subtraction of these two quantities. The social policy of charging a uniform price OP_3 to both users of air would be justified only if this net gain (if it is a gain) were greater than the loss to the other group; that is, if $(AGT-OP_3DE) > (OP_3MW_o)$.[1]

Consider now alternative (b), that is to impose a price OP_3 on users of air for waste disposal purposes only. As before, the social surplus accruing to users of air for sustenance purposes is AGT and the loss to the other group is OP_3MW_o. But this time the former group would not have to pay anything. Again, this policy would be justified only if the gain to one group exceeded the loss to the other. We cannot be certain on a priori grounds whether this is the case or not.[2] But we can conclude from the comparison we have made that alternative (b) is superior to alternative (a). It is easy to satisfy oneself that this will not be true only at price OP_3 but at any price between zero and OP_3.

There is a prima facie case, then, for imposing a price only on users of air for waste-disposal purposes instead of imposing it on both groups of users. This conclusion might appear trivial at first sight. Who would consider seriously

---

1 This disregards what could be done with the revenue derived from charging a price for air use. This question is discussed below.

2 That is, in some cases, the best policy may be to allow things to go on as they are.

charging people for breathing air or for related purposes? Besides the fact that it is good to rationalize our intuitive knowledge, however, such proof would have implications for the assignment of ownership to such resources as air, water, etc. For, following an established principle in welfare economics, if it can be shown that the benefits to society as a whole are greater if those rights are assigned to one group rather than the other, these rights should be assigned to the first group. In the case of air here, if the analysis is correct, it seems evident that, according to this criterion, not to mention common sense and political expediency, ownership rights should be assigned to users of air for sustenance purposes. This group then would have the right to charge a price to the other group for the right to use air for the alternative purpose instead of having to bribe its members for not doing so.[1]

As discussed in an earlier section, aside from questions of disparities in the transaction costs of bargaining, no case for such an assignment of rights has been made in the literature, with one exception. This exception is the argument made by

---

1 It is easy to see, for instance, that if society required only users of air for sustenance purposes to pay a price for this use, the result would represent a loss to society when compared with the present practice of not charging any price to either group. Referring to Figure 2-6, the imposition of a price OP_3 on the sustenance users would mean that they would have to pay an amount OP_3DE. Their position, therefore, deteriorates. Yet, there would be no gain at all for the other group.

Rothenberg; he states that

> There is an important asymmetry between those who spew gases in the air and those who only want to breathe it. The former do at least potential ill to the latter, but the latter do not do damage to the former. If this kind of asymmetry be granted, then it is not the case that neutrality (symmetry) of property rights is allocationally neutral.[1]

In any case, without claiming to have definitively resolved the issue, in what follows, it is assumed that only users of air for waste-disposal purposes will have to pay a price for air use.

This still leaves us with the question of what would be the optimum price. Before attempting to answer it, however, some assumption must be made as to what is to be done with the proceeds of selling the right to use air for waste-disposal purposes. We said, for example, that if society charged a price OP_3 (Figure 2-6) for the use of air as a waste-disposal medium, the loss to this group of users would be OP_3MW_o. This loss would have to be balanced against the gain to the other group of users (AGT). It must be recognized, however, that the sale of the right to use air would produce a revenue (OP_3MW_3 at price OP_3). This revenue can be put to some use. Hence, the net gain to society as a whole is more than the simple difference between the gain to one group and the loss to the other. We will disregard

1 J. Rothenberg, "The Economics of Congestion and Pollution: An Integrated View," American Economic Review, LXI (May, 1970), p. 115.

this fact, however, and proceed on the assumption that the net gain to society is the simple algebraic sum of losses and gains to the two groups. The following are justifications for this procedure: (a) it simplifies the analysis while the actual collection of revenue could be taken into account in any practical application of the theoretical apparatus; (b) since collection of revenue is not costless, some, or all, of the revenue could be used to offset the cost of collecting it; (c) such revenue could just go into general government tax receipts.

The question we would like to answer is: what is the optimum price which society should impose on users of air for waste-disposal purposes? Since charging a price for the use of air to this group reduces their social surplus while, as a result of the consequent improvement in air quality, the social surplus of the group that uses air for sustenance purposes increases, the optimum price must be that which results in the highest net additions to society as a whole.

Geometrically, we can find out what this optimum price will be by referring to Figure 2-7 (which is basically Figure 2-6 without many of the lines and symbols which cluttered it). Consider going from the present situation where no price is charged for the use of air to one where users of air for waste-disposal purposes are charged price OP_1. As a result, air quality improves from OA to OA^1. By the method described above, we would say that the loss of social surplus (call it SS_w) to users of air for waste-disposal purposes is OP_1FW_o. If the change in price

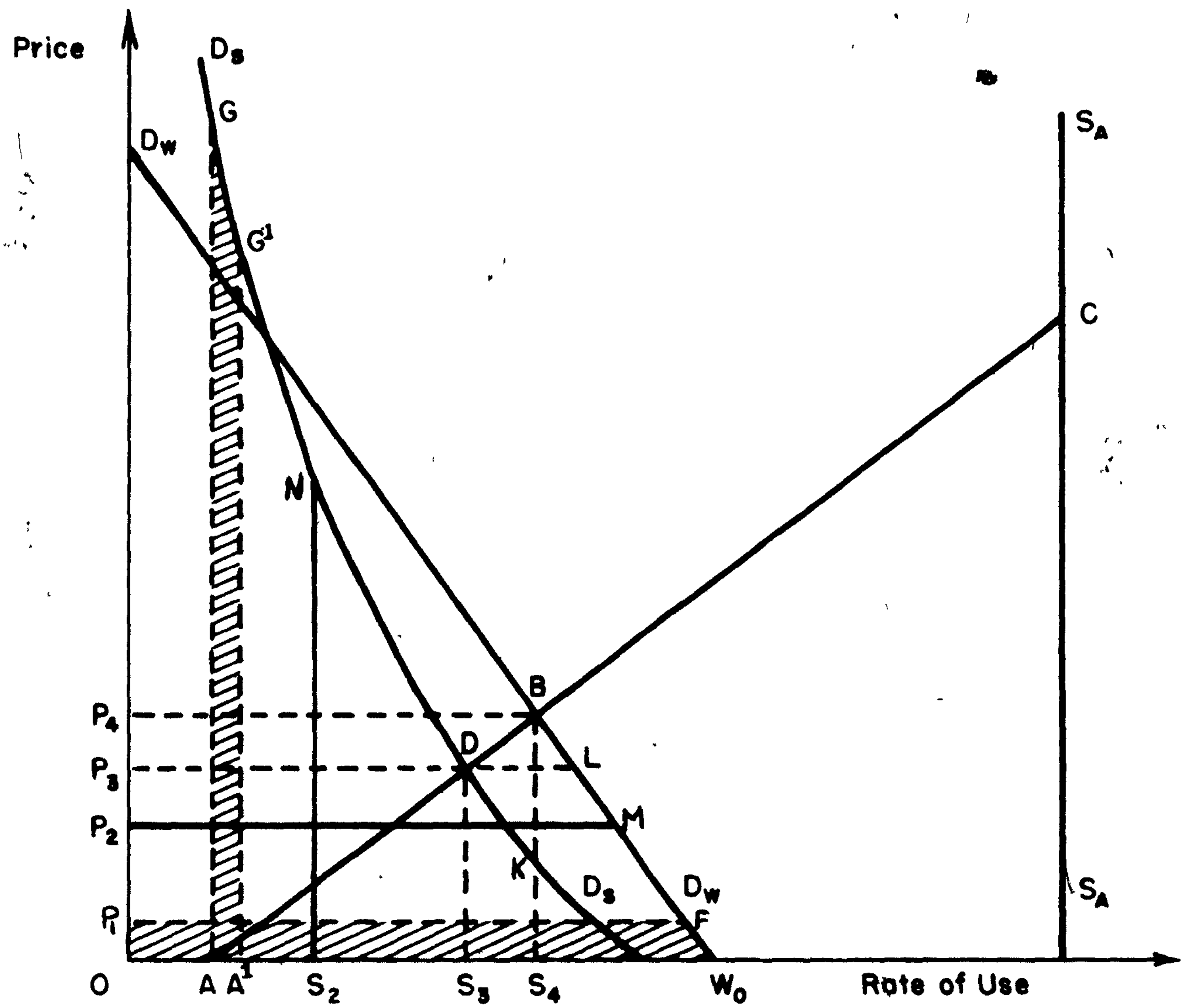

Figure 2-7: The Optimum Price of Air Use

were infinitesimally small, we could call the loss in social surplus to this group their marginal social surplus loss (MSS_W). We could also measure this MSS_W loss as the distance OW_0. Similarly, because of the resulting increase in air quality, the users of air for sustenance purposes would experience an increase in social surplus (SS_s) equal to AGG^1A^1. If the change in price were infinitesimally small, the marginal social surplus gain to this group (MSS_s) could be measured as the distance AG. Clearly, then, the action of increasing (from zero) the price by an infinitesimally small amount would be justified if $AG > OW_0$. Figure 2-7 is constructed in such a way that this is the case. The same reasoning could be made to justify any infinitesimally small price change (in either direction) and, by this method of measurement, clearly the optimum price is that where the vertical distance from D_sD_s to the abscissa is exactly equal to the horizontal distance from D_wD_w to the ordinate. Assuming Figure 2-7 to be constructed on the correct scale, for instance, we would judge price OP_4 to be excessive since $P_4B > KS_4$. Similarly, price OP_3 would be excessive since $P_3L > DS_3$. On the other hand, price OP_1 would be judged too low because $P_1F < A^1G^1$. The optimum price would be OP_2, since $P_2M = NS_2$. Charging this price would decrease the social surplus accruing to users of air for waste-disposal purposes by OP_2MW_0 and increase that of the users of air for sustenance purposes by $AGNS_2$. This policy would be justified, on efficiency grounds, if the latter exceeded the former.

Now, relevant questions are: what is the usefulness of the analysis? What are its weaknesses?

The approach has the advantage of focusing on the scarcity of a natural resource which heretofore was considered so aboundant that it lacked the status of economic good. Moreover, it seems to describe accurately the interactions among the various economic users of the resource. In particular, by illustrating the asymmetry in the interaction between the economic groups concerned and the asymmetry in resulting damage, the analysis may have something to say about the definition of property rights. That is, the analysis makes an argument for the assignment of property rights to potential pollutees. And it does so without appeal to disparities in transaction costs, size of groups involved, and so on.

On the other hand, since the pricing of a resource such as air could only be implemented by some government agency, this approach presupposes that government intervention other than a more clear definition of property rights or liability is required. We have seen in a previous section that this has not been demonstrated. So, in some sense, this approach prejudges this issue or presupposes its solution.

How could the scheme be implemented in practice? Air cannot be packaged and sold like an ordinary good; in some way, the inappropriability problem remains. Therefore, in practice, prices would have to take the form of emission taxes. That is, rates of use of the resource would have to be measured in terms of the quantities of emissions of wastes. Baumol and Oates believe that this translation of prices into taxes is a valid one. As they put it, "taxes would constitute a set of prices for the private use of social resources such as air and water."[1]

We have come back, then, a full circle, using an alternative analytical approach, to the prescription derived from the externality approach. This prescription may be open, therefore, to at least some of the objections raised in that discussion. In any case, most of this study is carried out using the traditional framework and terminology.

One further practical problem must be recognized. Since knowledge of the various demand schedules for air use is not likely to become known and no private market will make the decision, how can one calculate the optimal price (or, tax) in practice? Baumol and Oates recognize this problem and suggest an alternative approach which does not attempt to reach the optimal level of resource use. Rather, they suggest that the best practical alternative is to set somewhat arbitrary standards and then use prices to achieve those standards. For example, we, as a society, could decide that the acceptable level of sulfur dioxide in the air of urban areas is a certain percentage. Or that bodies of water should not contain more than a certain average concentration of given pollutants. Given these standards, society can set emission tax levels which will satisfy them. The strong advantage of this procedure, in the

---

1 W.J. Baumol and W.E. Oates, "The Use of Standards and Prices for the Protection of the Environment," <u>Swedish Journal of Economics,</u> LXXIII (March, 1971), p. 45). See also, W.J. Baumol, "Taxation and the Control of Externalities," <u>American Economic Review</u>, LXII (June, 1972), pp. 307-322.

words of Baumol and Oates, is that

> the information needed for iterative adjustments in tax rates would be easy to obtain: if the initial tax rates did not reduce the pollution... to satisfy the present acceptability standards, one would simply raise taxes. Experience would soon permit the authorities to estimate the tax levels appropriate for the achievement of a target reduction in pollution.[1]

Baumol and Oates go on to prove mathematically that, in any case, this method would achieve any given environmental standard at least cost.[2] It needs to be emphasized that such an approach can be used in practice whether one analyzes the problem of environmental pollution in the context of externality or of resource use pricing.

It must be conceded, however, that, since it is standards which will be satisfied rather than optimal standards, the

---

1 Baumol and Oates, op.cit., p. 45. The procedure is also endorsed by A. Myrick Freeman III and R.H. Haveman in their "Residual Charges for Pollution Control: A Policy Evaluation," Science, CLXXVII (July 28, 1972), pp. 322-329. Therein, Freeman and Haveman point out the similarity between residuals charges and more familiar ones, such as sewer user charges.

2 This proposal is similar in some respects and different in others to another fascinating one made by Dales. Dales would set the standard of air quality and determine the quantity of emissions that can be allowed. Then, he would set up a market for exactly that quantity of "pollution rights." The price of pollution rights in Dales' scheme is equivalent to the emission tax, except that it would be set by the market rather than by a government agency. See, J.H. Dales, Pollution, Property, and Prices, (Toronto: University of Toronto Press, 1968).

solution will be second best in any case. This need not detract from its usefulness, however. As Mishan so aptly states, "economists may like to remind themselves that the pursuit of the ideal is the enemy of the better."[1] There may be cases where such an approach would be clearly suitable.

---

1 Mishan, "The Postwar Literature on Externalities," p. 23.

CHAPTER III

THE ECONOMIC NATURE OF AIR POLLUTION: DISTRIBUTIVE ASPECTS

In the previous chapter attention was devoted solely to the question of increasing the welfare of society as a whole by reducing environmental pollution by some optimal amount. The alternative corrective measures discussed and the difficulties inherent in their implementation were examined solely from the point of view of their efficiency in attaining the optimal level (or some level) of pollution control. Most of the literature bearing on the problem of environmental pollution and other analogous manifestations of market failure deals almost exclusively with this aspect. It must be recognized, however, that any corrective social action, whether it takes the form of facilitating private bargaining through the legal assignment of property rights and liability, tax-subsidy schemes, or any other form, will affect in some way the distribution of costs and benefits between different individuals or groups of individuals. It is necessary, therefore, to examine the role of distributive considerations in environmental pollution control.

In terms of the model of common property resource pricing developed in the previous chapter, it is easy to measure in principle the distributive effects of such pricing. Assuming that only users of the resource for waste-disposal purposes were made to pay for that use, the distributive effects could be measured. The users of the resource for waste-disposal purposes would incur a loss of social surplus and the users of the resource for sustenance purposes would experience an increase in social surplus. In terms of Figure 2-7, Chapter II, the former would be OP_2MW_0 at price OP_2 and the latter $AGNS_2$. Unfortunately, no knowledge of the demand schedules for the use of the resource is, or is likely to be, available in that form. Therefore, no such straight-forward calculation of distributive effects can be made. Moreover, this method would not by itself reveal who are the different users in terms of the more familiar classifications of economic groups, such as groups with different income. Hence, the question must be considered in a different manner.

Several issues are involved. The first is whether distributive considerations should, or should not, be a factor having weight in public policies of the type which may insure optimal or acceptable levels of pollution control. If it is decided that they should, how much weight should they have? And how can such considerations be incorporated in the decision process? Obviously, an attempt to answer these questions presupposes a knowledge, at least approximate, of the distribution of damages from pollution and of the benefits which groups of individuals will derive from its control; it will similarly involve some knowledge of the apportionment of the costs which pollution control will entail.

The case for assigning a weight to distributive aspects in the management of the environment is part and parcel of the general argument for income redistribution. Weisbrod states this general case as follows.[1] Even when the market operates efficiently, "the degree to which incomes (are) determined in the private market depend on changeable forces over which the individual has, at best, limited control."[2] Examples of these forces are changes in consumer preferences which affect the demand for particular skills, and technological advances in production techniques which render some skills more valuable and some less so. This in itself may result in an income distribution which society may consider inequitable. The private market, as a rule, however, does not operate with perfect efficiency. As a consequence, the income distribution resulting from its operation may be both inequitable and "inefficient." Therefore, he states, "For both reasons, social action to influence the distribution of income has a rationale."[3] An analogous argument can be made with respect to the distribution of damages from environmental pollution and benefits and costs associated with its control. This is especially true since, as we have seen, environmental pollution is an instance of the "inefficient" functioning of the private market. Weisbrod also

---

1 B.A. Weisbrod, "Collective Action and the Distribution of Income: A Conceptual Approach," in Joint Economic Committee, U.S. Congress, <u>The Analysis and Evaluation of Public Expenditures: The PPB System</u>, (Washington: U.S. Government Printing Office, 1969), pp. 177-197.

2 <u>Ibid</u>., p. 178.

3 <u>Ibid</u>., p. 179.

shows that the three main functions of government (allocative efficiency, income redistribution, and economic stabilization) are interrelated, though they are often considered separately. That is, the idea of associating distributive consideration to the objective of efficiency is well grounded in Public Finance.

Similarly, in the context of benefit-cost analysis, Maas has argued that the objective function of most governments is complex and does contain, inter alia, distributive weights.[1] Economic efficiency is only one of a number of objectives. It is wrong, therefore, to base policy decisions solely on efficiency grounds. A policy decision should be based instead on all of the objectives which can be achieved by that decision. Sometimes, the objectives are complementary, in which case there is no problem; but, they may also be conflicting, in which case trade-offs must be estimated. In fact, there is no a priori reason to consider economic efficiency more important than redistribution. It all depends on society's welfare function. Moreover, Maas argues, the legislative process is capable of selecting these trade-offs.

The last assertion may be quite over-optimistic. The distributional impact of a given public expenditure is not confined simply to the immediate distribution of costs and benefits from the project. It consists also of secondary

1 A. Maas, "Benefit-Cost Analysis: Its Relevance to Public Investment Decisions," Quarterly Journal of Economics, LXXX (May, 1966), pp. 208-226.

effects arising, for instance, from increases in factor incomes through the respending process. These secondary effects, operating through the multiplier process would cause additional distributional changes.

Aside from this, however, there is the question of principle as to whether redistribution of income or welfare achieved through public expenditure is or is not achieved efficiently. The standard argument is that, if a given redistribution is desired, it will be more efficient to secure it through an income transfer than through a transfer of a particular good. The former type of transfer, by leaving the recipient the choice to exercise consumer sovereignty, will achieve a higher overall welfare for society as a whole than a transfer in kind of the same amount. Or, it would enable society to achieve a given redistribution of welfare with a smaller transfer of income. The argument concludes that, if redistribution of welfare in favour of a given group is desired, it would be more efficient to transfer given monetary sums to individuals in this group than, say, increase their welfare by controlling pollution in a manner which, as a specific objective, would transfer welfare to this group. Or, alternatively, if it is found that it would be inefficient to undertake some pollution control project, this decision should not be influenced by the fact that it imposes damages upon already disadvantaged groups, if these are compensated in monetary equivalent.

But, in fact, it is quite possible that society may be willing to transfer welfare to a particular group in kind while it would be unwilling to support an equivalent monetary transfer. That is, society may be willing to redistribute welfare in certain ways and not in others. Steiner, for example, states that

> It is sometimes argued that purely redistributional objectives which reflect a dissatisfaction with the initial situation of ownership of wealth and resources ought to be satisfied by income transfers rather than by provision of goods and services in order not to distort resource allocation. This familiar argument is unpersuasive if one regards as legitimate a desire of a society to interfere with the pattern of consumption that result from market determinations. A society may choose to affect jointly both income distribution and the pattern of consumption.[1]

In particular, society may legitimately prefer a less efficient distribution of welfare, provided that the distribution takes certain specified characteristics. For instance, society may be willing to devote resources to controlling pollution which predominantly affects a particular group, but not to give that group an equivalent monetary sum and let its members decide on whether they should or should not spend that sum, or part thereof, on pollution control.

There are several reasons for this possible preference on society's part. The first is probably a question of ethics.

---

1 P.O. Steiner, "The Public Sector and the Public Interest," in Joint Economic Committee, U.S. Congress, The Analysis and Evaluation of Public Expenditures, p. 23.

Perhaps the "good" which society is willing to redistribute is considered ethically superior to alternative goods and services which individuals of groups in whose favour a transfer is to be made would perhaps secure, if allowed to choose. Since society has no assurance that at least part of the money will not be spent on ethically inferior goods, society may wish to ascertain that this will not be the case by redistributing welfare in kind. Moreover, the argument about the inefficiency of redistribution in kind is usually made in term of static analysis. But society may be influenced by long term dynamic considerations. In the future, the behaviour of the groups whose welfare society wishes to increase will be determined in part by the form the redistribution of welfare takes now. And since, in the future, interaction between groups will remain, society, as a whole, may be interested in influencing this behaviour. That is, society, by making transfers in kind, may ultimately be furthering its welfare as a whole rather than just that of the recipients of the transfer. Perhaps, a more illuminating instance than pollution control is the case where society is willing to devote resources which eradicate the social and economic conditions which breed crime, while it would be unwilling to transfer the same amounts of money to the same groups to be used by them as they please. Obviously, the ultimate aim of society in making the transfer here is to protect itself.

Even if we conclude that redistribution of welfare is an objective which legitimately accompanies that of achieving greater efficiency by public intervention in an imperfect market economy, some difficult questions remain to be answered. Which group should benefit from a public activity and which group should bear the costs? To what extent should redistribution take place? And how important should be the goal of redistribution relative to that of efficiency (and others)?

With respect to the first question, the ethical assumption which is usually made, explicitly or implicitly, is that redistribution should be from higher income groups to lower ones. On the benefits side, this would mean giving higher priority to projects which, <u>ceteris paribus</u>, would result in a relatively higher proportion of benefits accruing to low income groups. On the cost side, redistribution in this direction could be achieved by allotting shares of the cost according to some measure of ability-to-pay as opposed to alternative measures, such as those based on the benefit principle, which would tend to be more neutral distributionally. Since the higher income groups would have a higher ability to pay, they would shoulder a higher share of the costs.

With respect to pollution control, the additional ethical judgement is frequently made that polluters must pay for pollution abatement.[1] In fact, the ultimate polluters are the consumers of the goods whose production, through various stages, generates pollution. Hence, this value judgement could be translated into saying that those who consume more of these

---

1 As we saw in Chapter II, this is tied in to the assignment by society to legal rights and liability.

products should pay more. It is quite probable, though not established, that these same individuals are also those who belong to higher income groups, so that the resulting redistribution of income or welfare could be considered in the right direction, according to the previously made value judgement.

The redistribution of welfare through air pollution control depends in part on the selection of the method through which control is to be achieved. Direct provision of air pollution control by the government would probably affect redistribution of welfare in the "right" direction if the costs of control would be financed through general income taxation, which is progressive, and the projects selected were those where pollution is most acute, which probably affects primarily lower income groups. If emission taxes were imposed, however, the prices of products whose production and consumption generates pollution would rise in some proportion to their propensity to pollute.[1] If it is found that higher income groups consume relatively larger shares of high polluting goods, such policy would achieve a redistribution of welfare from high income groups to low ones. If, on the other hand, the pattern of consumption is the opposite, the contrary redistribution would result. It is necessary, then, that, if a tax system of this type is to be implemented, to ascertain what this pattern of consumption is. Once this is done, the distribution of costs to different income groups can be assessed through a modified tax incidence analysis.

---

1 The propensity to pollute is meant here to be the waste generated in the process of producing and/or consuming the goods.

The modification to standard incidence analysis arises from the fact that an emission tax is different in its effect on the price of a product from either a unit excise tax or an _ad volorem_ excise tax. If one thinks, as it is usually done, of the effect of a tax on price as being what happens when, given the demand, the supply of the product shifts upward by the amount of the tax at each quantity, then the shift will be different in the case of an emission tax than in that of a unit tax or _ad volorem_ tax. The amount of the shift will depend on the propensity to pollute of the good rather than being some specified amount or some percentage of the pre-tax price.

On the benefit side, one must determine which groups benefit most from a given level of pollution reduction. In terms of the model developed in Chapter II, the marginal utility of air use for sustenance purposes diminishes as the quality of air increases. This suggests that the benefits from air pollution control will be greater for the groups who are subject to more severely polluted air. If it is found that these groups are low income ones, a given general reduction in air pollution will impart greater benefits on this group than on higher ones. This suggests that, on the benefits side, air pollution control would redistribute welfare from high to low income groups. Freeman reports evidence which suggests that this is the case with respect to pollution from sulfur oxides and particulates.[1]

1 A. Myrick Freeman, "Distribution of Environmental Quality," in A.V. Kneese and B.T. Bower (eds.), _Environmental Quality Analysis_, (Baltimore: The John Hopkins Press, 1972), pp. 243-278.

The main reason seems to be that air quality is worse in city centres and these centres are mainly inhabited by low income groups.

A difficult step is to place a monetary value on benefits from reductions in air pollution (or,conversely, on losses due to increases in air pollution). One type of benefit (or damage) presents relatively few problems of estimation. This is benefit derived from reductions in damages to materials, property, and so on experienced through improvements in air quality. Much more difficult problems of estimation are encountered when the attempt is made to quantify benefits from pollution control deriving from improvements in health and amenity.

Two approaches have been suggested. The first consists of estimating changes in mortality and morbidity associated with changes in air quality levels. Though much remains to be done, substantial statistical relationships between air quality and mortality and morbidity rates have been reported.[1] Conceptually, these relationships could be translated into healthy life expectancy as a function of different levels of air quality or air pollution. This has yet to be done and may be quite difficult

---

1 See, for example, L.B. Lave and E.P. Seskin, "Air Pollution and Human Health," Science, CLXIX (August 21, 1970), pp. 723-733. Also L.B. Lave, "Air Pollution Damage: Some Difficulties in Estimating Value of Abatement," in Kneese and Bower, Environmental Quality Analysis, pp. 213-241.

to achieve. The greatest obstacle is to find a satisfactory method of placing a value on life expectancy.[1] People do behave in ways that involve trade-offs between decreases or increases in life expectancy in order to obtain something else they value. People who drive racing cars in competitions are obvious examples. Still, estimates of value of life expectancy or even discomfort associated with illness remain very imperfect, even in principle. The most common measure of value of life expectancy used is the income foregone as a result of premature death and, in the case of illness, medical costs. Obviously, these measures understate the value of life and health considerably.

The other approach consists of attempting to correlate land and property values and air quality. The general idea is that people, ceteris paribus, will tend to move from areas where air quality is lower to areas where it is greater. Therefore, given the supply of land and property in each area the changes in demand for land and property would drive up prices in areas where air quality is higher and will push them down in areas where air quality is low. The evidence seems to suggest that this is indeed the case.[2] A general improvement in air quality

---

1 For a discussion of some of the problems involved, see E.J. Mishan, "Loss of Life and Limb," in his Benefit-Cost Analysis, (London: Allen and Unwin, 1971), pp. 153-174.

2 See, for example, R.G. Ridker and J.A. Henning, "The Determinants of Residential Property Values," Review of Economics and Statistics, XLIX (May, 1967), pp. 246-257.

would probably raise land and property values to a larger extent in areas of low air quality than in areas of already high air quality. Again, since it is probably true that lower income groups are located where air quality is lowest, it is probable that a general and uniform improvement in air quality would benefit lower income groups to a larger extent than higher ones. Again, however, the redistribution is difficult to quantify.

In conclusion then, any reduction of air pollution will result in some benefits and would entail some costs. Any assessment of the distributional effects of pollution control must assess who receives what benefits and who pays what costs. On the one hand, a given general reduction of pollution would benefit more those groups which are more severely damaged by the present levels of pollution. Probably, these are low income groups. On the other hand, if emission taxes are to be used to achieve pollution control, the cost shares will be proportional to the consumption by each group of products with different propensities to pollute. It must be established who these consumers are. An assessment of the distributional effects of air pollution control is the algebraic sum to each group of costs and benefits.

CHAPTER IV

SULFUR OXIDES: EMISSIONS, CONCENTRATIONS AND EFFECTS

Sulfur oxides gases (SO_x) are a major group of pollutants. They are emitted mostly in the form of sulfur dioxide (SO_2); only about 2% of emissions occur in the form of sulfur trioxide (SO_3). Eventually, though, the SO_2 is oxidized first to SO_3, and then to sulfuric acid (H_2SO_4). Ultimately, it will either settle in the form of sulfates or it will be washed out by rainfall. Table 4-1 is one estimate of total emissions of air pollutants in Canada in 1970 by major sources. Sulfur oxides, according to this estimate, amounted to 23.1% of the five primary air pollutants considered.

TABLE 4-1

ESTIMATED NATIONWIDE EMISSIONS - CANADA, 1970
(THOUSAND TONS PER YEAR)

SOURCE	CO	PARTICULATES	SO_x	HYDROCARBON	NO_x
Transportation	14,354	62	172	2,358	838
Fuel combustion in stationary sources	103	391	1,585	68	431
Industrial processes	759	1,320	5,445	111	15
Solid waste disposal	636	90	7	81	26
Miscellaneous	1,460	427	-	454	49
Total	17,312	2,290	7,209	3,072	1,359

Source: A Nationwide Inventory of Air Pollutant Emissions, Summary of Emissions for 1970. (Ottawa: Environment Canada, January, 1973), p. 2.

Emissions of sulfur oxides present some characteristics which make their abatement particularly amenable to an application of the control strategy discussed in Chapter II, i.e. the use of emission taxes to achieve acceptable concentrations of given pollutants. The main reason is that a very large proportion of total emissions of sulfur oxides is generated by a relatively small number of types of sources. Moreover, and this is important, these sources are stationary. Table 4-2 gives a slightly more detailed breakdown of sources of emissions of sulfur oxides than does Table 4-1. It can be seen that 97.5% of all emissions originated either from the combustion of fuels by stationary sources or from industrial processes. Table 4-3 gives the breakdown by industry of the emissions resulting from industrial processes. Only nine industries generated 75.5% of all estimated emissions of sulfur oxides in Canada. It can be seen from the figures in the three tables that, with one apparent exception, the two main sources of SOx pollutants account for relatively little of emissions of other pollutants, and vice versa. The apparent exception is emissions of particulates from industrial processes. But, as can be seen from Table 4-4, the industries from which most emissions of particulates originate are not the same as those from which emissions of sulfur oxides originate.

The great advantage of all this, of course, is that this situation makes it possible to treat the abatement of sulfur oxide pollution separately from the abatement of other pollutants without doing much violence to the interdependencies

TABLE 4-2

NATIONWIDE SULFUR OXIDES EMISSIONS - CANADA, 1970
(THOUSAND TONS PER YEAR)

SOURCE	EMISSIONS		PERCENT OF TOTAL	
TRANSPORTATION		172		2.4
Motor Vehicles	27		0.4	
Gasoline	(19)		(0.3)	
Diesel	(8)		(0.1)	
Aircraft	1		N	
Railroads	34		0.5	
Marine	108		1.5	
Non-highway use of motor fuels	2		N	
FUEL COMBUSTION IN STATIONARY SOURCES		1,585		22.0
Utilities and power generation	479		6.7	
Industrial and commercial	890		12.3	
Residential	216		3.0	
INDUSTRIAL PROCESSES		5,445		75.5
SOLID WASTE DISPOSAL		7		0.1
MISCELLANEOUS		N		N
Total		7,209		100.0

N - Negligible

Source: A Nationwide Inventory of Air Pollutant Emissions, p. 8.

TABLE 4-3

SULFUR OXIDES EMISSIONS FROM INDUSTRIAL PROCESSES - CANADA, 1970

INDUSTRY	EMISSIONS (TONS/YEAR)
Metallurgical coke	40,000
Primary aluminum	24,000
Primary copper and nickel	4,421,000
Primary lead and zinc	116,000
Petroleum refineries	33,000
Sulphuric acid	55,000
Kraft pulp mills	16,000
Sulphite pulp mills	149,000
Natural gas processing	593,000

Source: A Nationwide Inventory of Air Pollutant Emissions, p. 9.

and complementarities which exist between generation and abatement of different types of wastes. Rigor would seem to dictate that, because of the existence of these interdependencies and complementarities, it is necessary to deal with at least all of the major air pollutants simultaneously. Kohn, for example, builds a linear programming model where, given the cost of various control technologies for each air pollutant and source, he calculates the least cost of achieving given levels of annual

TABLE 4-4

PARTICULATE EMISSIONS FROM INDUSTRIAL PROCESSES - CANADA, 1970

INDUSTRY	EMISSIONS (TONS/YEAR)
Iron and steel	153,000
Other primary metals	111,000
Metallurgical coke	11,000
Petroleum refineries	1,000
Cement	248,000
Lime	54,000
Kraft pulp mills	86,000
Asbestos	80,000
Stone, sand, gravel	401,000
Grain handling	83,000
Grain Mills	4,000
Other	77,000

Source: A Nationwide Inventory of Air Pollutant Emissions, p. 7.

reduction of emissions for the St. Louis Airshed.[1] While such an approach on the surface seems more satisfactory, because it is more comprehensive, it has one basic weakness which detracts from its usefulness. The weakness is that the approach ignores

1 R.E. Kohn, "Linear Programming Model for Air Pollution Control: A Pilot Study of the St. Louis Airshed," Journal of the Air Pollution Control Association, XX (February, 1970), pp. 78-82.

some important aspects of the problem. For instance, it is possible to find the cost of reducing hydrocarbons, carbon monoxide, or nitrogen oxides emissions from motor vehicles through the installation of devices which prevent the emission of these pollutants and feed this data into the linear program. But the problem associated with motor vehicles is much wider. It is possible to reduce emissions by inducing people to drive fewer miles per year or to purchase vehicles with smaller engines. There is the whole issue of mass transit versus the use of the privately owned automobile; or, the problems of congestion and accidents which are complementary to that of pollution from motor vehicles; and even the very design of cities. So, it is quite unrealistic to treat in the same manner problems such as those associated with pollution by a relatively few types of stationary sources and the much more complex problems associated with emissions from mobile sources. Fortunately, as the figures show, by and large, the problems <u>can</u> be separated.

Even in terms of received economic doctrine, moreover, the problem presented by emission of sulfur oxides is of a relatively simple nature compared to that presented by emissions from mobile sources. If one thinks of emissions in terms of externalities, for instance, most emissions of sulfur oxides are of the unidirectional, separable type. Most emissions of these gases are generated by some well defined economic units and affect other economic units in a unidirectional way. Therefore, in this case, <u>inter alia</u>, there are fewer objections of principle to the use of control schemes such as emission taxes. Emissions from mobile sources, on the other hand, are mostly of the non-separable, reciprocal type of externalities and, therefore, are much more intractable , even in theory.

Incidentally, the relative importance of sources of emissions of sulfur oxides in Canada is quite different from that in the United States. In the United States, in 1970, 33.9 million tons of SOx were emitted. Of this total, fuel combustion from stationary sources accounted for 26.5 million tons or about 78%; industrial processes accounted for 6.0 million tons, or about 18%.[1] A major reason for the difference in the pattern of emission sources in the two countries is the difference in the methods of producing electric power. In the United States about 45% of total emissions of SOx are generated in the process of producing electric power. The main reason for this is that an overwhelming proportion of this power is produced by utilizing the thermal energy of fossil fuels. In Canada, by contrast, in 1966, 82% of the electricity generated was hydro-electric. This proportion, however, is expected to drop to 45% by 1990.[2] This indicates that, if no steps were taken to control SOx pollution, emissions would increase in Canada, even if emissions from sources other than the generation of electricity remained the same.

---

1 Environmental Quality, The Third Annual Report of the Council on Environmental Quality, (Washington: U.S. Government Printing Office, 1972), p. 6.

2 National Energy Board, Energy Supply and Demand in Canada, 1966-1990, (Ottawa, 1969), pp. 69-74.

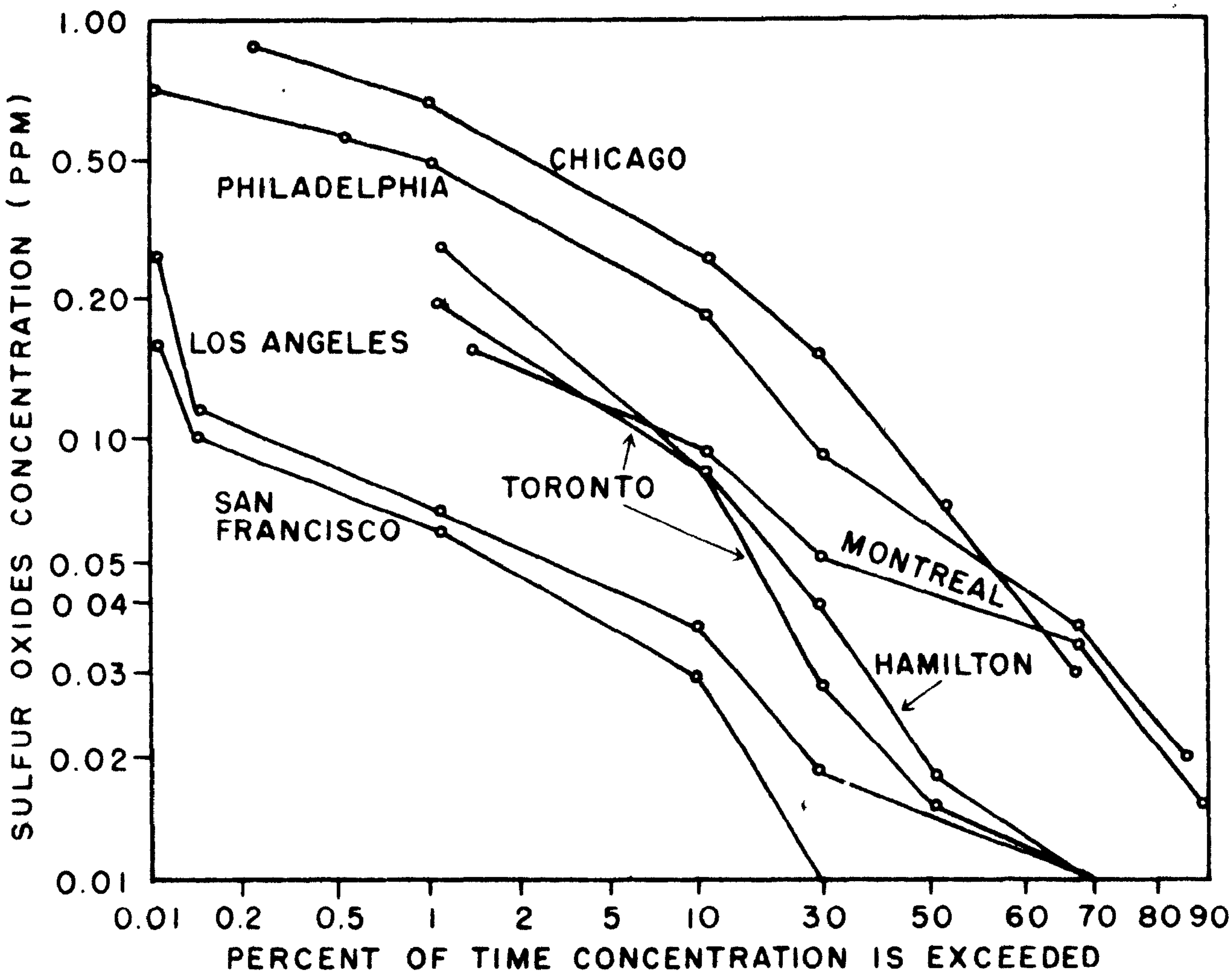

Figure 4-1: Frequency Distribution of Sulfur Dioxide Levels in Selected American and Canadian Cities.

Note: Montreal's figures are for September, 1968 to August, 1969, for the station situated at 1125 East, Ontario Street. Toronto and Hamilton's figures are for 1970, for stations situated at the University of Toronto and at Barton-Wenthworth respectively. These stations were chosen because they represented typical concentrations. Figures are one-hour means.

Sources: United States, Department of Health, Education and Welfare, Air Quality Criteria for Sulfur Oxides, (Washington: U.S. Government Printing Office, 1969), pp. 34-37. City of Montreal, La Pollution de l'Air par l'Anhydride, Sulfureux et les Particules Aeroportees, (Montreal, 1970). Ontario, Department of the Environment, Air Quality Monitoring Report, Vol. 2, (Toronto, 1970).

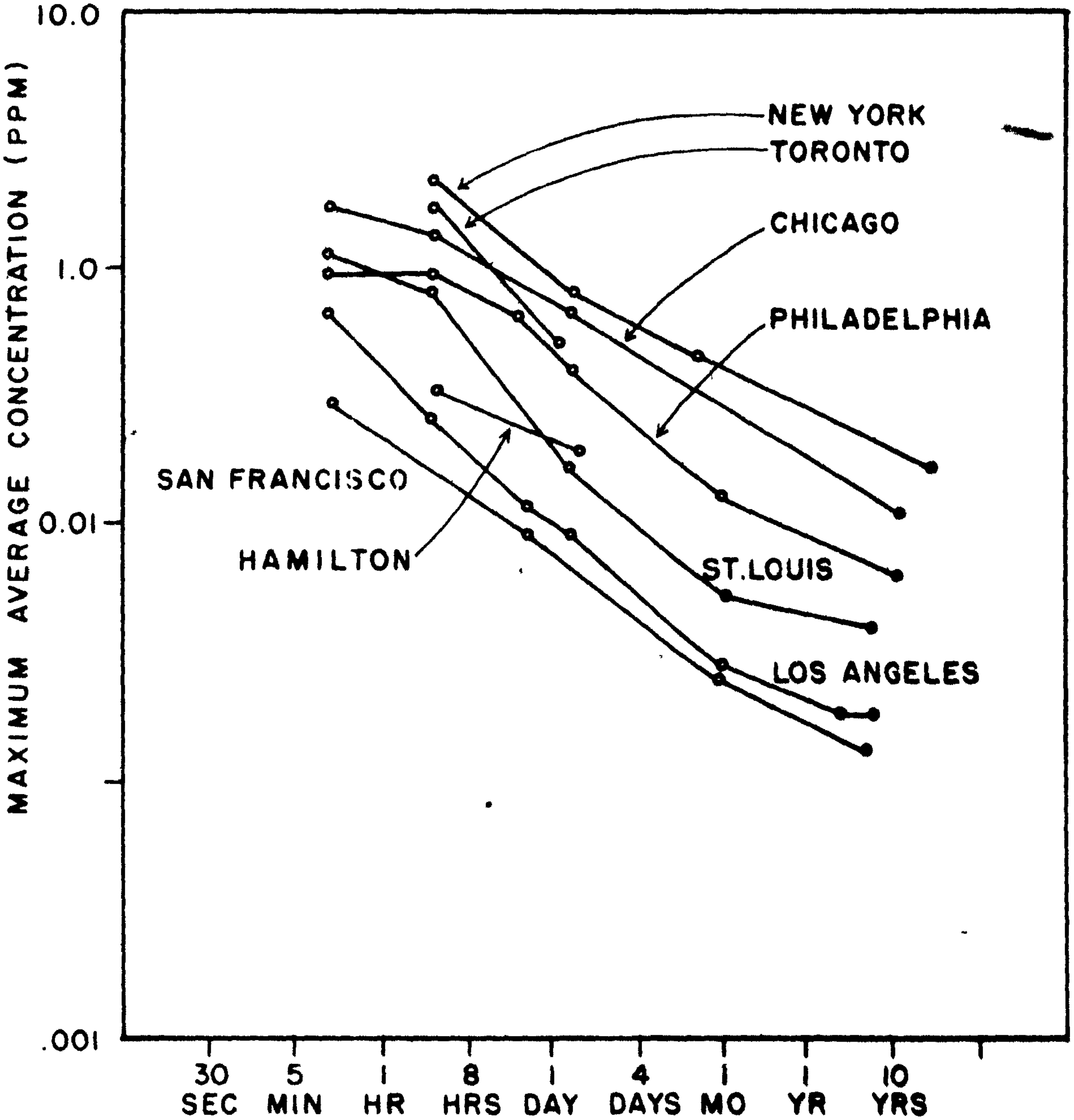

Figure 4-2 : Maximum Average Concentrations for Various Time Periods in Selected American and Canadian Cities.

Sources : U.S. Department of Health, Education and Welfare, Air Quality Criteria for Sulfur Oxides.
Ontario, Department of the Environment. Air Quality Monitoring Report.

This is also borne out by the projections made by the National Energy Board of the use of major fuels in Canada. These are reproduced in Table 4-5. Of these fuels, gas contains practically no sulfur; light fuel oil contains a moderate amount of sulfur (typically 0.7%); and coal (most of which is of the bituminous type) and heavy fuel oil contain high percentages of sulfur (typically 2-3%). We can see that the consumption of all fuels will increase in absolute terms. In relative terms, the consumption of high sulfur fuels (coal and heavy fuel oil) will increase even more. As a result, if nothing were done, we could expect an increase in the emissions from this type of source. Projected increases in total emissions of sulfur oxides for the years 1980 and 2000 have been estimated to be 1.8 and 3.5 times the 1966 total.[1]

For purposes of comparison, more relevant data are the observed concentrations of sulfur oxides in selected American and Canadian cities. This comparison is made in Figures 4-1 and 4-2. A cursory look at these figures will suffice to establish that the concentrations of sulfur oxides in Canadian cities are on a par with those of the largest American cities.

It is quite probable that in terms of concentrations, the pattern of emissions in Canada as estimated in Table 4-2 above underestimates the importance of emissions from the

---

1 E.R. Mitchell, "Inventories of National and Individual Air Pollution," (Ottawa: Department of Energy, Mines, and Resources, 1971).

TABLE 4-5

USE OF MAJOR FUELS IN CANADA - 1966-1990

FUEL	1966	1980	1990
Coal (M tons)	25,999	54,443	74,653
Light Fuel Oil (M Bbls)	78,978	93,110	102,850
Heavy Fuel Oil (M Bbls)	82,338	139,960	195,710
Gas (Bcf)	635.5	1,530.0	2,424.5

Source: National Energy Board, Energy Supply and Demand in Canada, Tables 16, 18, 20.

combustion of fuels. A large proportion of this fuel combustion takes place in urban areas, whereas emissions from such quantitatively important sources as metal smelters and natural gas processing take place in relatively isolated and well defined areas.[1] Evidence of this is the large disparities in concentrations observed in urban areas between winter and summer.[2]

1 Of course, often these areas contain small cities (such as Sudbury, Ont.). But, usually, these cities are inhabited by people directly or indirectly employed by the very industry from which emissions originate. This creates a special situation where these people are both damaged and benefited by the activity which generates pollution.

2 See, for example, City of Montreal, La Pollution de L'Air par Anhydride Sulfureux et les Particules Aeroportees, (Montreal, 1970).

The higher concentration observed in winter can be attributed only to the increase in fuel consumption for space heating.

For purposes of setting optimal or acceptable standards of air quality, it must be stressed that there is not necessarily a one-to-one relationship between quantities of emissions and the level of concentration of pollutants observed. The quantities of pollutants emitted are centainly the most important factor in determining the concentrations. But there are others, such as the height at which emissions occur, meteorological conditions prevailing in the given area, and so on. Emissions at ground level, for instance, take longer to disperse than emissions at the height of buildings, and the latter take longer to disperse than emissions from very tall industrial chimneys. This is especially true of emissions of particulates, but also of sulfur oxides. In order to establish the connection between quantities emitted and concentrations observed after diffusion, it is necessary to resort to the use of diffusion models.[1]

There is even less of a one-to-one relationship between quantities of emissions from individual sources and resulting damages since, in addition to the factors affecting the relationship between quantities of emissions and concentrations, this relationship is affected by other factors. The most important of these are the density of receptors around the source and their proximity.

---

1 See, for example, A.C. Stern (ed.), Proceedings of Symposium on Multiple-Source Urban Diffusion Models, (Research Triangle Park: Environmental Protection Agency, Air Pollution Control Office, 1970.)

All of these factors would have to be taken into account by the authority which would have to establish the desired level of reduction of emissions. Since it is not the purpose here to establish what this level should be, we will confine ourselves to the problem of costs and taxes associated with the reduction of given overall quantities of sulfur oxides emitted.

It is instructive, nevertheless, to examine briefly the correlations which have been observed between various concentrations of sulfur oxides and damage to humans, animals, vegetation, and materials.

Though the evidence is still rather impressionistic, it indicates that sulfur oxides corrode metals, spoil paint, decrease the strength of textile fabrics and leather, discolour paper and building materials, prevent the growth of vegetation, and increase the rate of morbidity and mortality in animals and man.[1]

One difficulty in attempting to estimate the damage caused by sulfur oxides is that of separating its effects from those of other pollutants, since, in practice, they all occur simultaneously. Moreover, damage is probably greater, for a given concentration of sulfur oxides, because of the interaction between sulfur oxides and other pollutants, especially particulate matter. Much of the damage by sulfur oxides is probably due to their conversion to the highly reactive sulfuric acid. The presence of particulate matter seems to promote this conversion by a factor of three or four.[2] Laboratory evidence suggests that

---

1 U.S. Department of Health, Education, and Welfare, Air Quality Criteria for Sulfur Oxides, (Washington: U.S. Government Printing Office, 1969).

2 Ibid., pp. 7-8.

the concentrations of sulfur oxides presently observed in urban areas would represent no significant health hazard if they occurred in the presence of no other pollutant. But, in the presence of particulates, increased morbidity and mortality has been observed when concentrations of SO_2 have risen above 0.25 parts per million (ppm).[1]

Nevertheless, attempts to trace damages to sulfur oxides have been made. A reduction of concentrations from average levels of 0.15 ppm to 0.05 ppm in Pittsburgh in the period 1926 to 1960 was associated with a four-fold reduction of the rate of corrosion of zinc.[2] Studies in Chicago and St. Louis indicated high correlation between the rates of corrosion of low-carbon steel panels and concentrations of sulfur oxides.[3] High concentrations of sulfurous and sulfuric acid have been shown to attack a wide variety of building materials, including limestone, marble, roofing slate, mortar, and carbonate-containing stone.[4] Sulfur oxides pollution has been shown to reduce the life of overhead power lines by one third.[5] The deterioration of priceless

---

1 United States Senate, Committee on Interior and Insular Affairs, <u>Summary Report of the Cornell Workshop on Energy and the Environment</u>, (Washington: Government Printing Office, May, 1972), pp. 44-45.

2 <u>Air Quality Criteria by Sulfur Oxides</u>, p. 52.

3 <u>Ibid</u>., pp. 52-53.

4 <u>Ibid</u>., p. 54.

5. <u>Ibid</u>., p. 53.

monuments and sculptures can largely be attributed to corrosion by these acids.[1] Plant damage was noted as far as 52 miles downwind from the smelter at Trail, British Columbia.[2] Increased mortality rates were noted at concentrations of sulfur oxides from 0.19 ppm to 0.52 ppm (24 hrs. means).[3] Increases in frequency of respiratory diseases were noted at concentrations from 0.11 ppm to 0.46 ppm.[4] Bates et al. found a greater incidence and severity of bronchitis and poor pulmonary function in the "dirty" cities of Montreal and Toronto as compared with the "clean" cities of Halifax and Winnipeg.[5] Lave and Seskin, in their review of studies on the effects of air pollution on health, conclude that a 50% reduction of air pollutant concentrations would reduce mortality from bronchitis by 50% and mortality from lung cancer by 25%.[6] They conclude that a 50% reduction in air pollution levels would probably reduce morbidity and mortality from respiratory deseases by 25%. However, they could not attribute specifically to any given pollutant the responsibility for the morbidity and mortality. Generally speaking, it seems that the threshold at which both human morbidity and

---

1 A particularly sad case concerning Venice is reported in Newsweek, (June 12, 1972).

2 Air Quality Criteria for Sulfur Oxides, p. 54.

3 Ibid., pp. 119-124.

4 Ibid., pp. 124-142.

5 Bates, D.V. et al., "Air Pollution and Chronic Bronchitis," Archives of Environmental Health, XIV (June, 1967) pp. 220-224.

6 L.B. Lave and E.P. Seskin, "Air Pollution and Human Health," Science, CLXIX (August, 1970), pp. 723-733.

mortality are directly affected is 0.14 ppm.[1] Prolonged exposure may affect health at much lower concentrations.

Table 4-6 shows ambient air quality standards which have been adopted or proposed in selected areas. There is a general agreement that the annual average concentration should not exceed 0.02 ppm and that the maximum 24 hrs. concentration should not be allowed to exceed the aforementioned threshold of 0.14 ppm.

TABLE 4-6

PROPOSED OR ADOPTED AIR QUALITY STANDARDS FOR SULFUR OXIDES IN SELECTED AREAS

AREA	CONCENTRATIONS	
	ANNUAL MEAN	MAXIMUM 24-HRS.
Canada	(60)	(300)
United States	0.02 (60)	0.10 (260)
Ontario	0.02	0.10
Montreal	0.02	0.10
Chicago	0.015	0.17
Boston	0.031	0.11

Note: Concentrations are expressed in ppm or if in parentheses, in micrograms per cubic meter.

Sources: City of Montreal, La Pollution de L'Air par l'Anhydride Sulfureux, Council on Environmental Quality, Environmental Quality, S.S. Ress and L.J. White, "International Pollution Control," Chemical Engineering, Deskbook Issue, LXXIX (May 8, 1972), pp. 137-141.

1 Summary Report of the Cornel Workshop..., p. 45.

CHAPTER V

ECONOMICS AND TECHNOLOGY OF SULFUR OXIDES CONTROL: AN OVERVIEW

This chapter attempts to put the technology of sulfur oxides pollution control in economic perspective. In doing so, it is convenient to consider separately the two main types of sources of sulfur oxides. As we have seen, these are the combustion of fossil fuels and industrial processes.

A. Control of Emissions from the Combustion of Fossil Fuels

There are several possible techniques to reduce emissions of sulfur oxides from the combustion of fossil fuels. These techniques may be substitutive or may be complementary. They can be categorized as follows.

(1) Substitution of Fuels

This technique involves the replacement of a fuel by another of the same type, the latter having a lower sulfur content (e.g., the replacement of high-sulfur coal by low-sulfur coal).

There are two major ways in which this substitution can be carried out:

(a) by obtaining the same type of fuel with lower sulfur content from alternative sources. This alternative fuel will probably command a higher price. The extent to which this substitution will be carried out will depend on the price differential and sometimes on the simple availability in a particular area of the lower-sulfur fuel.

(b) by desulfurizing the fuels presently used. This may be carried out to some extent at the present time. In this case, it is a question of carrying out the desulfurization further. Since this will involve some costs, it is to be expected that the desulfurized products will command a higher price than the fuels now used. This price differential and, in some cases, technological limitations will determine the extent to which this technique will be used.

The distinctive characteristic of fuel substitution as an abatement technique is that it does not involve modification or replacement of combustion equipment by the fuel user. Hence, the only additional cost which the user of the lower-sulfur fuel will incur is the price differential which is likely to exist between this fuel and the higher-sulfur one.

In previous chapters the suitability of an emission tax as a control strategy was discussed. Now, it is possible to predict the emissions of sulfur oxides from a particular source, given the sulfur content of the fuel used by that source.[1] So that, in this case, an emission tax could be levied in the form of a tax on the sulfur content of the fuel. The great advantage

---

1 See, U.S. Environmental Protection Agency, Compilation of Air Pollutant Emissions Factors, (Washington: U.S. Government Printing Office, 1972).

of this, of course, is that it greatly reduces the number of points from which the tax is to be collected. Basically, these would consist of a few major suppliers, such as refineries and coal mining companies. This would also make it easy for authorities to verify that there are no evasions. The authorities could rebate to a fuel user the tax paid on his behalf on any sulfur he recovered (and, hence, was not emitted into the air). This would be relatively simpler and less expensive than having to monitor emissions from all sources. Any sulfur recovered would be measured in terms of weight. This is a far simpler and cheaper procedure than that of monitoring concentrations of sulfur oxides in combustion flue gases. The method of monitoring emissions directly is conceivably cheaper only for large sources, such as power plants and some industrial processes. Of course, when it is, it should be used.

How would the levy of a tax on sulfur content operate to decrease emissions through fuel substitution? Simply by inducing fuel users to substitute a "cleaner" grade of fuel whenever the tax differential per unit of fuel exceeded the price differential between the "cleaner" and "dirtier" grades of fuels. Suppose that an emission tax t (i.e., t $ per unit of pollutants emitted) is deemed necessary to achieve a desirable air quality standard and that the emission factor is F. Then the tax on sulfur content per unit of fuel would be $tFS/100$, where S is the sulfur content of the fuel in percentage points. Now, suppose that two grades of a fuel, A and B, are available, where A and B are equivalent in every respect except sulfur content. Suppose that A contains more sulfur than B (i.e., $S_A > S_B$, where S_A and S_B are, respectively, the sulfur contents of grades A and B of the fuel in percentages). Then the user has an incentive to substitute B for A whenever

$$tF(S_A - S_B) \geqslant P_B - P_A.$$ [1]

As an example, suppose that an emission tax of 10¢ per pound of sulfur oxides is to be levied and that the emission factor is 2 (i.e., each pound of sulfur in the fuel will result in 2 pounds of sulfur oxides emissions). Then, the tax will amount to 20¢ per pound of sulfur in the fuel. Suppose that grade A contains 2% sulfur and grade B 1% sulfur. Then the tax on grades A and B would be 0.4¢ (i.e., 20 x 2/100) and 0.2¢ (i.e., 20 x 1/100) per pound respectively. A fuel user would have an incentive to purchase grade B whenever the price differential between the two grades is less than 0.2¢ per pound.

(2) <u>Switching of Fuels</u>

This method consists of replacing a fuel having a high sulfur content with another of a different type having a low sulfur content (e.g., the replacement of coal by natural gas). The low sulfur fuel which replaces the high sulfur fuel may be one which is already normally available or one which has undergone

---

1 This assumes that, if the tax is collected from the distributor of the fuel, he will pass it entirely on to the user.

desulfurization as mentioned above.[1]

The user who switches to a low sulfur fuel incurs not only the possible additional costs of obtaining the low sulfur fuel at a higher price, but also the costs of modifying or replacing his combustion equipment.[2] Moreover, since different combustion equipment may operate at different efficiencies, the user must take into account possible changes in combustion efficiencies.

Figure 5-1 presents a schematic diagram of the main possibilities of fuel switching. Some of these possibilities realistically apply only to some types of fuel combustion. For example, switching from low sulfur oil to electricity is a significant possibility only in the case of domestic fuel combustion.

One complication is the fact that the use of alternative fuels may affect equipment other than the firing equipment (and, hence, affect cost). Changing from high-sulfur to low-sulfur coal, for example, while it does not require modification of firing equipment, may affect the fly ash collection efficiency of electrostatic precipitators. Changing from a solid or a

---

1 One additional benefit which can possibly accrue from this method of abatement is the simultaneous decrease of emissions of pollutants other than sulfur oxides, especially particulates. This possibility is not considered here.

2 As will be discussed below, frequently in the case of industrial and commercial installations, furnaces are designed to burn any liquid, solid, or gaseous fuel. In these cases, no additional expenses on combustion equipment are involved.

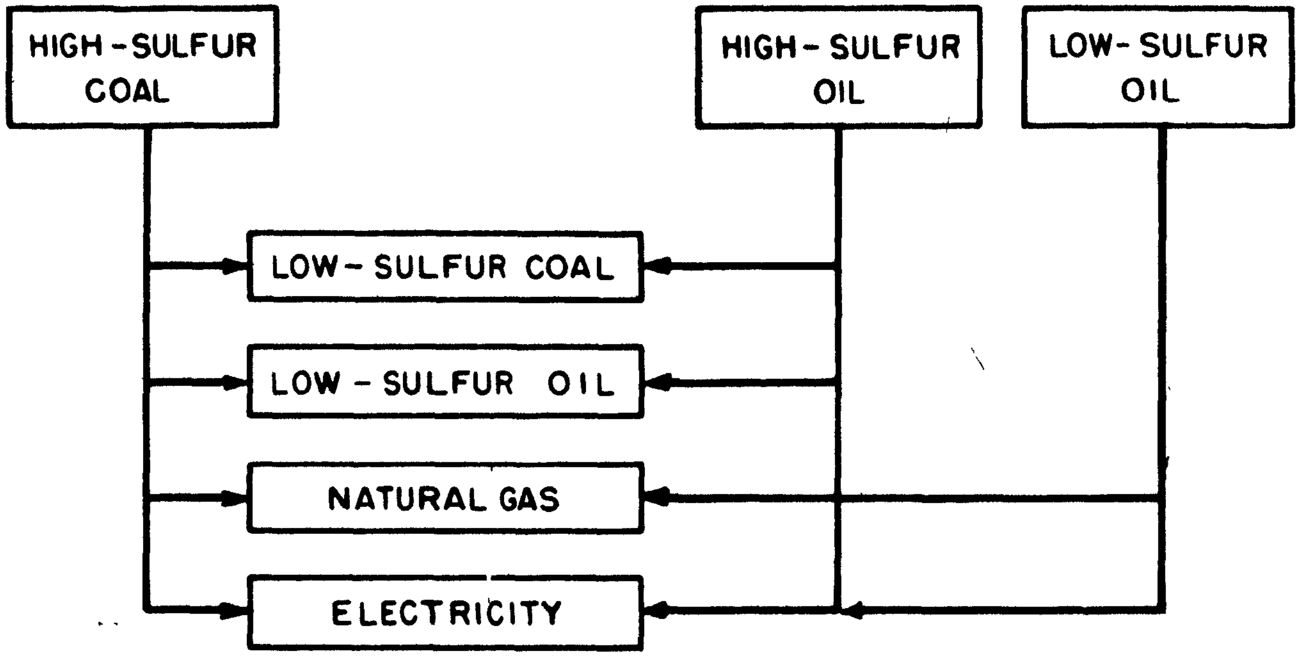

Figure 5-1: Fuel Switching Possibilities.

liquid fuel to a gaseous one, on the other hand, may eliminate or greatly reduce the need for storage and handling facilities and equipment. All of these factors would have to be taken into consideration by the fuel user.

What is the economic rationale for fuel switching? Clearly, a decision on whether to switch or not to switch fuel hinges on a comparison of the cost involved in doing so and other alternatives. In the case where an emission tax is to be levied in the form of a tax on the sulfur content of fuels, as discussed above, the comparison will be between the cost of switching (including the price-*cum*-tax of the new fuel) and the price-*cum*-tax of the presently used fuel.

Since, at any time, a number of alternative fuel switches are possible, the fuel user who is contemplating fuel switching must first decide the one for which he will opt. Aside from possible questions of availability of a particular fuel in a given area, the rational user will choose the cheapest alternative. It is necessary, therefore, to establish a procedure whereby the costs of alternative fuel switches can be calculated. The following procedure is deemed appropriate to accomplish this task.[1]

(1) Calculate the cost of using alternative fuels. This can be accomplished as follows.

Assume that the user is contemplating a switch from fuel A to an alternative fuel B. He knows the following:

P_A = the price per unit of fuel A

H_A = the energy content of fuel A (measured, say, in BTU per unit)

R_A = the combustion efficiency of the equipment which burns fuel A.

Q_A = the quantity of fuel A used per period of time (say, a year).

---

1 This procedure is a modified version of the one recommended in U.S. Department of Health, Education, and Welfare, Control Techniques for Sulfur Oxide Air Pollutants, (Washington: U.S. Government Printing Office, 1969), pp. 26-31. Note that, since fuels come under different physical states and, therefore, are sold in different units of measurement, comparisons must be made in terms of their energy output.

From this, he knows the total cost of the fuel A necessary to obtain the energy output he requires. This is simply $P_A \times Q_A$.[1] He also knows:

P_B = the price per unit of fuel B

H_B = the energy content of fuel B

R_B = the efficiency of the equipment which burns fuel B.

He would like to know Q_B, the quantity of fuel B required to produce the same net energy output per year. The latter is $Q_A.H_A.R_A$. Therefore,

$$Q_B.H_B.R_B = Q_A.H_A.R_A$$

and

$$Q_B = Q_A.H_A.R_A / H_B.R_B$$

Once Q_B is known, it is possible to calculate the cost per year of using fuel B, i.e., $P_B.Q_B$. The same procedure can be used to calculate the cost of using any fuel as an alternative to A. Thereafter, the cheapest alternative is known.

(2) To the cost of using the alternative fuel, add the annualized cost of converting the combustion equipment. This sum gives the total annual cost associated with using the alternative fuel.

(3) Given the sulfur content of each fuel and the emission factors associated with a given combustion equipment, calculate

1 The cost of maintaining the equipment is disregarded. It is difficult to estimate whether this is significantly different for different fuels.

the potential emissions resulting from the use of the presently used and of alternative fuels.

(4) Calculate the cost per unit of sulfur oxides abated.

(5) Compare the cost obtained in (4) with the differential in the tax on the sulfur content of the alternative fuels. The conversion would be warranted if the cost differential between any pair of fuels is less than the tax differential.

It must be pointed out that the above analysis applies only to fuel switching on an all or nothing basis. That is, the use of one fuel is completely abandoned and another is used in its place. It is frequently the case with some types of users, however, that the combustion equipment already in place is designed to burn more than one, or any, type of fuel.[1] In this case, the user would not have to install new equipment and his decision would be concerned with the optimal, or least cost, fuel mix required to produce a given output of useful energy.

We can spell out the rationale for this decision-making process by using the concept of the production function. Suppose that, in the production function, some inputs are substitutable for one another, but others are not substitutable. That is,

---

1 It is common, for example, for large users of natural gas to be supplied on an interruptible basis. Since, in that case, the supply of gas can be interrupted at any time, these users must be capable to switch to some other fuel at will. See, Control Techniques for Sulfur Oxide Air Pollutants, pp. 19-21.

the relationship embodied in the production function may be thought of as consisting not simply as a relationship between inputs and output, but, rather, as a relationship between groups of inputs and output. In some cases, no substitution is possible between groups of inputs. It may prove technically impossible, for example, to substitute more or less labour for less or more fuel in the production process. But some of these groups of inputs may be subdivided into sub-groups within which substitution is possible. It is possible, for instance, to substitute one fuel for another to obtain the same amount of usable energy. In this case, energy is both the output of a production process where the inputs are different types of fuels and is also an input into the production of some other output.

Suppose there are J fuels, Fi (i = 1,...,J). Then, the technical relation between fuels as inputs and total energy produced can be described as an energy production function which is analogous to that describing the relation between, say, labour and capital to output.

We can write the energy production function as

$$E = h(F_1 \ldots, F_J) .$$

This relation describes the possibility of substitution between each pair of Fi for a given level of energy Ei.

As shown diagrammatically in Figure 5-2, for any given level of energy, which we can call an iso-therm[1], there are

1 A Therm is a unit of heat energy used in engineering and is equivalent to 100,000 BTU. The word iso-therm is also used in physics to indicate constant temperature.

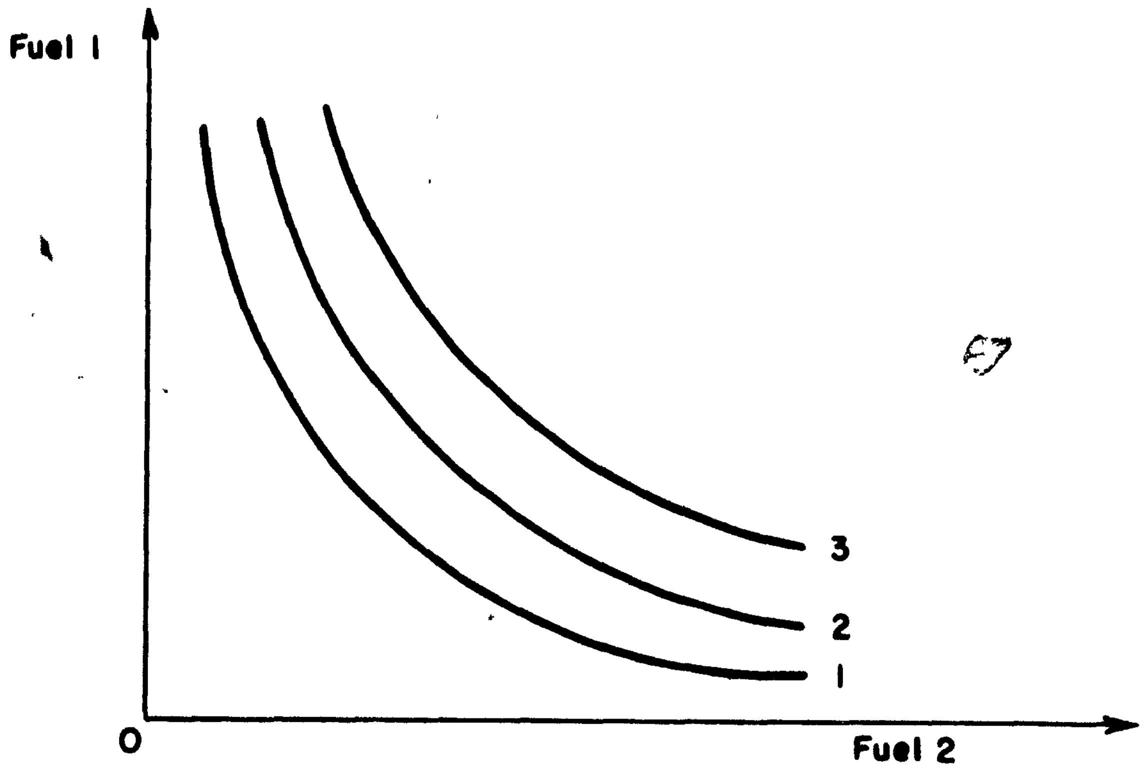

Figure 5-2 : The Energy Production Function.

various combinations of fuels (the geometry is restricted to two fuels) which produce the same quantity of energy.

We can trace an <u>energy map</u> which consists of a family of iso-therms. Each iso-therm represents all the possible combinations of fuels 1 and 2 required to produce the quantity of energy represented by that iso-therm; the family of iso-therms represents all the possible quantities of energy required to produce any given level of output.

Now, given the price of each fuel, the total cost of energy, Ce, is the sum of the cost of all fuels; the cost of each fuel, of course, is the product of its price and the quantity used. That is,

$$Ce = C_1 + C_2 + \ldots\ldots + C_J$$
$$= p_1F_1 + p_2F_2 + \ldots\ldots + p_JF_J$$

where

Ci $(i = 1, \ldots, J)$ is the cost of fuel i

Pi $(i = 1, \ldots, J)$ is the price of fuel i

Fi $(i = 1, \ldots, J)$ is the quantity of fuel i.

Given the cost function Ce and the energy production function E, the optimizing behaviour of the fuel user will be

$$\text{Minimize Cost} \quad Ce = \sum_{i=1}^{J} P_iFi \ .$$

Subject to the energy production function $E = h(F_1, \ldots, F_J)$, the solution gives the optimal conditions, namely

$$P_i/P_j = h/F_i \big/ h/F_j \quad (i \neq J) \ .$$

That is, the user will employ any pair of fuels in such a way as to equalize the ratios of their prices and their marginal productivities. This, of course, is perfectly analogous to the way the firm uses other inputs.

For the two fuels case, we can show the same thing geometrically; this is done in Figure 5-3. We will also use Figure 5-3 to illustrate what happens when the relative prices of fuels change as a result of a tax on sulfur content.

Suppose that, for a firm, to produce a given level of output, an amount of energy is required as represented by iso-therm 1. The optimal combination chosen is that represented by R. Suppose also, in order to adapt the example to our context,

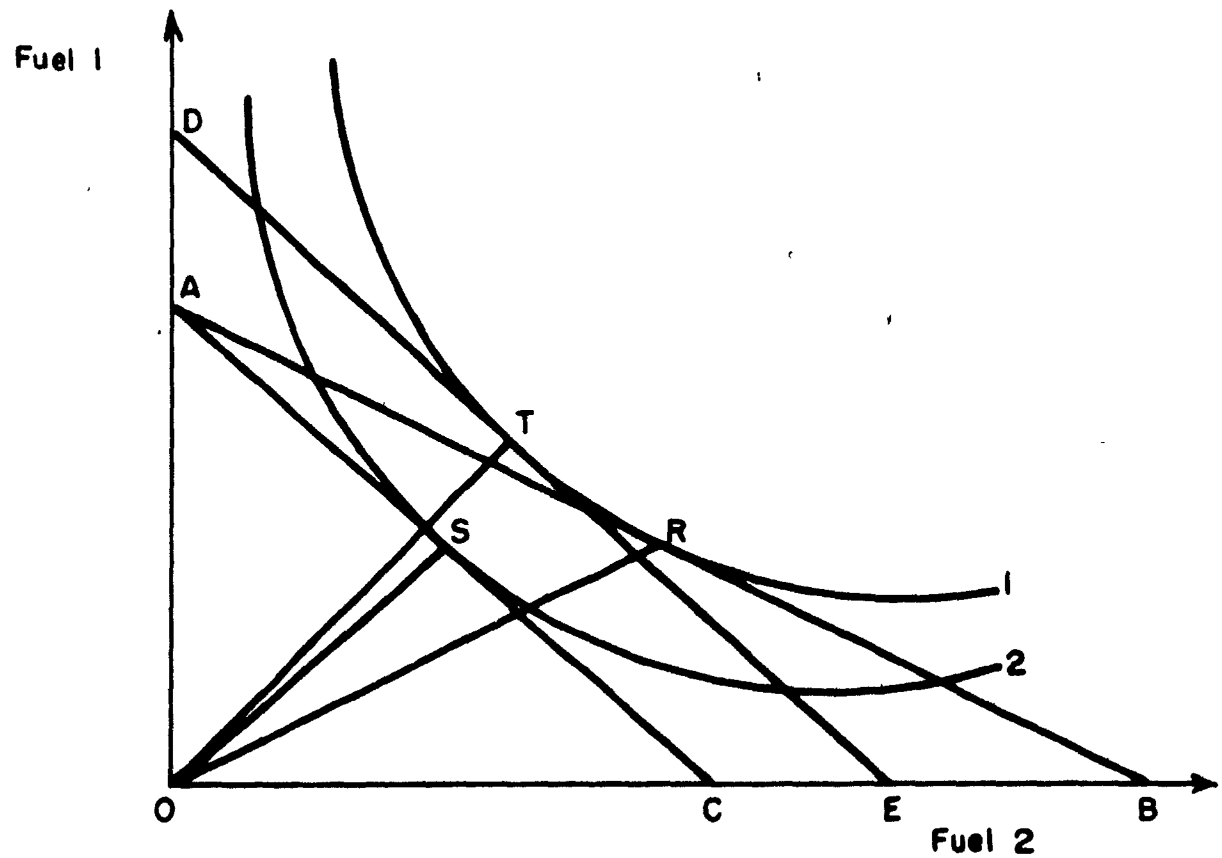

Figure 5-3 : Effect of a Tax on Sulfur Content on Fuel Switching.

that fuel 2 contains a certain percentage of sulfur, while fuel 1 contains no sulfur. Suppose, further, that a tax proportional to sulfur content is imposed on the burning of fuels and that this tax is passed on (in whole or in part) to the fuel user through higher fuel prices. Since fuel 1 contains no sulfur, its price does not change; but the price of fuel 2 will increase.[1] This can be shown by rotating the budget line from AB to AC. The

1 This disregards possible changes in prices arising from changes in demand for the fuels.

same cost outlay on energy would purchase only the lower quantity of energy represented by iso-therm 2; the optimal combination of fuels chosen would be now that represented by S. Nevertheless, the proportion in which fuels 1 and 2 are used would change. Initially, they would be used in the proportion represented by the ray OR; after the tax is imposed, they would be used in the proportion OS; that is, the relative use of fuel 1 would increase and that of fuel 2 would decrease. We can call this the substitution effect of the tax. If the firm would still want to purchase the amount of energy represented by iso-therm 1 (because, say, the firm does not want to reduce output perhaps because energy costs are small relative to total costs), it would have to increase its outlay on energy (by an amount represented by $AD \cdot P_1 = CE \cdot P_2$); the optimal combination used would be that represented by the point T. This could be called the output effect of the tax and it could either reinforce or offset the substitution effect.

(3) Removal of Sulfur Oxides from Waste Gases

This control technique consists of preventing sulfur oxides from being emitted into the atmosphere either by capturing them following the combustion of sulfur-containing fuels or by adding materials into the furnace during the combustion process. In one case, devices are required which separate sulfur oxides from other flue gases; in the other, sulfur oxide gases will react with the added materials to form solid particles which are thereafter removed by particulate-collecting equipment.

With this technique of abatement, the costs incurred by the fuel user are the annualized cost of the additional equipment required, the cost of maintaining and operating such equipment and, if required, the cost of the additional materials which are added to the combustion process.

Equipment of the type required is not likely to be suitable or economical to be used with small sources of sulfur oxides. To take an obvious example, such equipment would not be used to capture sulfur oxides emitted from residential space heating. Most likely, this technique of abatement is a realistic option only for very large sources of emissions or large fuel users, such as thermal power plants.

What incentive a tax on the sulfur content of fuels offers to the fuel user to adopt this abatement technique? Recall that a tax on the sulfur content of fuels is equivalent to an emission tax, provided that a tax rebate is given for the sulfur oxides which, though present in the fuel at combustion, are not emitted in the atmosphere but are somehow captured.

Aside from cost comparison with the other abatement techniques described above,[1] the fuel user will make the following calculation. Given

---

1 Obviously, the rational fuel user will always choose the cheapest of the available techniques when these are substitutes.

t	=	emission tax (\$/unit of SO_x)
F	=	emission factor of combustion equipment
S_A	=	sulfur content of fuel A (in percentage points)
tFS_A	=	tax per unit of fuel A
Q_A	=	quantity of fuel A used per period of time (say, per year)
S_r	=	quantity of sulfur oxides recovered (as sulfur) per period of time
C_K	=	annualized cost of equipment, including maintenance, operation, and additional materials per period of time.

Then, the fuel user has an incentive to adopt this abatement technique when

$$(tFS_A \cdot Q_A) - (S_r \cdot t) \geqslant C_K$$

That is, when the cost of using this technique is inferior (or, at the limit, equal) to the tax which is not rebatable.

(4) Other Techniques

We will mention here two other possible abatement techniques, but these will not be considered any further, for reasons stated.

(a) Increased Dispersal of Pollutants

This abatement technique applies both to the combustion of fuels and to industrial processes. As we have seen from previous chapters, damage from pollution occurs when emissions exceed the natural dispersal capacity of the environment. Increased dispersion can be obtained by taking better advantage of the natural dilution capability of the environment. This involves such things as the height, design, and location of stacks, as well as the location of some important emission sources. It would be undesirable, for example, to locate a large refinery in a site such that winds blow its emissions in the direction of a nearby city most of the time when an alternative downwind site is possible. The most important factor to consider here is the prevailing meteorogical conditions in a given area. Again, diffusion models are useful in this respect.

This abatement technique will not be considered further because it is felt that this alternative is important only in calculating the damage function from emissions and, hence, in setting the ambient air quality standard, but not as a strategy to reduce emissions, once the standard is set. As discussed in the previous chapter, it is only with the latter aspect that we are concerned here. This is not to deny that some incentive should be provided to encourage emitters to take steps which minimize damages from given emissions. But this is a different, if related, problem.

(b) Increased Combustion Efficiency

Increased combustion efficiency decreases sulfur oxides emissions by reducing the amount of fuel burned to produce given amounts of heat energy. This technique is of significance mainly to large installations, such as power plants.[1]

---

1 See, for example, J.A. Moore and H. Ferguson, "Squeezing More Megawatts from Fewer BTUs," Power, CXII (February, 1968), pp. 76-98. Also, F.H.S. Brown, "The Prospects for Alternative Methods of Generation of Electric Power: A Comprehensive Review," Combustion, XXXIII (May, 1967), pp. 23-28.

It involves more scrupulous maintenance and operation of existing equipment or the design of more efficient equipment.

While conceivably being an important factor in determining emissions from large sources, this abatement technique cannot be placed in the same category as the others discussed since it involves less readily quantifiable variables, such as the scrupulousness with which a given equipment is cleaned and tuned, and advances in the technology of combustion equipment. For these reasons, this technique is not considered any further here. Presumably, though, an emission tax levied on emissions which are actually monitored, as contrasted with potential emissions calculated from the sulfur content of a given fuel, would provide an incentive to use this technique. Since the technique is of importance only for large sources, the continuous monitoring of emissions involved may be feasible at relatively low cost.

B. Control of Emissions from Industrial Processes

Some industrial processes, besides generating emissions of sulfur oxides because they require the combustion of fuels, generate emissions of these gases which are attributable to the industrial processes themselves. This section discusses the economic effects of the control strategy with respect to the latter type of emissions.

Assuming that an emission tax is the desired control strategy, the question arises as to how to apply this tax. In the case of fuels, it was suggested that the problem might be solved by applying the tax on the sulfur in the fuel, in the knowledge that, if not removed, virtually all of the sulfur would eventually be emitted as sulfur oxides. But things are not always so simple in the case of industrial processes.

The simplest way to apply the tax apparently would be to actually tax emissions from individual sources. But this requires continuous monitoring of those emissions. Even if possible, this could be an expensive process adaptable only to large sources. A less satisfactory arrangement would be to take periodic samples of emissions. The main problem with this method is that of obtaining representative samples, given variations in the production process.[1] If the output of an industrial plant is produced in batches, for example, at what stage of production should the sample be taken? Moreover, this method of measurement could encourage evasion. Suppose, for example, that the responsibility for taking the sample is assigned to the industrialist. He then has an incentive to take samples that, by an appropriate choice of sampling intervals and locations, understate the true quantity of emissions. Or suppose that some inspector from a control agency is assigned the task of collecting the sample. The industrialist might still be able to influence the sampling procedure in his favour, given his more intimate knowledge of

---

1 See, for example, N.L. Morrow and R.S. Brief, "Air Sampling and Analysis," Chemical Engineering, Deskbook Issue, LXXIX (May 8, 1972), pp. 125-132.

the production process. Or, if he knows in advance of the timing of sampling, he can schedule his operations in such a way as to minimize emissions at the moment of sampling.

Another consideration is that, in order to minimize administrative costs and facilitate administrative procedures, it is desirable to reduce the number of points from which the tax would be collected. Now, in the case of emissions of sulfur oxides from industrial processes, it is true that all of the emissions are generated by the use of some sulfur-containing input in the production process. In the case of smelters, for example, emissions arise from the use of ores or ore concentrates. It would seem reasonable, therefore, to conclude that a tax on the sulfur content of whatever input contains the sulfur would be appropriate.[1] While such a tax should not be ruled out in some cases, it is clearly inadequate in others.

Consider the case of emissions from the sulfite pulping process, for example. In this process, sulfur dioxide is actually one of the chemicals required to produce pulp and is produced by burning sulfur.[2] Clearly, the effects of taxing this sulfur would not be the same as those resulting from taxing the sulfur which serves no purpose but which just happens

---

1 Always with the proviso of a rebate for whatever sulfur is recovered.

2 See, M. Benjamin _et al_. "A General Description of Commercial Wood Pulping and Bleaching Processes," _Journal of the Air Pollution Control Association_, XIX (March, 1969) pp. 155-161.

to be present in other inputs such as fuels or ores. A tax on the sulfur used on this process would distort the efficient allocation of inputs in the production process.

These considerations lead to the conclusion that the form in which the emission tax is to be administered depends on the individual case.

For purposes of estimating emissions, the easiest, if not the most accurate, method is to use emission factors. These factors are average values obtained by previous source-testing of several similar processes.[1] We shall make use of some of these factors in the next chapter.

Whatever form the emission tax takes, the firm which emits sulfur oxides faces the following non-mutually exclusive alternatives:

(a) pay the tax and continue the emissions;

(b) reduce some of the emissions by reducing output;

(c) eliminate or reduce the emissions by the addition of anti-pollution devices;

(d) eliminate or reduce the emissions by the introduction of production process changes.

---

1 The most comprehensive compilation of these factors is to be found in U.S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. Also, TRW Systems Group, Air Pollutant Emission Factors and Air Pollutant Emission Factors, Supplement, (McLean, Va.: TRW Systems Group, 1970).

The last two alternatives are different in an engineering sense, but not in an economic sense. Both amount to an increase in the firm's outlay on fixed capital equipment.[1] Therefore, here the problem will be discussed in terms of alternative (c). An additional reason for doing so is that process changes may incorporate technological advances which cannot be quantifiable in the kind of framework used here.

We can examine the rationale of the choices among the available alternatives in terms of the common property resource approach developed in Chapter II, where the emission tax is viewed as a price on the use of air for waste-disposal purposes. In this setting, it can be said that air is a factor of production which the firm uses in conjunction with other inputs and which is substitutable with them. Firms, in deciding how much of this factor, air, to use, apply the same economic rationale as they do to other factors. Since, in this setting, the phrases "pricing of air use" and "emission tax" are equivalent, we will use the former.

Assuming perfectly competitive factor and product markets where firms are profit maximizers and cost minimizers, consider a typical firm which uses the factors or production X_1, X_2, ..., X , and A to produce a given output Q, where X_1, X_2, ..., X , are the usual factors of production, and A is

---

1 This assumes that operating or variable costs do not vary appreciably in the two cases. This may be a strong assumption.

the factor, air. Its production function is

$$Q = Q\ (X_1,\ X_2,\ \ldots,\ X\ ,\ A).$$

Since the firm is a cost minimizer, we know that it will use factors in the proportions

$$\frac{MPx_1}{Px_1} = \frac{MPx_2}{Px_2} = \ldots\ \ldots = \frac{MPx_n}{Px_n} = \frac{MP_A}{P_A} = \lambda$$

where MPx_1, ..., MPx_n, MP_A are, respectively, the marginal products of factors X_1, ..., X_n, A and Px_1, ..., Px_n, P_A are their prices; λ is the marginal rate of technical substitution between the factors. When the services of the factor air can be had for free, the firm will use them until $MP_A = \lambda \cdot P_A = 0$. When a price for air use $(P > 0)$ is to be paid, the firm will use air only to an extent where $MP_A > 0$. Given that diminishing returns apply to this factor as to others, as it must, the firm will thereby reduce its use of this factor.

While it is conceivable that any factor which the firm uses is substitutable for air, some factors are technically more easily substitutable than others. Equipment capable of removing particulate or gaseous wastes from flue gases is much more efficient than putting men to do the same job. To simplify the exposition, assume a firm using only two factors of production, equipment (E) and raw materials (R), of which only E is technically substitutable for the use of air to dispose of wastes.[1] Initially, the firm uses air for waste-

---

1 The absence of the input labor can be justified by assuming that the plant is completely automated. Note also that, with respect to emissions of sulfur oxides from industrial processes, raw materials and air use for waste-disposal purposes are not only non-substitutable, but they are directly correlated.

disposal purposes free. Therefore, it will use as much air and as little equipment as possible. It will also use factors E and R in proportions such that the ratios of their marginal products over prices are equal. When the firm must pay for the use of air, it will substitute equipment for air use. Let us call these additions to the firm's total equipment its anti-pollution equipment (APE).

Based on past public regulations, the firm might find itself in one of two alternative positions:

(a) it is already using a minimum of anti-pollution equipment (e.g., it has a chimney stack) and the technical constraints are such that it is not possible to withhold all wastes;

(b) it has the choice of using no anti-pollution equipment at all or of installing equipment capable of withholding all wastes.[1]

Figure 5-4, an adaptation of the isoproduct-isocost technique usually employed in the firm's production theory, depicts alternative (a). The isoquant Q_1Q_1 shows the technical possibilities of producing Q_1 units of output. In order to produce this output, the firm must use a minimum amount of anti-pollution equipment OK. If the firm were to use only this amount of APE, it would have to use air to an extent OJ. Similarly, the firm cannot reduce its use of air below an amount OG. In

1 Other alternatives are possible, but they would fall between these two. In reality, situation (a) is much more likely.

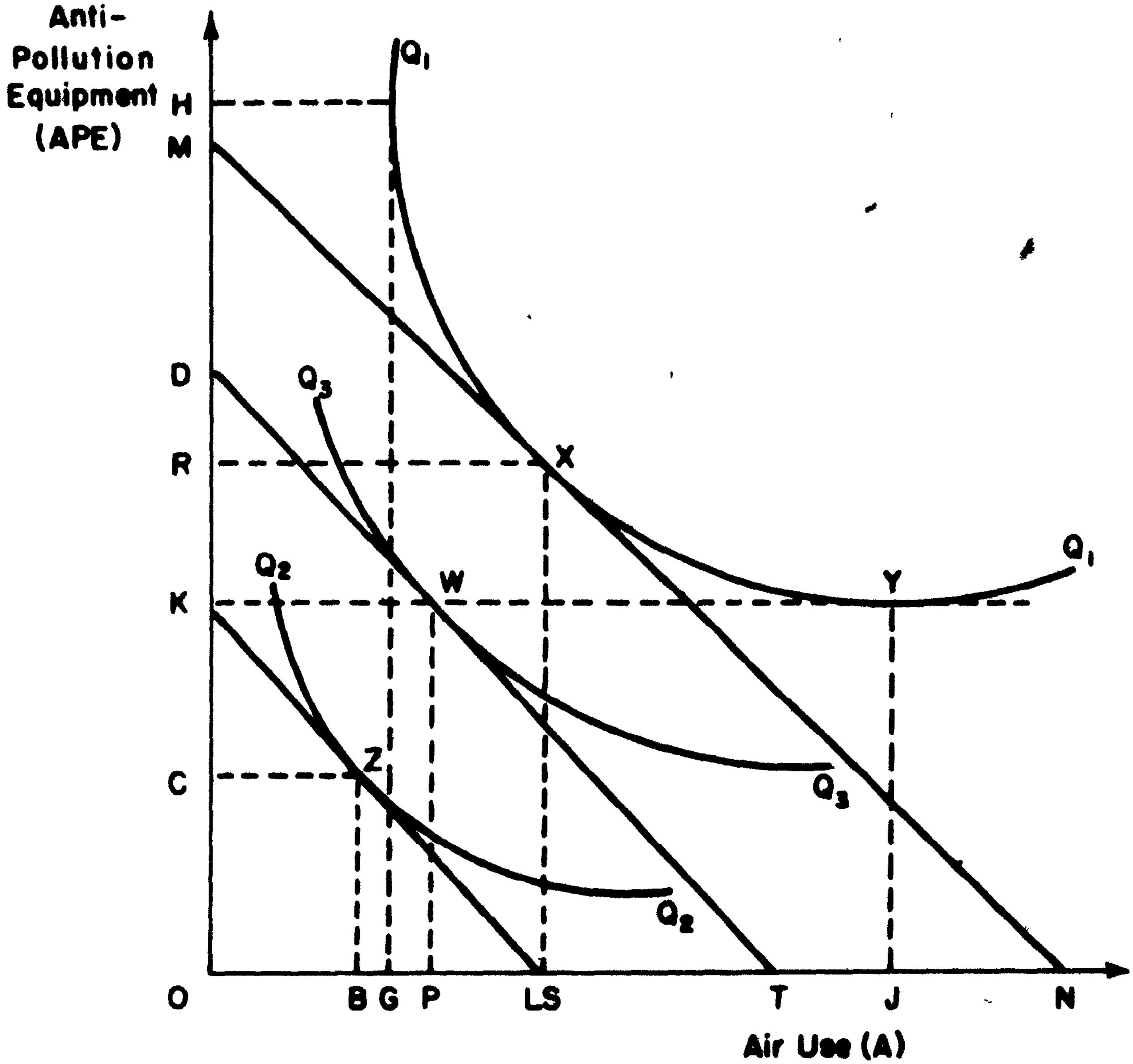

Figure 5-4: Substitution of Anti-Pollution Equipment (A).

order to be able to use only this amount, it would have to install an amount of anti-pollution equipment OH.[1]

The line MN is an isocost line whose slope reflects the ratio of the prices of A and APE. Since the firm will try to minimize the cost of producing output Q_1, it will employ the factors to the extent indicated by the tangency of the isocost and isoproduct lines (i.e., point X). At this point,

$$\frac{MP_{APE}}{P_{APE}} = \frac{MP_A}{P_A}$$

Before it was properly priced, air was free. Hence, the firm would use air to the maximum possible extent OJ, (where $MP_A = 0$), and install the minimum anti-pollution equipment possible OK (point Y).[2] The pollution control cost to the firm of producing output Q_1 is C_1 and is equal to OK units of APE times their price.

---

1 It is possible to question the possibility of defining units of APE. But the difficulty of obtaining such units is no greater than that of defining units of capital as usually employed in production theory. The same could be said about the difficulty of visualizing small changes in anti-pollution equipment as shown in the diagram. Such equipment is likely to consist of relatively large units. This is a common difficulty occurring in the discussion of the role of capital in the production function. The usual way out is to specify that by capital is meant the service of the equipment rather than the physical units themselves. In this way, lumpy machines become infinitesimally divisible. We apply the same rationale to APE.

2 At this point, the isoproduct line becomes horizontal and parallel to the A axis.

After the price of air use becomes positive, the firm will use OR units of APE and air to the extent OS. If the firm insisted on producing output Q_1, it would increase its APE by an amount KR and reduce its use of air by SJ. We could call this the <u>Substitution Effect</u> of pricing air properly. The cost to the firm would increase, however, since the firm would have to install more APE than before and, in addition, pay for the air it does use.[1]

Alternately, the firm could decide to produce a lower output for the same cost outlay on pollution control as before the price of air became positive (i.e., C_1). This cost, at the new prices, is depicted in Figure 5-4 by isocost line KL. At this cost outlay, the firm could produce output Q_2 (depicted by isoproduct line Q_2Q_2). This decrease in output could be designated as the <u>Output Effect</u> of the pricing of air use. When producing this output, the firm would want to use an amount of APE OC, and use air to the extent OB.

However, the firm faces the constraint that it cannot use an amount of APE lower than OK.[1] Therefore, Q_1-Q_2 is a theoretical output effect which the firm could not "realize" if it wished to do so. The maximum technically possible output effect is Q_1-Q_3, where Q_3 is an output depicted by isoproduct line Q_3Q_3 (and $Q_2 < Q_3 < Q_1$) such that the tangency point

---

1 The extra cost would be $KR \cdot P_{APE} + OS \cdot P_A$.

2 A typical example would be a firm having a chimney stack. The chimney stack is there and is indivisible.

with an isocost line (such as DT) occur at a level of APE equal to Ok. At this point (W) the firm would use the minimum APE it already has and it will use air by an amount OP. But the pollution control cost outlay of producing output Q_3 will still be greater to the firm than C_1, the anti-pollution cost associated with producing the greater output Q_1 when the price of air use was zero. In this situation then, the pricing of air use must result in a greater cost of pollution control, even if the firm were to reduce its output by the technically feasible output effect.

Figure 5-5 depicts alternative (b), that is, the firm is capable of eliminating the discharge of all wastes by installing enough anti-pollution equipment, or it can choose not to use any anti-pollution equipment at all. Q_1Q_1 is an isoproduct line representing combinations of quantities of anti-pollution equipment and air use which would be associated with the production of a given level of output Q_1. The firm could install enough APE that no air at all would be used (that is, no wastes would be released). This amount would be OB. Alternatively, the firm could choose to install no APE and use air to disperse wastes (to the extent OD). The latter is the position the firm will choose when the price of air use is zero. In this case, the cost of pollution control to the firm would be zero. When the price of air use becomes positive, however, the firm would want to install some anti-pollution equipment and reduce its use of air. Given the prices of APE and air use, the firm would minimize the cost of control associated with

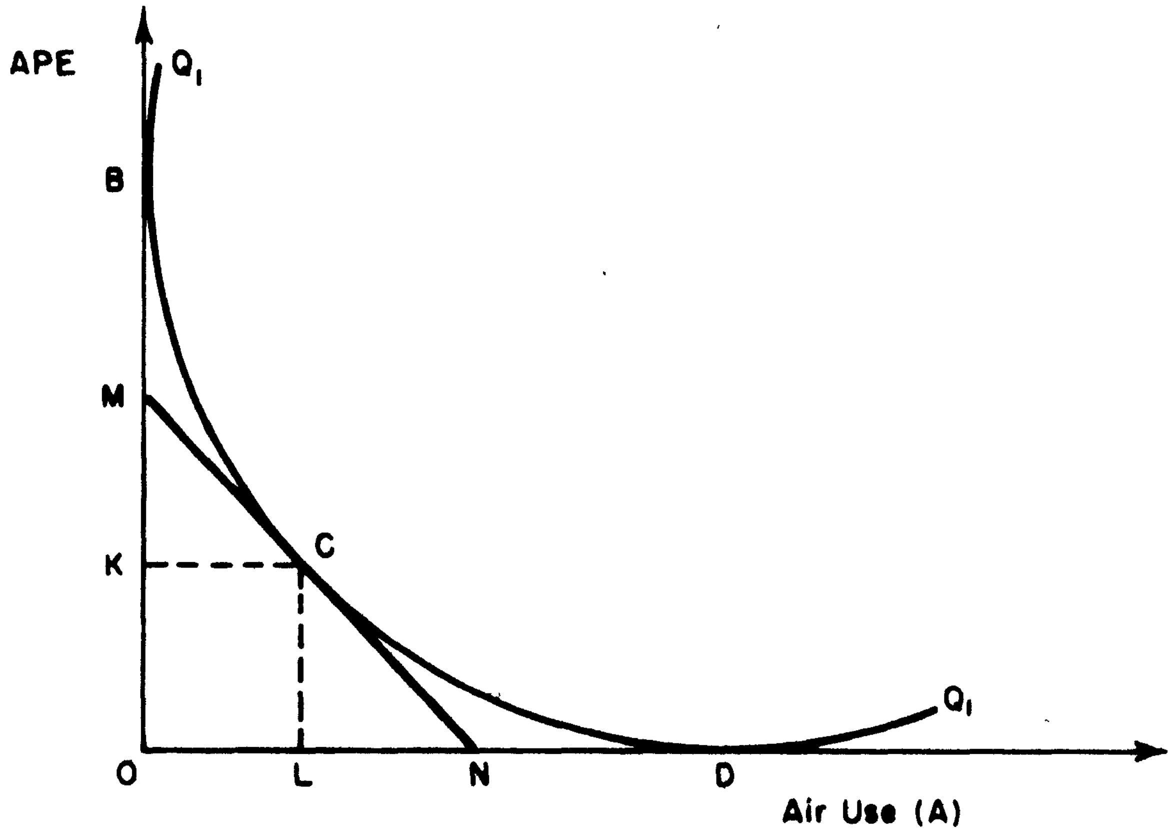

Figure 5-5 : Substitution of Anti-Pollution Equipment (B).

producing output Q_1 by choosing combination C, where the iso-product line Q_1Q_1 is tangent to the isocost line MN. At this point, the marginal rate of technical substitution between APE and A is equal to the ratio of their prices. This indicates that there is a reduction in the use of air LD and the installation of APE of an amount OK. This is the substitution effect. There is no meaningful output effect in this case because, to reduce the cost of control to zero as before the change in the price of air use, the firm would have to reduce its output to zero, that is, cease producing.

In Figure 5-6 the firm's production map is drawn with respect to air use and anti-pollution equipment. Successive

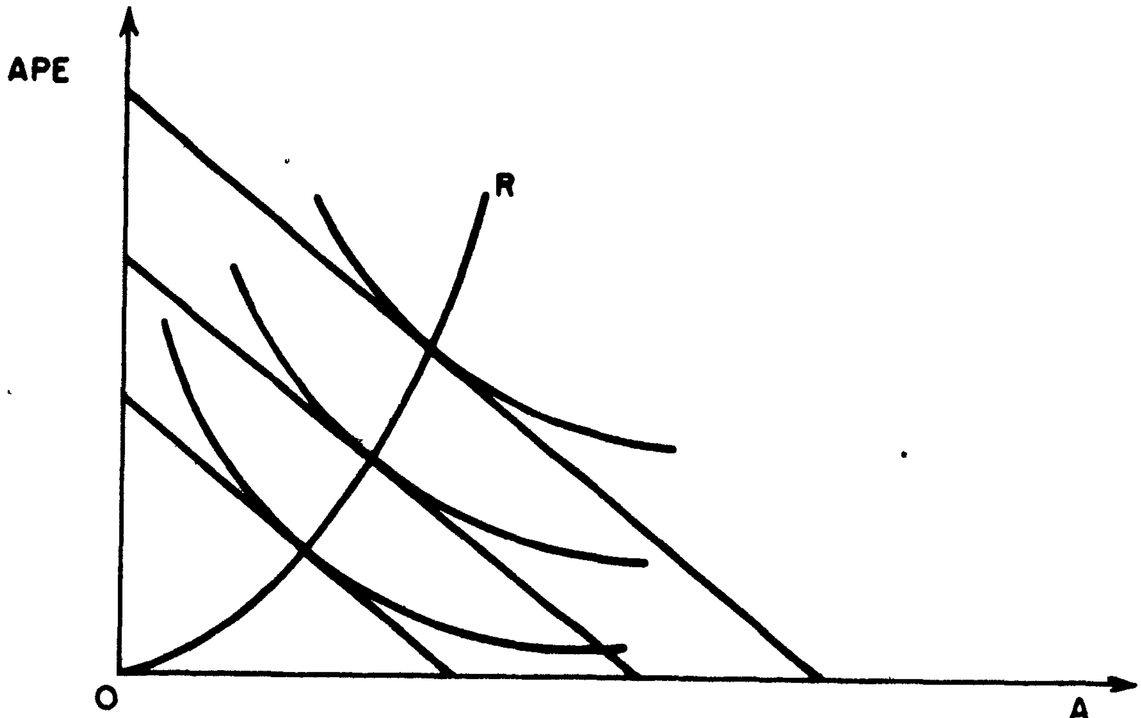

Figure 5-6 : The Air Pollution Control Path.

points of tangency between isoproduct and isocost lines generate the line OR, which might be called control path curve.[1] This curve shows combinations of anti-pollution equipment and air use which the firm will employ at various levels of output. From the control path curve it is possible to derive a cost of control curve, which indicates the minimum additional cost which the firm must incur at each level of output as a result of being given a choice to pay for air use or to install anti-pollution equipment. At each output, the cost of control to the firm is the sum of the number of units of APE times their

1 A similar curve could have been obtained when discussing alternative (a) above. If we assumed that the production function were linearly homogeneous, OR would be a straight line.

price plus the number of units of air use time their price. With this information, standard cost analysis can be used to show the effect of pricing air use on the output decisions of the firm.

CHAPTER VI

ABATEMENT OF SULFUR OXIDES: TECHNIQUES AND COSTS

Framework of Research

This chapter addresses itself to the following question: if an emission tax were chosen as the abatement strategy, what is the order of magnitude of the tax required to achieve some agreed-upon reduction in the overall quantity of emissions? Since no such agreed-upon reduction has been established, what must be determined is the order of magnitude of emission taxes associated with a range of emission reductions. This is to be achieved by a detailed examination of the costs of abating emissions of sulfur oxides from different types of sources.

In order to put in perspective the empirical work to be done here, let us reiterate, in a somewhat different manner, the argument that an emission tax is a least cost method of achieving an exogenously determined level of reduction of emissions. For this purpose, refer to Figure 6-1.

It is found, for example, that in year X, OY tons of sulfur oxides would be emitted, if no change in the economic incentives is enforced. The decision-makers decide that, in that year, a total emission of OZ tons of the pollutant would be acceptable. Hence, YZ tons of the pollutant must be abated. The question is: how to achieve this abatement at least cost?

Suppose that only two sources, A and B are responsible for all of the emissions. MC_A and MC_B in Figure 6-1 are the marginal costs of abatement for the two sources; MC_{A+B} is the horizontal sum of MC_A and MC_B and represents the level of

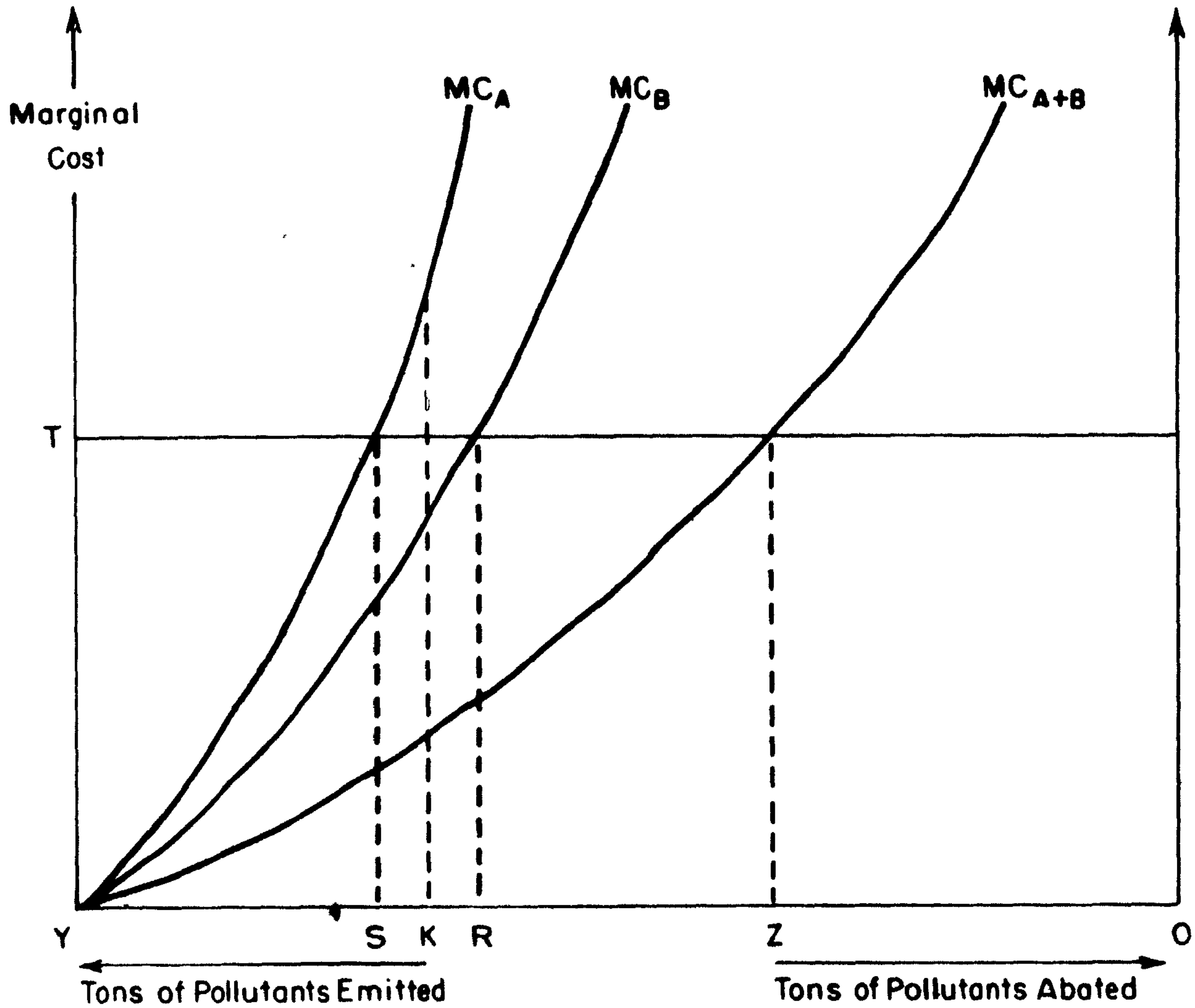

Figure 6-1: Least-Cost Abatement of Pollutants.

total reduction of the pollutant emissions when the two sources incur the same marginal cost of abatement.

Now, suppose that a reduction of emissions YZ is desired. Then, a tax YT per ton of pollutant emitted would achieve this result at lowest cost. It would achieve this result because each source would find it cheaper to reduce emissions than pay the tax as long as the marginal cost of abatement is lower than the tax - and vice versa thereafter. To show that it would do so at lowest cost, suppose that the authority would require each of the two sources to abate $\frac{1}{2}$ YZ = YK. Though the same standard would be achieved, it is easy to see that it would be achieved at a higher cost. The marginal cost of abating the K^{th} unit of pollutant is higher for source A than for source B. Hence, it would be cheaper (in total terms) to require A to abate one fewer unit and B one more unit of the pollutant. This will be true as long as the marginal costs of abatement are different for the two sources. These will be equal only when A abates YS and B, YR units of the pollutant. The taxation solution would give this result.[1] It is evident, then, that if the marginal cost of abatement curves are known, they can be integrated and a tax rate which will effectively enforce the desired standard at least cost could be established.

A very important question is whether it is possible to get the numerical value of the marginal costs of abatement for each source. Here, an attempt is made to show that this is possible if one makes a few simplifying assumptions (which hopefully are not too far removed from reality) and takes account of some of the constraints of pollution control technology.

Limiting our discussion to SO_x abatement, it must first be recognized that an emitter does not have in practice the

---

1 Of course, the same least cost solution would be achieved if the authority ordered A to reduce its emissions by YS and B by YR. However, in a world of many sources, this would probably be difficult and expensive to do. The use of taxation substitutes the impersonal working of market forces to fallible and costly human judgements.

unlimited number of choices implied by smoothly rising marginal cost curves. What is more likely is that he has a choice between a small number of alternative methods of abatement, each of which represents different marginal and average costs of abatement. Moreover, it is likely that, for each particular alternative or method, the average cost remains constant for most of the range of abatement levels; hence, over that range, the average and marginal costs of abatement are equal. What this amounts to is that each source has a step function marginal cost curve. This is shown in Figure 6-2. The solid line is the marginal cost of abatement (say, for source A). The flat portions of the MC curve coincide with substantial portions of the AC of alternative pollution abatement technologies (AC_1, AC_2, AC_3 for technologies 1, 2, and 3 respectively); where AC and MC differ, the former is traced as a dotted line. The advantage of assuming (with some plausibility) a step function such as shown in Figure 6-2 is that this makes it possible to calculate the marginal cost of abatement from engineering studies of alternative pollution control technologies. These studies usually estimate average costs of abatement. But it seems quite plausible that in most cases marginal and average costs are equal over most of the range of abatement levels.[1] A user of fuel, for example, who has the choice of using a higher priced fuel (but one containing less sulfur) as one possible SO_2 control

1 One could argue, moreover, that the emitter will really only take account of the average cost of abatement for each pollution control technology for the very fact that this is the only figure which is calculated by his engineers.

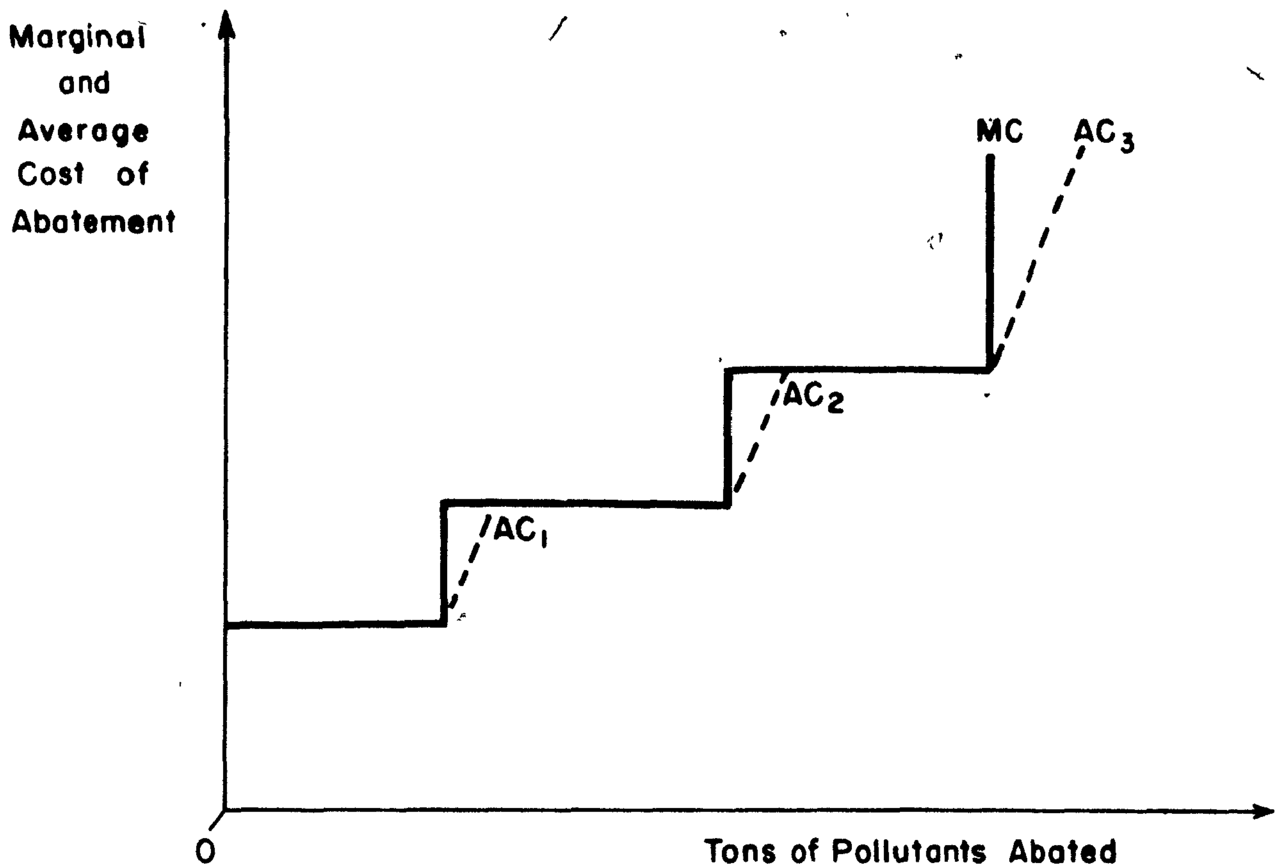

Figure 6-2: Step-Function Marginal Cost of Abatement.

alternative, will incur a marginal and average cost of control equal to the price differential between the fuels (assuming that the increased demand for the fuel does not increase its price). Of course, in cases where engineering studies actually do calculate marginal costs of control, these can be used directly. But these are rare. As with smooth curves, individual step function MC curves can be summed up horizontally, thus allowing the calculation of total levels of abatement with different tax levels. Figure 6-3 offers a numerical example of how this is done. The dotted lines are the individual marginal cost curves and the solid line is the sum of the two individual

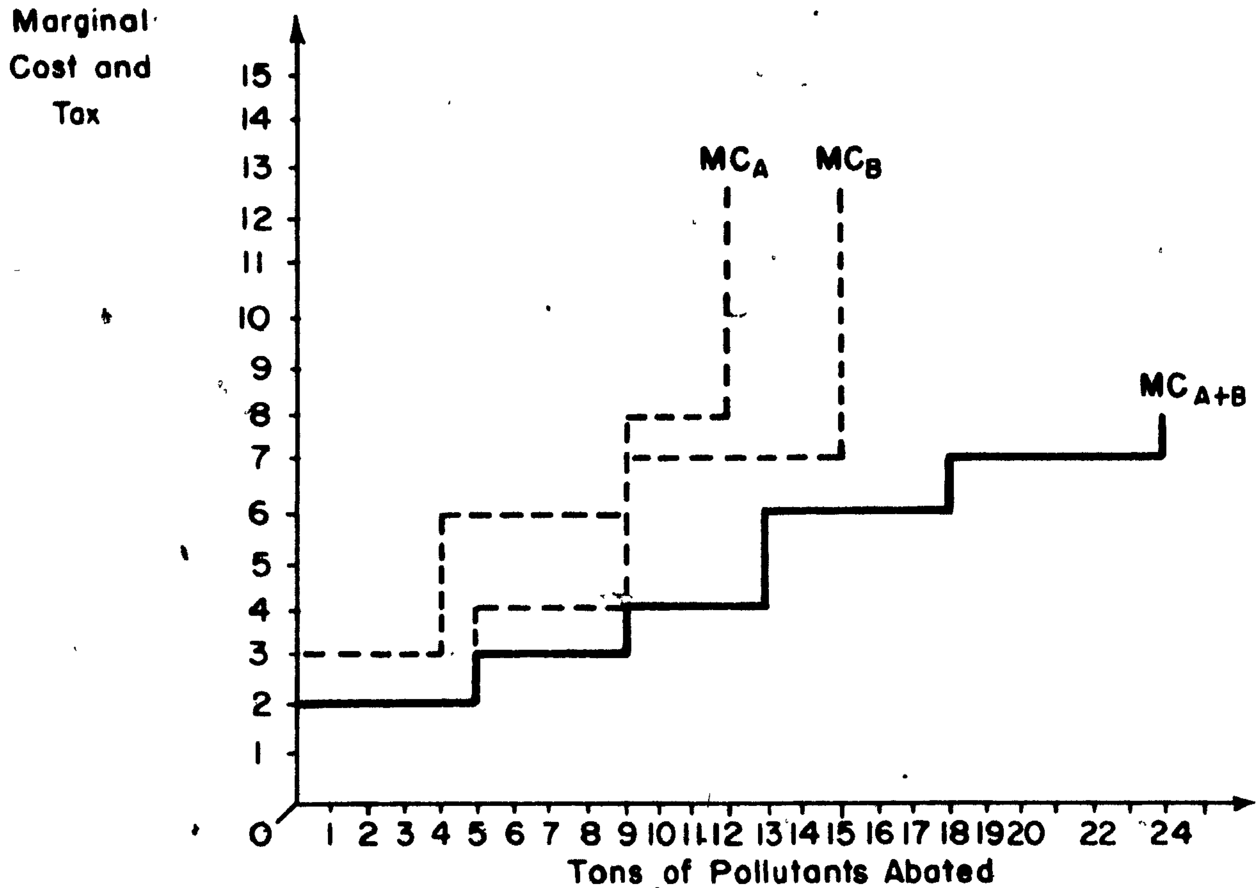

Figure 6-3: Summation of Step-Function Marginal Cost Curves.

curves. Table 6-1 shows the quantities of pollutants abated at each tax level.

When one looks more closely at the technology and other constraints involved in abatement of a particular pollutant, however, one realizes the problem is somewhat more complicated than our hypothetical example would indicate. The difficulties are encountered in the attempt to identify points on the marginal cost of abatement curves, even if the figures with respect to each abatement technique exist.

TABLE 6-1

TAX REQUIRED TO ACHIEVE GIVEN LEVELS OF ABATEMENT: HYPOTHETICAL EXAMPLE

TAX ($/TON OF POLLUTANT EMITTED)	TOTAL NUMBER OF TONS ABATED
1	0
2	5
3	9
4	13
5	13
6	18
7	24

One problem is that abatement techniques are not simply additive or substitutive, but they are both simultaneously. In order to explain what is meant let us consider a number of cases.

There are, for instance, a large number of processes which are capable of removing sulfur oxides from waste gases.[1] These are in various stages of technological development and, at the moment, only a few have reached the stage where they are being used in industrial or power plants; a few have good

1 For a comprehensive survey, see H.P. Dibbs, Methods for the Removal of Sulfur Dioxide from Waste Gases, (Ottawa: Information Canada, November, 1971).

prospects of being used in the near future.[1] It may be that, for any type of emission source, such as an industry, this, on paper, seems the cheapest alternative. Therefore, one would expect that this technique would be chosen by all individual emitters of that type, such as every plant in an industry. But it may very well be that the techniques is unsuitable for some individual sources of emissions. Perhaps the equipment designed to remove sulfur oxide would interfere with the ordinary production processes. Or, perhaps, the equipment specifications are such that it just cannot be installed in a particular plant. As a result, some plants may be unable to adopt the cheapest alternative. Only intimate knowledge of the production process of each industrial plant or other source would point out which is the most suitable specific method. Since this is very difficult to achieve within the scope of a study such as the present one, one must allow for the simultaneous existence of at least a small number of alternatives, each involving different cost of abatement. So, the task is, on the one hand, to sort out the abatement processes which evidence indicates to be generally suited to abate emissions from a given type of source, such as an industry, and on the other, to recognize that one is much more likely to come up with a <u>range</u> of cost estimates than with a single figure.

---

1 See, for example, C.G. Cortelyou, "Commercial Processes for SO_2 Removal," Chemical Engineering Progress, LXV (September, 1969), pp. 69-77. J.C. Davis, "SO_2 Removal Still Prototype," Chemical Engineering, LXXIX (June 12, 1972), pp. 53-56. "SO_2 Technology Enters Growth Phase," Environmental Science and Technology, VI (August, 1972, pp. 688-691.

This conclusion is reinforced by the consideration that, in the case of some abatement techniques, close examination reveals that, even for a single type of abatement process, there is a range of cost estimates rather than a single figure. Take, for instance, the technique of removing sulfur from coal prior to its combustion. Sulfur can be removed from coal either by dry or wet process and the degree of sulfur removal depends on the type of process used and, in addition, on the types of sulfur present (pyrites, organic compounds, or sulfates) and on the amount of each type present. These factors, plus others such as the size of the coal cleaning plant, transport costs, and so on, yield a range of costs for this abatement technique.[1]

An additional constraint can arise from supply conditions. Consider, for instance, abatement by fuel switching. It may be that, for some category of sources, the cheapest technique of abatement is to switch from the use of a sulfur-containing fuel, such as oil, to natural gas, which contains no sulfur. But it may very well be that, in a particular area, no natural gas is available, or is not available all of the time, as in the case of customers served on an interruptible basis. If alternative abatement measures are more costly and some sources are forced to adopt them at least part of the time, again, for this type of source, abatement costs will be in the nature of a range rather than single values.

1 See, for example, B. Putman and M. Manderson, "Iron Pyrites from High Sulfur Coal," Chemical Engineering Progress, LXIV (September, 1968), pp. 60-65.

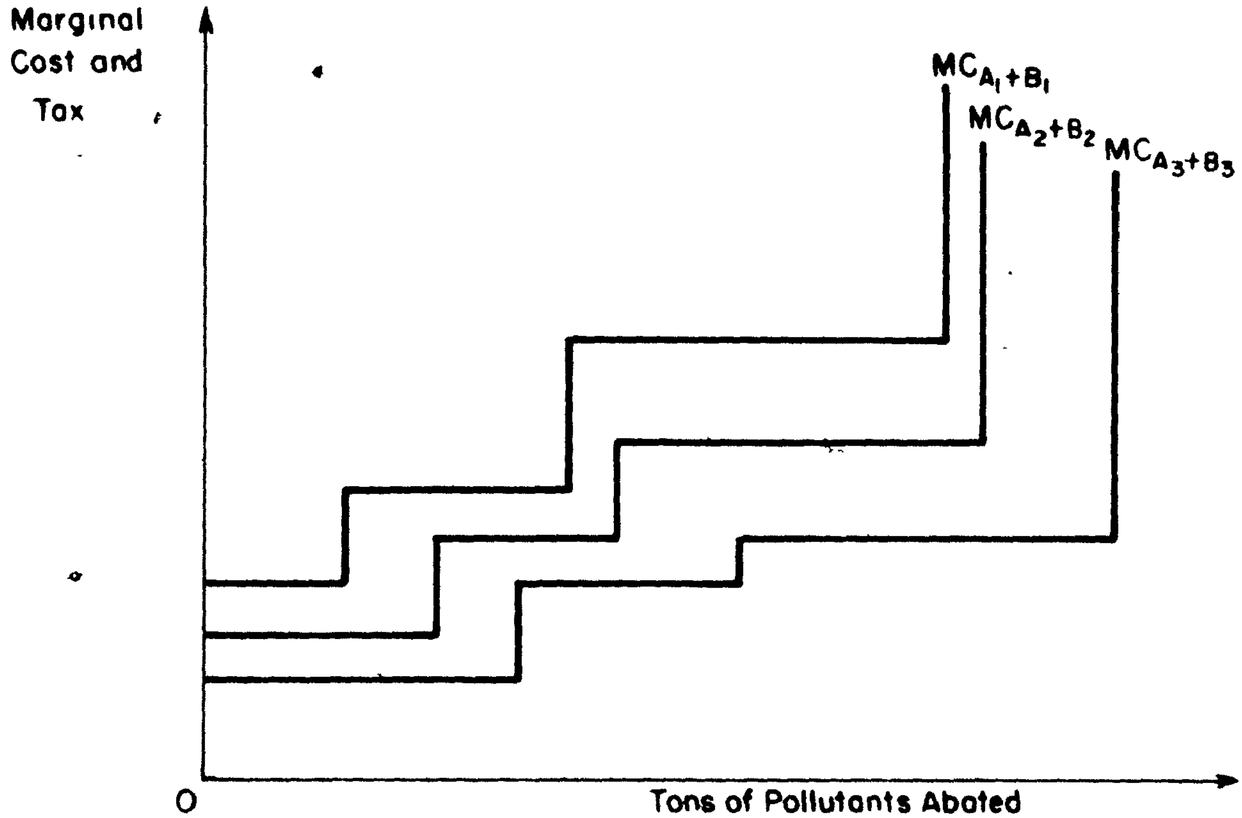

Figure 6-4 : The Range of Marginal Cost: Step Functions.

How are we to deal with this problem? The suggestion made here is to modify the model represented by Figure 6-3 to one where, from a judicious choice of abatement processes, a number of marginal cost of abatement curves (each of which is the sum of the marginal cost of abatement for each type of source) is estimated so as to give the range of costs described above.

Figure 6-4 reproduces three such curves (the individual MC curves are omitted). The subscripts indicate different cost estimates of abating given number of units of pollutants, either by the same method or by a different one, from sources A and B.

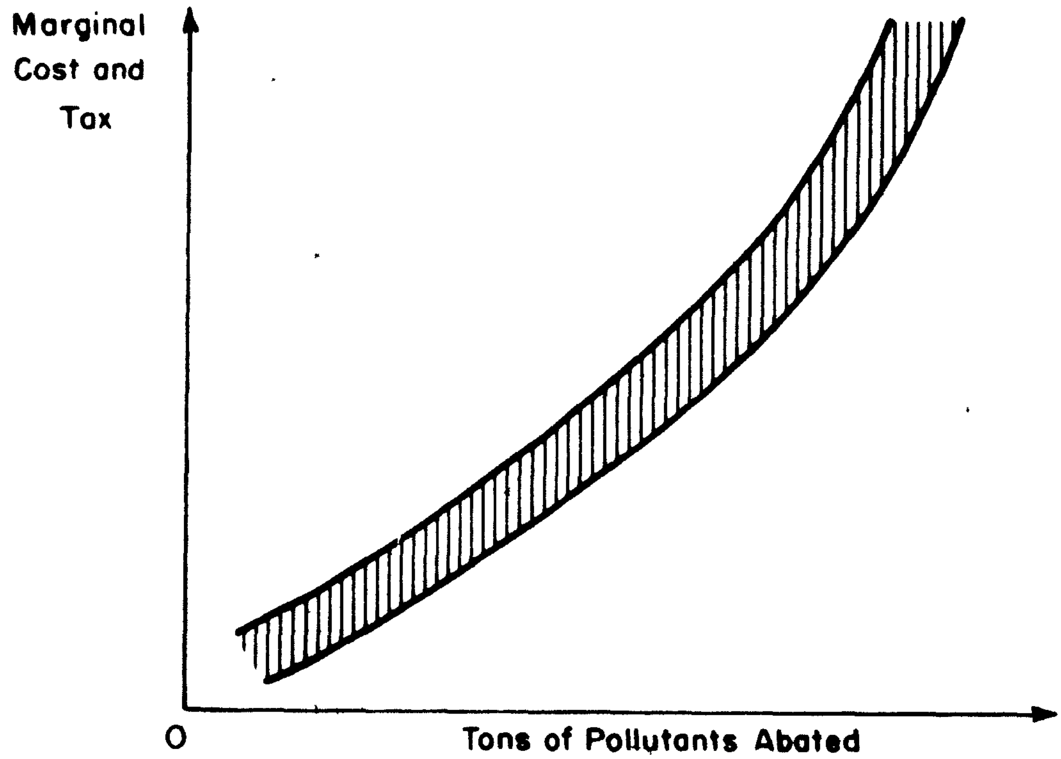

Figure 6-5 : The Range of Marginal Cost : Smooth Curves

This amounts to saying that, if we were dealing with smooth marginal cost curves, we would obtain a range of costs as indicated by the shaded area of Figure 6-5, instead of a single marginal cost curve. The actual cost of abatement would be anywhere in the range though one would think that economic forces would tend, with time, to push the actual cost of abatement towards the rightward (or lower) hedge of the range.

While this procedure yields results which are not as neat as one might wish, it is a good reflection of reality.[1] Hopefully, the range will not turn out to be very wide.

---

1 In a way, this procedure could remove any objections one may have to the assumption of constant marginal cost within a given abatement technique made above. When it is a question of a range of marginal costs, the constancy assumption is to some extent removed.

1. CONTROL OF EMISSIONS FROM RESIDENTIAL FUEL COMBUSTION (SOURCE 1)

(A) Residential Fuel Combustion, Emissions, and Equipment

In attempting to estimate emissions and abatement costs, the base year 1969 was chosen because it is the most recent year for which a detailed balance sheet of sources and disposition of fuels exists.[1] Columns 2 and 3 of Table 6-2 list residential and farm consumption of fuels in natural (or physical) units and in energy units, respectively. From these figures, emissions of sulfur dioxide and sulfur trioxide (columns 4 and 5, respectively) are estimated.

The energy balance sheet does not distinguish between the specific uses to which the consumption of fuels is devoted in the residential and farm sector. However, the following is a list of the typical uses to which particular fuels are put:

- Coal - space heating, heating piped water, cooking;
- Coke - space heating, heating piped water, cooking;
- Kerosene - space heating, heating piped water, cooking;
- Liquified Petroleum Gas (LPG) - heating piped water, cooking;
- Diesel Fuel Oil - operation of farm machinery;
- Light Fuel Oil - space heating, heating piped water;
- Heavy Fuel Oil - space heating;
- Natural Gas - Space heating, heating piped water;
- Electricity - space heating, heating piped water, operation of appliances.

---

1 Statistics Canada, Detailed Energy Supply and Demand In Canada, 1958-1969, (Ottawa: Information Canada, November, 1972).

TABLE 6-2

RESIDENTIAL AND FARM FUEL CONSUMPTION AND ESTIMATES OF ASSOCIATED EMISSIONS OF SULFUR OXIDES - CANADA, 1969

FUEL	QUANTITY (NATURAL UNITS)	QUANTITY (MILLION BTU)	SO_2 (TONS)	SO_3 (TONS)	SO_x (TONS)
(1)	(2)	(3)	(4)	(5)	(6)
Coal (a)	892,562 Tons	18,300,081	80	2	82
Coke	19,247 Tons	477,325	(b)	(b)	(b)
Liquified Petroleum Gas	11,117,539 Barrels	45,526,323	-	-	-
Kerosene (c)	14,265,019 "	80,928,513	12,000	319	12,319
Diesel Fuel Oil (d)	6,153,597 "	35,860,085	11,000	-	11,000
Light Fuel Oil (e)	68,600,856 "	399,771,488	140,000	3,600	143,600
Heavy Fuel Oil (f)	6,320,255 "	39,737,970	53,000	1,337	54,337
Natural Gas	231,464,921 Mcf.	231,464,921	-	-	-
Electricity	40,446,333,000 Kwh.	138,002,888	-	-	-
Total		990,123,594	216,000	5,258	221,258

Notes:

(a) It is assumed that all coal is anthracite containing 0.5% sulfur. The emission factor was assumed to be the same as that for commercial hand-fired anthracite furnaces; that is, 38S lbs. of SO_2, where S is the sulfur content in percentage points. See, Environmental Protection Agency, Compilation of Emission Factors, (Washington: U.S. Government Printing Office, 1972), p. 1-5.

(b) No emission factors could be obtained. Given the small quantities involved, emissions from this source are disregarded.

(c) Kerosene has a specific gravity of 0.825 and an average sulfur content of 0.3%. It is assumed that 98% of the sulfur burns to SO_2 and 2% to SO_3. See, F.D. Friedrich and E.R. Mitchell, First Addendum to Mines Branch Information Circular IC211, Air Pollution in Canada from Fuel Combustion, (Ottawa: Department of Energy, Mines, and Resources, May, 1970), pp. 19-21.

(d) Diesel fuel oil has a specific gravity of 0.85 and the average sulfur content was assumed to be 0.6%. It is assumed that all of the sulfur burns to SO_2. See, Friedrich and Mitchell, First Addendum..., pp. 22-27.

(e) Light fuel oil has a specific gravity of 0.85 and the average sulfur content is assumed to be 0.7%. It is assumed that 98% of the sulfur burns to SO_2 and 2% to SO_3. See, Friedrich and Mitchell, First Addendum..., pp. 18-19.

(f) Heavy fuel oil has a specific gravity of 0.97 and the average sulfur content is assumed to be 2.5%. It is assumed that 98% of the sulfur burns to SO_2 and 2% to SO_3. See, Friedrich and Mitchell, First Addendum..., pp. 35-37.

Source: Statistics Canada, Detailed Energy Supply and Demand in Canada, pp. 138-139, 284-285.

Here we will be concerned with the abatement of sulfur oxides emissions from only the two major sources, the combustion of light and heavy fuel oil. As estimated, (in Table 6-2), these two sources account for about 90% of all emissions from the residential and farm sector.[1] Moreover, it is assumed that these two fuels are used exclusively for space heating. The plausibility of this assumption is supported by the data in Tables 6-3 and 6-4. Table 6-3 lists the fuels used for heating piped water in Canadian households in 1969. According to this data, only about 10% of households used oil to heat water. And these may use kerosene or stove oil as well as light fuel oil, more probably the former.[2] Table 6-4 lists the fuel used by cooking equipment in Canadian households in 1969. The number of households which use oil for cooking is very small, and the oil is usually kerosene.[3]

---

1 The rest of the emissions from this sector are not significant. In 1970, they accounted for only 0.3% of all emissions of sulfur oxides.

2 See, R.B. Engdahl, "Stationary Combustion Sources," in A.C. Stern, (ed.), Air Pollution, Second Edition, Vol. 1, (New York: Academic Press, 1968), pp. 3-54.

3 Even if not absolutely exact, the assumption that all light and heavy fuel oil is used for space heating would not affect abatement of emissions or abatement costs with respect to some abatement techniques, such as the desulfurization of fuel oil. It would make some difference in terms of the costs of abatement by other techniques, such as fuel switching.

TABLE 6-3

FUEL USED FOR PIPED HOT WATER SUPPLY
CANADA, MAY, 1969

FUEL	NUMBER OF HOUSEHOLDS (THOUSANDS)
Electricity	2,902
Piped Gas	1,554
Bottled Gas	71
Coal or Coke	41
Oil	536
Other (Mainly Wood)	68
Total	5,172

Source: Dominion Bureau of Statistics, Household Facilities and Equipment, (Ottawa: Queen's Printer, 1970), p. 14.

TABLE 6-4

COOKING EQUIPMENT - CANADA, 1969

EQUIPMENT	NUMBER OF HOUSEHOLDS (THOUSANDS)
Electric Stoves	4,228
Wood or Coal Stoves	251
Piped Gas Stoves	675
Bottled Gas Stoves	151
Kerosene or Oil Stoves	185
Other	11
No Cooking Equipment	13
Total	5,514

Source: Dominion Bureau of Statistics, Household Facilities and Equipment, p. 16.

Table 6-5 lists the heating equipment by fuel in Canada in 1969. Heating stoves and cookstoves typically use kerosene. Therefore, the light and heavy fuel oil consumed by the residential and farm sector in 1969 was burned in furnaces. A total of 2,615 thousands of such units were in operation in Canada in 1969.

TABLE 6-5

PRINCIPAL HEATING EQUIPMENT BY FUEL
CANADA, MAY, 1969 (THOUSANDS OF HOUSEHOLDS)

FUEL	TOTAL HOUSE-HOLDS	STEAM OR HOT WATER FURNACES	HOT AIR FURNACES	COOK-STOVES OR RANGES	HEATING STOVES	OTHER
Total	5,514	1,212	3,142	148	809	203
Coal or Coke	144	48	54	16	25	-
Oil	3,213	847	1,768	58	536	4
Wood	207	-	67	66	72	-
Piped Gas	1,691	312	1,208	7	158	6
Bottled Gas	65	-	43	-	18	-
Electricity	192	-	-	-	-	192

Source: Dominion Bureau of Statistics, Household Facilities and Equipment, p. 12.

There is no estimate of the number of furnaces which use heavy fuel oil and the number which use light fuel oil. Since this information is needed below, these numbers are estimated as follows. The proportion of furnaces using heavy fuel oil to the total number of furnaces is assumed to be the same as the proportion of the energy input from heavy fuel oil to the total input of energy for both heavy and light fuel oil in the residential and farm sector.[1] This proportion is 0.0904.[2] Therefore, it is estimated that, of the 2,615,000 furnaces in operation in Canadian households in 1969, 236,000 used heavy fuel oil and 2,379,000 used light fuel oil. Each of these furnaces required an average input of about 168 MBTU per year or 1000 gallons of fuel oil. Alternatively, this average furnace would consume 168 Mcf. of natural gas or 36,700 Kwh. of electricity.[3]

---

1 In other words, a furnace in the residential and farm sector is assumed to require the same energy input, whether it uses heavy or light fuel oil.

2 That is, 39,737,970/39,737,970 + 399,771,488 = 0.0904. The figures are from column 3 of Table 6-2.

3 The same efficiencies are assumed for furnaces consuming natural gas and fuel oil. It is further assumed that this efficiency is 75%. Electric heating equipment, on the other hand, is assumed to be 100% efficient. The lower efficiency of oil or gas fired furnaces is due to the fact that about 25% of the heat output of these furnaces escapes through the chimney with the combustion gases. Since electric heating requires no furnace or chimney, no such loss occurs. The 75% figure is approximate and varies slightly depending on a number of factors (such as the length of time the equipment has been in operation). A study made by the Corporation des Maitres Mecaniciens en Tuyouterie du Quebec on four identical houses in a suburb of Montreal (Brossard) obtained the following efficiencies:

Electricity	- 100%
Oil - warm water	- 74.2%
Gas	- 77.9%
Oil - warm air	- 75.3%

See, Corporation des Maitres Mecaniciens due Quebec, "Etude Experimentale de la Consommation d' Energie dans les Maisons Unifamiliales Munies de Divers Systemes de Chauffage," (mimeographed, 1971), p. 5.

(B) Techniques and Costs of Abatement

Technique A_1

Substitute heavy fuel oil containing 1% sulfur for heavy fuel oil containing 2.5% sulfur.

Results are summarized in Table 6-6.

TABLE 6-6

COST OF ABATEMENT - (SOURCE 1, TECHNIQUE A_1)

Total Reduction of Emissions (Tons)	32,602
Total Cost of Abatement ($)	5,960,695
Cost of Abatement per Unit SOx ($/Ton)	183

Note: From Table C-2, Appendix C, the price differential between heavy fuel oil containing 1% sulfur and heavy fuel oil containing 2.5% sulfur is 2.7¢/Gal., or 15¢/MBTU.

Technique B_1

Substitute heavy fuel oil containing 0.25% sulfur for heavy fuel oil containing 2.5% sulfur.

Results are summarized in Table 6-7.

TABLE 6-7

COST OF ABATEMENT - SOURCE 1, TECHNIQUE B_1)

Total Reduction of Emissions (Tons)	48,903
Total Cost of Abatement ($)	10,729,252
Cost of Abatement per Unit SOx ($/Ton)	219

Note: From Table C-2, Appendix C, the price differential between heavy fuel oil containing 0.25% sulfur and heavy fuel oil containing 2.5% sulfur is 4.8¢/Gal., or 27¢/MBTU.

Technique C_1

Substitute light fuel oil containing 0.25% sulfur for light fuel oil containing 0.7% sulfur.

Results are summarized in Table 6-8.

TABLE 6-8

COST OF ABATEMENT - (SOURCE 1, TECHNIQUE C_1)

Total Reduction of Emissions (Tons)	92,314
Total Cost of Abatement ($)	31,981,716
Cost of Abatement per Unit SOx ($/Ton)	346

Note: From Table C-2, Appendix C, the price differential between light fuel oil containing 0.25% sulfur and light fuel oil containing 0.7% sulfur is 1.3¢/Gal., or 8¢/MBTU.

Technique D_1

Switch from the combustion of heavy fuel oil to that of natural gas.

Results are summarized in Table 6-9.

TABLE 6-9

COST OF ABATEMENT - (SOURCE 1, TECHNIQUE D_1)

Total Reduction of Emissions (Tons)	54,337
Heavy Fuel Oil Required per Furnace (Gallons)	1,000
Natural Gas Required per Furnace (Mcf.)	168
Total Heavy Fuel Oil Required (Gallons)	236,000,000
Total Natural Gas Required (Mcf.)	39,648,000
Total Cost of Heavy Fuel Oil ($)	22,420,000
Total Cost of Natural Gas ($)	41,233,920
Excess Cost of Natural Gas Over Oil ($)	18,813,920
Annual Cost of Conversion per Furnace ($)	82
Total Cost of Conversion ($)	19,352,000
Total Cost of Abatement ($)	38,165,920
Cost of Abatement per Unit SOx ($/Ton)	702

Note: From Table B-4, Appendix B, the price of heavy fuel oil and of natural gas is 9.5¢/Gal. and $1.04/Mcf. respectively. The annual fuel cost per household for heavy fuel oil and natural gas is $95 and $174 respectively.

Technique E_1

Switch from the combustion of light fuel oil to that of natural gas.

Results are summarized in Table 6-10.

TABLE 6-10

COST OF ABATEMENT - (SOURCE 1, TECHNIQUE E_1)

Total Reduction of Emissions (Tons)	143,600
Light Fuel Oil Required per Furnace (Gallons)	1,000
Natural Gas Required per Furnace (Mcf.)	168
Total Light Fuel Oil Required (Gallons)	2,379,000,000
Total Natural Gas Required (Mcf.)	399,672,000
Total Cost of Light Fuel Oil ($)	466,284,000
Total Cost of Natural Gas ($)	415,658,880
Excess Cost of Natural Gas Over Oil ($)	50,625,120
Annual Cost of Conversion per Furnace ($)	82
Total Cost of Conversion ($)	195,078,000
Total Cost of Abatement ($)	144,452,880
Cost of Abatement per Unit SOx ($/Ton)	1,006

Note: From Table B-4, Appendix B, the price of light fuel oil and of natural gas is 19.6¢/Gallon and $1.04/Mcf. respectively. The annual fuel cost per household for light fuel oil and natural gas is $196 and $174 respectively.

Technique F_1

Switch from the combustion of heavy fuel oil to electricity.

Results are summarized in Table 6-11.

TABLE 6-11

COST OF ABATEMENT - (SOURCE 1, TECHNIQUE F_1)

Total Reduction of Emissions (Tons)	54,337
Heavy Fuel Oil Required per Furnace (Gallons)	1,000
Additional Electricity Required per House (Kwh)	36,700
Total Heavy Fuel Oil Required (Gallons)	236,000,000
Total Electricity Required (Kwh.)	8,661,200,000
Total Cost of Heavy Fuel Oil ($)	22,420,000
Total Cost of Electricity ($)	105,666,640
Excess Cost of Electricity Over Oil ($)	83,246,640
Annual Cost of Conversion per House ($)	88
Total Cost of Conversion ($)	20,768,000
Total Cost of Abatement ($)	104,014,640
Cost of Abatement per Unit SOx ($/Ton)	1,914

Note: From Table B-4, Appendix B, the price of heavy fuel oil and of electricity is 9.5¢/Gallon and $1.22/Kwh. respectively. The annual fuel cost per household for heavy fuel oil and electricity is $95 and $477 respectively.

Technique G_1

Switch from the combustion of light fuel oil to electricity.

Results are summarized in Table 6-12.

TABLE 6-12

COST OF ABATEMENT - (SOURCE 1, TECHNIQUE G_1)

Total Reduction of Emissions (Tons)	143,600
Light Fuel Oil Required per Furnace (Gallons)	1,000
Additional Electricity Required per Home(Kwh)	36,700
Total Light Fuel Oil Required (Gallons)	2,379,000,000
Total Electricity Required (Kwh.)	87,309,300,000
Total Cost of Light Fuel Oil ($)	466,284,000
Total Cost of Electricity ($)	1,065,173,460
Excess Cost of Electricity Over Oil ($)	598,889,460
Cost of Conversion per Home ($)	88
Total Cost of Conversion ($)	209,352,000
Total Cost of Abatement ($)	808,241,460
Cost of Abatement per Unit SOx ($/Ton)	5,628

Note: From Table B-4, Appendix B, the price of light fuel oil and of electricity is 19.6¢/Gallon and $1.22/Kwh. respectively. The annual fuel cost per household for light fuel oil and electricity is $196 and $447 respectively.

2. CONTROL OF EMISSIONS FROM COMMERCIAL FUEL COMBUSTION (SOURCE 2)

(A) Commercial Fuel Combustion, Emissions and Equipment

Estimates of emissions from the commercial combustion of fuels in Canada in 1969 are summarized in Table 6-13. The combustion of these fuels takes place mostly, though not exclusively, in boilers installed in such things as hospitals, hotels, schools, office buildings, and so on. A portion of the fuels is consumed in equipment other than boilers, such as commercial cooking. Here we will be concerned only with the abatement of emissions from the commercial combustion of coal, light fuel oil, and heavy fuel oil which takes place in boilers. Since there are no Canadian statistics concerning the quantity of fuels which is burned in boilers and that which is not, but there are estimates of the percentages of fuels burned in boilers in the United States, it was assumed that these percentages are the same in Canada. These are summarized in Table 6-14. Given these percentages, it was possible to estimate the commercial combustion of fuels which took place in boilers in Canada in 1969, and the associated emissions of sulfur oxides. This data is summarized in Table 6-16.

There is no inventory, to the knowledge of the author, of the types and quantities of units in which the combustion of commercial fuels takes place in Canada. An attempt is made here to estimate the number of such units.

TABLE 6-13

COMMERCIAL FUEL CONSUMPTION AND ESTIMATES OF ASSOCIATED EMISSIONS OF SULFUR OXIDES - CANADA, 1969

FUEL	QUANTITY (NATURAL UNITS)	QUANTITY (MILLION BTU)	SO_2 (TONS)	SO_3 (TONS)
Coal (a)	583,000 tons	14,705,103	33,250	-
Crude Oil	59,435 Barrels	344,901	(b)	(b)
Kerosene (c)	1,848,237 Barrels	10,492,441	1,617	41
Diesel Fuel Oil (d)	2,688,310 Barrels	15,666,126	4,800	-
Light Fuel Oil (e)	16,337,220 Barrels	95,205,149	33,270	847
Heavy Fuel Oil (f)	33,198,077 Barrels	208,729,589	282,500	7,062
Natural Gas	181,760,657 Mcf.	181,760,657	-	-
Electricity	38,538,828,000 Kwh.	131,494,481	-	-
Total		658,398,447	355,437	7,950

Notes: (a) It is assumed that all coal is of the bituminous type and that its average sulfur content is 3.0%. The emission factor is 38S lbs. of SO_2, where S is the sulfur content of the coal in percentage points. See, Environmental Protection Agency, Compilation of Emission Factors, p. 1-3.

(b) No emission factors could be obtained. Given the small quantities involved, emissions from this source were disregarded.

(c) The same assumptions as in Note (c), Table 6-2, are made.

(d) The same assumptions as in Note (d), Table 6-2, are made.

(e) The same assumptions as in Note (e), Table 6-2, are made.

(f) The same assumptions as in Note (f), Table 6-2, are made.

Source: Statistics Canada, Detailed Energy Supply and Demand in Canada, pp. 138-139, 284-285.

TABLE 6-14

PERCENT OF FUEL BURNED IN BOILERS ACCORDING TO USER
UNITED STATES, 1967

USER	PERCENT OF FUEL BURNED IN BOILERS			
	COAL	LIGHT FUEL OIL	HEAVY FUEL OIL	GAS
Commercial	100	90	90	50
Industrial	77	70	70	30
Utilities	100	-	100	100

Source: J.R. Ehrenfeld et al., Systematic Study of Air Pollution from Intermediate-Size Fossil - Fuel Combustion Equipment, (Cambridge, Mass.: Walden Research Corporation, July, 1971), p. 117. Note that the relatively small proportion of fuels used in industrial boilers indicate that sizable quantities are used directly in the production process, such as in kilns, driers, and so on.

In the United States, it was found that, in 1967, in 298 metropolitan areas (which included about 85% of the U.S. population), there were 952,000 commercial-institutional combustion units.[1] These units consumed 4.3 million tons of coal, 2.67 million barrels of fuel oil, and 1.58 trillion cubic feet of gas.[2] In terms of energy, these units consumed 3.24×10^9 MBTU. Therefore, the average consumption per unit was 3,400 MBTU.

The consumption of fuels in boilers depends, in part,

1 D.A. LeSourd et al., Comprehensive Study of Specified Air Pollution Sources to Assess the Economic Effects of Air Quality Standards, (Research Triangle Park, N.C.: Research Triangle Institute, December, 1970), p. IV-10.

2 Ibid.

on their load factor. The load factor is the fraction of the year a boiler operates at rated capacity. Load factors of commercial boilers have been estimated for the United States.[1] Since in commercial installations most of the fuel is burned for purposes of space heating, one can expect the load factor to be higher in areas where cold temperatures prevail than in areas where warm temperatures prevail. In fact, the load factor was found to vary from 0.05 in Florida to 0.31 in Maine. Table 6-15 lists the load factors of commercial boilers in selected areas. From this data, it seemed reasonable to the author to assume an average load factor in Canada of 0.30. This means that, in Canada, the average commercial boiler uses 1.5 times the energy input of the average commercial boiler in the United States. This gave an estimated annual energy consumption of 5,100 MBTU.

Given this figure and the estimated total amount of energy and fuels consumed in this type of boiler (as shown in Table 6-16), it was possible to estimate the number of commercial boilers and their distribution by fuel in Canada. Also, given the energy conversion factors and the total quantity of emissions from this source, it was possible to estimate the average quantity of each fuel consumed per boiler and the quantity of emissions per boiler. All of this data is summarized in Table 6-17.

---

1 J.R. Ehrenfeld et al., Systematic Study of Air Pollution From Intermediate-Size Fossil - Fuel Combustion Equipment, (Cambridge, Mass.: Walden Research Corp., July, 1971), pp. A15-A21.

TABLE 6-15

LOAD FACTORS OF COMMERCIAL BOILERS IN SELECTED AREAS - UNITED STATES, 1967

STATE	CITY	LOAD FACTOR
Montana		0.25
Washington	Seattle	0.27
Connecticut		0.25
New York		0.25
Pennsylvania	Philadelphia	0.22
Wisconsin	Milwakee	0.25
Illinois	Chicago	0.23
Michigan	Detroit	0.25
California	Los Angeles	0.16
New Hampshire		0.27
Vermont		0.29
Texas	Dallas	0.11
Florida		0.05
National Average		0.20

Source: Ehrenfeld et al., Systematic Study..., pp. A15-A21.

TABLE 6-16

COMMERCIAL FUEL CONSUMPTION IN BOILERS AND ASSOCIATED EMISSIONS OF SULFUR OXIDES - CANADA, 1969

FUEL	QUANTITY (NATURAL UNITS)	QUANTITY (MILLION BTU)	SO_2 (TONS)	SO_3 (TONS)	SO_x (TONS)
Coal	583,000 Tons	14,705,103	33,250	-	33,250
Light Fuel Oil	14,703,498 Barrels	85,684,634	29,943	762	30,705
Heavy Fuel Oil	29,878,269 Barrels	187,856,630	254,250	6,355	260,605
Natural Gas	90,880,328 Mcf.	90,880,328	-	-	-
Total		379,126,695	317,443	7,117	324,560

TABLE 6-17

NUMBER OF COMMERCIAL BOILERS BY FUEL, AND
EMISSIONS OF SULFUR OXIDE PER BOILER
CANADA, 1969

FUEL	NUMBER OF BOILERS	ANNUAL CONSUMPTION OF FUEL PER BOILER	ANNUAL EMISSIONS OF SO_x PER BOILER
Coal	2,883	202 Tons	11.5 Tons
Light Fuel Oil	16,800	30,631 Gallons	1.8 Tons
Heavy Fuel Oil	36,835	28,390 Gallons	7.0 Tons
Natural Gas	17,820	5,100 Mcf.	-
Total	74,338	-	-

(B) Techniques and Costs of Abatement

Technique A_2

Substitute coal averaging 1.0% sulfur for coal averaging 3.0% sulfur.

Results are summarized in Table 6-18.

TABLE 6-18

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE A_2)

Total Reduction of Emissions (Tons)	22,166
Total Cost of Abatement ($)	524,700
Cost of Abatement per Unit SOx ($/Ton)	24

Note: From Table C-2, Appendix C, the price differential between coal averaging 1.0% sulfur and coal averaging 3.0% sulfur is 90¢/Ton.

Technique B_2

Switch from the combustion of coal in commercial boilers to that of heavy fuel oil.

Results are summarized in Table 6-19.

TABLE 6-19

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE B_2)

Total Reduction of Emissions (Tons)	12,973
Coal Required per Boiler (Tons)	202
Heavy Fuel Oil Required per Boiler (Gallons)	28,390
Total Coal Required (Tons)	583,000
Total Heavy Fuel Oil Required (Gallons)	81,848,370
Total Cost of Coal ($)	6,996,000
Total Cost of Heavy Fuel Oil ($)	6,220,476
Excess Cost of Heavy Fuel Oil Over Coal ($)	775,524
Annual Cost of Conversion per Boiler ($)	2,000
Total Cost of Conversion ($)	5,766,000
Total Cost of Abatement ($)	4,990,476
Cost of Abatement per Unit SOx ($/Ton)	385

Note: From Table B-4, Appendix B, the commercial price of coal and heavy fuel oil is $12/Ton and 7.6¢/Gallons respectively.

Technique C_2

Switch from the combustion of coal in commercial boilers to that of light fuel oil.

Results are summarized in Table 6-20.

TABLE 6-20

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE C_2)

Total Reduction of Emissions (Tons)	27,965
Coal Required per Boiler (Tons)	202
Light Fuel Oil Required per Boiler (Gallons)	30,631
Total Coal Required (Tons)	583,000
Total Light Fuel Oil Required (Gallons)	88,309,173
Total Cost of Coal ($)	6,996,000
Total Cost of Light Fuel Oil ($)	14,835,941
Excess Cost of Light Fuel Oil Over Coal ($)	7,838,941
Annual Cost of Conversion Per Boiler ($)	1,700
Total Cost of Conversion ($)	4,901,100
Total Cost of Abatement ($)	12,740,041
Cost of Abatement per Unit SOx ($/Ton)	455

Note: From Table B-4, Appendix B, the commercial price of coal and light fuel oil is $12/Ton and 16.8¢/Gallon respectively.

Technique D_2

Switch from the combustion of coal in commercial boilers to that of natural gas.

Results are summarized in Table 6-21.

TABLE 6-21

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE D_2)

Total Reduction of Emissions (Tons)	33,250
Coal Required per Boiler (Tons)	202
Natural Gas Required per Boiler (Mcf.)	5,100
Total Coal Required (Tons)	583,000
Total Natural Gas Required (Mcf.)	14,703,300
Total Cost of Coal ($)	6,996,000
Total Cost of Natural Gas ($)	10,439,343
Excess Cost of Natural Gas Over Coal ($)	3,443,343
Annual Cost of Conversion per Boiler ($)	700
Total Cost of Conversion ($)	2,018,100
Total Cost of Abatement ($)	5,461,443
Cost of Abatement per Unit SOx ($/Ton)	164

Technique E_2

Substitute light fuel oil averaging 0.25% sulfur for light fuel oil averaging 0.7% sulfur.

Results are summarized in Table 6-22.

TABLE 6-22

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE E_2)

Total Reduction of Emission (Tons)	19,739
Total Cost of Abatement ($)	6,854,791
Cost of Abatement per Unit SOx ($/Ton)	347

Note: From Table C-2, Appendix C, the price differential between light fuel oil containing 0.25% sulfur and light fuel oil containing 0.7% sulfur is 1.3¢/Gallon or 8¢/MBTU.

Technique F_2

Substitute heavy fuel oil averaging 1.0% sulfur for heavy fuel oil averaging 2.5% sulfur.

Results are summarized in Table 6-23.

TABLE 6-23

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE F_2)

Total Reduction of Emissions (Tons)	156,363
Total Cost of Abatement ($)	28,178,494
Cost of Abatement per Unit SOx ($/Ton)	180

Note: From Table C-2, Appendix C, the price differential between heavy fuel oil averaging 2.5% sulfur and heavy fuel oil averaging 1.0% sulfur is 2.7¢/Gallon or 15¢/MBTU.

Technique G_2

Substitute heavy fuel oil averaging 0.25% sulfur for heavy fuel oil averaging 2.5% sulfur.

Results are summarized in Table 6-24.

TABLE 6-24

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE G_2)

Total Reduction of Emissions (Tons)	234,544
Total Cost of Abatement ($)	50,721,290
Cost of Abatement per Unit SOx ($/Ton)	216

Note: From Table C-2, Appendix C, the price differential between heavy fuel oil averaging 0.25% sulfur and heavy fuel oil averaging 2.5% sulfur is 4.8¢/Gallon or 27¢/MBTU.

Technique H_2

Switch from the combustion of heavy fuel oil to that of natural gas.[1]

Results are summarized in Table 6-25.

TABLE 6-25

COST OF ABATEMENT - (SOURCE 2, TECHNIQUE H_2)

Total Reduction of Emissions (Tons)	260,605
Heavy Fuel Oil Required per Boiler (Gallons)	28,390
Natural Gas Required per Boiler (Mcf.)	5,100
Total Heavy Fuel Oil Required (Gallons)	1,045,745,650
Total Natural Gas Required (Mcf.)	187,858,500
Total Cost of Heavy Fuel Oil ($)	79,476,670
Total Cost of Natural Gas ($)	133,379,535
Excess Cost of Natural Gas Over Oil ($)	53,902,865
Cost of Conversion per Boiler ($)	850
Total Cost of Conversion ($)	31,309,750
Total Cost of Abatement ($)	85,212,615
Cost of Abatement per Unit SOx ($/Ton)	327

Note: From Table B-4, Appendix B, the commercial price of heavy fuel oil and of natural gas is 7.6¢/Gallon and $0.71/Mcf. respectively.

1 The technique of switching from light fuel oil to natural gas was not considered because the cost of abatement per ton of SOx was negative ($-369/Ton). Hence, the incentive to switch already exists. Since it did not take place, there must be factors (such as the unavailability of natural gas), which prevent the switch. Hence, this technique was not considered viable.

3. CONTROL OF EMISSIONS FROM INDUSTRIAL FUEL COMBUSTION (SOURCE 3)

(A) Industrial Fuel Combustion, Emissions, and Equipment

Estimates of emissions from the industrial combustion of fuels in Canada, in 1969, are summarized in Table 6-26. Here we will be concerned only with the abatement of emissions from the industrial combustion of coal, light fuel oil, and heavy fuel oil which takes place in boilers. (The rest of emissions and their control are examined in connection with individual industrial processes.). Using the data shown in the second row of Table 6-14, the consumption of these fuels in industrial boilers and the associated emissions of sulfur oxides are calculated. These are summarized in Table 6-27.

As in the case of commercial boilers, there is no inventory of the quantity and distribution by fuel of industrial boilers in Canada. Therefore, as before, based on U.S. data, an attempt is made to estimate the fuel consumption of a typical industrial boiler and, given the total quantities of fuels consumed in industrial boilers, to estimate their number and distribution by fuel.

It was found that, in the United States, in 1967, there were 307,000 industrial boilers.[1] These consumed a total of 72.9 million tons of coal, 17.97 million barrels of light fuel

1 Le Sourd *et al.*, *Comprehensive Study...*, p. IV-11.

oil, 170 million barrels of heavy fuel oil, and 1.98 trillion cubic feet of natural gas; in terms of energy, they consumed about 5×10^9 MBTU.[1] This works out to about 16,300 MBTU per boiler.

Fuel is burned in industrial boilers both for the purposes of space heating and to produce steam necessary to the industrial process. Since there is no estimate of the proportion of fuel used in industrial plants for these two purposes, it is assumed that the fuel required for space heating by the average industrial outfit is the same as for a commercial one. That is, it is assumed that 5,100 MBTU are required in Canada to provide space heating in the average industrial plant in Canada as compared with 3,400 MBTU in the U.S. Therefore, in order to adjust for the greater consumption of fuel for this purpose in Canada by the average outfit, it is estimated that the average industrial boiler in Canada consumes 18,000 MBTU per year.[2] Given this figure, the total consumption of each fuel by industrial boilers, and associated emissions of sulfur oxides (as shown in Table 6-27), it is possible to estimate the number and distribution by fuel of boilers, the average quantity of each fuel consumed per boiler, and the average emissions per boiler. This data is summarized in Table 6-28.

---

1 Ehrenfeld _et al._, _Systematic Study..._, p. 118.

2 That is, 16,300 + (5,100 - 3,400) = 18,000.

TABLE 6-26

INDUSTRIAL FUEL CONSUMPTION AND ESTIMATES OF ASSOCIATED EMISSIONS OF SULFUR OXIDES - CANADA, 1969

FUEL	QUANTITY (NATURAL UNITS)	QUANTITY (MILLION BTU)	SO_2 (TONS)	SO_3 (TONS)	SO_x (TONS)
Coal (a)	4,588,986 Tons	113,457,157	261,630	-	261,630
Coke (b)	4,608,316 "	112,504,213	-	-	-
Coke Oven Gas	73,365,183 Mcf.	36,682,591	-	-	-
Liquified Petroleum Gas	1,710,409 Barrels	7,004,124	-	-	-
Kerosene (c)	2,899,232 "	16,458,941	2,500	65	2,565
Still Gas	1,726 "	10,852	-	-	-
Diesel Fuel Oil (d)	10,411,531 "	60,673,197	18,600	-	18,600
Light Fuel Oil (e)	8,269,017 "	48,187,696	16,875	430	17,305
Heavy Fuel Oil (f)	39,423,907 "	247,873,673	335,000	8,375	343,375
Natural Gas.	368,575,616 Mcf.	368,575,616	-	-	-
Electricity	94,435,253,000 Kwh.	322,213,085	-	-	-
Total		1,333,641,145	634,605	8,870	643,475

Notes: (a) The same assumptions as Note (a), Table 6-13, are made.

(b) Coke is produced by the destructive (i.e. low oxygen) distillation of coal and is used in metallurgical operations. Therefore, emissions from its use will be included under emissions from industrial processes and are not estimated here.

(c) The same assumptions as in Note (c), Table 6-2, are made.

(d) The same assumptions as in Note (d), Table 6-2, are made.

(e) The same assumptions as in Note (e), Table 6-2, are made.

(f) The same assumptions as in Note (f), Table 6-2, are made.

Source: Statistics Canada, Detailed Energy Demand and Supply in Canada, pp. 138-139, 284-285.

TABLE 6-27

INDUSTRIAL FUEL CONSUMPTION IN BOILERS AND ASSOCIATED EMISSIONS OF SULFUR OXIDES - CANADA, 1969

FUEL	QUANTITY (NATURAL UNITS)	QUANTITY (MILLION BTU)	SO_2 (TONS)	SO_3 (TONS)	SO_x (TONS)
Coal	3,533,519 Tons	87,362,010	201,455	-	201,455
Light Fuel Oil	5,788,312 Barrels	33,731,387	11,812	301	12,113
Heavy Fuel Oil	27,596,735 Barrels	173,511,571	234,500	5,862	240,362
Natural Gas	110,572,685 Mcf.	110,572,685	-	6,163	-
Total		405,177,653	447,767	6,163	453,930

TABLE 6-28

NUMBER OF INDUSTRIAL BOILERS BY FUEL AND EMISSIONS OF SULFUR OXIDES PER BOILER - CANADA, 1969

FUEL	NUMBER OF BOILERS	ANNUAL CONSUMPTION OF FUEL PER BOILER	ANNUAL EMISSIONS PER BOILER
Coal	4,853	728 Tons	41.5 Tons
Light Fuel Oil	1,874	108,106 Gallons	6.5 Tons
Heavy Fuel Oil	9,640	100,116 Gallons	25.0 Tons
Natural Gas	6,143	18,000 Mcf.	-

Note: Statistics Canada reports that there were an average of 12,352 industrial customers for natural gas in 1969. See, Statistics Canada, Gas Utilities, 1969, (Ottawa: Information Canada, April, 1973), p. 13. But this included sales of natural gas for all purposes. As shown in Table 6-14 above, only an estimated 30% of natural gas is burned in boilers.

(B) Techniques and Costs of Abatement

Technique A_3

Substitute coal averaging 1% sulfur for coal averaging 3% sulfur.

Results are summarized in Table 6-29.

TABLE 6-29

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE A_3)

Total Reduction of Emissions (Tons)	134,303
Total Cost of Abatement ($)	3,180,167
Cost of Abatement per Unit SOx ($/Ton)	24

Note: From Table C-2, Appendix C, the price differential between coal averaging 1% sulfur and coal averaging 3% sulfur is 90¢/Ton.

Technique B_3

Switch from the combustion of coal in industrial boilers to that of heavy fuel oil.

Results are summarized in Table 6-30.

TABLE 6-30

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE B_3)

Total Reduction of Emissions (Tons)	80,075
Coal Required per Boiler (Tons)	728
Heavy Fuel Oil Required per Boiler (Gallons)	100,116
Total Coal Required (Tons)	3,533,519
Total Heavy Fuel Oil Required (Gallons)	485,862,948
Total Cost of Coal ($)	42,402,228
Total Cost of Heavy Fuel Oil ($)	36,925,584
Excess Cost of Heavy Fuel Oil Over Coal ($)	-5,476,644
Annual Cost of Conversion per Boiler ($)	4,000
Total Cost of Conversion ($)	19,412,000
Total Cost of Abatement ($)	13,935,356
Cost of Abatement per Unit SOx ($/Ton)	174

Note: From Table B-4, Appendix B, the industrial price of coal and heavy fuel oil is $12/Ton and 7.6¢/Gallon respectively.

Technique C_3

Switch from the combustion of coal in industrial boilers to that of light fuel oil.

Results are summarized in Table 6-31.

TABLE 6-31

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE C_3)

Total Reduction of Emissions (Tons)	169,855
Coal Required per Boiler (Tons)	728
Light Fuel Oil Required per Boiler (Gallons)	108,106
Total Coal Required (Tons)	3,533,519
Total Light Fuel Oil Required (Gallons)	524,638,418
Total Cost of Coal ($)	42,402,228
Total Cost of Light Fuel Oil ($)	88,139,254
Excess Cost of Light Fuel Oil Over Coal ($)	45,737,026
Annual Cost of Conversion per Boiler ($)	4,000
Total Cost of Conversion ($)	19,412,000
Total Cost of Abatement ($)	65,149,026
Cost of Abatement per Unit SOx ($/Ton)	384

Note: From Table B-4, Appendix B, the industrial price of coal and light fuel oil is $12/Ton and 16.8¢/Gallon respectively.

Technique D3

Switch from the combustion of coal in industrial boilers to that of Substitute Natural Gas (SNG).

Results are summarized in Table 6-32.

TABLE 6-32

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE D3)

Total Reduction of Emissions (Tons)	201,455
Coal Required per Boiler (Tons)	728
SNG Required per Boiler (MBTU)	18,000
Total Coal Required (Tons)	3,533,519
Total SNG Required (MBTU)	87,354,000
Total Cost of Coal ($)	42,402,228
Total Cost of SNG ($)	96,089,400
Excess Cost of SNG Over Coal ($)	53,687,172
Annual Cost of Conversion per Boiler ($)	3,400
Total Cost of Conversion ($)	16,500,200
Total Cost of Abatement ($)	70,187,372
Cost of Abatement per Unit SOx ($/Ton)	348

Note: From Table B-4, Appendix B, the price of industrial coal and of SNG are $12/Ton and $1.10/MBTU respectively.

Technique E_3

Substitute light fuel oil averaging 0.25% sulfur for light fuel oil averaging 0.7% sulfur.

Results are summarized in Table 6-33.

TABLE 6-33

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE E_3)

Total Reduction of Emissions (Tons)	7,787
Total Cost of Abatement ($)	2,698,510
Cost of Abatement per Unit SOx ($/Ton)	347

Note: From Table C-2, Appendix C, the price differential between light fuel oil averaging 0.25% sulfur and 0.7% sulfur is 1.3¢/Gallon or 8¢/MBTU.

Technique F_3

Switch from the combustion of light fuel oil in industrial boilers to that of Substitute Natural Gas (SNG).

Results are summarized in Table 6-34.

TABLE 6-34

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE F_3)

Total Reduction of Emissions (Tons)	12,113
Light Fuel Oil Required per Boiler (Gallons)	108,106
SNG Required per Boiler (MBTU)	18,000
Total Light Fuel Oil Required (Gallons)	202,590,644
Total SNG Required (MBTU)	33,732,000
Total Cost of Light Fuel Oil ($)	34,035,228
Total Cost of SNG ($)	37,105,200
Excess Cost of SNG Over Light Fuel Oil ($)	3,069,972
Annual Cost of Conversion per Boiler ($)	1,200
Total Cost of Conversion ($)	2,248,800
Total Cost of Abatement ($)	5,318,772
Cost of Abatement per Unit SOx ($/Ton)	439

Note: From Table B-4, Appendix B, the industrial price of light fuel oil and of SNG are 16.8¢/Gallon and $1.10/MBTU respectively. The cost of conversion for boiler from light fuel oil to gas is assumed to be the same as that of converting a boiler from heavy fuel oil to gas.

Technique G_3

Substitute heavy fuel oil averaging 1.0% sulfur for heavy fuel oil averaging 2.5% sulfur.

Results are summarized in Table 6-35.

TABLE 6-35

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE G_3)

Total Reduction of Emissions (Tons)	144,217
Total Cost of Abatement ($)	20,026,736
Cost of Abatement per Unit SOx ($/Ton)	180

Note: From Table C-2, Appendix C, the price differential between the price of heavy fuel oil averaging 1.0% and heavy fuel oil averaging 2.5% is 2.7¢/Gallon or 15¢/MBTU.

Technique H_3

Substitute heavy fuel oil averaging 0.25% sulfur for heavy fuel oil averaging 2.5% sulfur.

Results are summarized in Table 6-36.

TABLE 6-36

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE H_3)

Total Reduction of Emissions (Tons)	216,326
Total Cost of Abatement ($)	46,848,314
Cost of Abatement per Unit SOx ($/Ton)	216

Note: From Table C-2, Appendix C, the price differential between heavy fuel oil averaging 0.25% sulfur and heavy fuel oil averaging 2.5% sulfur is 4.8¢/Gallon or 27¢/MBTU.

Technique I_3

Switch from the combustion of heavy fuel oil in industrial boilers to that of Substitute Natural Gas (SNG).

Results are summarized in Table 6-37.

TABLE 6-37

COST OF ABATEMENT - (SOURCE 3, TECHNIQUE I_3)

Total Reduction of Emissions (Tons)	240,362
Heavy Fuel Oil Required per Boiler (Gallons)	100,116
SNG Required per Boiler (MBTU)	18,000
Total Heavy Fuel Oil Required (Gallons)	965,118,240
Total SNG Required (MBTU)	173,520,000
Total Cost of Heavy Fuel Oil ($)	73,348,986
Total Cost of SNG ($)	190,872,000
Excess Cost of SNG Over Oil ($)	117,523,014
Annual Cost of Conversion per Boiler ($)	1,200
Total Cost of Conversion ($)	11,568,000
Total Cost of Abatement ($)	129,091,014
Cost of Abatement per Unit SOx ($/Ton)	537

Note: From Table B-4, Appendix B, the price of industrial heavy fuel oil and SNG is 7.6¢/Gallon and $1.10/MBTU respectively.

4. CONTROL OF EMISSIONS FROM THERMAL POWER PLANTS (UTILITIES) (SOURCE 4)

(A) Utilities Fuel Combustion, Emissions, and Equipment

Estimated emissions from fuel combustion by electricity-generating utilities in Canada, in 1969, are summarized in Table 6-38. It is assumed that all of the coal and heavy fuel oil is burned in boilers in thermal power plants.[1] Here we will be concerned with the control of emissions of sulfur oxides from the combustion of these two fuels only. This accounts for about 99% of emissions of sulfur oxides by utilities.

Since the author was unable to obtain information about the number and distribution by fuel of boilers in power plants, it was necessary to estimate these by the same method used to estimate the number of commercial and industrial boilers, that is, based on U.S. data.

In the U.S., in 1967, there were 2984 power plant steam boilers.[2] These consumed about 273 million tons of coal, 150 million barrels of heavy fuel oil, and 2.65 trillion cubic feet of gas. Their estimated energy consumption was 10,668 x 10^6 MBTU.[3]

---

1 Given the small quantities involved, crude oil and light fuel oil are disregarded. In all probability, most of the gas was also burned in boilers in thermal power plants. It is assumed that all of it is. It is assumed that liquified petroleum gas, diesel fuel oil, and aviation turbo-fuel is burned in either internal combustion or gas turbine power plants. These two types accounted for 3.3% of installed generator capacity in Canada in 1969. See, Dominion Bureau of Statistics, Electric Power Statistics, Vol. III, (Ottawa: Information Canada, March, 1971), p. 12.

2 Le Sourd et al., Comprehensive Study..., p. IV-14.

3 Ehrenfeld et al., Systematic Study..., p. 118.

This works out to an average 3.6×10^6 MBTU per boiler. Assuming that the energy input of the average boiler is the same in Canada and, given the energy consumption of Canadian steam power plants in Canada in 1969, the number and distribution by fuel of power plant boilers are estimated. Also, given the total quantities of each fuel consumed and of associated emissions (as shown in Table 6-38), the fuel consumption and emissions per boiler are estimated.[1] This data is summarized in Table 6-39.

---

1 Note that the estimate of emissions of SOx from power plants shown in Table 6-38 exceeds considerably the estimate of emissions from this source in 1970 provided by Environment Canada, as shown in Table 4-2, Chapter IV. The following are possible explanations of the discrepancy:

(1) The estimate of emissions in the Environment Canada study take account of the abatement systems already in place, whereas the estimate here is of emissions which would have occurred with no controls.

(2) The estimate of emissions in the Environment Canada study is based on answer by major utilities in Canada to a questionnaire sent to them by the consulting firm which undertook the study for Environment Canada. These answers provided information on such matters as fuel consumption, sulfur content of fuel used, existing control equipment, operating efficiency, and so on. (See, Environment Canada, A Nationwide Inventory of Air Pollutant Emissions, 1970, (Ottawa: Environment Canada, January, 1973), p. 85. It is not impossible that, in their answers, the utilities may have tended to underestimate the potential emissions and overestimate the degree of control.

TABLE 6-38

FUEL CONSUMPTION BY THERMAL POWER PLANTS (UTILITIES) AND ASSOCIATED EMISSIONS OF SULFUR OXIDES - CANADA, 1969

FUEL	QUANTITY (NATURAL UNITS)	QUANTITY (MBTU)	SO_2 (TONS)	SO_3 (TONS)	SO_x (TONS)
Coal (a)	11,873,750 Tons	266,657,028	662,970	13,530	676,500
Liquified Petroleum Gas	8,384 Barrels	32,130	-	-	-
Crude Oil	343,973 "	2,168,311	b	b	b
Diesel Fuel Oil (c)	963,406 "	5,549,659	1,718	-	1,718
Light Fuel Oil (d)	568,961 "	3,198,159	6,530	167	6,697
Heavy Fuel Oil (e)	10,166,673 "	63,921,940	86,290	2,156	88,446
Aviation Turbo Fuel	1,616 "	8,482	b	b	b
Natural Gas	58,853,928 Mcf.	63,865,881	-	-	-
Total		405,984,323	757,508	15,853	773,361

Notes: (a) The same assumptions as in Note (a), Table 6-13, are made.

(b) No emission factors could be obtained. Given the small quantities involved, emissions from this source are disregarded.

(c) The same assumptions as in Note (d), Table 6-2, are made.

(d) The same assumptions as in Note (e), Table 6-2, are made.

(e) The same assumptions as in Note (f), Table 6-2, are made.

Source: Statistics Canada, Detailed Energy Supply and Demand in Canada, pp. 138-139, 284-285.

TABLE 6-39

NUMBER OF POWER PLANT (UTILITIES) BOILERS
AND EMISSIONS OF SULFUR OXIDES PER BOILER
CANADA, 1969

FUEL	NUMBER OF BOILERS	ANNUAL FUEL CONSUMPTION PER BOILER	ANNUAL EMISSIONS OF SULFUR OXIDES PER BOILER
Coal	74	160,456 Tons	9,142 Tons
Heavy Fuel Oil	18	19,768,525 Gal.	4,911 Tons
Natural Gas	18	3,269,662 Mcf.	-
Total	110		

(B) Techniques and Costs of Abatement

Technique A4

Substitute coal averaging 1% sulfur for coal averaging 3% sulfur.

Results are summarized in Table 6-40.

TABLE 6-40

COST OF ABATEMENT - (SOURCE 4, TECHNIQUE A4)

Total Reduction of Emissions (Tons)	451,000
Total Cost of Abatement ($)	10,686,375
Cost of Abatement per Unit SOx ($/Ton)	24

Note: From Table C-2, Appendix C, the price differential between coal averaging 1% sulfur and coal averaging 3% sulfur is 90¢/Ton.

Technique B4

Switch from the combustion of coal in utilities' boilers to that of heavy fuel oil.

Results are summarized in Table 6-41.

TABLE 6-41

COST OF ABATEMENT - (SOURCE 4, TECHNIQUE B4)

Total Reduction of Emissions (Tons)	313,094
Coal Required per Boiler (Tons)	160,456
Heavy Fuel Oil Required per Boiler (Gallons)	19,768,525
Total Coal Required (Tons)	11,873,750
Total Heavy Fuel Oil Required (Gallons)	1,462,870,850
Total Cost of Coal ($)	75,992,000
Total Cost of Heavy Fuel Oil ($)	87,772,251
Excess Cost of Heavy Fuel Oil Over Coal ($)	11,780,251
Annual Cost of Conversion per Boiler ($)	10,500
Total Cost of Conversion ($)	777,000
Total Cost of Abatement ($)	12,557,251
Cost of Abatement per Unit SOx ($/Ton)	40

Note: From Table B-4, Appendix B, the utilities price of coal and heavy fuel oil is $6.4/ton and 6¢/gallon respectively.

Technique C_4

Switch from the combustion of coal in utilities' boilers to that of Substitute Natural Gas (SNG).

Results are summarized in Table 6-42.

TABLE 6-42

COST OF ABATEMENT - (SOURCE 4, TECHNIQUE C_4)

Total Reduction of Emissions (Tons)	676,500
Coal Required per Boiler (Tons)	160,456
SNG Required per Boiler (MBTU)	3,600,000
Total Coal Required (Tons)	11,873,750
Total SNG Required (MBTU)	266,400,000
Total Cost of Coal ($)	75,992,000
Total Cost of SNG ($)	239,760,000
Excess Cost of SNG Over Coal ($)	163,768,000
Annual Cost of Conversion per Boiler ($)	4,000
Total Cost of Conversion ($)	296,000
Total Cost of Abatement ($)	164,064,000
Cost of Abatement per Unit SOx ($/Ton)	242

Note: From Table B-4, Appendix B, the utilities of coal and SNG is $6.4/Ton and $0.90/MBTU respectively.

Technique D4

Substitute heavy fuel oil averaging 1% sulfur for heavy fuel oil averaging 2.5% sulfur.

Results are summarized in Table 6-43.

TABLE 6-43

COST OF ABATEMENT - (SOURCE 4, TECHNIQUE D4)

Total Reduction of Emissions (Tons)	53,068
Total Cost of Abatement ($)	9,588,291
Cost of Abatement per Unit SOx ($/Ton)	180

Note: From Table C-2, Appendix C, the price differential between heavy fuel oil averaging 1% sulfur and heavy fuel oil averaging 2.5% sulfur is 2.7¢/Gallon or 15¢/MBTU.

Technique E_4

Substitute heavy fuel oil averaging 0.25% sulfur for heavy fuel oil averaging 2.5% sulfur.

Results are summarized in Table 6-44.

TABLE 6-44

COST OF ABATEMENT - (SOURCE 4, TECHNIQUE E_4)

Total Reduction of Emissions (Tons)	79,601
Total Cost of Abatement ($)	17,258,924
Cost of Abatement per Unit Sox ($/Ton)	216

Note: From Table C-2, Appendix C, the price differential between heavy fuel oil averaging 0.25% and heavy fuel oil averaging 2.5% is 4.8¢/Gallon or 27¢/MBTU.

Technique F_4

Switch from the combustion of heavy fuel oil in utilities' boilers to that of Substitute Natural Gas (SNG).

Results are summarized in Table 6-45.

TABLE 6-45

COST OF ABATEMENT - (SOURCE 4, TECHNIQUE F_4)

Total Reduction of Emissions (Tons)	88,446
Heavy Fuel Oil Required per Boiler (Gallons)	19,768,525
SNG Required per Boiler (MBTU)	3,551,220
Total Heavy Fuel Oil Required (Gallons)	355,833,450
Total SNG Required (MBTU)	63,921,940
Total Cost of Heavy Fuel Oil ($)	21,350,000
Total Cost of SNG ($)	57,529,746
Excess Cost of SNG Over Oil ($)	36,179,746
Annual Cost of Conversion per Boiler ($)	1,800
Total Cost of Conversion ($)	32,400
Total Cost of Abatement ($)	36,212,146
Cost of Abatement per Unit SOx ($/Ton)	410

Note: From Table B-4, Appendix B, the price of heavy fuel oil and of SNG to utilities is 6.0¢/Gallon and $0.90/MBTU respectively.

Technique G_4

Install systems which remove SOx from power plant (100 MW and over) stack gases.

Results are summarized in Table 6-46.

TABLE 6-46

COST OF ABATEMENT - (SOURCE 4, TECHNIQUE G_4)

Total Reduction of Emissions (Tons)	390,122
Total Cost of Abatement ($)	17,165,368
Cost of Abatement per Unit SOx ($/Ton)	44

Note: The assumptions underlying these calculations are spelled out in Appendix E.

INDUSTRIAL PROCESSES

The year 1970 was chosen as a base in attempting to estimate the costs of controlling sulfur oxides emissions from industrial processes. The reason is that there exists a survey of emissions for that year.[1] A summary of emissions of sulfur oxides from industrial processes, taken from that survey has already been presented (see Table 4-3, Chapter IV). Here, an attempt will be made to estimate emissions independently using different procedures. It should not be surprising if these should turn out to be different (generally higher) than those in the existing survey; for the survey estimates emissions with given existing levels of control. The procedure used here is to estimate emissions which would occur with <u>no</u> controls.[2] In spite of this expected difference, it is preferable to use the same base year, in order to have a sort of check for the estimates produced here.

The procedure of estimating emissions with no controls and then attempting to estimate the costs of control is not inconsistent with the emission tax scheme, since emitters would be rebated the tax paid for sulfur oxides recovered. This means, however, that the costs of controlling given amounts of sulfur oxides include the costs of the control already undertaken.

---

1 <u>A Nationwide Inventory of Air Pollutant Emissions, 1970</u>, (Ottawa: Environment Canada, January, 1973).

2 The exception is the natural gas processing industry where a relatively high level of control is necessary as part of the production process.

For each industrial process examined, a brief introduction will review data and processes pertinent to emissions in order to put their control in proper perspective.

In the case of most industries considered here (more precisely, sources 5 to 11), the procedure used to estimate the cost of abatement is that of the Model Plant. This procedure is used in a study undertaken for the U.S. Department of Health, Education, and Welfare.[1] It consists of estimating the cost of abatement of a plant of average capacity and characteristics. This cost is then multiplied by the ratio of the total industry capacity to the capacity of the model plant. This technique is valid if the industry plant size distribution is symmetrical about the mean or if the cost of abatement is a linear function of the size of the plant. No attempt was made here to verify whether these conditions are always satisfied in the industries considered.

---

1 National Emissions Standards Study, Report Appendix, (Washington: U.S. Department of Health, Education, and Welfare, March, 1970), 3 Vols.

5. CONTROL OF EMISSIONS FROM PRIMARY ALUMINUM SMELTING (SOURCE 5)

Aluminum is produced by a three-stage process. First, bauxite ore is mined, purified, dried, and milled. Second, pure alumina is produced from bauxite by the Bayer process. Since it takes about 2 tons of bauxite to produce one ton of alumina, there is a tendency to produce alumina in plants situated near bauxite mines. Third, alumina is reduced to metallic aluminum by the Hall-Herault process, which consists of dissolving the alumina in electrolytic cells charged with molten cryolite and other fluoride salts, and recovering it as metal. This reduction from alumina to aluminum requires large amounts of electricity and, hence, smelting plants are usually located near power plants. This last stage accounts for about 2/3 of the cost per ton of producing primary aluminum.[1]

Bauxite, though found in North America, is found in deposits which do not warrant its mining. Canada imports both alumina and bauxite. In 1970, total Canadian production of primary aluminum was 1,071,718 tons (about 12% of the world total).[2]

---

1 Charles River Associates Inc., "Aluminum" in Environmental Protection Agency, The Economic Impact of Pollution. A Summary of Recent Studies, (Washington: U.S. Government Printing Office, March, 1972), p. 171. Bauxite is estimated to represent only 5 to 10 percent of the cost of aluminum.

2 Canadian Minerals Yearbook, 1970, (Ottawa: Department of Energy, Mines, and Resources, 1972), p. 94.

Air pollution from aluminum smelters consists of hydrogen fluoride and sulfur dioxide gases and of particulates (containing about 20% fluorine).[1]

The characteristics of the model plant are summarized in Table 6-47. The available estimate of costs of abatement deals with techniques for the simultaneous abatement of all three major pollutants from this source. Therefore, they will be dealt simultaneously here and costs of abatement will be expressed in terms of dollars per ton of pollutant. The control system, the expected pollutant reduction efficiencies, and the cost of control are also shown in Table 6-47.

The Canadian production and capacity consisted in 1970 of eleven model plants.[2] Therefore, estimated emissions (with no control) are 60,676 tons of pollutants.

Given this, Table 6-48 summarizes the results of implementing the control system.

---

1 National Emissions Standards Study, p. E38.

2 There were six aluminum smelters in Canada in 1970. Table F-1, Appendix F, lists their location, ownership, and capacity.

TABLE 6-47

MODEL PLANT CHARACTERISTICS AND COST OF ABATEMENT
PRIMARY ALUMINUM SMELTING

Annual Output (Tons)	100,000
Production Rate (Tons/Day)	274
Annual Hours of Operation	8,750
Annual Emissions with No Control (Tons)	
Hydrogen Sulfide	1,046
Particulates	2,960
Sulfur Dioxide	1,510
Total:	5,516
Gas Volumes (Scfm.)	
Prebaked Electrolytic Cell	822,000
Potroom	2,000,000
Anode Plant Furnace	25,000
Emissions Control System	
8 Multicyclones (Scfm., each)	103,000
1 Electrostatic Precipitator (Scfm.)	822,000
8 Three-stage Floating Bed Cell Scrubbers (Scfm., each)	103,000
2 Scrubbers (Scfm., each)	1,000,000
1 Two-stage Floating Bed Cell Scrubber	
Reduction of Emissions Efficiency	
Hydrogen fluoride	99%
Particulates.	98%
Sulfur Dioxide	97%
Total Annual Cost of Abatement	
Low ($)	1,032,000
High ($)	1,626,000

Source: National Emission Standards Study, pp. E38-E40.

TABLE 6-48

COST OF ABATEMENT - (SOURCE 5)

Total Reduction of Emissions (Tons)		58,000
Total Cost of Abatement ($)	Low	11,352,000
	High	17,886,000
Cost of Abatement per Unit ($/Ton)	Low	192
	High	303

Note: Estimate from figures given in A National Standards Study, p. E40.

6. CONTROL OF EMISSIONS FROM PRIMARY COPPER AND NICKEL SMELTING (SOURCE 6)

Copper and nickel are produced basically in the same manner and, frequently, in the same smelters. Therefore, their production will be considered as a single source of emissions of sulfur oxides.

Copper and nickel are produced from low-grade sulfide ores. These are concentrated by gravity and flotation and then are roasted in multiple hearth furnaces prior to being charged in the smelter. The charge is then converted to primary metal and refined.

In 1970, Canadian production of primary copper was 673,747 tons, or about 10 percent of the world total; production of primary nickel was 308,042 tons, or about 45 percent of the world total.[1]

Air pollution from copper-nickel smelters consists mainly of emissions of sulfur oxides. About 80 percent of potential emissions of particulates are already recovered.[2] According to Table 4-3, Chapter IV, the primary copper-nickel industry was the source of 4,421,000 tons of sulfur oxides emissions in 1970. As discussed below, it is probable that this estimate is high. But, even if the lower estimate made below were the accurate one, this industry is still the largest single source of sulfur oxides emissions in Canada.

---

1 Canadian Minerals Yearbook, 1970, p. 200. This yielded a combined production of the two metals of 981,789 tons.

2 A Nationwide Emissions Inventory, p. 47.

A number of processes are capable of reducing emissions of sulfur oxides from smelters. Though at least one process that reduces the gases to elemental sulfur has recently been put into operation,[1] the most common and most widely tested technologically are processes which yield sulfuric acid as a byproduct.[2]

The characteristics of the model plant are summarized in Table 6-49. Given the Canadian production of copper and nickel, the Canadian capacity is equivalent to about thirteen model plants (assuming plant utilization not to be too far from 100 percent).[3] Therefore, emissions of SOx from copper-nickel smelters are estimated to be 3,003,000 tons in 1970. This contrasts with the estimate of 4,421,000 tons given in Table 4-3, Chapter IV. As mentioned, it is quite possible that this estimate is high. W.A. Gow, for example, using different assumptions, (i.e., estimating emissions by making assumptions about the sulfur content of ores processed), has estimated that, based on the 1968-69 production, annual emissions of sulfur oxides from all smelters (i.e., including iron, lead, and zinc, besides copper and nickel) would be 1,424,000 tons of sulfur or

---

1 W.D. Hunter and J.P. Wright, "SO_2 Converted to Sulfur in Stackgas Cleanup Route," Chemical Engineering, LXXIX, (October 2, 1972), pp. 50-51.

2 Arthur G. McGee & Co., Systems Study for Control of Emissions, Primary Non-Ferrous Smelting Industry, 3 Vols., (San Francisco, Calif.: Arthur G. McGee & Co., May, 1969).

3 As shown in Table F-2, Appendix F, there were seven smelters in Canada in 1970. They operated at about 99% of rated capacity. See, Canadian Minerals Yearbook, p. 199.

about 3,000,000 tons of sulfur oxides (with no control).[1] Because this estimate is based on the lower 1968-69 production and because it accounts only for the sulfur contained in ores (and not, for example, for that contained in the fuel used to treat the ore), it may be low.[2] Since the estimate produced here is somewhere in between the other two, it is quite probable that it is reasonably accurate.

The abatement system consists of combining the gases from the roaster and converters and conveying them to a contact sulfuric acid plant. The gases from the reverberatory furnace would be vented to a limestone slurry to scrub out the sulfur oxides.[3] An overall efficiency of 91.3% is assumed for this control system.[4] This means that sulfur oxides would be reduced from 231,000 tons to 19,173 tons per year per model plant. The results of applying this technique are summarized in Table 6-50.

---

1 W.A. Gow, "Estimates of Sulfur Present in Sulfide Concentrates Treated by Canadian Smelters," (Mimeographed, January 15, 1970).

2 The combined production of copper and nickel was 195,000 tons higher in 1970 than in 1969.

3 <u>National Emission Standard Study</u>, pp. E41-E42.

4 <u>Ibid</u>., p. E42.

TABLE 6-49

MODEL PLANT CHARACTERISTICS -
PRIMARY COPPER AND NICKEL SMELTING

Annual Output (Tons)	75,900
Production Rate (Tons/Day)	230
Number of Roasters	1
Number of Reverberatory Furnaces	1
Number of Converters	2
Annual Emissions of Sulfur Oxides (Tons)	
Roaster	121,400
Reverberatory Furnace	16,200
Converters	93,400
Total:	231,000
SOx in Offgas After Air Dilution	
Roaster (Temp. = 550°F)	8.0% Vol.
Reverberatory Furnace (Temp. = 550°F)	0.9% Vol.
Converter (Temp. = 640°F)	3.8% Vol.

Source: National Emission Standards Study, p. E-41.

TABLE 6-50

COST OF ABATEMENT - (SOURCE 6)

Total Reduction of Emissions (Tons)	2,753,751
Total Cost of Abatement ($)	
Low	0
High	41,847,000
Cost of Abatement per Unit SOx ($/Ton)	
Low	0
High	15

Note: Estimated from figures given in National Emission Standards Study, p. E42. The difference between the low and high cost is due to the sale of sulfuric acid. If the acid can be sold profitably, its value covers the annual cost of abatement. The ultimate cost to the individual smelter, then, depends on the local market for sulfuric acid.

7. CONTROL OF EMISSIONS FROM PRIMARY LEAD SMELTING (SOURCE 7)

Primary lead is produced from the reduction of ores which vary considerably in lead content. The most important ore is galena, a sulfide of lead. Lead ore concentrate is obtained by selective flotation of ore which contains both lead and zinc. The lead ore concentrate is converted to lead oxide prior to its reduction to metal, a process called sintering. It is in the process of sintering that most emissions of sulfur oxides occur. Subsequently, a mixture of sinter, iron, coke, and fluxes is charged into a blast furnace. Air circulated through the charge burns the coke to carbon monoxide and carbon dioxide; these gases reduce the lead oxide to molten lead metal which is recovered and, subsequently, refined to recover such important byproducts as silver, bismuth , and antimony.

In 1970, Canadian primary lead production was 383,208 tons.[1] The smelting process occurred in two smelters. The first owned by Cominco Ltd., is located at Trail, B.C., and has an annual capacity of 670,000 tons of charge. The second, owned by the East Coast Smelting and Chemical Co., is located at Belledune, N.B., and has an annual capacity of 180,000 tons.[2]

Air pollution from the smelting of lead consists mostly of emissions of sulfur oxides. About 95% of potential emissions of particulates are already recovered.[3] Dust collectors are

---

1 Canadian Minerals Yearbook, 1970, p. 292.

2 Statistics Canada, Smelting and Refining, 1971, (Ottawa: Information Canada, June, 1973), p. 13.

3 A Nationwide Inventory of Emissions, p. 50.

used for this task whose primary purpose is to collect valuable byproducts, such as precious metals, contained in the dust. This explains the high percentage of particulates recovery undertaken.

Table 6-51 summarizes the characteristics of the model plant. The Canadian capacity is equivalent to four model plants. Therefore, estimates of sulfur oxides emissions from this source (with no controls) are 184,000 tons per year.

The sulfur oxides control system consists of conveying the gases which have already passed through the aforementioned dust collectors to a contact sulfuric acid plant.[1] The efficiency of this control system would be about 93 percent. Table 6-52 summarizes the results of applying this abatement technique.

---

1 National Emission Standards Study, p. E45.

TABLE 6-51

MODEL PLANT CHARACTERISTICS -
PRIMARY LEAD SMELTING

Annual Output (Tons)	94,400
Production Rate (Tons/Day)	286
Annual Hours of Operation	7,920
Annual Emissions of SOx with No Control	46,000
Offgas from Sintering After Air Dilution	
Temperature (^oF)	400
Sulfur Dioxide (Vol. %)	5.00
Sulfur Trioxide (Vol. %)	0.29
Oxygen (Vol. %)	12.00
Offgas from Furnace After Air Dilution	
Temperature (^oF)	700
Sulfur Dioxide (Vol. %)	0.06
Oxygen (Vol. %)	4.00

Source: National Emission Standards Study, pp. E44-E45.

TABLE 6-52

COST OF ABATEMENT - (SOURCE 7)

Total Reduction of Emissions (Tons)	171,120
Total Cost of Abatement ($)	
Low	0
High	3,085,600
Cost of Abatement per Unit SOx ($/Ton)	
Low	0
High	18

Note: The difference between the high and the low depends on the market for sulfuric acid.

8. CONTROL OF EMISSIONS FROM PRIMARY ZINC SMELTING (SOURCE 8)

Primary zinc is produced primarily from sulfide ores, the most important of which is sphalerite (ZnS). Frequently, these ores have to be separated from lead-containing ores by selective flotation methods. The ore is concentrated, roasted, and converted to zinc oxide prior to its reduction to metallic zinc. Another important source of zinc is the slag from lead smelting. The slag is heated in a mixture of air and pulverized coal; this process yields zinc oxide. A typical ore concentrate contains 60 percent zinc, 30 percent sulfur, and 5 to 10 percent iron. Roasting takes place in a variety of vessels: multiple hearth (Herreshoff) furnaces, fluid-bed roasters, flash roasters, and sintering furnaces. It is this step that generates most of the emissions of sulfur oxides. Metallic zinc is produced from the roasted charge by retort or electrolytic processes or by fractional distillation. In 1970, Canadian production of (refined) primary zinc was 466,351 tons.[1]

Air pollution from zinc smelting consists primarily of emissions of sulfur oxides. As in the case of lead smelting, about 95% of potential particulate emissions are recovered (primarily for the purpose of recovering valuable metals). Table 6-53 summarizes the characteristics of the model plant.

The sulfur oxides control system consists of conveying the sulfur oxides emissions from the roaster to a contact sulfuric acid plant.[2] Other offgases would be passed through

---

1 Canadian Minerals Yearbook, 1970, p. 580.

2 National Emission Standards Study, p. E-47.

fabric filters as usual and allowed into the atmosphere. This system would reduce emissions of SOx in the model plant from 60,600 tons per year to 4,242 tons per year; that is, it would have an efficiency of about 93 percent.[1]

The Canadian capacity consists of six model plants.[2] This yields estimated emissions of sulfur oxides (with no controls) of 312,700 tons.[3] Table 6-54 summarizes the results of implementing the control technique.

---

1 Ibid., p. E-48.

2 As shown in Table F-3, Appendix F, there were five primary zinc smelters in Canada in 1970. They operated at 86% of rated capacity. See, Canadian Minerals Yearbook, p. 579.

3 That is, 60,600 x 6 x 0.86 = 312,700.

TABLE 6-53

MODEL PLANT CHARACTERISTICS - ZINC SMELTING

Annual Output (Tons)	113,200
Production Rate (Tons/Day)	343
Annual Hours of Operation	7,920
Annual Emissions of SOx with No Controls	60,600
Process Equipment	
Roaster	1
Dryer	1
Sinter Machine	1
Coker	1
Retort	1
Offgas from Roaster After Air Dilution	
Temperature (^{o}F)	600
Sulfur Oxides (% Vol.)	7.2
Oxygen (% Vol.)	10.9
Offgas from Sintering After Air Dilution	
Temperature (^{o}F)	500
Sulfur Oxides (% Vol.)	.05
Oxygen (% Vol.)	18.0

Source: National Emission Standards Study, p. E47.

TABLE 6-54

COST OF ABATEMENT - (SOURCE 8)

Total Reduction of Emissions (Tons)	287,500
Total Cost of Abatement ($)	
Low	0
High	8,784,000
Cost of Abatement per Unit SOx ($/Ton)	
Low	0
High	30

Note: The difference between the high and the low costs depend on the state of the local market for sulfuric acid.

9. CONTROL OF EMISSIONS FROM PETROLEUM REFINING (SOURCE 9)

Petroleum refining is a technologically intricate process which is constantly undergoing change. As a result, each refinery is in some ways unique with respect to its size, equipment, operations, and so on. Nevertheless, the refining process can be classified into four basic steps: separation, conversion, treating, and blending. Separation is accomplished by distillation, a process which yields "fractions," such as gasoline, kerosene, fuel oil, etc.; the relative quantities of these fractions depend largely on the composition of the crude oil. Since these quantities may not correspond to the expected demand for each, portions of them are "converted" into others (eg. naptha to gasoline) by craking and reforming. This splits, unites, or rearranges the molecules so as to obtain the desired products. Next, the separated and converted products are treated to remove the small quantities of impurities they contain. This may be done by physical or chemical methods, the most common of which is hydrogenation. Finally, the refined base stocks are blended in innumerable combinations with each other or with additives in order to obtain products which meet given specifications.

Air pollution from petroleum refineries consists of emissions of hydrocarbons, sulfur oxides, nitrogen oxides, carbon monoxide, and malodorous materials.[1] Emissions of particulates are controlled to a high degree in order to recover valuable catalysts. Table 6-55 summarizes the characteristics of the model plant.

---

1 The sulfur in the crude first goes into the gas stream as hydrogen sulfide (H_2S), but this is usually burned to sulfur oxides.

TABLE 6-55

MODEL PLANT CHARACTERISTICS - PETROLEUM REFINING

Annual Crude Input (Barrels)	12,410,000
Crude Input Rate (Barrels/Day)	34,000
Process Gas Volume (acfm.)	10,000
Process Gas Temperature	Ambient
Annual Emissions of SOx with No Controls (Tons)	8,000
Annual Hours of Operation	8,400

Source: National Emissions Standards Study, pp. E56-E57.

It is possible in the case of refineries, to have control systems which reduce emissions of various pollutants selectively. It is possible, for example, to have a system to control only emissions of hydrocarbons, or of particulates, or of sulfur oxides.[1] We will be concerned here only with the last one. This control system consists of conveying the sulfur oxide gases to a recovery plant which converts the sulfur oxides to elemental sulfur.[2] This plant should produce 10 tons of sulfur per day. Overall efficiency of this control system is 90%. This should reduce emissions of sulfur oxides from the model plant, from 8,000 tons per year to 800 tons per year.

1 National Emission Standards Study, pp. E55-E60.

2 Ibid.

The Canadian capacity is equivalent to 40 model plants.[3] This yields an estimate of emissions (without controls) of 320,000 tons of sulfur oxides.

Table 6-56 summarizes the results of implementing this system of control.

TABLE 6-56

COST OF ABATEMENT (SOURCE 9)

Total Reduction of Emissions (Tons)	288,000
Total Cost of Abatement ($)	
Low	3,000,000
High	6,000,000
Cost of Abatement per Unit SOx ($/Ton)	
Low	11
High	22

1 As shown in Table F-4, Appendix F, there were 39 refineries in Canada in 1970. Their total capacity was 1,350,000 barrels per day. The amount of petroleum which these refineries did refine can be taken as the crude oil deliveries to them. This, in 1970, averaged 1,281,065 barrels per day, an indication that they operated at close to full capacity. See, Petroleum Refineries in Canada, January, 1971, (Ottawa: Department of Energy, Mines, and Resources, March, 1971).

10. CONTROL OF EMISSIONS FROM SULFURIC ACID MANUFACTURING (SOURCE 10)

Surfuric acid is one of the most widely used chemicals. It is produced mostly by the contact process. In this process, sulfur dioxide is catalyzed to sulfur trioxide. The latter is absorbed by weak sulfuric acid to form a stronger acid. The sulfur dioxide is either produced by burning elemental sulfur or pyrites, or is contained in the offgases of such processes as mineral smelting or petroleum refining. In 1970, production of (100%) sulfuric acid in Canada was 2,728,000 tons.[1]

Air pollution from sulfuric acid production consists of sulfur dioxide which escapes catalytic conversion and of acid mists emitted from the absorption tower. Acid plants operate with a single absorption step which results in a conversion of SO_2 to SO_3 of about 97%. Table 6-57 summarizes the model plant characteristics.

The Canadian sulfuric acid industry is equivalent to 20 model plants.[2] This yields an estimate of emissions (without controls) of 125,000 tons of sulfur oxides.

---

1 Statistics Canada, Manufacturers of Industrial Chemicals, 1970, (Ottawa: Information Canada, January, 1973), p. 12.

2 This number of model plants seems capable of producing more than the actual production of sulfuric acid. The number seems reasonable, however, given the fact that a plant of this capacity usually produces an average of 126,000 tons of H_2SO_4 per year. See, The Cost of Clean Air, First Report of the Secretary of Health, Education, and Welfare to the Congress of the United States, (Washington: U.S. Government Printing Office, 1969), p. 37. As shown in Table F-5, Appendix F, there were 23 plants which produced sulfuric acid in 1970 in Canada.

TABLE 6-57

MODEL PLANT CHARACTERISTICS - SULFURIC ACID

Annual Output (Tons)	180,000
Production Rate (Tons/Day)	663
Annual Hours of Operation	8,750
Gas Volume (acfm)	40,000
Gas Stream Temperature (^{o}F)	150
Emissions of SOx with No Controls (Tons/Yr.)	6,250
Total Annual Cost of Abatement ($)	
Low	76,400
High	161,000

Source: National Emission Standards Study, pp. E73-E74.

The control system consists of adding a further secondary absorption step.[1] The equipment involved consists of two heat exchangers, an absorption tower, demisters, pump, pump tank, and acid coolers. The primary absorption step, by removing some of the sulfur trioxide, would improve the oxygen to SO_2 ratio, thereby increasing the conversion from 97% to 99.5%. The secondary absorption is required to complete the recovery of

1 National Emissions Standards Study, p. E74. See also, The Economics of Clean Air, Annual Report of the Administrator of the Environmental Protection Agency, (Washington: U.S. Government Printing Office, March, 1972), pp. 4-158 to 4-169.

SO_3 as acid.[1] The addition would reduce emissions of sulfur oxides in the model plant from 6,250 tons to 590 tons per year. Table 6-58 summarizes the results of implementing this control system.

TABLE 6-58

COST OF ABATEMENT - (SOURCE 10)

Total Reduction of Emissions (Tons)	113,000
Total Cost of Abatement (4)	
Low	1,528,000
High	3,220,000
Cost of Abatement per Unit SOx ($/Ton)	
Low	13
High	27

1 The technological aspects are discussed in T.J. Browder, "Modern Sulfuric Acid Technology" in Sulfur and SO_2 Developments, (New York: American Institute of Chemical Engineers, 1971), pp. 91-96. See also, I. Shah, "Removing SO_2 and Acid Mist with Venturi Scrubbers," Ibid., pp. 97-102, and G.W. Tucker and J.R. Burleigh, "SO_2 Emission Control from Acid Plants," Ibid., pp. 103-109.

11. CONTROL OF EMISSIONS FROM METALLURGICAL COKE MANUFACTURING (SOURCE 11)

Coke is a solid produced by heating coal in the absence of air, a process called destructive distillation. Coke is the major fuel used in blast furnaces to produce iron and steel. There are two processes for producing coke: the Behive and the Byproduct processes. In the former no attempt is made to recuperate and use gases released during the distillation of coal; in the latter, it is. Virtually all coke is produced in Canada by the Byproduct process.[1] In 1970, coke production in Canada was 5.7 million tons.[2] This required the carbonization of 6.9 million tons of coal.[3]

Several pollutants are emitted during the process of coke production. This process consists of four basic steps, each of which is the source of characteristic emissions. These steps are: (a) coal charging, (b) oven pushing, (c) coke quenching, and (d) underfiring.[4] Coal charging results in the emission of carbonaceous smoke, tar mist, dust, and organic gases.

---

1 A Nationwide Inventory of Air Pollutant Emissions, p. 43.

2 Canadian Minerals Yearbook, p. 183.

3 Ibid.

4 For a detailed description of the process, see, T.M. Barnes, Evaluation of Process Alternatives to Improve Control of Air Pollution from Production of Coke. Final Report, (Columbus, Ohio: Battelle Memorial Institute, January 31, 1970).

Fine particulates and smoke are emitted in the oven pushing step. Particulates are also emitted as a result of coke quenching. Underfiring consists of extracting and burning the gases released during the coking process in order to provide heat for the coke ovens. The sulfur in the coal is released in the coke ovens as hydrogen sulfide (H_2S), but is oxidized to SO_2 in the process of underfiring. Some of this SO_2 is emitted. Table 6-59 summarizes the model plant characteristics.

TABLE 6-59

MODEL PLANT CHARACTERISTICS - COKE MANUFACTURING (BYPRODUCT PROCESS)

Annual Production (Tons)	980,000
Production Rate (Tons/Day)	2,800
Annual Hours of Operation	8,400
Gas Volume (Underfiring) (cfm)	30,000
Gas Temperature (Underfiring) ($^{\circ}F$)	70
Annual Emissions with No Controls (Tons)	
Particulates (from coal charging)	700
Particulates (from quench tower)	200
Sulfur Oxides (from underfiring)	7,850
Annual Cost of SOx Control System	
Low	37,300
High	60,000

Source: National Emissions Standards Study, pp. E20-E21.

The Canadian coke manufacturing industry is equivalent to five model plants.[1] Therefore, with no control, estimated emissions of sulfur oxides are 32,250 tons.[2]

There is no technically satisfactory way of controlling emissions from coal charging or oven pushing, though emissions are reduced a little by steam jets. Systems for controlling emissions from the quench tower and from underfiring do exist. We are concerned here with a system to control emissions of sulfur oxides from the latter step.

The control system consists of (a) steam nozzles in ascension pipes; (b) baffles arrangements plus spray nozzles; and (c) a 10 ton per day elemental sulfur recovery unit.[3] This system has a control efficiency of 90%. This means that emissions of sulfur oxides from the model plant will be reduced from 7,850 to 785 tons per year.

Table 6-60 summarizes the costs of implementing such a control system.

---

1 As shown in Table F-6, Appendix F, there were seven coke production plants in Canada in 1970.

2 Note that this estimate is lower than that reproduced in Table 4-3, Chapter IV. It seems that the latter estimate is high. An independent estimate can be obtained by considering that coke production has been found to result in the emissions of 10.02 lbs. of sulfur oxides per ton of coal used. See, Environmental Protection Agency, Compilation of Emission Factors, Table 7-2 . Since 6.9 million tons of coal were used in 1970, by this estimate emissions of sulfur oxides were 34,500 tons.

3 National Emissions Standards Study, p. E21.

TABLE 6-60

COST OF ABATEMENT - (SOURCE 11)

Total Reduction of Emissions (Tons)	28,325
Total Cost of Abatement ($)	
Low	186,500
High	300,000
Cost of Abatement per Unit SOx ($/Ton)	
Low	7
High	11

12. CONTROL OF EMISSIONS FROM NATURAL GAS PROCESSING (SOURCE 12)

Virtually the sole constituent of natural gas, as it is sold to consumers, is methane (CH_4), though it may also contain small quantities of ethane (C_2H_6) and propane (C_3H_8). However, raw natural gas, as it exists in underground reservoirs, contains several other constitutents in proportions which may vary considerably from field to field. For various reasons, these constituents are removed prior to marketing the gas. It is their removal which is designated as natural gas processing.

The processing begins with the removal of the liquid hydrocarbons and water which condense in the reservoir or at the wellhead. This is done by means of equipment called separators. The separation is achieved basically through gravity. The hydrocarbons are recovered as byproducts. They range from propane to octane to crude oil.[1] The gas coming out of the separators contains hydrogen sulfide (H_2S) and carbon dioxide (CO_2). For different reasons, both gases are removed. Hydrogen sulfide is both toxic and corrosive. The hydrogen sulfide content of raw natural gas can be as high as 95% by weight.[2] Carbon

1 The group of hydrocarbons which includes hexane, heptane, and octane is also referred to as natural gasoline or naphta. It is a valuable byproduct. In fact, frequently, gas which has already been processed is reintroduced into the reservoirs in order to maintain pressure therein and increase the recovery of hydrocarbons. In some fields, as much as two thirds of processed gas is returned to the reservoirs for this purpose. See, Canadian Minerals Yearbook, p. 347.

2 P.R. Cote, Canadian Elemental Sulfur from Sour Natural Gas, (Ottawa: Department of Energy, Mines, and Resources, 1972), p. 12.

dioxide, if present in sufficient quantity to dilute the flammable hydrocarbons, lowers the heat value of the natural gas.

The gas containing both the H_2S and CO_2 is passed through a solution which contains any one of the following: diethanolamine, monoethanolamine, hot potassium carbonate, or sulfinol.[1] The solution absorbs the H_2S and CO_2. The "sweetened" gas is dried and sent to the pipelines. The solution containing the H_2S and CO_2, on the other hand, is sent to a stripper tower where it is heated. The two gases are liberated and the solution is regenerated for reuse. If the quantity of H_2S in the liberated gas is judged worth recovering, the gases are sent to a sulfur recovery plant. Otherwise they are burned and the H_2S is oxidized to and emitted as SOx. These emissions constitute part of the total emissions of SOx from the natural gas processing industry. The main factors which affect the decision as to whether to recover the sulfur or not are the size of the processing plant and the concentration of H_2S in the raw gas feed.

Emissions of sulfur oxides from the natural gas industry occur also from plants equipped with sulfur recovery units, however. The recovery process is basically the Claus process and varies from plant to plant only in detail.[2] The H_2S is burned in an atmosphere of low oxygen to SO_2, which itself reacts further with unburned H_2S to produce sulfur vapor. This vapor

---

1 *Ibid.*, p. 13.

2 *Ibid.*, p. 12.

is condensed and stored as either a liquid or, most often, as a solid. The Claus process, which usually has two or three stages, typically removes about 95% of the sulfur contained in the gas.[1] The remaining 5% is emitted as SOx (together with the CO_2).

In 1970, the Canadian natural gas production was 2,276,578 million cubic feet.[2] In that year, there were 172 gas processing plants.[3] Of these, only 38 had sulfur recovery units.[4] These plants produced 3.7 million tons of sulfur.[5] Assuming a 95% recovery rate these 38 plants were the source of the emission of 370,000 tons of sulfur oxides.[6] If this estimate and that of Table 4-3, Chapter IV, are both accurate, the rest of the natural gas processing plants were the source of 223,000 tons of SOx emissions.

---

1 Ibid., p. 31.

2 Canadian Minerals Yearbook, p. 345.

3 Natural Gas Processing Plants in Canada, January, 1971, (Ottawa: Information Canada, 1971).

4 Ibid. See also, Cote, Canadian Elemental Sulfur..., p. 9.

5 Canadian Minerals Yearbook, p. 514. Table F-7, Appendix F, lists the location, ownership, and capacity of these 38 plants.

6 That is, $3.7 \times 10^6 \times 0.05 \times 2 = 370,000$.

Now, not sufficient information is available to estimate the cost of abatement from plants which at the moment do not recover any sulfur. Therefore, the estimates of the costs of abatement made here will be confined to the abatement of emissions from the plants which already recover sulfur. Table F-7 summarizes data pertaining to these plants.

Several processes are capable of reducing sulfur oxide emissions from these plants, including processes developed with the main aim of reducing emissions from power plants.[1] All of these processes are basically of the "add-on" type; that is, they do not require modification of the presently used Claus recovery units. They would use as feed the gas escaping from Claus units.[2] Typical investment costs of increasing sulfur recovery from gas processing plants from the present 95% average to an average of 99% by these methods have been estimated.[3]

---

1 These are discussed in Appendix E. One process, the SCOT process developed by Shell, is claimed to be capable of eliminating emissions of sulfur oxides completely. See, "Coping with Pollution is Tough for the CPI," <u>Canadian Chemical Processing</u>, LVII (March, 1973), pp. 27-30.

2 See, C.B. Barry, "Reduce Claus Sulfur Emissions," <u>Hydrocarbon Processing</u>, LI (April, 1972), pp. 102-106. Increasing the recovery of sulfur entails some operating costs as well. But these would be covered by the sale of the additional sulfur recovered. See, P.R. Cote, <u>Canadian Elemental Sulfur</u>, p. 31. Therefore, operating costs are ignored here.

3 Barry, "Reduce Claus Sulfur Emissions," p. 105.

They vary directly with the sulfur feed rate at the plant. Since sulfur feed rates vary from plant to plant, a range of control costs was estimated here.[1] The <u>low</u> cost was estimated on the assumption that all plants have a feed rate of 100 long tons of sulfur per day. The <u>high</u> cost was estimated on the assumption that all plants have a sulfur feed rate of 2,000 long tons per day. The low cost was estimated to be $700,000 per plant; the high cost was estimated to be $5,000,000 per plant.[2] For the 38 plants, therefore, the investment cost would be: Low - $26,600,000; High - $190,000,000. The annualized cost of this investment[3] was calculated to be: Low - $4,330,000; High - $30,900,000.

Table 6-61 summarizes the costs of implementing this system of abatement.

---

1 An approximate measure of the feed rate is the daily sulfur capacity of the plant as listed in the last column of Table F-7, Appendix F.

2 These costs were estimated from the graphical functions provided by Barry, <u>op. cit</u>.

3 The annual cost of the investment was calculated by the Capital Recovery Method. See, G.A. Taylor, <u>Managerial and Engineering Economy</u>, (New York: D. Van Nostrand, 1966), pp. 141-162. A 10% rate of return and a 10 year recovery period was used.

TABLE 6-61

COST OF ABATEMENT - (SOURCE 12)

Total Reduction of Emissions (Tons)	296,000
Total Cost of Abatement ($)	
Low	4,330,000
High	30,900,000
Cost of Abatement per Unit SOx ($/Ton)	
Low	15
High	100

P

13. CONTROL OF EMISSIONS FROM PULP AND PAPER MANUFACTURING (SOURCE 13)

The manufacture of paper and related products can be separated into two stages, the production of pulp from wood and that of paper and other products from pulp. Ordinarily, the latter stage is the source of little air pollution. Therefore, attention is devoted here exclusively to the pulping process.

Wood pulp is produced either mechanically or chemically. Physical means are used to produce pulp by mechanical processes. Groundwood, defibrated, and exploded pulps are the main types of pulp produced in this way. In the chemical processes, wood compounds other than cellulose, such as lignin, are dissolved by chemical reagents, allowing the recovery of the cellulose. It is only the chemical processes that give rise to significant quantities of emissions of sulfur oxides. The most important of these processes, in terms of quantity of pulp produced, are the sulfate (Kraft) and the sulfite processes. Table 6-62 shows the 1970 production of wood pulp by type in Canada. Further attention will be given here only to the sulfate and sulfite processes.

(a) Sulfate (Kraft) Process

In the sulfate (Kraft) process, wood chips are cooked in a digester in a solution composed of sodium hydroxide (caustic soda) and sodium sulfide. This solution is referred to as "white liquor." It dissolves the lignin which bonds cellulose fibers. Steam is used to maintain the temperature and pressure in the digester at the required level during the cooking period.

TABLE 6-62

PRODUCTION OF WOOD PULP - CANADA, 1970

TYPE	QUANTITY (TONS)
Sulfite	2,815,261
Sulfate (Kraft)	6,707,091
Semi-chemical	325,624
Groundwood	7,649,851
Exploded or Defibrated	285,855
Other	524,160
Total	18,307,852

Source: Statistics Canada, Pulp and Paper Mills, 1970, (Ottawa: Information Canada, August, 1972), p. 13.

At the end of this period, the mixture is transferred to a tank where the pulp is washed free of the spent (black) liquor. The black liquor contains about 15% solids. The proportion of solids is made to increase up to 65% in a multiple-effect evaporator. This strong black liquor is then burned in a recovery furnace where a molten smelt is produced. This smelt contains chemicals which are recovered for reuse. The smelt is sent from the recovery furnace to a tank where it is dissolved in water and mixed with slaked lime. This regenerates the white liquor, which is reused, and leaves a residue, calcium carbonate, which is burned in a lime kiln to produce lime which is also reused.

Emissions of air pollutants occur at all the stages ~~as~~

follows:

Digester - H_2S, SOx, mercaptan, dimethyl sulfide, dimethyl disulfide.

Evaporator - Mercaptan, dimethyl sulfide, dimethyl disulfide.

Recovery Furnace - Particulates, SOx, H_2S.

Lime Kiln - H_2S, SOx, mercaptan, dimethyl sulfide, dimethyl disulfides, particulates.

Emissions of SOx are small except from the recovery furnace.[1] Emissions from the latter are considerable but they are still a minor part of total emissions. Table 6-63 shows typical emissions from the recovery furnace of a 500 tons/day sulfate pulp mill. In Canada, in 1970, emissions of sulfur oxides from sulfate pulp mills were estimated to be 16,000 tons.[2]

The relative importance of emissions of sulfur oxides is even lower than can be inferred by comparisons of weight of pollutants released. This is because sulfur oxides are much less harmful than hydrogen sulfide and the organic sulfur compounds. These are quite poisonous as well as extremely malodorous, as anybody who ever went near a sulfate pulp mill can attest. Therefore, it would be unrealistic to postulate emission control systems which aimed at controlling SOx emissions selectively. Any SOx control system would have to form an integral part of a control system which would have as its primary

---

1 National Emissions Standards Study, p. D23.

2 See Table 4-3, Chapter IV.

aim the control of the other, more obnoxious, pollutants. For this reason, no attempt will be made here to estimate the cost of abatement of emissions of SOx from this source.

TABLE 6-63

TYPICAL EMISSIONS FROM RECOVERY FURNACE
(500 TONS/DAY PULP MILL)

POLLUTANT	QUANTITY (LB./TON OF PULP)	QUANTITY (LB./DAY)
Sodium Salts	150 - 200	75,000 - 100,000
Hydrogen Sulfide	25 - 28	12,500 - 14,000
Mercaptan	8 - 40	4,000 - 20,000
Dymethyl Sulfide	3 - 7.5	1,500 - 3,750
Sulfur Oxides	25 - 40	12,500 - 20,000
Total	211 - 315.5	105,500 - 157,750

Source: I.S. Shaw, "Pulp Plant Pollution Control," Chemical Engineering Progress, LXIV (September, 1968), p. 68.

(b) Sulfite Process

In the sulfite process, wood chips are cooked in an acid-base liquor in a digester. This dissolves the lignin. The cooking liquor is a mixture of a bisulfite solution and excess sulfurous acid. This solution is produced by reacting SO_2 with one of four bases (ammonium, calcium, magnesium, or sodium) in an absorber. The SO_2 is produced by burning elemental sulfur or pyrites. The cooking liquor is usually pumped into a digester cold and then is heated with steam. As the temperature rises, it becomes necessary to vent the digester, allowing gases which are rich in sulfur dioxide to escape. These can be collected in accumulators and be reused. Because the chemical reactions involved in the separation of the pulp fibers from the lignin are different from those in the Kraft process, sulfite cooking does not yield volatile reduced sulfur compounds such as methyl mercaptan and dimethyl sulfide.

Upon completion of the cooking cycle, the pulp is "blown" into a dump tank and is washed. This operation results in the release of sulfur dioxide and other volatile material. Much of the sulfur dioxide, however, can be recovered in an absorption tower. The spent liquor, on the other hand, is sent to multiple-effect evaporators to strengthen it and, subsequently, is burned in a recovery furnace in order to recover the SO_2.

Though sulfur oxides can be recovered at every stage of the pulping process, emissions do occur at every stage because recovery is never, or rarely, complete. Table 6-64, shows the main stages from which emissions originate.

Given a Canadian production of 2,815,261 tons of sulfite pulp in 1970, total emissions of sulfur oxides from this source are estimated to be 148,000 tons. Of these, 20,000 tons originated from the absorption tower, 124,000 tons from the blow pit and dump tank, and 4,000 from miscellaneous sources.[1]

---

1 The author was unable to obtain a list of the mills which produced sulfite pulp in Canada in 1970. Table F-8, Appendix F, shows the ownership and location of the 35 mills which produced some grade or other of sulfite pulp in 1967. It is assumed that there was no change between 1967 and 1970.

TABLE 6-64

TYPICAL EMISSIONS OF SO_x FROM SULFITE PULP MILLS
(POUNDS/TON OF PULP)

PULPING STAGE	RANGE	AVERAGE
Digester Discharge	20-150	85
Absorption Tower	10-20	15
Miscellaneous	5	5
Total		105

Source: A Nationwide Inventory of Air Pollutant Emissions, pp. 65-66.

Techniques and Cost of Abatement

Absorption Tower (Control Technique A_{13})

Most mills have a single absorption tower. Its emissions control efficiency is about 90 percent.[1] The control system consists of adding a second tower. Data on the efficiency of this system is not available. It is assumed, therefore, that the second tower has the same efficiency as the first. That is, it will prevent the emission of 90% of the sulfur oxides which escape from the first tower. If so, the emissions of SOx from the absorption tower complex would be reduced from an average of 15 lbs. per ton of pulp to 1.5 lbs. Hence, total reduction of emissions of SOx from this source would be 18,000 tons (based on the 1970 sulfite pulp production).[2]

The cost of this control system varies with the capacity of the mill. The annualized cost varies from $2,600 for a 300 tons/day mill to $6,500 for a 1,200 tons/day mill.[3]

It is assumed that each of the 35 mills requires a second absorption tower. Since data on mill capacity could not be obtained, a range of costs was calculated. The Low cost is the cost of installing the tower on the assumption that all mills have a 300 tons/day capacity. The High cost is the cost of installing

---

1 E.R. Hendrickson et al., Control of Atmospheric Emissions in the Wood Pulping Industry, (Gainsville, Fla.: Environmental Engineering, March, 1970), Vol. 2, pp. 5-151.

2 That is, 20,000 x .9 = 18,000.

3 Henderickson, et al., Control of Atmospheric Emissions..., pp. 5-152.

the tower on the assumption that all mills have a 1,200 tons/day capacity. Table 6-65 summarizes the cost of installing such a system of abatement.

TABLE 6-65

COST OF ABATEMENT - (SOURCE 13, TECHNIQUE A_{13})

Total Reduction of Emissions (Tons)	18,000
Total Cost of Abatement ($)	
Low	91,000
High	227,000
Cost of Abatement per Unit SOx ($/Ton)	
Low	5
High	13

Blow Pit and Dump Tank (Technique B_{13})

The control system consists of replacing existing multiple wooden blow stacks with an SOx recovery system which includes: (a) a condenser with cyclone and absorption tower; and (b) a packed tower.[1] The efficiency of this system is 95%. Hence, based on the 1970 Canadian sulfite pulp production, the total reduction of SOx would be 118,000 tons.

The capital cost of installing such control systems vary from $48,000 for a 200 tons/day mill to $95,000 for an 800

1 Ibid., p. 5-153.

tons/day mill.[1] But the value of the SO_2 recovered, which can be reused, more than offsets the annualized cost of this investment.[2] Hence, the cost of control is assumed here to be zero. Table 6-66 summarizes this result.

TABLE 6-66

COST OF ABATEMENT - (SOURCE 13, TECHNIQUE B_{13})

Total Reduction of Emissions (Tons)	118,000
Total Cost of Abatement ($)	0
Cost of Abatement per Unit SOx ($/Ton)	0

1 *Ibid.*, p. 5-154

2 *Ibid.*

SUMMARY OF EMPIRICAL FINDINGS

Table 6-67 summarizes the emissions of sulfur oxides in Canada from the thirteen sources considered here with no controls.[1]

Table 6-68 summarizes the total and marginal (average) costs of abatement of emissions from the thirteen sources by various techniques as found in this chapter. Where a single technique is postulated for abating emissions from a given source, the Low and High costs are designated as Lx and Hx respectively, where x indicates the source of emissions. This is done in order to have a code for the construction of Table 6-69. Table 6-69 shows the range of emissions reductions which would result under various tax levels. Column 1 lists selected tax levels. Column 2, labelled "Effective Techniques," shows the techniques which an emitter has an inducement to use, because the annualized cost of doing so is equal to or lower than the tax. The maximum and minimum are constructed as follows. When a technique becomes effective it is used to show the maximum reduction of emissions which would result from using that technique. If at a higher tax level a substitute technique becomes effective which results in a greater reduction of emissions (but at a higher cost), the difference in the reduction in emission and in the cost of abatement is reported. If at the higher tax level a technique which is not a substitute to any other, but which is "additive," becomes effective, the effects of using this technique are put in the

1 Recall that emissions from the combustion of fuels (sources 1 to 4) are based on the 1969 consumption of fuel. Industrial emissions (sources 5 to 13) are based on the year 1970.

"minimum." Notes to Table 6-69 shows in detail how each technique is used to determine the range emissions reduction and the cost of abatement.

TABLE 6-67

ESTIMATED EMISSIONS OF SOx FROM THIRTEEN SOURCES WITH NO CONTROLS - CANADA

SOURCE	DESCRIPTION OF SOURCE	EMISSIONS (TONS)
1	Residential and Farm Fuel Consumption	221,258
2	Commercial Fuel Consumption (Boilers)	324,560
3	Industrial Fuel Consumption (Boilers)	453,930
4	Fuel Consumption by Power Plants (Utilities)	773,361
5	Primary Aluminum Smelting	58,000
6	Primary Copper and Nickel Smelting	3,003,000
7	Primary Lead Smelting	184,000
8	Primary Zinc Smelting	312,700
9	Petroleum Refineries	320,000
10	Sulfuric Acid	125,000
11	Metallurgical Coke	32,250
12	Natural Gas Processing (38 Plants)	370,000
13	Sulfite Pulp Mills	148,000
	Total	6,326,059

Note: Notice that total emissions under existing controls, as shown in Table 4-1, Chapter IV, exceed total emissions with no controls as estimated here. Recall, however, that the former include emissions from sources excluded in the latter. Examples are emissions from transportation (175,000 tons), natural gas plants which have no existing controls (223,000 tons), and non-utility power plants. Moreover, as shown above, it is quite probable that Table 4-1, Chapter IV, includes excessive estimates of emissions from copper and nickel smelting.

TABLE 6-68

TECHNIQUES AND COSTS OF ABATEMENT - SUMMARY

SOURCE	TECHNIQUE OR RANGE	REDUCTION OF EMISSIONS (TONS)	COST OF ABATEMENT ($)	COST OF ABATEMENT PER UNIT SOx ($/TON)
(1)	(2)	(3)	(4)	(5)
1	A_1	32,602	5,960,695	183
	B_1	48,903	10,729,252	219
	C_1	92,314	31,981,716	346
	D_1	54,337	38,165,920	702
	E_1	143,600	144,452,880	1,006
	F_1	54,337	104,014,640	1,914
	G_1	143,600	808,241,460	5,628
2	A_2	22,166	524,700	24
	B_2	12,973	4,990,476	385
	C_2	27,965	12,740,041	455
	D_2	33,250	5,461,443	164
	E_2	19,739	6,854,791	347
	F_2	156,363	28,178,494	180
	G_2	234,544	50,721,290	216
	H_2	260,605	85,212,615	327
3	A_3	134,303	3,180,167	24
	B_3	80,075	13,935,356	174
	C_3	169,855	65,149,026	384
	D_3	201,455	70,187,372	348
	E_3	7,787	2,698,510	347
	F_3	12,113	5,318,772	439

TABLE 6-68
(continued)

SOURCE	TECHNIQUE OR RANGE	REDUCTION OF EMISSIONS (TONS)	COST OF ABATEMENT ($)	COST OF ABATEMENT PER UNIT SOx ($/TON)
(1)	(2)	(3)	(4)	(5)
3	G_3	144,217	20,026,736	180
	H_3	216,326	46,848,314	216
	I_3	240,362	129,091,014	537
4	A_4	451,000	10,686,375	24
	B_4	313,094	12,557,251	40
	C_4	676,500	164,064,000	242
	D_4	53,068	9,588,291	180
	E_4	79,601	17,258,924	216
	F_4	88,446	36,212,146	410
	G_4	390,122	17,165,368	44
5	L_5	58,000	11,352,000	192
	H_5	58,000	17,886,000	303
6	L_6	2,753,751	0	0
	H_6	2,753,751	41,847,000	15
7	L_7	171,120	0	0
	H_7	171,120	3,085,600	18
8	L_8	287,500	0	0
	H_8	287,500	8,784,000	30
9	L_9	288,000	3,000,000	11
	H_9	288,000	6,000,000	22
10	L_{10}	113,000	1,528,000	13
	H_{10}	113,000	3,220,000	27

TABLE 6-8
(continued)

SOURCE	TECHNIQUE OR RANGE	REDUCTION OF EMISSIONS (TONS)	COST OF ABATEMENT ($)	COST OF ABATEMENT PER UNIT SOx ($/TON)
(1)	(2)	(3)	(4)	(5)
11	L_{11}	28,325	186,500	7
	H_{11}	28,325	300,000	11
12	L_{12}	296,000	4,330,000	15
	H_{12}	296,000	30,900,000	100
13	A_{13} (Low)	18,000	91,000	5
	A_{13} (High)	18,000	227,000	13
	B_{13}	118,000	0	0

TABLE 6-69

LEVELS OF SOx EMISSION REDUCTION ASSOCIATED WITH SELECTED EMISSION TAX LEVELS

TAX ($/TON SOx)	MINIMUM				NOTES
	EFFECTIVE TECHNIQUES	REDUCTION OF EMISSIONS (TONS)	CUMULATIVE REDUCTION OF EMISSIONS (TONS)	CUMULATIVE COST OF ABATEMENT ($)	
(1)	(2)	(3)	(4)	(5)	(6)
0	-	0	0	0	
10	L_6, L_7, L_8, B_{13}	3,330,371	3,330,371	0	A
20	H_6, H_7, H_{11}, A_{13} (High)	46,325	3,376,696	527,000	B
30	H_8, H_9, H_{10}	688,500	4,065,196	18,531,000	
40	B_4	313,094	4,378,290	31,088,251	
50	G_4	390,122	4,455,318	35,696,368	D
100	H_{12}	296,000	4,751,318	66,596,368	
200	B_3	80,075	4,831,393	80,531,724	
300		-	-	-	
400	B_2, H_5	70,973	4,902,366	103,408,200	
500	C_2	14,992	4,917,358	111,157,765	H

TABLE 6-69
(continued)

TAX ($/TON SOx)	MAXIMUM				NOTES
	EFFECTIVE TECHNIQUES	REDUCTION OF EMISSIONS (TONS)	CUMULATIVE REDUCTION OF EMISSIONS (TONS)	CUMULATIVE COST OF ABATEMENT ($)	
(1)	(7)	(8)	(9)	(10)	(11)
0	L_6, L_7, L_8, B_{13}	3,330,371	3,330,371	0	
10	L_{11}, A_{13} (Low)	46,325	3,376,696	277,500	
20	L_9, L_{10}, L_{12}	697,000	4,073,696	9,135,500	
30	A_2, A_3, A_4	607,496	4,681,165	23,526,742	
40	-	-	-	-	C
50	-	-	-	-	C
100	-	-	-	-	
200	$A_1, D_2, F_2, G_3, D_4, L_5$	455,334	5,136,499	104,069,701	E
300	H_3, B_1, C_4, E_4, G_2	418,624	5,555,123	319,250,890	F
400	C_1, E_2, H_2, D_3, E_3	213,053	5,768,176	451,284,444	G
500	F_3, F_4	13,171	5,781,347	473,857,928	I

Notes:

A - Given a low cost of abatement of zero for sources 6, 7, 8, and 13 (Technique B_{13}), any positive tax (eg. \$10/ton SO_x) should induce sources to effectively control emissions.

B - Since techniques H_6 and H_7 are substitutes for techniques L_6 and L_7 respectively, only techniques H_{11} and A_{13} (High) add to the cumulative minimum reduction of emission and cost of abatement.

C - Techniques B_4 and G_4 are substitutes for technique A_4. But they result a lower quantity of emissions reduction than the latter. Hence, the maximum abatement is not increased.

D = Technique G_4 is a substitute for technique B_4. But it reduces a greater quantity of emissions. Only the difference in the quantity of emissions abated and costs of abatement are reported.

E - Technique D_2 is a substitute for technique A_2. Therefore, only the difference in emissions abated and costs of abatement is included in the maximum.

F - Techniques B_1, G_2, H_3, C_4, and E_4 are substitutes for technique A_1, F_2, G_3, A_4, and D_4 respectively. Therefore, only differences in quantity of emissions abated and cost of abatement are included in the maximum.

G - Technique H_2 is a substitute for techniques F_2 and G_2. Technique C_3 is a substitute for technique A_3. But technique D_3 is a substitute for techniques A_3 and C_3. Only differences in emissions reduced and costs of abatement between techniques H_2 and G_2 and between D_3 and A_3 are included in the maximum.

H - Technique C_2 is a substitute for technique B_2. Only differences in quantities of emissions abated and costs of abatement are included in the minimum.

I - Techniques F_3 and F_4 are substitutes for techniques E_3 and E_4 respectively. Only differences in emissions abated and costs of abatement are included in the maximum.

How could we interpret the results summarized in Table 6-69.

To begin with, it is necessary to explain why even with a zero tax (that is, under existing conditions) we could expect the abatement of a maximum of 3,330,371 tons of SO_x per year. It must be remembered that some of this abatement is, in fact, taking place. Recall that emissions estimated here are those which would occur with no controls. Some industries, however, do recover SO_x, mainly to transform these gases into valuable byproducts, such as sulfuric acid and elemental sulfur. However, if the estimates of emissions with no controls provided here and those of emissions with existing controls shown in Table 4-1, Chapter IV, are both approximately accurate, there is still much scope for abatement of emissions at no additional cost to the polluters.

Why would such abatement not be carried out if it does not cost anything? The following are possible explanations. While it is true that annualized costs are zero, it is not true that investment costs are zero. Firms may not want to spend funds on pollution abatement equipment even though they will eventually recover them. Moreover, they will recover their investment only if they sell the byproducts of recovering SO_x, usually sulfuric acid or elemental sulfur. But they may feel uncertain about the demand for these byproducts. Sulfuric acid is a product which cannot be transported economically over long distances; and local markets may be saturated. The market for sulfur has been volatile in the recent past and there are indications of a market glut.[1] This combination of circumstances may make firms reluctant to undergo the required investment costs. It is reasonable to conclude, however, that this reluctance will disappear if they are faced with the alternative of disbursing substantial sums in emission taxes. The "minimum" portion of the first row of Table 6-69 shows the abatement that would result, based on the assumption that a tax of $10/ton of SO_x would be sufficient to provide such an incentive.

The rest of the table is not difficult to interpret. For example, the "maximum" portion of the second row shows that the imposition of a $10/ton would render techniques L_{11} and A_{13} (Low) effective. This would render economical the abatement of an additional 46,325 tons of SO_x. The cumulative maximum increases accordingly. On the other hand, if the true costs of reducing SO_x from sources 11 and 13 exceed $10, then a tax of more than $10/ton (e.g. $20) would be required to make the appropriate techniques effective. The contribution of these techniques to abatement increases the cumulative "minimum" (third row) because with a tax of $20/ton the techniques <u>must</u> be effective. The rest of the table is constructed in similar manner. The details, when not obvious, are spelled out in the Notes to the table.

---

1 See, for example, <u>Canadian Minerals Yearbook</u>, pp. 513-527.

CHAPTER VII

SUMMARY AND CONCLUSIONS

This study has attempted to demonstrate a number of propositions regarding the economics of air pollution control. First, it attempted to provide a synthesis and an appraisal of the economic nature of air pollution and its control. Second, based on that analysis, it attempted to evaluate alternative control policies. Third, it selected and argued in favour of the use of one of these policies, namely, the use of emission taxes designed to achieve predetermined standards of air quality. This policy was seen to be particularly appropriate to control emissions of sulfur oxides. The economics of applying that policy to the control of this type of pollutant were worked out. Finally, there was an attempt to estimate, within a range, the level of emission taxes necessary to achieve given reductions of emissions of sulfur oxides in Canada. This chapter attempts to reiterate the broad outlines of the issues involved and to suggest some areas where the work done here needs improvement and extensions.

The problem of environmental pollution can be analyzed from several economic points of view. Most frequently, economists regard occurrences of pollution as instances of external diseconomies. This is certainly the case. In fact, the most important single development arising from this recognition is the realization of how pervasive externalities really are in the economy. Indeed, as the model of materials balance demonstrates, externalities are inherent in most economic activity.

The externality concept, however, is a very complex one. It is also a concept that lends itself to a variety of interpretations. As a result, it has been used in so many ways that its analytical potency has been somewhat weakened.

There have been several attempts in the last decade or so to classify and clarify the meaning of externalities. The materials balance model, for example, by emphasizing their pervasiveness, suggests that they should be viewed in a general equilibrium framework rather than in a partial equilibrium one as they have been treated traditionally. Unfortunately, the implementation of policies suggested by the analysis of externalities in a general equilibrium setting is much more difficult because it requires much more information (data) than is and is likely to be available in the near future. The most promising development in this area is the use of input-output techniques. Even in the partial equilibrium setting, however, the attempt to classify externalities has shown the variety and the complexity of the ways in which they occur. Externalities can be Pareto-relevant or Pareto-irrelevant, unidirectional or reciprocal, separable or non-separable, or combinations of these. Depending on whether they are of one type or another, they may or may not have allocative significance, or they may call for different corrective policies.

One consequence of this state of affairs is to cast doubt on the appropriateness of the solution to the problem which, since Pigou, has usually been advocated by economists. This is the use of corrective taxes (or, in the case of external economies, subsidies). Some authors have shown that the taxation solution leads to an improvement in welfare only if externalities are of a certain type and not of others. If externalities are reciprocal and/or non-separable, for example, the tax (subsidy) solution may be either impractical or inappropriate. The suitability of the alternative solutions suggested will be discussed in a different context below.

Aside from the appropriateness of the use of corrective taxes as such, however, there is another important issue connected with their use. This concerns the relative efficiency of different types of taxes. Traditionally, by corrective taxes, economists have meant output (or consumption) taxes. But the nature of pollution control is such that these may be, from the efficiency point of view, the least desirable type of taxes among the possible alternatives. The reason is that these taxes provide an incentive to reduce the external diseconomy in only one way: by reducing output (or consumption). In the case where the externality is due to the use of a specific input, however, it may be preferable to tax the input rather than the output, since the input tax will lead to the elimination of the externality (by using less of the polluting input) with a smaller decrease in output. Moreover, in some cases, it may be preferable, because it is cheaper, to reduce output even less or not at all, and reduce pollution through the installation of devices which capture pollutants or through modifications of the production process. Neither output (or consumption) nor input taxes would provide an incentive to polluters to use such abatement techniques. Taxes that would provide such an incentive are emissions (also called effluent charges) and damage taxes. The former would be a function of the quantity of emissions and the latter of the damage such emissions would cause.

As discussed in this study, the only type of tax which is fully adequate, from the efficiency point of view, is a tax equal to the marginal damage of pollution. Such a tax would provide an incentive to reduce the external diseconomy by precisely the optimal amount (i.e., up to the point where the marginal damage would equal the amount of the tax) and to reduce that diseconomy by using the most efficient (i.e., cheapest) technique. Therefore, the optimal reduction in the diseconomy would be accompanied by the minimum possible reduction in output (or consumption). But the attempt to levy such a tax implies the calculation of the damage function of pollution. Now, no such damage function has been estimated yet. Nor is it likely to be estimated in the near future, especially on a pollutant-by-pollutant basis. It is difficult enough to obtain reliable estimates (in money terms) of damages to such "objective" entities as materials, structures, crops, animals, and human health (measured by the costs of medical care) at the levels of pollution we do experience. It is much more difficult to estimate what this damage would be at different hypothetical levels of pollution. Yet, data in this form are necessary if marginal damage is to be estimated. Add to this the even greater difficulty of assessing the "subjective" damage of pollution, such as the discomfort and pain experienced from pollution-caused diseases and early death, and the offense to aesthetic sense. These damages would be difficult to estimate even by individuals who were willing to try and were willing to reveal their true extent. If one considers, in addition, that individuals may have an incentive to overstate or understate, depending on the circumstances, this type of damage, the task becomes a truly impossible one.

Because of the difficulty, perhaps the impossibility, of assessing a truly optimal tax, this study has argued in favour of the use of emission taxes. It is possible to levy a tax such that the total level of emissions of given pollutants is reduced to such an extent that a generally acceptable standard of air quality, in terms of concentrations of pollutants, is achieved. The order of magnitude of such a tax can be determined. Presumably, consensus as to what the standard should be would be achieved through public debate, involving, among others, the scientific community, and through the political process. To the economist, this solution, though definitely second best, is acceptable because it permits the achievement of the given standard in the most efficient manner. At the moment, with the available information, this is the most that can be achieved.

The use of taxation as a control policy has not been unanimous among economists. As discussed in this study, it is possible to view environmental pollution as one instance of market failure. The concept of market failure encompasses that of externalities but is more comprehensive and general. Environmental pollution and its control, for example, share in the nature not only of externalities but also of public goods (and 'bads') and of joint supply. These are also causes of market failure. From the use of this more comprehensive concept, it is possible to probe deeper into the causes of environmental pollution and, from an examination of these causes, infer possible alternative control or corrective policies.

The single most important suggestion that can be derived from the use of the concept is that a situation of market failure of the type involved in environmental pollution will lead to a more explicit delineation of property rights; in turn, the assignment of property rights will induce polluters and pollutees to bargain in such a way as to reduce pollution by an optimum amount; in the process, both groups gain. The superiority of this approach is postulated on grounds that it may not always be optimal from the point of view of society as a whole to have the polluters reduce the external diseconomies they are imposing on others, since that reduction may decrease the welfare of the polluters by a greater amount than it will increase that of the pollutees. The success of bargaining can be seen as a test that the reduction is warranted.

As far as it goes, the logic of this argument is impeccable. It fails to be convincing, however, because it does not reflect accurately the real circumstances pertaining to most situations involving environmental pollution, especially air pollution. It was argued in this study that the argument is valid in situations involving a small number of parties, each of whom has equal, or approximately equal, bargaining strength. In most occurrences of air pollution, however, the number of individuals affected is large and there is a disparity in bargaining power, usually favouring polluters. The number of polluters usually is smaller than the number of pollutees. Therefore, the former will find it less difficult to organize into a bargaining group, or even a lobbying group to articulate their case, than the latter. Also, the costs of bargaining will be lower for the smaller group. On the other hand, the fact that the number of pollutees is large and that exclusion from the benefits of pollution control is not possible will encourage individuals to be free riders. Moreover, it could be argued that human beings have an inherent right to reasonably clean air and that the polluters just do not have the right to maintain their own welfare at the expense of that right.

In short, private bargaining, facilitated by a clearer delineation of property rights, cannot be relied upon to provide satisfactory solutions. The basic reason is that the theoretical foundations upon which this reliance is based do not reflect the realities of most situations involving air pollution. From the practical point of view, government intervention through taxation is, generally speaking, a more effective policy.

This study touched on the use of benefit-cost analysis in pollution control. This type of analysis is concerned primarily with the assessment of the "worthiness" and other economic aspects of government-financed projects. Therefore, it can be very useful in the evaluation of government-initiated pollution control projects such as water purification plants, garbage recycling plants, and so on. But there is not much scope for government-financed air pollution control projects, except in government-operated enterprises, such as municipal incinerators and utilities. And, even these can be considered within the framework of the general analysis. A more promising variation of benefit-cost analysis is cost-effectiveness analysis. This technique can be used to evaluate the relative cost of achieving a given objective by alternative methods. However, because its use in air pollution control requires a large amount of data, its use has been fairly limited.

An alternative method of analyzing air pollution was suggested in this study. This method adapted the simple concepts of demand and supply to simulate a market for the use of air. This entailed an examination of the economic roles of the good or resource air. It was shown that one of the two categories of uses of air, the waste-disposal one, is competitive with the other one, the sustenance one - but not vice versa. Therefore, an increase in the use of air for waste-disposal purposes above some critical rate will diminish air quality. This establishes the scarcity of air in an economic sense. Hence, the use of air, contrary to traditional practice, should command a positive price. Yet, the impossibility of parcelling and appropriating air prevents the market from charging such a price. Nevertheless, the theoretically optimal price of air use was established. A case was made for charging such a price only to users of air for waste-disposal purposes. This was viewed as evidence that the right to the resource, air, should be assigned to potential pollutees rather than to polluters.

Since a true market for air cannot be implemented, it was recognized that, in practice, the price would have to be imposed in the form of a tax. The analysis, therefore, is only an alternative route for arriving at the same conclusions derived from the more traditional theory. It would be equally difficult, for example, to establish in practice what the optimum price should be as to establish what the optimum tax should be. Therefore, the (second) best attainable alternative would be to set prices of air use that would lead to the attainment of some given standard. Most of the study, therefore, was developed using the traditional framework and terminology.

Environmental pollution and its control obviously have distributive implications, as well as allocative ones. Yet, only a rudimentary analysis of these distributive aspects exists. The discussion in this study was limited to an exposition of the few ideas contained therein.

The argument for giving weight to distributive considerations in the implementation of pollution control policies is part and parcel of the general argument for income redistribution. But there is the additional fact that it is quite legitimate for society to use pollution control as an instrument of redistribution to the exclusion of more traditional ones, such as the redistribution of money income. That is, society may agree to redistribute income only if income is redistributed in the form of benefits from pollution control or of an alleviation of the burden of control costs. This could be done, for example, by selecting pollution control measures which favour low income groups to a greater extent than they do high income ones. Or, aside from the repartition of the benefits, it could be done by controlling pollution through policies which let the higher income groups shoulder a larger part of the costs of control. Since low income groups generally live in urban cores which are more severely polluted, any overall reduction in pollution, such that some uniform standard of air quality is satisfied, would probably redistribute welfare in favour of these groups. If emission taxes are used to control air pollution, however, the shouldering of the costs will depend on the pattern of consumption of different income groups. It can be expected that emission taxes will increase the prices of goods in proportion to the potential emissions which accompany their production. Therefore, the income groups which will shoulder more of the costs of pollution control are those that consume more of those goods. In other words, emission taxes will be shifted on the consumers of the products. A fruitful area of research, which could not be carried out here, is the assessment of the incidence of such potential taxes.

An attempt was made to estimate the order of magnitude of an emission tax which would lead to the reduction of emissions of one important type of pollutant, sulfur oxides. It was shown that sulfur oxides occur in Canadian urban areas in concentrations which exceed the standards which have been established in many localities. Also, based on a selection of the rather impressionistic data available, it was inferred that these concentrations are responsible for considerable damage to materials, human health, and so on. Again, it must be reiterated that, for reasons explained earlier, no truly satisfactory estimate of the potential benefits, or damage avoided, deriving from given reductions of emissions is possible or was attempted.

The calculation of a tax on the emissions of sulfur oxides necessary to achieve given reductions of emissions is comparatively easy because most emissions of sulfur oxides originate from stationary sources. Emissions from mobile sources, such as motor vehicles, are more difficult to deal with because the range of methods by which they can be reduced encompasses alternatives which imply radical changes in the economic life-style of present-day society. Reduction of pollution, in fact, may be only one of several factors which may call for those changes.

Emissions of sulfur oxides originate from two types of sources. The first, characterized by a large number of small and a few large individual sources, consists of emissions from the combustion of fossil fuels.[1] The methods by which these emissions could be reduced are fuel substitution (either of naturally-occurring lower-sulfur fuel or of desulfurized fuel), fuel-switching, or the capture of pollutants after combustion.

---

1 Emissions from this source account for about 22% of all emissions of sulfur oxides in Canada.

An emission tax would provide incentive to use any (presumably the cheapest, when possible) of these methods whenever the cost of doing so would be lower than the tax. The other type of source is a few easily identifiable industries. It was shown that only nine industries account for about 75% of all emissions of sulfur oxides in Canada. It is a relatively easy matter to examine the techniques which can be used in these industries to reduce emissions. Again, an emission tax would induce emitters to implement these techniques when doing so is cheaper than paying the tax.

One complication did arise. There is no guarantee that any specific technique, even if it is, generally speaking, the cheapest, can be always put into effect to reduce emissions from any individual source. For example, switching from the use of coal to that of natural gas may be the cheapest and most convenient abatement technique for a large power plant; but natural gas may not be available in the particular area where the plant is situated. It was not possible, as a result, to calculate <u>specific</u> taxes which would lead to given reductions in the overall amount of sulfur oxides emissions. Rather, a <u>range</u> of taxes necessary to achieve these reductions was estimated. Alternatively, the figures could be read as the range of reduction of emissions that could result from the imposition of a given tax.

Since the results are based on imperfect information, they should be taken as being indicative rather than definitive.

An attempt by policymakers to implement such a scheme should involve at least the following improvements upon the work done here.

1. An effort should be made to improve the quality of the data. To begin with, much of the data used here had to be transposed from American data without assurance that the transposition is always valid. Use of actual Canadian data would be preferable. People who would carry out research on behalf of the policymakers could be empowered with the means to obtain (from emitters, firms which sell pollution control equipment, etc.) information which was not available to the author.

In addition, of course, more up-to-date information regarding such things as fuel prices, byproduct prices, and costs of control would be required. These are all areas where changes are taking place at a fast pace.

2. In the study, it has been assumed that the same emission standards should apply to the whole of the country. Hence, the same emission tax would apply everywhere. This may not be desirable from the economic point of view, not to mention the constitutional difficulties which could arise in a federal country such as Canada. Society may not care very much about emissions which take place in sparsely populated areas and may be concerned to a larger extent about emissions in urban areas, where the potential damage of given pollutant concentrations is greater. Then, taxes should be higher in areas where a higher standard is desired. Of course, to find out the magnitude of these taxes, a detailed inventory of emissions in such areas is required.

3. Efforts should be made to estimate the marginal damage function of emissions. This would enable policymakers to impose a set of taxes such that the reduction of emissions would approximate the optimal one. Unfortunately, little work has been done to estimate the marginal damage function, especially on a pollutant-by-pollutant basis. The little work that has been done has been limited to estimates of the <u>total</u> costs of air pollution.

4. If it can be shown that emission taxes are appropriate and effective means of reducing emissions of other pollutants, and that the order of magnitude of such taxes can be determined, then a tax on the emissions of sulfur oxides will have to be part of a package. There will be trade-offs between reducing more of one pollutant and less of another (and the corresponding damage) or vice versa. These trade-offs will have to be determined and an appropriate package of taxes will have to be set. In the interim, however, taxation of individual pollutants, such as sulfur oxides, could be used.

BIBLIOGRAPHY

I. BOOKS

Baumol, W.J. Welfare Economics and the Theory of the State. 2nd edition. London: Bell and Sons, 1969.

Buchanan, J.M. Fiscal Theory and Political Economy. Chapel Hill: University of North Carolina Press, 1960.

Dales, J.H. Pollution, Property, and Prices. Toronto: University of Toronto Press, 1968.

Jarrett, H., ed. Environmental Quality in a Growing Economy. Baltimore: Resources for the Future, 1966.

Kneese, A.V., Ayres, R.V., and D'Arge, R.C. Economics and the Environment. Washington: Resources for the Future, 1970.

__________, and Bower, B.T. Managing Water Quality: Economics, Technology, and Institutions. Baltimore: The Johns Hopkins, 1968.

__________, eds. Environmental Quality Analysis. Baltimore: The Johns Hopkins Press, 1972.

McKean, R.N. Public Spending. New York: McGraw-Hill, 1968.

Mishan, E.J. Welfare Economics: Ten Introductory Essays. New York: Random House, 1969.

__________. Benefit and Cost Analysis. London: Allen and Unwin, 1971.

Olson, M. The Logic of Collective Action. Cambridge, Mass: Harvard University Press, 1965.

Pigou, A.C. The Economics of Welfare. 4th ed., London: Macmillan and Co., 1950.

Stern, A.C., ed. Air Pollution. 2nd ed. New York: Academic Press, 1968. 3 Vols.

Taylor, G.A. Managerial and Engineering Economy. New York: D. Van Nostrand. 1966.

Victor, P. Pollution: Economy and Environment. London: George Allen and Unwin, 1972.

II. PERIODICAL ARTICLES

Aalund, L. "Hydrodesulfurization Technology Takes On The Sulfur Challenge," Oil and Gas Journal, LXX (September 11, 1972), 79.

Alheritiere, D. "Les Problemes Constitutionels de la Lutte Contre la Pollution de l'Espace Atmospherique au Canada," The Canadian Bar Review, L (December, 1972), 561-579.

Audibert, F., and Havergne, J.C. "Upgrading Residues by the IFP Process," Chemical Engineering Progress, LXVII (August, 1971), 71-74.

Ayres, R.V., and Kneese, A.V. "Production, Consumption, and Externalities," American Economic Review, LIX (June, 1969), 282-297.

Barry, C.B. "Reduce Claus Sulfur Emissions," Hydrocarbon Processing, LI (April, 1972), 102-106.

Bassett, L.R., and Borchwerding, T.E. "Externalities and Output Taxes," Southern Economic Journal, XXXVI (April, 1970), 462-464.

Bates, D.V., et al. "Air Pollution and Chronic Bronchitis," Archives of Environmental Health, XIV (June, 1967), 220-224.

Bator, F.M. "The Simple Analytics of Welfare Maximization," American Economic Review, XLVII(March, 1957), 22-59.

__________. "The Anatomy of Market Failure," Quarterly Journal of Economics, LXXII (August, 1958), 351-379.

Baumol, W.J. "Taxation and the Control of Externalities," American Economic Review, LXII (June, 1972), 307-322.

__________, and Oates, W.E. "The Use of Standards and Prices for the Protection of the Environment," Swedish Journal of Economics, LXXIII (March, 1971), 42-54.

Benjamin, M. et al. "A General Description of Commercial Wood Pulping and Bleaching Processes," Journal of the Air Pollution Control Association, XIX (March, 1969), 155-161.

Bresler, S.A., and Ireland, J.D. "Substitute Natural Gas: Processes, Equipment, and Costs," Chemical Engineering, LXXIX (December 16, 1972), 94-108.

Brown, F.H.S. "The Prospects for Alternative Methods of Generation of Electric Power: A Comprehensive Review," Combustion, XXXVIII (May, 1967), 23-28.

Buchanan, J.M. "Joint Supply, Externality, and Optimality," Economica, XXXIII (November, 1966), 404-415.

__________. "Cooperation and Conflict in Public Goods Interaction," Western Economic Journal, V (March, 1967), 109-121.

__________. "A Behavioral Theory of Pollution," Western Economic Journal, VI (December, 1968), 347-358.

__________. "External Diseconomies, Corrective Taxes, and Market Structure," American Economic Review, LIX (March, 1969), 174-177.

__________, and Stubblebine, W.C. "Externality," Economica, XXIX (November, 1962), 371-384.

Calabresi, G. "Transaction Costs, Resource Allocation and Liability Rules - A Comment," Journal of Law and Economics, XI (April, 1968), 67-73.

Coase, R.H. "The Problem of Social Cost," Journal of Law and Economics, III (October, 1960), 1-44.

"Coping with Pollution is Tough for CPI," Canadian Chemical Processing, LVII (March, 1973), 27-30.

Cortelyou, C.G. "Commercial Processes for SO_2 Removal," Chemical Engineering Progress, LXV (September, 1969), 69-77.

Cover, A.E. et al. "Kellog's Coal Gasification Process," Chemical Engineering Progress, LIX (March, 1973), 31-36.

Davis, J.C. "SO_2 Removal Still Prototype," Chemical Engineering, LXXIX (June 12, 1972), 53-56.

Davis, O.A., and Whinston, A. "Externalities, Welfare, and the Theory of Games," Journal of Political Economy, LXX (June, 1962), 241-262.

De Alessi, L. "Implications of Property Rights of Government Investment Choices," American Economic Review, LIX (March, 1969), 13-24.

Desmetz, H. "Some Aspects of Property Rights," Journal of Law and Economics, IX (October, 1966), 61-70.

__________. "Toward a Theory of Property Rights," American Economic Review, LVII (May, 1967), 347-373.

__________. "Information and Efficiency: Another Viewpoint," Journal of Law and Economics, XII (April, 1969), 1-22.

Fraser, R.D. "Externalities and Corrective Taxes: A Comment," Canadian Journal of Economics, I (May, 1968), 473-475.

Freeman, Myrick A. III, and Haveman, R.H. "Residual Charges for Pollution Control: A Policy Evaluation," Science, CLXXVII (July 28, 1972), 322-329.

Gordon, Scott H. "The Economic Theory of Common Property Resource: The Fishery," Journal of Political Economy, LXII (April, 1954), 124-142.

Hazelbon, J.P., and Tennyson, R.N. "SNG Refinery Configurations," Chemical Engineering Progress, LXIX (July, 1973), 97-101.

Head, J.G. "Public Goods and Public Policy," Public Finance, XVII, No. 3 (1962), 197-220.

Hegarty, W.P., and Moody, B.E. "Evaluating the Bi-Gas SNG Process," Chemical Engineering Progress, LXIX, (March, 1973), 37-42.

Heubler, J. et al. "Pipeline Gas from Crude Oil," Chemical Engineering Progress, LXIX (May, 1973), 91-93.

H.M.M. "SO_2 Removal Technology Enters Growth Phase," Environmental Science and Technology, VI (August, 1972), 688-691.

Hunter, W.D., and Wright, J.P. "SO_2 Converted to Sulfur in Stackgas Cleanup Route," Chemical Engineering, LXXIX (October 2, 1972), 50-51.

J.P.H. "SNG: The Process Options," Chemical Engineering, LXXIX (April 17, 1972), 64-66.

Kneese, A.V. "Environmental Pollution: Economics and Policy," American Economic Review, Papers and Proceedings, XLI (May, 1971), 153-166.

Knight, F.H. "Some Fallacies in the Interpretation of Social Cost," Quarterly Journal of Economics, XXXVII (August, 1924), 582-606.

Kohn, R.E. "Linear Programming Model for Air Pollution Control: A Pilot Study of the St. Louis Airshed," Journal of the Air Pollution Control Association, XX (February, 1970), 78-82.

Lave, L.B., and Seskin, E.P. "Air Pollution and Human Health," Science, CLXIX (August 21, 1970), 723-733.

Leontief, W. "Environmental Repercussions and the Economic Structure: An Input-Output Approach," Review of Economics and Statistics, LII (August, 1970), 262-271.

Maas, A. "Benefit-Cost Analysis: Its Relevance to Public Investment Decisions," Quarterly Journal of Economics, LXXX (May, 1966), 208-226.

Maunce, W., and Rubin, R.S. "The H-Oil Route for Hydro-processing," Chemical Engineering Progress, LXVII (August, 1971), 81-85.

McKean, R.N., and Minasian, J.R. "On Achieving Pareto Optimality Regardless of Cost," Western Economic Journal, VII (December, 1969), 14-23.

Meredith, H.H. "Desulfurization of Caribbean Fuel," Journal of the Air Pollution Control Association, XVII (November, 1967), 719-723.

Mishan, E.J. "Reflections on Recent Developments in the Concept of External Effects," The Canadian Journal of Economics and Political Science, XXXI (February, 1965), 1-34.

__________. "Pareto Optimality and the Law," Oxford Economic Papers, XIX (November, 1967), 247-280.

__________. "The Relationship Between Joint Products, Collective Goods, and External Effects," Journal of Political Economy, LXXVII (May/June, 1969), 329-348.

__________. "The Postwar Literature on Externalities: An Interpretative Essay," Journal of Economic Literature, IX (March, 1971), 1-28.

Moore, J.A., and Ferguson, H. "Squeezing More Megawatts From Fewer BTUs," Power, CXII (February, 1968), 76-98.

Moritz, K.H. et al. "The GO-firing and RESID-firing Processes," Chemical Engineering Progress, LXVII (August, 1971), 63-70.

Morrow, N.L., and Brief, R.S. "Air Sampling and Analysis," Chemical Engineering, Deskbook Issue, LXXIX (May 8, 1972), 125-132.

"New Process Out for SO_2 Removal," Oil and Gas Journal, LXXI (June 15, 1973), 59.

Niskanan, W. "Non-market Decision Making: The Peculiar Economics of Bureaucracy," American Economic Review, LVIII (May, 1968), 293-305.

Oakland, W.H. "Joint Goods," Economica, XXXVI (August, 1969), 253-268.

Paradis, S.G. et al. "Isomax Process for Residuum and Whole Crude," Chemical Engineering Progress, LXVII (August, 1971), 57-62.

Plott, C.R. "Externalities and Corrective Taxes," Economica, XXXIII (February, 1966), 84-87.

Prest, A.R., and Turvey, R. "Cost-Benefit Analysis: A Survey," Economic Journal, LXXV (December, 1965), 683-735.

Putman, B., and Manderson, M. "Iron Pyrites from High Sulfur Coal," Chemical Engineering Progress, LXIV (September, 1968), 60-65.

Ridker, R.G., and Henning, J.A. "The Determinants of Residential Property Values," Review of Economics and Statistics, XLIX (May, 1967), 246-257.

Ross, S.S., and White, L.S. "International Pollution Control," Chemical Engineering, Deskbook Issue, LXXIX (May 8, 1972), 137-141.

Rothenberg, J. "The Economics of Congestion and Pollution: An Integrated View," American Economic Review, Papers and Proceedings, LXI (May, 1970), 114-121.

Samuelson, P.A. "The Pure Theory of Public Expenditure," Review of Economics and Statistics, XXXVI (November, 1954), 387-389.

__________. "Diagrammatic Exposition of a Theory of Public Expenditure," Review of Economics and Statistics, XXXVII (November, 1955), 347-356.

Scitovsky, T. "Two Concepts of External Economies," Journal of Political Economy, LXII (April, 1954), 143-151.

Shaw, I.S. "Pulp Plant Pollution Control," Chemical Engineering Progress, LXIV (September, 1968), 66-77.

Shearer, H.A. "The COED Process plus Char Gasification," Chemical Engineering Progress, LXIX (March, 1973), 43-49.

Squires, A.M. "Air Pollution: The Control of SO_2 from Power Stacks, Part I - The Removal of Sulfur from Fuels," Chemical Engineering, LXXIV (November, 1967), 260-268.

Turvey, R. "On Divergencies between Social Cost and Private Cost," Economica, XXX (August, 1963), 309-312.

Viner, J. "Cost Curves and Supply Curves," Zeitschrift fur National Okonomie, III (September, 1931), 23-46.

Watkins, C.H. "Desulfurize Kuwait Reduced Crude," Hydrocarbon Processing, LII (May, 1973), 89-92.

Watkins, C.H., and Czajkowski, C.J. "Hydro-desulfurization of Gas Oils," Chemical Engineering Progress, LXVII (August, 1971), 75-80.

Wenders, J.T. "Profit Maximization, Pollution Abatement, and Corrective Taxes," Journal of Economic Issues, VI (September, 1972), 137-140.

Zerbe, R.O. "Theoretical Efficiency in Pollution Control," Western Economic Journal, VIII (December, 1970), 364-376.

III. GOVERNMENT PUBLICATIONS

A. Canada

City of Montreal, Department of Health, La Pollution de L'Air par l'Anhydride Sulfureux et les Particules Aeroportees. Montreal, 1970.

Cote, P.R. Canadian Elemental Sulfur from Sour Natural Gas. Mineral Bulletin MR 121. Ottawa: Mineral Resources Branch, Department of Energy, Mines, and Resources, 1972.

Davis, J. Canada's Energy Prospects. Royal Commission on Canada's Economic Prospects. Ottawa: Queen's Printer, 1957.

Department of Energy, Mines, and Resources, Mineral Resources Branch, Canadian Mineral Yearbook, 1970. Ottawa, 1972.

________. Metallurgical Works in Canada, Non-ferrous and Precious Metals, January, 1971. Operators List 1. Ottawa, March, 1971.

________. Natural Gas Processing Plants in Canada, January 1971. Operators List 7. Ottawa, March, 1971.

________. Petroleum Refineries in Canada, January 1971. Operators List 5. Ottawa, March, 1971.

Department of Industry, Trade, and Commerce. Canadian Chemical Register, 1971. Ottawa: Information Canada, 1971.

Dibbs, H.P. Methods for the Removal of Sulfur Dioxide from Waste Gases. Department of Energy, Mines, and Resources, Mines Branch. Information Circular IC272. Ottawa: Information Canada, November, 1971.

Dominion Bureau of Statistics. Electricity Bills for Domestic, Commercial, and Small Power Service, 1969. Catalogue 57-203. Ottawa: Queen's Printer, February, 1971.

__________. Electric Power Statistics, 1969, Vol. III. Inventory of Prime Mover and Electric Generating Equipment. Catalogue 57-504. Ottawa: Information Canada, March, 1971.

__________. Household Facilities and Equipment, May, 1969. Catalogue 64-202. Ottawa: Queen's Printer, 1970.

__________. Pulp and Paper Mills, 1967. Catalogue 36-204. Ottawa: Queen's Printer, September, 1969.

Environment Canada. A Nationwide Inventory of Air Pollutant Emissions, 1970. Ottawa, January, 1973.

__________. A Nationwide Inventory of Air Pollutant Emissions. Summary of Emissions for 1970. Ottawa, January, 1973.

Friedrich, F.D., and Mitchell, E.R. First Addendum to Mines Branch Information Circular IC211: Air Pollution in Canada from Fuel Combustion. Ottawa: Department of Energy, Mines, and Resources, May, 1970.

Mitchell, E.R. Inventories of National and Individual Air Pollution. Information Circular IC269. Ottawa: Department of Energy, Mines, and Resources, Mines Resources Branch, 1971.

National Energy Board. Energy Supply and Demand in Canada, 1966-1990. Ottawa: Information Canada, 1971.

Ontario, Department of the Environment. Air Quality Monitoring Report, 1970. Toronto, 1970.

Statistics Canada. Detailed Energy Supply and Demand in Canada, 1958-1969. Catalogue 57-505. Ottawa: Information Canada, November, 1972.

__________. Electric Power Statistics, 1969. Vol. II. Catalogue 57-202. Ottawa: Information Canada, June, 1972.

__________. Energy Statistics. Service Bulletin, Vol. 6, No. 50. Ottawa: Information Canada, October, 1971.

__________. Gas Utilities, 1969. Catalogue 57-205. Ottawa: Information Canada, April, 1973.

__________. Manufacturers of Industrial Chemicals, 1970. Catalogue 46-219. Ottawa: Information Canada, January, 1973.

Statistics Canada. Prices and Price Indexes, August, 1972. Catalogue 62-002. Ottawa: Information Canada, October, 1972.

__________. Pulp and Paper Mills, 1970. Catalogue 36-204. Ottawa: Information Canada, August, 1972.

__________. Smelting and Refining, 1971. Catalogue 41-214. Ottawa: Information Canada, June, 1973.

Visman, J. The Coal Washery Design - The E.M.R. Process. Technical Bulletin TB 141. Ottawa: Department of Energy, Mines, and Resources, Mines Branch, September, 1971.

B. United States

Arthur D. Little, Inc. A Study of Process Costs and Economics of Pyrite Coal Utilization. Cambridge, Mass. Prepared for the Department of Health, Education, and Welfare, Contract No. PH86-27-258, March, 1968.

Arthur G. McKee & Co. Systems Study for Control of Emissions, Primary Non-Ferrous Smelting Industry. San Francisco, Ca. Prepared for the National Air Pollution Control Administration, Public Health Service, Department of Health, Education, and Welfare, Contract No. 86-65-85, May, 1969. 3 Vols.

Barnes, T.M. Evaluation of Process Alternatives to Improve Control of Air Pollution from Production of Coke. Final Report prepared for the Department of Health, Education, and Welfare, National Air Pollution Control Administration. Columbus, Ohio: Battelle Memorial Institute, January 31, 1970.

Bituminous Coal Research. An Evaluation of Coal Cleaning Processes and Techniques for Removing Pyritic Sulfur from Fine Coal. Monroeville, Pa. Prepared for the Air Pollution Control Office, Environmental Protection Agency, Contract No. CPA 70-26, April, 1971.

Department of Health, Education, and Welfare, Public Health Service. Air Quality Criteria for Sulfur Oxides. National Air Pollution Control Administration Publication No. AP-50. Washington: U.S. Government Printing Office, 1969.

__________. Control Techniques for Sulfur Oxide Air Pollutants. National Air Pollution Control Administration Publication No. AP-52. Washington: U.S. Government Printing Office, 1969.

Department of Health, Education, and Welfare, Public Health Service. National Emission Standards Study. Report Appendix. A Report to the Congress of the United States by the Secretary of Health, Education, and Welfare. March, 1970. 3 Vols.

Ehrenfeld, J.R. et al. Systematic Study of Air Pollution from Intermediate-Size Fossil-Fuel Combustion Equipment. Prepared for the Environmental Protection Agency, Contract No. CPA 22-69-85. Cambridge, Mass.: Wolden Research Corporation, July, 1971.

Environmental Protection Agency, Office of Air Programs, Compilation of Air Pollutant Emission Factors. Publication No. AP-42. Washington: U.S. Government Printing Office, February, 1972.

Environmental Quality. The Third Annual Report of the Council and Environmental Quality. Washington: U.S. Government Printing Office, 1972.

Ernst & Ernst. A Cost-Effectiveness Study of Air Pollution in the National Capital Area. Report prepared for the U.S. Department of Health, Education, and Welfare, National Air Pollution Control Administration, Contract No. PH 86-68-37. Washington: Ernst & Ernst, January, 1969.

__________. The Fuel of Fifty Cities. Report prepared for Department of Health, Education, and Welfare, National Air Pollution Control Administration. Washington: Ernst & Ernst, November, 1968.

Hendrickson, E.R. et al. Control of Atmospheric Emissions in the Wood Pulping Industry. Final Report prepared for the Department of Health, Education, and Welfare, National Air Pollution Control Administration, Contract No. CPA 22-69-18. Gainsville, Fla.: Environmental Engineering, Inc., March 15, 1970. 3 Vols.

Hittman Associates, Inc. Cost Nomographs of Selected Sulfur Dioxide Abatement Methods. Prepared for the Environmental Protection Agency, Office of Air Programs, Contract No. EHSD-71-43. Columbia, Md.: Hittman Associates, Inc., January, 1972.

Hoffman, L. et al. The Physical Desulfurization of Coal - Major Considerations of SO_2 Emission Control. Prepared for the Department of Health, Education, and Welfare, National Air Pollution Control Administration, Contract No. F196228-68-C-0365. McLean, Va.: Mitre Corp., November, 1970.

Le Sourd, D.A. et al. Comprehensive Study of Specified Air Pollution Sources to Assess the Economic Effects of Air Quality Standards. Final Report Prepared for Environmental Protection Agency, Air Pollution Control Office, Contract No. CPA 70-60. Research Triangle Park, N.C.: Research Triangle Institute, December, 1970.

M.W. Kellog Co. Evaluation of SO_2 - Control Processes. Final Report Submitted to Environmental Protection Agency, Office of Air Programs, Contract No. CPA 70-68. Piscataway, N.J.: M.W. Kellog Co., October 15, 1971.

Stern, A.C., ed. Proceedings of Symposium on Multiple-Source Urban Diffusion Models. U.S. Environmental Protection Agency, Air Pollution Control Office Publication No. AP-86. Washington: U.S. Government Printing Office, 1970.

The Cost of Clean Air. First Report of the Secretary of Health, Education, and Welfare to the Congress of the United States. Washington: U.S. Government Printing Office, 1969.

The Economics of Clean Air. Annual Report of the Administrator of the Environmental Protection Agency. Washington: U.S. Government Printing Office, March, 1972.

The Economic Impact of Pollution Control. A Summary of Recent Studies. Prepared for the Council on Environmental Quality, and Environmental Protection Agency. Washington: U.S. Government Printing Office, March, 1972.

TRW Systems Group. Air Pollutant Emissions Factors. Prepared for the Department of Health, Education, and Welfare, National Air Pollution Control Administration, Contract No. CPA 22-69-119. McLean, Va.: TRQ Systems Group, April, 1970.

__________. Air Pollutant Emission Factors. Supplement. Prepared for the Department of Health, Education, and Welfare, National Air Pollution Control Administration, Contract No. CPA 22-69-119. McLean, Va.: TRW Systems Group, August, 1970.

United States Congress, Joint Economic Committee. The Analysis and Evaluation of Public Expenditures: The PBB System. Washington: U.S. Government Printing Office, 1969. 3 Vols.

United States Senate, Committee on Interior and Insular Affairs. Summary Report of the Cornell Workshop on Energy and the Environment. Washington: U.S. Government Printing Office, May, 1972.

__________, Committee on Public Works. Some Environmental Implications of National Fuel Policies. Washington: U.S. Government Printing Office, December, 1970.

IV. ESSAYS IN COLLECTIONS

Arrow, K.J. "The Organization of Economic Activity: Issues Pertinent to the Choice of Market Versus Nonmarket Allocation," in U.S. Congress, Joint Economic Committee, The Analysis and Evaluation of Public Expenditures: The The PBB System. Vol. I. Washington: U.S. Government Printing Office, 1969.

Browder, T.J. "Modern Sulfuric Acid Technology," in Sulfur and SO_2 Developments. New York: American Institute of Chemical Engineers, 1971, 91-96.

Buchanan, J.M. "Positive Economics, Welfare Economics, and Political Economy," in his Fiscal Theory and Political Economy. Chapel Hill, N.C.: University of North Carolina Press, 1960, 105-124.

Burleigh, J.R. "SO_2 Emission Control from Acid Plants," in Sulfur and SO_2 Developments. New York: American Institute of Chemical Engineers, 1971, 103-109.

Charles Rivers Associates, Inc. "Aluminum," in The Economic Impact of Pollution Control. A Summary of Recent Studies. Environmental Protection Agency. Washington: U.S. Government Printing Office, March, 1972, 169-190.

Engdahl, R.B. "Stationary Combustion Sources," in A.C. Stern, ed., Air Pollution, 2nd ed. Vol. I. New York: Academic Press, 1968, 3-54.

Freeman, A. Myrick III. "Distribution of Environmental Quality," in A.V. Kneese, and B.T. Bower, eds., Environmental Quality Analysis. Baltimore: The Johns Hopkins Press, 1972, 243-278.

Kneese, A.V., and D'Arge, R.C. "Pervasive External Costs and the Response of Society," in U.S. Congress, Joint Economic Committee, The Analysis and Evaluation of Public Expenditures: The PBB System. Vol. I. Washington: U.S. Government Printing Office, 1969, 87-115.

Lave, L.B. "Air Pollution Damage: Some Difficulties in Estimating Value of Abatement," in A.V. Kneese, and B.T. Bower, eds., Environmental Quality Analysis. Baltimore: The Johns Hopkins Press, 1972, 213-241.

Mishan, E.J. "Loss of Life and Limb," in his Benefit and Cost Analysis. London: Allen and Unwin, 1971, 153-174.

Shah, I. "Removing SO_2 and Acid Mist with Venturi Scrubbers," in _Sulfur and SO_2 Developments_. New York: American Institute of Chemical Engineers, 1971, 97-102.

Steiner, P.O. "The Public Sector and the Public Interest," in U.S. Congress, Joint Economic Committee, _The Analysis and Evaluation of Public Expenditures: The PBB System_. Vol. I. Washington: U.S. Government Printing Office, 1969.

Turvey, R. "The Side Effects of Resource Use," in H. Jarrett, ed., _Environmental Quality in a Growing Economy_. Baltimore: Resources for the Future, 1966.

Weisbrod, B.A. "Collective Action and the Distribution of Income: A Conceptual Approach," in U.S. Congress, Joint Economic Committee, _The Analysis and Evaluation of Public Expenditures: The PBB System_. Washington: U.S. Government Printing Office, 1969, 177-197.

V. OTHER SOURCES

Corporation des Maitres Mechaniciens du Quebec. _Etude Experimentale de la Consommation d'Energie dans les Maisons Unifamilliales Munies de Divers Systemes de Chauffage_. Mimeographed, 1971.

Frank R. Volvoda and Associates. _An Analysis of Cost Factors Associated with Oil-Fired Heating Systems_. Mimeographed, 1969.

Gow, W.A. _Estimates of Sulfur Present in Sulfide Concentrates Treated in Canadian Smelters_. Mimeographed, January 15, 1970.

Hedlin Menzies & Associates. _Initial Study of the Dimension of Pollution in Canada_. Mimeographed, July, 1969.

Private Communication with D. Dexter, Statistics Canada.

Private Communication with B. Duthie, Statistics Canada.

Private Communication with D. Morgan, National Energy Board.

Private Communication with E.R. Mitchell, Department of Energy, Mines, and Resources.

Sulfur and SO_2 Developments. New York: American Institute of Chemical Engineers, 1971.

APPENDIX A

UNITS OF MEASUREMENT, STOICHIOMETRIC PROPORTIONS, AND ENERGY CONVERSION FACTORS

The following units of measurement, stoichiometric proportions, and energy conversion factors underly the calculations in the text.

UNITS OF MEASUREMENT

COAL - Short Ton	= 2000 lbs.
FUEL OIL - Barrel	= 35 Canadian gallons.
	= 42 American gallons.
Gallon	= (10 x Specific Gravity) lbs.
NATURAL GAS - Mcf.	= 1000 cubic feet at 760 mm Hg. and 60°F.
ELECTRICITY - Kwh.	= Kilowatt - hour.
SULFUR OXIDES - Short Ton	= 2000 lbs.

STOICHIOMETRIC PROPORTIONS

SULFUR DIOXIDE (SO_2) - 64/32 = 2

SULFUR TRIOXIDE (SO_3) - 80/32 = 2.5

These proportions show that a lb. of sulfur which would burn to SO_2 or to SO_3 completely would produce 2 lbs. of SO_2 or 2.5 lbs. of SO_3.

ENERGY CONVERSION FACTORS

Table A-1 summarizes the energy conversion factors used. The energy of fuels is expressed in British Thermal Units (BTU) or a multiple, million BTUs (MBTU). A BTU is the energy required to raise the temperature of one lb. of water by one degree Farenheit.

TABLE A-1

ENERGY CONVERSION FACTORS

FUEL	UNIT	ENERGY CONVERSION FACTOR (MBTU)
Anthracite Coal	Ton	25.4000
Imported Bituminous Coal	Ton	25.8000
Canadian Bituminous Coal	Ton	25.2000
Kerosene	Barrel	5.6770
Light Fuel Oil	Barrel	5.8275
Heavy Fuel Oil	Barrel	6.2874
Natural Gas	Mcf.	1.0700/1.0000
Manufactured Gas	Mcf.	0.550
Electricity	1000 Kwh.	3.4120

Sources: Statistics Canada, Detailed Energy Supply and Demand in Canada, 1958-1969, (Ottawa: Information Canada, November, 1972), p. 3. J. Davis, Canada Energy Prospects, Royal Commission on Canada's Economic Prospects, (Ottawa: Queen's Printer, 1957), p. 366.

APPENDIX B

PRICES OF FUELS

Whenever fuel switching or fuel substitution are considered as possible techniques of abatement of emissions from the combustion of fuels, it is necessary to compare the (say, annual) costs of different fuels. Therefore, the prices of fuels must be known. Unfortunately, such information is not always straight-forward. The information that can be more readily obtained is the retail price of fuels. But, the most important consumers of these fuels, such as commercial, institutional, industrial, and power plant users rarely pay these prices. Usually, the price of the fuel varies according to the type of user. Moreover, the price of fuels varies with the area and other factors, including, in some cases, sulfur content. Since all of these variables would be quite difficult to handle, an attempt is made here to estimate average prices to each type of user of each fuel, recognizing that such price is an average of not one but of all sorts of things.

COAL

Table B-1 lists the retail price of coal in selected areas in 1968 (the latest year for which, according to Statistics Canada, the figures are available).

Presumably, small buyers of coal pay these prices. However, in 1969, twenty industry groups purchased 4,083,547 tons of bituminous coal (of which 1,678,514 tons was domestic and 2,405,033 tons was imported coal).[1] The total cost of this coal to these twenty industry groups was $49,271,000. Hence, the average cost per ton to these industries was $12 per ton. It is assumed here that this is the average price for industrial coal in 1969.

Since it was not possible to estimate the average price of coal to commercial-institutional users, it was assumed that they pay the same price as industrial users, that is, $12 per ton.

On the other hand, in 1969, power plants purchased a total of 11,873,750 tons of coal at a total cost of $76,368,754.[2] This works out to an average cost per ton of $6.40.

LIGHT FUEL OIL (RESIDENTIAL)

Table B-2 shows the retail prices of light fuel oil in twelve Canadian cities in August 1972. The average retail price of light fuel oil in Canada in 1969 was estimated to be the unweighed average of these prices deflated by the increase in the price index of light fuel oil between December, 1969, and August, 1972. This index was: December, 1969 = 114.0; August, 1972 = 133.4.[3] This yielded an estimated price of

1 Statistics Canada, Energy Statistics, Service Bulletin, Vol. 6, No. 50, (Ottawa: Information Canada, October, 1971), pp. 5-6.

2 Statistics Canada, Electric Power Statistics, 1969, Vol. II, (Ottawa: Information Canada, June, 1972), p. 36.

3 Statistics Canada, Prices and Price Indexes, August, 1972, (Ottawa: Information Canada, October, 1972), p. 36.

TABLE B-1

AVERAGE RETAIL PRICES OF COAL - CANADA, 1968

LOCATION	TYPE OF COAL	PRICE ($/TON)
St. John's	Domestic Bituminous (Screened)	16.00
Halifax	Domestic Bituminous (Screened)	17.40
St. John	Domestic Bituminous (Screened)	17.74
Toronto	U.S. Bituminous (Stoker)	16.79
Toronto	U.S. Bituminous (Slack)	11.89
Montreal	U.S. Bituminous (Slack)	13.09
Montreal	Domestic Bituminous (Slack)	13.79

Source: Private communication with B. Duthie, Statistics Canada.

19.6¢/gal. It was assumed that this is the price which residential users paid for light fuel oil.

HEAVY FUEL OIL (RESIDENTIAL)

The only information which the author could obtain concerning the retail price of heavy fuel oil was the average price of this fuel containing 1.75% to 2% sulfur in Montreal and in Toronto in January, 1971. These prices were 10.3¢/gal. and 12.3¢/gal., respectively.[1] The average retail price of heavy fuel oil in Canada in 1969 was estimated to be the unweighed average of these two prices, deflated by the increase in the price index of heavy fuel oil between December, 1969, and January, 1971. This index was: December, 1969 = 100.9; January, 1971 =

1 Private communication with D. Morgan, National Energy Board.

119.2.[1] This yielded an estimated average retail price of heavy fuel oil in 1969 of 9.5¢/gal. It was assumed that residential users paid this price.

TABLE B-2

AVERAGE RETAIL PRICES OF LIGHT FUEL OIL
CANADA, AUGUST, 1972

CITY	PRICE (¢/GAL.)
St. John's	27.9
Halifax	22.7
Saint John	22.7
Quebec	23.4
Montreal	22.9
Ottawa	24.0
Toronto	22.9
Thunder Bay	24.2
Winnipeg	19.9
Regina	19.8
Edmonton	20.2
Vancouver	23.3
Average	22.8

Source: Private communication with D. Dexter, Statistics Canada.

1 Statistics Canada, Prices and Price Indexes, p. 36.

LIGHT FUEL OIL (POWER PLANTS)

In 1969, power plants purchased 19,913,624 gallons of light fuel oil at total cost of $2,573,044.[1] This works out to an average cost of 13¢/gal. It was assumed that this is the price paid by power plants.

HEAVY FUEL OIL (POWER PLANTS)

In 1969, power plants purchased 367,667,050 gallons of heavy fuel oil at a total cost of $23,093,481.[2] This works out to an average cost of 6¢/gal. It was assumed that this is the price paid by power plants.

LIGHT AND HEAVY FUEL OIL (INDUSTRIAL)

In 1969, twenty industry groups purchased 1,963,000 millions of gallons of heavy and light fuel oil at a total cost of $164,247,000.[3] This works out to an average cost of 8.4¢/gal. No breakdown between light and heavy fuel oil was given. Therefore, the average price of each of these fuels had to be estimated.

Power plants, as shown above, spent $22,666,525 for 387,580,674 gallons of light and heavy fuel oil. This works out to an average of 6.6¢/gal. It was assumed that the price ratios of light and heavy fuel oil to fuel oil of both kinds was the same for industrial as for power plants. These ratios

---

1 Statistics Canada, <u>Electric Power Statistics</u>, p. 36.

2 <u>Ibid</u>.

3 Statistics Canada, <u>Energy Statistics</u>, p. 11.

were:

Light fuel oil - 13/6.6 = 2.0

Heavy fuel oil - 6/6.6 = 0.9

Following this procedure, it was estimated that the price paid by industrial customers for fuel oil was the following:

Light fuel oil - 8.4 x 2.0 = 16.8¢/gal.

Heavy fuel oil - 8.4 x 0.9 = 7.6¢/gal.

HEAVY AND LIGHT FUEL OIL (COMMERCIAL)

Since there was no way to estimate the price which commercial customers paid for heavy and light fuel oil, it was assumed that these prices were the same prices paid by industrial customers; that is, 16.8¢/gal. for light fuel oil and 7.6¢/gal. for heavy fuel oil.

NATURAL GAS

The average price of natural gas was taken to be the average revenue from total sales of natural gas to each type of customer. In 1969, this average was:

Residential customers - $1.04/Mcf.[1]

Commercial customers - $0.71/Mcf.[2]

---

1 Statistics Canada, Gas Utilities, 1969, (Ottawa: Information Canada, April, 1973), p. 13. This publication includes gas sold to power plants under the category "industrial." Therefore, the price paid for natural gas by industrial and power plants was estimated independently (see below).

2 Ibid.

Industrial customers - \$0.43/Mcf.[1]

Power Plants - \$0.20/Mcf.[2]

SUBSTITUTE NATURAL GAS (SNG)

It was assumed in the text and it is assumed here that industries and power plants are taking all of the natural gas which can now be supplied to them. Therefore, barring some unforeseen discovery of large new reserves of natural gas, large increases in the use of gas through fuel switching will have to take place by supplying these users with manufactured gas. The most promising source of this gas, in terms of technology and economics, is the gasification of coal. Several processes are capable of producing pipeline quality gas (*inter alia*, containing only traces of sulfur), by gasifying coal.[3]

---

1 The industrial price of natural gas was taken to be the average cost of natural gas to twenty industry groups. See, Statistics Canada, *Energy Statistics*, p. 13.

2 The average price paid by power plants was taken to be the average cost of natural gas to power plants. See, Statistics Canada, *Electric Power Statistics*, p. 36.

3 See, for example, A.E. Cover *et al.*, "Kellogg's Coal Gasification Process," *Chemical Engineering Progress*, LIX (March, 1973), pp. 31-36. W.P. Hegarty and B.E. Moody, "Evaluating the Bi-Gas SNG Process," *Chemical Engineering Progress*, LIX (March, 1973), pp. 37-42. H.A. Shearer, "The COED Process plus Char Gasification," *Chemical Engineering Progress*, LIX (March, 1973), pp. 43-49. S.A. Bresler and J.D. Ireland, "Substitute Natural Gas: Processes, Equipment and Costs," *Chemical Engineering*, LXXIX (December 16, 1972), pp. 94-108. J.H.P. "SNG: The Process Options," *Chemical Engineering*, LXXIX (April 17, 1972), pp. 64-66.

This gas is frequently referred to as Substitute Natural Gas (SNG).[1] The estimated price at which such gas would sell varies from $0.66 to $1.64 per MBTU.[2] In the light of these estimates and the price differentials which are observed with respect to other fuels between power plants and industries, it seems reasonable to assume that industries will pay a price of $1.10/MBTU for this gas and power plants a price of $0.90/MBTU.[3]

ELECTRICITY

As with other fuels, the price of electricity varies across the country and, in the same area, it varies according to the type of customer and the amount of electricity used per period of time. Usually, rates vary in a step function manner. These rates are not readily available and, therefore, the average price of electricity must be estimated. For our purposes, we will need estimate only the price of electricity paid by residential customers.

---

1 It is estimated that large scale production of SNG will commence by 1980 in the United States. See, U.S. Senate, Committee on Public Works, Some Environmental Implications of National Fuels Policies, (Washington: U.S. Government Printing Office, 1970), p. 11.

2 See publications in footnote 3 on previous page.

3 Prices approximately in this range have also been forecast for SNG produced from crude oil. See, J. Heubler et al., "Pipeline Gas from Crude Oil," Chemical Engineering Progress, LIX (May, 1973), pp. 91-93, and J.P. Hazelbon and R.N. Tennyson, "SNG Refinery Configurations," Chemical Engineering Progress, LIX (July, 1973), pp. 97-101.

It was judged that an adequate estimate of the price of the additional electricity required to switch from fuel oil to electricity for purposes of residential space heating would be the increase in the average electricity bill divided by the additional electricity used. The cost per Kwh of electricity in Canada in 1969 was taken to be the unweighed average of using 5000 Kwh per month in twelve Canadian cities. This average monthly bill, the actual 1969 average monthly domestic consumption of electricity, and the cost of electricity per Kwh are summarized in Table B-3. Most residential customers in these (and other) cities used an average amount of electricity which was between 400 and 700 Kwh. Since switching to electric space heating would have added on an estimated 3050 Kwh per month (as estimated in the text), then 5000 Kwh per month is a close enough approximation of the electricity consumption by the residential user for the purpose of estimating the rates he would have to pay.

Table B-4 summarizes the prices of fuels by type of user in Canada, in 1969, as estimated in this Appendix. These are the prices which are used in the text to calculate the cost of fuel switching as a technique of abatement.

TABLE B-3

COST OF ELECTRICITY - CANADA, 1969

CITY	AVERAGE MONTHLY CONSUMPTION (Kwh)	MONTHLY BILL BASED ON 5000 Kwh. ($)	COST PER Kwh (¢/Kwh)
St. John's	618	67.77	1.35
Halifax	499	70.50	1.41
Saint John	315	69.50	1.38
Montreal	538	55.62	1.11
Quebec	600	55.62	1.11
Hamilton	530	50.00	1.10
Ottawa	734	81.86	1.63
Toronto	486	54.40	1.09
Winnipeg	931	42.47	0.84
Regina	440	73.38	1.46
Edmonton	391	52.00	1.04
Vancouver	394	57.23	1.14
Average			1.22

Source: Dominion Bureau of Statistics, Electricity Bills for Domestic, Commercial, and Small Power Service, (Ottawa: Queen's Printer, 1971).

TABLE B-4

PRICES OF FUELS BY USER - CANADA, 1969

FUEL	RESIDENTIAL	COMMERCIAL	INDUSTRIAL	POWER PLANTS
Coal ($/Ton)	-	12.0	12.0	6.4
Light Fuel Oil (¢/Gal)	19.6	16.8	16.8	13.0
Heavy Fuel Oil (¢/Gal)	9.5	7.6	7.6	6.0
Natural Gas ($/Mcf)	1.04	0.71	0.43	0.2
Substitute Natural Gas ($/MBTU)	-	-	1.10	0.90
Electricity (¢/Kwh)	1.22	-	-	-

APPENDIX C

COST OF FUEL DESULFURIZATION

One technique for reducing emissions of sulfur oxides is fuel substitution. Whenever naturally occurring low-sulfur fuels are not available to carry out the substitution, it may be possible to produce such low-sulfur fuels by removing some of the sulfur from high-sulfur fuels.

This Appendix attempts to assess the costs of desulfurizing coal and fuel oil. It is assumed that all of these costs will be passed on to the fuel buyer and that, therefore, they are the price differentials which the fuel buyer must pay.[1] These price differentials will be used in the text to calculate the costs of abatement through fuel substitution.

COAL

Several studies indicate that the sulfur content of coal can be reduced to about 1 per cent.[2] It seems that a realistic

---

1 The fact that it is probable that the desulfurized fuel will have a slightly higher energy content and, therefore, reduce somewhat the cost to the fuel buyer will be disregarded here.

2 See, L. Hoffman *et al.*, The Physical Desulfurization of Coal - Major Considerations of SO_2 Emissions Control, (McLean: Mitre Corp., November, 1970). Bituminous Coal Research, An Evaluation of Coal Cleaning Processes and Techniques for Removing Pyritic Sulfur from Fine Coal, (Monroeville: Bituminous Coal Research, April, 1971). J. Visman, The Coal Washery Design - The E.M.R. Process, (Ottawa: Mines Branch, Dept. of Energy, Mines, and Resources, September, 1971). Visman claims that the E.M.R. Process is designed especially for cleaning the highly friable coals found in Western Canada.

measure of doing so is about 90¢ per ton of coal.[1] This figure is also approximately equal to the premium which users can be expected to pay for naturally occurring coal containing one per cent sulfur or less.[2]

HEAVY FUEL OIL

As assumed in the text, heavy fuel oil now contains an average of about 2.5% sulfur. The technical literature suggests that available technology, such as hydrodesulfurization (HDS), is capable of reducing this sulfur content considerably.[3] A

---

1 See publications in the previous footnote. Visman, for example, estimates the cost of the cleaning process to vary from 76¢ to $1.00 per ton depending on the size of the cleaning plant. See, also, D.A. LeSourd et al., Comprehensive Study of Specified Air Pollution Sources to Assess the Economic Effects of Air Quality Standards, (Research Triangle Park: Research Triangle Institute, December, 1970), pp. 14-16.

2 See, for example, Arthur D. Little, Inc., A Study of Process Costs and Economics of Pyrite Coal Utilization, (Cambridge, Mass.: Arthur D. Little, Inc., March, 1968).

3 See, U.S. Department of Health, Education, and Welfare, Public Health Service, Control Techniques for Sulfur Oxide Air Pollutants, (Washington: U.S. Government Printing Office, 1969), pp. 40-48. A.M. Squires, "Air Pollution: The Control of SO_2 from Power Stacks. Part 1 - The Removal of Sulfur from Fuels," Chemical Engineering, LXXIV (November 6, 1967), pp. 260-268. H.H. Meredith, "Desulfurization of Caribbean Fuel," Journal of the Air Pollution Control Association, XVII (November, 1967), pp. 719-723. S.G. Paradis et al., "Isomax Process for Residuum and Whole Crude," Chemical Engineering Progress, LXVII (August, 1971), pp. 57-62. K.H. Moritz et al., "The GO-firing and RESID-firing Processes," Chemical Engineering Progress, LXVII (August, 1971), pp. 63-70. F. Audibert and J.C. Havergne, "Upgrading Residues by the IFP Process," Chemical Engineering Progress, LXVII (August, 1971), pp. 71-74. C.H. Watkins and C.J. Czajkowski, "Hydro-desulfurization of Gas Oil," Chemical Engineering Progress, LXVII (August, 1971), pp. 75-80. W. Maunce and R.S. Rubin, "The H-Oil Route for Hydroprocessing," Chemical Engineering Progress, LXVII (August, 1971), pp. 81-85.

summary of the most promising of the various processes of desulfurization, the sulfur content of the processed product, and recent estimates of the costs entailed by these processes has been reported by L. Aalund, Refining Editor of the Oil and Gas Journal.[1] These are reproduced in Table C-1 (columns 2, 3, and 4). Column 5 was estimated from column 4, given the energy conversion factors (see Appendix A).

From these figures and from others reported in the technical literature,[2] it seems reasonable to assume that the costs of desulfurization of heavy fuel oil will be:

(i) to 1% sulfur - 15¢/MBTU;

(ii) to 0.25% sulfur - 27¢/MBTU.

LIGHT FUEL OIL

As assumed in the text, light fuel oil has an average sulfur content of 0.7%. From the figures in Table C-1, it seems reasonable to assume that the cost of reducing the sulfur content to 0.25% will be 8¢/MBTU.

Table C-2 summarizes the costs of desulfurizing fuels as estimated in this appendix, both in terms of physical and of energy units. These costs are used in the text to estimate the cost of abatement of emissions of sulfur oxides through

---

1 L. Aalund, "Hydrodesulfurization Technology Takes on the Sulfur Challenge," Oil and Gas Journal, LXX (September 11, 1972), p. 79. The same issue of this Journal contains short articles by the developers of the processes, Chevron, Esso, Gulf, Standard Oil, etc., explaining the nature of the processes.

2 See publications in the footnote above.

TABLE C-1

COST OF FUEL OIL DESULFURIZATION

SOURCE OF CRUDE OIL	PROCESS	SULFUR IN PRODUCT (%)	COST (CENTS/BARREL)	COST (CENTS/MBTU)
(1)	(2)	(3)	(4)	(5)
Kuwait	Direct Residuum HDS	1.0	95-110	15-17
Kuwait	Solvent Deasphalting	1.1	86-96	14-15
Kuwait	Indirect Vacuum Gas Oil HDS	2.6	43-47	7
Venezuela	Indirect Vacuum Gas Oil HDS	1.5	37-41	6-7
Kuwait	Whole Crude Desulfurization	0.6	135-150	21-24
Kuwait	Direct Residuum HDS	0.5	125-140	20-22
Venezuela	Direct Residuum HDS	0.6	115-130	18-21
Kuwait	Delayed Coking	0.25	180-220	29-35
Kuwait	Flexicoking	0.25	140-170	22-27
Venezuela	Flexicoking	0.22	125-150	20-24

Source: L. Aalund, "Hydrodesulfurization Technology Takes On The Sulfur Challenge," Oil and Gas Journal, LXX (September 11, 1972), p. 79.

fuel substitution.[1]

TABLE C-2

COST OF DESULFURIZATION OF FUELS

FUEL	SULFUR REMAINING (%)	COST (¢/PHYSICAL UNIT)	COST (¢/MBTU)
Coal	1.0	90/ton	3.5
Light Fuel Oil	0.25	1.3/gallon	8
Heavy Fuel Oil	1.0	2.7/gallon	15
Heavy Fuel Oil	0.25	4.8/gallon	27

1 After the above was written, the author came across another estimate of the cost of desulfurization of fuel oil, based on the latest developments in technology. The estimated costs were:

(i) 1% sulfur - 86.7¢/barrel or 14.9¢/MBTU;
(ii) 0.3% sulfur - 117.9¢/barrel or 20¢/MBTU.

These estimates were judged sufficiently close to the ones already assumed that no changes were made in the calculations. See, C.H. Watkins, "Desulfurize Kuwait Reduced Crude," Hydrocarbon Processing, LII (May, 1973), pp. 89-92.

APPENDIX D

COST OF CONVERSION OF COMBUSTION EQUIPMENT

In addition to the possible additional cost of alternative fuels, the cost of switching fuels includes the annualized cost of converting combustion equipment or of installing new equipment. This Appendix attempts to assess this cost. The costs to the various types of fuel users are used in the text to estimate the cost of abatement.

RESIDENTIAL FURNACES

It is no easy matter to estimate the cost of converting residential heating systems for the simple reason that figures are difficult to obtain. To make the task easier, it is assumed that somebody switching from an oil heating system to one using an alternative fuel would incur the full cost of installing the new system. Even with this assumption, it is difficult to make comparisons of great exactitude. Heating systems, aside from capacity, differ in a number of details and, therefore, in cost. Moreover, the author was unable to find a source of published costs for this type of equipment. So, he set out to obtain the information by telephoning directly a number of contractors which install these heating systems.[1] From their answers, the author believes that the data in Table D-1 reflect relatively well the typical cost of

---

1 Of those who supplied the information, 8 were in Montreal, 6 in Toronto, and 2 in Kingston, Ontario.

heating systems which use different types of fuels, for a 3-bedroom home.[1]

TABLE D-1

COST OF RESIDENTIAL SPACE HEATING SYSTEMS BY FUEL

FUEL	COST OF INSTALLATION	ANNUAL COST[a]
Gas	$750	$ 82
Electricity	$800	$ 88
Oil-Warm Air	$800	$ 88
Oil-Hot Water	$1450	$160

a. The annual cost was obtained by the Capital Recovery Method, assuming a 10% rate of return and a 25 years recovery period. For a description of the use of this method, see G.A. Taylor, Managerial and Engineering Economy, (New York: D. Van Nostrand Co., 1964).

Table D-2 summarizes the annual costs of converting a typical commercial, industrial, and power plant boiler from one fuel to another.

1 A three-bedroom home was chosen as representing the average Canadian home because it is the most common in Canada and it is a sort of average of the number of bedrooms in Canadian homes. See, Dominion Bureau of Statistics, Household Facilities and Equipment, May, 1969, (Ottawa: Queen's Printer, 1970), p. 9.

TABLE D-2

ANNUAL COSTS OF BOILER CONVERSION
(INCLUDING OPERATION AND MAINTENANCE)

TYPE OF CONVERSION	CLASS OF USER		
	Power Plants	Industrial	Commercial
Coal to heavy oil	$10,500	$4,000	$2,000
Coal to gas	4,000	3,400	700
Coal to gas and light fuel oil on an interruptible basis	9,500	4,000	1,700
Heavy fuel oil to gas and fuel oil on an interruptible basis	2,750	2,400	900
Heavy fuel oil to gas	1,800	1,200	850

Source: Ernst & Ernst, The Fuel of Fifty Cities, (Washington: Ernst & Ernst, November, 1968), p. vi-5.

APPENDIX E

REMOVAL OF SULFUR OXIDES FROM POWER PLANT STACK GASES

There are a large number of processes at various stages of development potentially capable of removing sulfur oxides from power plant stack gases.[1] None of them is in widespread commercial use at the moment, though a number of them are or are scheduled to be in operation. Table E-1 gives a selected list of such power plants.

TABLE E-1

SULFUR OXIDES REMOVAL SYSTEMS IN SELECTED THERMAL POWER PLANTS

	CAPACITY (MW)	START-UP DATE	FUEL	ABATEMENT PROCESS
Union Electric Co. (St. Louis)	140	1968	3% S Coal	Limestone
Kansas Power and Light Co.	430	1971	3.5% S Coal	Limestone
Kansas City Power & Light Co.	820	1972	5.2% S Coal	Limestone
Northern States Power Co.	1360	1976	0.8% S Coal	Limestone
Ohio Edison	1800	1974	Coal	Limestone
Boston Edison	150	1972	2.5% S Oil	Magnesium Oxide
Illinois Power	100	1972	3.5% S Coal	Cat. Ox.

Source: HMM, "SO_2 Removal Technology Enters Growth Phase," Environmental Science and Technology, VI (August, 1972), pp. 688-691.

---

1 H.P. Dibbs, for example, has reviewed the technological nature of several dozen processes. See his Methods for the Removal of Sulfur Dioxide from Waste Gases, (Ottawa: Mines Branch, Department of Energy, Mines and Resources, November, 1971).

The M.W. Kellog Co. has evaluated twelve of the most promising processes for the Air Pollution Control Office of the U.S. Environmental Protection Agency, both in terms of technological and of economic feasibility.[1] These processes are the following: Limestone - Dry Injection; Limestone - Wet Scrubbing; CAT - OX; Molten Carbonate; Potassium Formate; Ammonia Scrubbing (Base); Ammonia Scrubbing (Steam Stripping); Ammonia Scrubbing (Thermal Decomposition); TYCO Modified Chamber; Magnesium Oxide; Zinc Oxide; Citrate. Of these, the limestone and ammonia scrubbing (base) processes do not yield byproducts. The others yield sulfur, sulfuric acid, and/or nitric acid. There seems to be some agreement that the dry limestone process is the most suitable for smaller power plants (up to 350 MW), while the wet limestone is the most promising for larger power plants (say, 400 MW and over).

The number of factors which affect the cost of removing sulfur oxides from power plants is large and the relationships between the various factors are complex. Important factors are the size or capacity of the power plant, the sulfur content of the fuel it uses, the type of fuel, the plant load factor, the gas flow rate, the percentage of sulfur recovered, and, for processes which yield byproducts, the price of byproducts. Given the still somewhat experimental state of the technology, estimates of costs have been made only with respect to hypothetical power plants based on a number of assumptions regarding the aforementioned

---

1 M.W. Kellog Co., Evaluation of SO_2 - Control Processes, (Piscataway, N.J.: M.W. Kellog Co., October 15, 1971).

factors. Table E-2 lists costs of control for selected processes based on given assumptions (some of which are not shown) as calculated by Hitman Associates.[1] Table E-3 lists additional estimates of the costs of removing sulfur oxides from power plant stack gases. It is obvious that it is no easy matter to propose a single average figure. Hedlin Menzies & Associates suggest an average figure of $1.50 per ton of coal input.[2] This works out to an average of $44/ton of SOx abated, assuming a conservative 60% of sulfur recovered. This figure seems quite reasonable in the light of the evidence given here and it is the figure assumed in the calculations in the text. The same figure is also assumed for emissions arising from the combustion of heavy fuel oil by power plants.

It is clear that this type of abatement technique is cheaper, <u>inter alia</u>, the larger the size of the power plant. Hence, it is quite possible that it may prove economical, compared to other techniques, only for larger power plants. It is assumed here that this technique can economically be applied only to power plants of 100 MW and over. In Canada, of 154 thermal power plants in operation in 1969 (both utilities and industrial) only 23 had a capacity of 100 MW or more.[3] These,

---

1 The figures for the 1000 MW power plants are the same as those given in the M.W. Kellog study.

2 Hedlin Menzies & Associates, Initial Study of the Dimension of Pollution in Canada, (Toronto, July, 1969), pp. 8-9.

3 Dominion Bureau of Statistics, Electric Power Statistics, Vol. III, (Ottawa: Information Canada, March, 1971), pp. 65-93.

however, accounted for 85% of all installed capacity. For lack of better estimates, it is assumed here and in the text that these plants also consume 85% of the fuel and, hence, are responsible for 85% of the emissions of sulfur oxides from thermal power plants.

TABLE E-2

COSTS OF REMOVAL OF SULFUR OXIDES FROM HYPOTHETICAL POWER PLANT STACK GASES

PLANT CAPACITY (MW)	SULFUR CONTENT OF FUEL (%)	PER CENT OF SULFUR RECOVERY	CONTROL PROCESS	GROSS COST OF ABATEMENT ($/ton SOx)	NET COST OF ABATEMENT ($/Ton SOx)
175	3.5	50	Dry Limestone	68	-
350	5	50	" "	48	-
350	3.5	50	" "	56	-
350	2	50	" "	78	-
400	3.5	90	Wet Limestone	35	-
700	3.5	90	" "	34	-
1000	5	93	" "	26	-
1000	3.5	90	" "	33	-
1000	2	82.5	" "	48	-
400	3.5	95	Magnesium Oxide	68	50
700	3.5	95	" "	59	40
1000	5	96.5	" "	43	24
1000	3.5	95	" "	56	36
1000	2	91	" "	86	67

TABLE E-2

(continued)

PLANT CAPACITY (MW)	SULFUR CONTENT OF FUEL (%)	PER CENT OF SULFUR RECOVERY	CONTROL PROCESS	GROSS COST OF ABATEMENT ($/Ton SOx)	NET COST OF ABATEMENT ($/Ton SOx)
400	3.5	90	CAT-OX	94	82
700	3.5	90	" "	87	75
1000	5	93	" "	55	44
1000	3.5	90	" "	79	67
1000	2	82.5	" "	148	133
400	3.5	87.5	Modified Chamber	87	70
700	3.5	87.5	" "	75	59
1000	5	91	" "	47	32
1000	3.5	87.5	" "	69	52
1000	2	78	" "	134	114
400	3.5	95	Molten Carbonate	94	85
700	3.5	95	" "	81	72
1000	5	96.5	" "	57	48
1000	3.5	95	" "	74	65
1000	2	91	" "	117	108

Source: Hitman Associates, Inc., Cost Nomographs of Selected Sulfur Dioxide Abatement Methods, (Columbia, Md.: Hitman Associates, Inc., January, 1972), pp. B8-B13.

TABLE E-3

ADDITIONAL COSTS OF REMOVAL OF SULFUR OXIDES FROM POWER PLANT STACK GASES

PLANT CAPACITY (MW)	SULFUR CONTENT OF FUEL (%)	% OF SULFUR RECOVERY	CONTROL PROCESS	COST OF ABATEMENT PER UNIT SOx ($/Ton)
1000	3.5	50	Dry Limestone	24
1000	3.5	35-40	" "	45-40
1000	3.5	55-60	" "	29-27
800	3.0	91	Wet Limestone	18
1300	3.5	95	Potassium Sulphite	12
750	2.7	90	Manganese Oxide	10
300	1.5	90	Reinfuft	47
800	3	90	CAT-OX	32-20
800	3	95	Molten Carbonate	22
1200	3.5	90	Stone & Webster	25
-	3.0	90	" "	42
-	3.0	90+	Magnesium Oxide	45
1300	3.5	90+	Potassium Formate	20-30

Source: Estimates from a survey of the technical literature provided in a private communication by E.R. Mitchell, Department of Energy, Mines, and Resources.

APPENDIX F

MAJOR INDUSTRIAL SOURCES OF SULFUR OXIDES

This Appendix lists the location, ownership, and other relevant data pertaining to the industrial sources of sulfur oxides considered in this study.

TABLE F-1

ALUMINUM SMELTER CAPACITY - CANADA, 1970

OWNERSHIP	PLANT LOCATION	CAPACITY (TONS/YR.)
Alcan	Arvida, Que.	435,000
"	Beauharnois, Que.	45,000
"	Ile Maligne, Que.	130,000
"	Shawinigan, Que.	90,000
"	Kitimat, B.C.	300,000
Can. Reynolds Metal Co.	Baie Comeau, Que.	175,000
Total		1,175,000

Source: Canadian Minerals Year Book, 1970, (Ottawa: Department of Energy, Mines, and Resources, 1972), p. 99.

TABLE F-2

COPPER-NICKEL SMELTER CAPACITY - CANADA, 1970

OWNERSHIP	PLANT LOCATION	PRODUCT	CAPACITY (TONS/YR.)
Falconbridge Nickel Mines Ltd.	Falconbridge, Ont.	Copper-Nickel	650,000
Gaspe Copper Mines Ltd.	Murdockville, Que.	Copper	370,000
Hudson Bay Mining & Smelting Co.	Flin Flon, Man.	Copper	575,000
INCO	Coniston, Ont.	Copper-Nickel	800,000
INCO	Copper Cliff, Ont.	Copper-Nickel	4,000,000
INCO	Thompson, Man.	Nickel	600,000
Noranda Mines Ltd.	Noranda, Que.	Copper	1,700,000

Note: Capacity is expressed in terms of ore charge. This explains the large difference between capacity and production.

Sources: Canadian Minerals Yearbook, 1970, pp. 219-220, 378. Metallurgical Works in Canada, Non-Ferrous and Precious Metals, January, 1972, (Ottawa: Department of Energy, Mines, and Resources, January, 1971).

TABLE F-3

ZINC SMELTING CAPACITY - CANADA, 1970

OWNERSHIP	LOCATION	CAPACITY (TONS/YR.)
Canadian Electrolytic Zinc Ltd.	Valleyfield, Que.	140,000
Cominco Ltd.	Trail, B.C.	263,000
East Coast Smelting & Chemical Co. Ltd.	Belledune, N.B.	42,000
Hudson Bay Mining & Smelting Co. Ltd.	Flin Flon, Man.	79,000
Sherbrooke Metallurgical Co. Ltd.	Port Maitland, Ont.	105,000
		629,000

Sources: Canadian Minerals Yearbook, 1970, p. 586. Metallurgical Works in Canada, pp. 12-15.

TABLE F-4

PETROLEUM REFINING CAPACITY - CANADA, 1970

OWNERSHIP	LOCATION	CAPACITY (BARRELS/DAY)
Golden Eagle Canada Ltd.	Holyroad, Nfld.	14,000
Imperial Oil Enterprises Ltd.	Dartmouth, N.S.	64,300
Texaco Canada Ltd.	Halifax, N.S.	16,000
Irving Refining Ltd.	Saint John, N.B.	45,000
BP Refinery Canada Ltd.	Ville D'Anjou, Que.	75,000
Gulf Oil Canada Ltd.	Montreal East, Que.	67,500
Imperial Oil Enterprises Ltd.	Montreal East, Que.	106,000
Petrofina Canada Ltd.	Pointe-aux-Trembles, Que.	63,000
Shell Canada Ltd.	Montreal East, Que.	100,000
Texaco Canada Ltd.	Montreal East, Que.	66,000
BP Refinery Canada Ltd.	Oakville, Ont.	38,000
Gulf Oil Canada Ltd.	Clarkson, Ont.	55,400
Imperial Oil Enterprises Ltd.	Sarnia, Ont.	126,800
Regent Refining (Canada) Ltd.	Port Credit, Ont.	40,000
Shell Canada Ltd.	Oakville, Ont.	40,000
Shell Canada Ltd.	Corunna, Ont.	56,000
Sun Oil Co. Ltd.	Sarnia, Ont.	33,000
Imperial Oil Enterprises Ltd.	Winnipeg, Man.	22,000
Shell Canada Ltd.	St. Boniface, Man.	26,500
Consumers Cooperative Refineries Ltd.	Regina, Sask.	21,500
Gulf Oil Canada Ltd.	Moose Jaw, Sask.	10,350
Imperial Oil Enterprises Ltd.	Regina, Sask.	32,200
Northern Petroleum Corp.	Kamsock, Sask.	1,200

TABLE F-4

(continued)

OWNERSHIP	LOCATION	CAPACITY (BARRELS/DAY)
Gulf Oil Canada Ltd.	Edmonton, Alta.	72,000
Gulf Oil Canada Ltd.	Calgary, Alta.	6,750
Husky Oil Ltd.	Lloydminster, Alta.	8,500
Imperial Oil Enterprises Ltd.	Edmonton, Alta.	39,900
Imperial Oil Enterprises Ltd.	Calgary, Alta.	20,000
Shell Canada Ltd.	Bowden, Alta.	5,000
Texaco Canada Ltd.	Edmonton, Alta.	20,000
Gulf Oil Canada Ltd.	Port Moody, B.C.	30,000
Gulf Oil Canada Ltd.	Kamloops, B.C.	5,900
Imperial Oil Enterprises Ltd.	Iaco, B.C.	33,000
Pacific Petroleums Ltd.	Taylor, B.C.	10,400
Shell Canada Ltd.	Burnaby, B.C.	20,500
Chevron Canada Ltd.	Burnaby, B.C.	18,000
Union George Co. of Canada Ltd.	Prince George, B.C.	8,000
Imperial Oil Ltd.	Norman Wells, N.W.T.	2,800
Total		1,350,000

Source: Petroleum Refineries in Canada, January, 1971, (Ottawa: Department of Energy, Mines, and Resources, March, 1971).

TABLE F-5

SULFURIC ACID PLANTS - CANADA, 1970

OWNERSHIP	LOCATION
Allied Chemical Canada Ltd.	Valleyfield, Que.
Aluminum Co. of Canada Ltd.	Arvida, Que.
Border Chemical Co. Ltd.	Transcona, Man.
Canadian Electroytic Zinc Ltd.	Valleyfield, Que.
Canadian Industries Ltd.	Beloeil, Que.
" " "	Copper Cliff, Ont.
" " "	Hamilton, Ont.
Canadian Titanium Pigments Ltd.	Varennes, Que.
Caminco Ltd.	Kimberley, B.C.
" "	Trail, B.C.
Cyanamid of Canada Ltd.	Niagara Falls, Ont.
Dupont of Canada Ltd.	North Bay, Ont.
East Coast Smelting and Chemical Co. Ltd.	Belledune, N.B.
Gulf Oil Canada Ltd.	Shawinigan, Que.
Imperial Oil Ltd.	Redwater, Alta.
Inland Chemicals Canada Ltd.	Fort Saskatchewan, Alta.
" " " "	Prince George, B.C.
Northwest Nitro-Chemicals Ltd.	Medicine Hat, B.C.
Sea Mining Corp. Ltd.	Stephenville, Nfld.
Sherbrooke Metallurgical Co. Ltd.	Dunnsville, Ont.
Sulco Chemicals Ltd.	Elmira, Ont.
Western Cooperative Fertilizers Ltd.	Calgary, Alta.
Allied Chemical Canada Ltd.	Copper Cliff, Ont.

Source: Department of Industry, Trade, and Commerce, Canadian Chemical Register, 1971, (Ottawa: Information Canada, 1971).

TABLE F-6

COKE PRODUCTION PLANTS - CANADA, 1970

OWNERSHIP	LOCATION	CAPACITY (1000 TONS PER YR.)	PRODUCTION (1000 TONS)
Algoma Steel Corp. Ltd.	Sault Ste. Marie, Ont.	2,700	1,619
Steel Co. of Canada Ltd.	Hamilton, Ont.	2,670	1,874
Dominion Foundries and Steel Ltd.	Hamilton, Ont.	1,400	960
Cape Breton Development Corp.	Sidney, N.S.	900	586
Gas Metropolitan, Inc.	Ville LaSalle, Que.	626	266
Manitoba & Saskatchewan Coal Co. Ltd.	Bienfait, Sask.	110	N.A.
Kaiser Resources Ltd.	Natal, B.C.	245	190
Total		4,631	

Source: Canadian Minerals Yearbook, 1970, p. 184.

TABLE F-7

NATURAL GAS PROCESSING PLANTS - CANADA, 1970

OWNERSHIP	LOCATION	H_2S IN RAW GAS (%)	RAW GAS CAPACITY (MMCF/DAY)	SULFUR CAPACITY (LONG TONS PER DAY)
Shell Canada	Jumping Pound, Alta.	3-5	250	240
" "	Innisfail, Alta.	14	15	115
" "	Waterton, Alta.	18-25	468	1,650
" "	Simonette, Alta.	-	15	90
" "	Burnt Timber, Alta.	-	54	190
Gulf Oil Canada	Turner Valley, Alta.	4	45	35
" " "	Pincher Creek, Alta.	10	204	675
" " "	Nevis, Alta.	3-7	91	198
" " "	Rimbey, Alta.	1-3	422	328
" " "	Strachan, Alta.	-	250	830
Imperial Oil	Redwater, Alta.	3	22	21
" "	Quirk Creek, Alta.	-	90	225
Jefferson Lake Petrol.	Taylor Flats, B.C.	3	-	325
" "	Savannah Creek, Alta.	13	-	375
Texas Gulf Sulfur	Okotoks, Alta.	33	30	430
" " "	Windfall, Alta.	16	-	1,875
Chevron Standard	Nevis, Alta.	7	79	204
Petrogas Processing	Crossfield, Alta.	31	315	1,970
Home Oil	Carstairs, Alta.	1	334	142
Canadian Fina Oil	Wildcats Hills, Alta.	4	112	137
Steelman Gas	Steelman, Sask.	1	38	12
Hudson Bay Oil and Gas	Edson, Alta.	3	377	304

TABLE F-7
(continued)

OWNERSHIP	LOCATION	H_2S IN RAW GAS (%0	RAW GAS CAPACITY (MMCF/DAY)	SULFUR CAPACITY (LONG TONS PER DAY)
Hudson Bay Oil and Gas	Lone Pine Creek, Alta.	8-17	51	176
" "	Caroline, Alta.	-	45	26
" "	Kaybob South, Alta	2-17	212	1,044
" "	" " "	-	170	1,004
" "	Sylvan Lake, Alta.	-	59	11
" "	Sturgeon Lake, Alta.	-	12	50
" "	Brazeau River, Alta.	-	104	50
Tenneco Oil & Minerals	Nordegg, Alta.	-	66	25
Banff Oil Ltd.	Rainbow Lake, Alta.	-	38	70
Atlantic Rich-field	Gold Creek, Alta.	-	60	100
Amerade Hess Corp.	Olds, Alta.	11	100	600
Mobil Oil Canada	Wimborne, Alta.	14	60	244
Canadian Superior Oil	Harmathon-Elkton, Alta.	53	42	805
Canadian Delhi Oil	Minnehik-Buck Lake, Alta.	-	108	18
Amoco Canada Petroleum	East Crossfield, Alta.	34	107	1,480
" "	Bigstone, Alta.	19	48	320

Sources: P.R. Cote, Canadian Elemental Sulfur from Sour Natural Gas, (Ottawa: Department of Energy, Mines, and Resources, 1972), p. 9. Also, Natural Gas Processing Plants in Canada, January, 1971, (Ottawa: Department of Energy, Mines, and Resources, 1971).

TABLE F-8

SULFITE PULP MILLS - CANADA, 1967

OWNERSHIP	LOCATION
Abitibi St. Anne Paper Co.	Beaupre, Que.
Anglo-Canadian Pulp & Paper Mills Ltd.	Quebec, Que.
Canadian International Paper Co.	Gatineau, Que.
" " "	La Tuque, Que.
" " "	Temiskaming, Que.
" " "	Trois Rivieres, Que.
Consolidated Bathurst Ltd.	Grand-Mere, Que.
" " "	Port Alfred, Que.
" " "	Shawinigan, Que.
Domtar Newsprint Ltd.	Dolbeau, Que.
" " "	Donnacona, Que.
" " "	Trois Rivieres, Que.
Eddy E.B. Co.	Hull, Que.
Gaspesia Pulp & Paper Co. Ltd.	Chandler, Que.
The McLaren, James Co. Ltd.	Masson, Que.
Price Co. Ltd.	Kenogami, Que.
" " "	Alma, Que.
Quebec North Shore Paper Co.	Baie Comeau, Que.
St. Raymond Paper Ltd.	Desbiens, Que.
Abitibi Paper Co.	Fort William, Ont.
" " "	Port Arthur, Ont.
" " "	Sault Ste. Marie, Ont.
Abitibi Provincial Paper Ltd.	Port Arthur, Ont.
Canadian International Paper Co.	Hawkesbury, Ont.
Domtar Fine Papers Ltd.	Cornwall, Ont.
Domtar Pulp & Paper Ltd.	St. Catherines, Ont.
Great Lakes Paper Co. Ltd.	Fort William, Ont.

TABLE F-8

(continued)

OWNERSHIP	LOCATION
Ontario-Minnesota Pulp & Paper Co. Ltd.	Kenora, Ont.
Ontario Paper Co. Ltd.	Thorold, Ont.
Spruce Falls Power & Paper Co. Ltd.	Kapuskasing, Ont.
Abitibi Manitoba Paper Ltd.	Pine Falls, Man.
Columbia Cellulose Co. Ltd.	Prince Rupert, B.C.
Crown Zellerbach Canada Ltd.	Ocean Falls, B.C.
MacMillan, Bloedel Ltd.	Powell River, B.C.
Rayonier Canada Ltd.	Woodfire, B.C.

Source: Dominion Bureau of Statistics, Pulp and Paper Mills, 1967, (Ottawa: Queen's Printer, September, 1969), pp. 15-16.