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September 1987

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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ASSESSING THE BENEFITS OF OHER RESEARCH: THREE CASE STUDIES

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ABSTRACT

This research was undertaken to estimate the societal benefits and costs of selected past research performed for the Office of Health and Environmental Research (OHER) of the U.S. Department of Energy (DOE). Three case studies of representative OHER and DOE research were performed. One of these, the acid rain case study, includes research conducted elsewhere in DOE. The other two cases were the OHER marine research program and the development of high-purity germanium that is used in radiation detectors.

The acid rain case study looked at the research benefits and costs of furnace sorbent injection and duct injection, technologies that might reduce acid deposition precursors. Both appear to show benefits in excess of costs. We examined in detail one of the OHER marine research program's accomplishments--the increase in environmental information used by the Outer Continental Shelf leasing program to manage bidding for off-shore oil drilling. The results of an econometric model show that environmental information of the type supported by OHER is unequivocally linked to government and industry leasing decisions. The germanium case study indicated that the benefits of germanium radiation detectors were significant.

EXECUTIVE SUMMARY

This report was prepared by Pacific Northwest Laboratory (PNL) for the Office of Health and Environmental Research (OHER) of the Department of Energy (DOE). The research was undertaken 1) to estimate the societal benefits and costs of selected past OHER research and 2) to assess whether the evaluation methods used in this project would be useful in evaluating the benefits and costs of OHER research. Such a method of evaluation would provide qualitative and quantitative information that will help OHER demonstrate the value of its research program.

BACKGROUND

Federal agencies who are requesting funding are increasingly being required to provide stronger analytic justifications for continued government funding. Policy makers or budget reviewers deciding on the level of federal R&D often compare societal returns or benefits with the R&D costs. In this view, federal R&D is another form of public investment; resources are expended in one period in expectation of some return in the future. An examination of an agency's past research results may help provide evidence of the value of its ongoing research.

Such evaluations are already a part of OHER's planning. Other studies have provided OHER with some information and knowledge of the economic benefits of its past research. The DOE's Office of Program Analysis studied a broad range of OHER research. The studies indicated that OHER research often contributes in ways far removed from the original research objectives.

Our research builds on these previous studies. We have chosen a few OHER research projects and have conducted a more in-depth investigation of their benefits. Our approach in this analysis is consistent with that used to measure the benefits of many other federal investments. Thus, this research is part of a continuing program by DOE and OHER to understand and assess the consequences of its research. The next phase of this program could be to continue quantifying the benefits of one of these case studies or to assess another OHER research program.

OBJECTIVES

The specific objectives of the research are to

- estimate the economic and societal benefits of three representative, past research projects supported by OHER
- test the usefulness of the analytical techniques for estimating societal benefits
- document problems and uncertainties in applying the techniques to OHER programs and recommend ways of overcoming these problems.

We specifically avoided two topics. First, the project was not an evaluation of the scientific quality of the original research. Second, we did not attempt to evaluate whether OHER properly funded or managed these programs. Our goal was to estimate societal benefits resulting from the programs.

SCOPE

Since previous broad assessments of OHER research were available as a starting point, we conducted three case studies of representative OHER research programs. One of these, the acid rain case study, also includes research conducted elsewhere in DOE and by other federal agencies. However, the efforts represented by the federal acid rain research closely resemble the research funded by OHER. The other two case studies were the development of high-purity germanium that is used in radiation detectors and the OHER marine research program.

It became apparent in the initial phases of the research that resources and time were not sufficient to exhaustively assess each of the case study programs. After the accomplishments of each research program were reviewed, we focused on estimating the benefits of a few accomplishments from each program.

CONCLUSIONS

The principal conclusions of our case studies and of our evaluation of the techniques for assessing OHER research are described below.

Acid Rain Case Study

The acid rain case study looked at the benefits and research costs of two technologies that might reduce acid deposition precursors. The technologies were furnace sorbent injection and duct injection. At least three broad conclusions can be drawn based on the results of the acid rain case study.

- Both technologies appear to show benefits in excess of research costs over a wide range of emission reductions and regulatory conditions
- Net research benefits of duct injection appear to be substantially greater than those for furnace sorbent injection. This conclusion holds over nearly all sensitivity analyses
- The pattern of positive net benefits for both technologies is consistent with a primary objective of the National Acid Precipitation Assessment Program to develop lower cost alternatives of meeting the requirements of acid-rain-oriented emission reduction bills.

The above conclusions should be interpreted with appropriate regard for the uncertainties associated with forecasting commercial performance of these two technologies and future R&D costs.

Marine Research Case Study

Our research indicates that the OHER marine research has improved society's knowledge of ocean currents and its ability to predict the movement of energy-related pollutants in the ocean. We examined in detail one of the contributions of OHER research--the environmental information used by the Outer Continental Shelf (OCS) leasing program, which manages bidding for off-shore oil drilling. In particular, we examined the contribution that OHER made to the leasing of the Georges Bank off the northeastern United States. Specific conclusions are listed below.

- Marine environmental research of the type conducted by OHER is unequivocally linked to governmental decisions about which OCS areas to offer for lease and to industrial decisions on whether to bid. For example, we found statistical evidence that a one percent change in the probability of oil reaching a shore has more effect on leasing decisions by the U.S. Department of Interior than determining the site has $1 million worth of additional oil.

- The societal benefit of OHER research in the Georges Bank is estimated to be $2.75 million.
- The societal benefit of OHER research to the entire OCS leasing program is estimated to be $165 million. There is considerably more uncertainty in this estimate than in our estimate for Georges Bank.
- On the basis of our estimates for Georges Bank and the entire OCS leasing program and the qualitative information on the other achievements of the OHER marine research program, it seems almost certain that the benefits of this OHER research are significantly greater than the research costs.

Germanium Research Case Study

It was apparent from our discussions with the users of high-purity germanium detectors that OHER's research support has provided an improved radiation detector that has lead to a number of new applications. However, because of the lack of necessary data and the limited availability of proprietary production information, the societal benefits for the new applications could not be estimated. These benefits are, nonetheless, very real and appear to be very large.

More specific conclusions of the research are listed below.

- High-purity germanium detectors overcame significant difficulties associated with its predecessor, the lithium-drifted detector. Particularly, the portability of the high-purity detector and the reduced need to constantly cool the detector were cited as significant advantages.
- Germanium detectors, both high-purity and lithium-drifted, represent significant cost savings over the use of laboratory analysis. One source estimated the costs at approximately $100 for an analysis with a germanium detector versus $1,000 to $4,000 for a laboratory analysis. We were able to verify previous estimates that the cost savings in one application, nuclear power plants, were approximately $200 million.
- The advantages of the high-purity germanium detector lie in the quality of the germanium crystal. OHER's research was the principal source of

improvements in the growing of the crystal. Thus, it is appropriate to attribute the benefits of the detector to OHER.

GENERAL CONCLUSIONS

On the basis of results from the three case studies, we feel that retrospective assessments of the societal benefits of basic and applied research are both feasible and useful. The benefits of our research include the insights gained and the importance of having estimates of the size of several of OHER's major accomplishments. However, this conclusion is tempered with several caveats listed below.

- The data requirements restrict our ability to exhaustively assess the benefits of complete programs. However, tracing and describing the accomplishments is an important by-product of our research. Also, quantitative estimates of even some of the research accomplishments indicate the value of OHER research.
- While the economic techniques are useful for measuring the accomplishments of past OHER research, we feel they would not be especially helpful for deciding which research project to fund or the appropriate level of funding.

RECOMMENDATIONS

Based on this phase of the research project we recommend that OHER

- collect and publish information on its on-going research projects. There is currently no central repository or source describing past and on-going OHER projects, funding and results. Lack of this information increases the costs of either retrospective assessments or assessments of on-going projects. It also limits dissemination of the results of OHER research and, thus, the potential social benefits of OHER research.
- perform an in-depth assessment, with appropriate funding, of at least one on-going or past research program or examine in greater detail one of these cases studied in this report. Although our studies were more sophisticated and in-depth than previous studies, financial and time constraints prevented us from estimating more than a few of each program's

accomplishments. Although we feel that the benefits of OHER research programs greatly exceed the costs, we cannot say by how much.

ACKNOWLEDGMENTS

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CONTENTS

TABLES

1.0 INTRODUCTION

This report was prepared by Pacific Northwest Laboratory (PNL) for the Office of Health and Environmental Research (OHER) of the Department of Energy (DOE). OHER is responsible for planning and directing DOE research related to health and environmental issues associated with energy activities. Our research was undertaken to assist OHER in 1) estimating the societal benefits and costs of selected past OHER research and 2) assessing whether the evaluation methods used in this project would be useful in evaluating the benefits and costs of OHER research. The research will provide OHER with qualitative and quantitative information that will help OHER demonstrate the value of its research program.

The research initiated in FY 1987 with case studies of the costs and benefits of three OHER and federal government research activities. The first case study assessed the benefits of the federal government's decision to accelerate research into the causes and effects of acid deposition rather than to require acid deposition controls. The second of the case studies is OHER research related to dispersion of radionuclides and other energy pollutants in marine ecosystems. The third case study relates to the OHER research and development of high-purity germanium, which has widespread applications in instruments that monitor and measure radioactive materials.

1.1 OHER MISSION AND PROGRAM

OHER traces its origins back over forty years to the nuclear research established as part of the World War II's Manhattan Project. Following the war, biomedical research became an established activity of the U.S. Atomic Energy Commission (AEC). The AEC program was intended to help ensure the health of workers involved in nuclear facilities as well as to conduct basic research into the uses of nuclear technologies in biological and medical sciences (DOE 1983).

The program was transferred to the Energy Research and Development Administration (ERDA) and finally to DOE when the latter was established in 1977. OHER's research program later expanded to include nonnuclear issues including both health and environmental research associated with fossil fuels and renewable resources.

Presently, OHER plans and directs the Biological and Environmental Research (BER) Program, the basic health and environmental research arm of DOE. The basic goals of OHER's BER Program are (OHER 1983, p.4)

- to provide, through basic and applied research, the scientific information required to understand the effects and reduce the health and environmental uncertainties associated with those energy technologies, policies, and operations that are required to meet the Nation's future energy and national security needs.
- to develop new or improved methods for using modern energy technologies in the diagnosis and treatment of human disease.

The first of these goals (environmental and health research) involves the integration of three areas of study. The first area of investigation is the source or cause of the pollutant or agent of concern and its measurement. For example, OHER research in this area has involved radiation detection instruments. The second area of study is the transport or pathway the pollutant takes from its point of release to its ultimate deposition. Examples of OHER research in this area include studies of wet and dry acid deposition and research on the transportation pathways of energy-related materials through fresh and ocean waters. The third area of study is the effect the pollutant has on humans and the environment. While OHER research in this area initially focused almost exclusively on the effects of radionuclides, recent research has investigated ecological responses to natural and artificial stresses as well as human health effects from nonnuclear pollutants.

The second of the BER Program goals relates to the use of nuclear technologies in diagnosing and treating human disease. The program has successfully developed and promoted instruments that have become common in today's medical laboratories.

1.2 BACKGROUND AND OBJECTIVES

Federal agencies are being encouraged, and in some cases required, to quantitatively compare the costs and benefits of their programs. For example, Executive Order 12291 requires an agency to analyze proposed regulations and to choose the alternative that imposes the least cost on society. The Executive Order strongly recommends comparing the benefits and costs of the regulation in monetary terms. There is increasing agreement that quantitative assessments such as benefit-cost analysis or cost-effectiveness analysis will help policy makers make better decisions.

Similarly, in times of increasing examination of federal budgets, especially research and development (R&D) programs, it is prudent to evaluate which government expenditures are the most worthy of continued or expanded funding. The Office of Management and Budget and other federal agencies are increasingly requiring stronger analytic justifications for continuing government funding. In this view, federal R&D is another form of public investment; resources are expended in one period in expectation of some return in the future. Policy makers or budget reviewers deciding on the level of federal R&D often compare societal returns or benefits with the R&D costs. An examination of past OHER results may help provide evidence of the value of ongoing OHER research.

Other studies have provided OHER with some information and knowledge of the economic benefits of its past research. An 1983 analysis of a broad range of OHER research indicated that OHER research often contributes in ways far removed from the original research objectives.

Our research builds on this previous analysis. We have chosen a few examples of OHER research to conduct a more in-depth investigation of its benefits. In addition, the approach taken in this analysis is consistent with that used to measure the benefits of many other federal investments. Thus, this research is part of a continuing program by DOE and OHER to understand and assess the consequences of its research.

Our objectives were to further quantify OHER achievements and to determine the usefulness of quantitative techniques such as benefit-cost analysis (BCA) or cost-effectiveness analysis (CEA) in establishing the societal benefits of OHER research. As a result of this research, OHER will have better information with which to justify its budget decisions. In addition, OHER can use the analytic techniques on future research decisions.

The specific objectives of this research are to

- estimate the economic and societal benefits of three representative past research projects supported by OHER
- test the usefulness of the analytical techniques for estimating societal benefits
- document problems and uncertainties in applying the techniques to OHER programs and recommend ways of overcoming these problems.

1.3 REPORT OUTLINE

In Chapter 2, we present our conclusions and recommendations resulting from the research. In Chapter 3 we present our approach to estimating the benefits of selected OHER research programs. Chapter 3 also discusses other approaches to evaluate or assess research and presents the conclusions of two reviews, one by the National Academy of Sciences and one by the Government Accounting Office, of the potential for using economic techniques to assess the consequences of research investments.

Chapters 4 through 6 present the case studies chosen for this research. These are the OHER Marine Research Program, portions of the federal acid rain research program, and OHER's development of germanium radiation detectors. Each of these chapters roughly follows a similar structure. First, the research program is described and major accomplishments noted. Next, we describe in more detail our approach to estimating the value of those accomplishments that could be quantified within the scope of this research. Finally, we present our results and assess the sensitivity of our estimates to key assumptions.

1.4 REFERENCES FOR CHAPTER 1.0

U.S. Department of Energy (DOE). 1983. A Plan for the Biological and Environmental Research Program FY 1985-1990. Office of Energy Research, Washington, D.C.

2.0 CONCLUSIONS AND RECOMMENDATIONS

As discussed in the Introduction, this research was designed to provide OHER with quantitative and qualitative information on the societal benefits of three OHER and federal government research programs. It was also designed to assess the usefulness of the techniques we used to estimate the benefits of the three programs.

In Section 2.1 we provide our conclusions and recommendations from our case studies to estimate the societal benefits of three representative past OHER research projects. Sections 2.1.1, 2.1.2 and 2.1.3 discuss the estimates we obtained for the acid rain, marine research and germanium radiation detector case studies,respectively. Section 2.2. then discusses what we learned from the project that may help OHER better assess the benefits of its research.

2.1 CASE STUDIES CONCLUSIONS

The major effort in this project consisted of assessing the benefits of three representative DOE and OHER research programs. We discovered that even within each case study there were more research accomplishments than could be included in the scope of this research. For that reason, we were forced to limit our quantitative estimates of the benefits of the case study projects to a few significant accomplishments. We also wanted to test several techniques that could be used to estimate research benefits and so, used that as an additional criteria to decide what benefits within each case study to estimate quantitatively.

2.1.1 Acid Rain Case Study

The acid rain case study looked at the benefits and research costs of two technologies that might reduce acid deposition precursors. The technologies were furnace sorbent injection and duct injection. At least three broad conclusions can be drawn based on the results of the acid rain case study.

- Both technologies appear to show benefits in excess of research costs over a wide range of emission reductions and regulatory conditions
- Net research benefits at duct injection appear to be substantially greater

than those for furnace sorbent injection. This conclusion holds over nearly all sensitivity analyses

- The pattern of positive net benefits for both technologies is consistent with a primary objective of the National Acid Precipitation Assessment Program to develop lower cost alternatives of meeting the requirements of acid rain-oriented emission reduction bills.

The above conclusions should be interpreted with appropriate regard for the uncertainties associated with forecasting commercial performance of these two technologies and future R&D costs.

2.1.2 Marine Research Case Study

Our research indicates that the OHER Marine Research program contributed to numerous improvements in society's knowledge of ocean currents and the fate of energy-related pollutants. We examined in detail one of the contributions of OHER research--the environmental information that the research contributed to the Outer Continental Shelf (OCS) leasing program. The OCS leasing program manages bidding for off-shore oil drilling. In particular, we examined the contribution that OHER made to the leasing on the Georges Bank off the Northeastern United States. Specific conclusions are listed below.

- Marine Environmental research of the type conducted by OHER is unequivocally linked to governmental and industrial decisions on which OCS areas to offer for lease. For example, we found statistical evidence that a one percent change in the probability of oil reaching a shore has more effect on leasing decisions by the U.S. Department of Interior than a million dollars of additional oil.

- The societal benefit of OHER research in the Georges Bank is estimated to be $2.75 million.

- The societal benefits of OHER research on the entire OCS leasing program is estimated to be $165 million. There is considerably more uncertainty in this estimate than our estimate for Georges Bank.

- On the basis of our estimates for Georges Bank and the entire OCS leasing program and the qualitative information on the other achievements of the

OHER Marine Research program, it seems almost certain that the benefits of this OHER research were significantly greater than the research costs.

2.1.3 Germanium Research Case Study

It was apparent from our discussions with the users of high-purity germanium detectors that OHER's research support has provided an improved radiation detector that has lead to a number of new applications. However, because of the lack of necessary data and the limited availability of proprietary production information, it was impossible to estimate the societal benefits for the new applications. However, based on comparisons made by detector users, these benefits are, nonetheless, very real and very large.

More specific conclusions of our research are listed below.

- The high-purity germanium detector overcame significant difficulties associated with its predecessor, the lithium-drifted detector. Particularly, the portability of the high-purity detector and the reduced need to constantly cool the detector were cited as significant advantages.
- Germanium detectors, both high-purity and lithium-drifted, represent significant cost-savings over the use of laboratory analysis. One source estimated the costs at approximately $100 for an analysis with a germanium detector versus $1,000 to $4,000 for a laboratory analysis.
- The advantages of the high-purity germanium detector lie in the quality of germanium crystal. OHER's research was the principal source of improvements in the growing of the crystal. Thus, it is appropriate to attribute the benefits of the detector to OHER.
- Although the market for high-purity detectors is relatively small, $20-25 million sales worldwide, three U.S. firms are the major producers. These U.S. firms sell their detectors to a wide variety of users worldwide.

2.2 GENERAL CONCLUSIONS/RECOMMENDATIONS

Based on the research on the three case studies, we feel that retrospective assessments of the societal benefits of basic and applied research are both feasible and useful. However, this conclusion is tempered with several caveats.

First, the data requirements for some of the accomplishments make it very difficult to quantitatively estimate their associated benefits. However, we feel that tracing the original research to its accomplishments and describing these accomplishments qualitatively is an important by-product of our research. We also feel that quantitative estimates of even some of the research accomplishments indicate the value of OHER research.

Second, our research indicates that these evaluation techniques would probably not be especially useful for deciding which basic research projects to fund. The techniques are very useful for retrospective studies of applied research. They are somewhat less useful for allocating research funds among potential applied research projects. The reason for the difficulty in applying the techniques to basic research is that it is simply too difficult to forecast the many potential applications of a basic research program.

3.0 APPROACH

Research and development (R&D) is undertaken in both the private and public sectors for a wide variety of reasons. In the private sector, R&D investments are usually motivated by the anticipation of higher profits that can be earned by reducing the costs of an existing product, by capturing new sales in an existing market with an improved product, or by capturing sales in a new market with a new product. However, in both the private and public sectors, research also takes place that would be considered more fundamental or basic and is less likely to be focused on some immediate application. Often a major objective of this type of research is to better understand some scientific process or problem. Finally, another reason for performing research is to obtain new information to help make better decisions. For example, administrators in the federal government routinely initiate studies of the environmental and health effects associated with new chemicals and then use this information to determine whether the product should be sold commercially. Similarly, firms in the private sector generally conduct research to characterize the market for a new product before producing or marketing it.

Evaluating R&D investments is complicated by the wide variety of reasons that motivate these investments and by the uses to which such evaluations may be put. For example, it may be inappropriate to use the same set of criteria to evaluate an investment by the federal government in theoretical physics and an investment made by an automobile firm to increase the fuel efficiency of a new car. By the same token, the criteria used in either of the above two cases would also vary somewhat depending upon the nature and timing of the evaluation. Typically, the methods and criteria used to evaluate a research decision before the investment is made (ex ante evaluation) are not exactly the same as the methods and criteria used to evaluate the performance of research investment after it has been made (ex post evaluation).

Given this very general introduction, the purpose of this chapter is to familiarize the reader with a number of the different approaches that the private and public sectors can use in evaluating R&D investments and to then focus in more detail on the type of approach used to conduct the assessments of OHER research. We conclude that the use of economic techniques, such as those applied on an ex post basis in this report, may not be fully appropriate for making either ex ante or ex post decisions regarding the funding of more basic research by OHER. However, we suggest that economic techniques can produce information that is more helpful for evaluating the ex post performance of less basic research than it is for evaluating ex ante decisions, such as the case studies contained in this report.

This chapter of the report is divided into four major sections. Section 3.1 outlines the justification for public sector investment in R&D and then relates this to the various objectives associated with sponsorship of R&D by the federal government. Section 3.2 discusses different types of approaches used to evaluate R&D investment decisions, while Section 3.3 describes in some detail the conceptual basis for the economic approach that underlies each of the case studies in this report. Finally, Section 3.4 discusses some of the more fundamental problems associated with this approach and provides some conclusions regarding its applicability to different types of OHER investments.

3.1 JUSTIFICATION AND OBJECTIVES OF PUBLIC SECTOR R&D

Federal investment in R&D plays an important and growing role in the U.S. economy. Rosenberg (1985) estimated federal expenditures on R&D in 1940 to be about $75 million. By 1986, this figure had increased by a factor of almost 700 to $58 billion. In this section, we first discuss the reasons generally given to support public (as opposed to private) sector funding of basic and applied R&D and then relate this to the varied objectives of R&D.

3.1.1 Rationale for Public Sector Funding of R&D

The involvement of the federal government in conducting and funding basic and applied research is so prevalent that we rarely debate whether any involvement by the federal government in R&D is justified. Support for research in such diverse areas as human health, national defense, and environmental quality, to name a few, is assumed to be a rightful--if not necessary--responsibility of the public sector in general and the federal government in particular. While there tends to be some disagreement about the focus of this involvement, Americans seldom argue that research in these areas ought to be conducted entirely by the private sector.

This broad view of the federal role in supporting R&D has not always been the case. Indeed, when, in 1830, James Smithson left the U.S. government a large bequest for "the increase and diffusion of knowledge among men" such a gift was so alien to the U.S. Congress that it took 16 years of debate before its members agreed to establish the institution that now bears his name (Rosenberg 1985). Even federal support for agriculture, first through the Morrill Act (1862), which established a system of land grant universities, and then through the Hatch Act (1887), which provided federal funding for agricultural experiment stations, was hotly contested in the Congress. In fact, as Rosenberg (1985) points out, the current consensus regarding the federal role in R&D was not forged until after World War II.

The justification for public sector involvement in R&D is fundamentally an economic argument in which research is viewed as a production process whose output is information. According to Arrow (1962), perfect competition and reliance on the private market place is not the "best" (socially optimal) way to allocate information because of three features frequently associated with the production of information: 1) indivisibilities, 2) inappropriability and 3) uncertainty. A discussion of how each of these features of the R&D process can be used to justify public sector investment in R&D follows.

The term "indivisibilities" is used in this context to describe a situation in which the scale of the equipment cannot be increased or decreased in small increments. In some cases the production of information involves the use of large amounts of physical capital, for example particle accelerators and nuclear reactors, which, for either scientific or engineering reasons, have a single most efficient size. In these cases, it may not be scientifically prudent or technically feasible to make the equipment a different size, or the costs of production (of information) associated with other equipment sizes may be higher. In this situation the total cost of producing information increases less than proportionally with output and the long-run average cost of producing information also decreases with output.

Indivisibilities in production can produce situations in which competition between firms will not lead to a socially optimal allocation of resources. Indivisibilities constitute a particularly serious problem to resource allocation when decreasing average costs hold over a range of output large enough to satisfy the entire market for a particular kind of information. In this situation, a single firm can produce the information more cheaply than two or more firms. This type of firm is referred to as a "natural monopoly." Natural monopolies, like other forms of monopoly, are able to charge higher prices at lower levels of output than would occur under perfect competition. More importantly, the benefits that society enjoys when a natural monopoly produces information are not as great as the benefits that could be created when information is produced under conditions of perfect competition. Consequently, it is argued that public sector involvement is appropriate to correct for the effects of the market distortions created by indivisibilities and, thus, to ensure that the level of production is socially optimal.

A second justification for public sector investment in R&D is inappropriability, i.e., when the benefits of information cannot be fully appropriated by those who produce it. According to Arrow (1962) the problem lies in the fact that, while new information is often very expensive to produce, the owner cannot, without special legal protection, sell this information on the open market and expect to reap the full extent of the social benefits that it creates. This is because any one purchaser can reproduce the information at little or no cost and pass it along to others. Under these conditions, the optimal strategy for a firm is to become a "free rider." That is, the firm simply waits until other firms produce this information and then acquires it at a much lower cost--a situation that leads society to underinvest in new information.

Arrow argues that this problem can be eased by legal protections through the patent system and various types of royalty schemes. However, he concludes that no amount of legal protection can make so intangible a product as information into a thoroughly appropriable commodity. In fact, complete protection would guarantee monopoly power to the owner of information. The owner would then be able to appropriate all of the potential benefits created by the information, but at the expense of the users of this information who would have to pay higher prices for less information. In short, the information would be underused.

The problem of appropriability applies not only to information as a commodity, but also to R&D in areas where property rights to goods and services are, for theoretical or political reasons, not defined or are poorly defined. The case of public goods, such as national defense, represents a broad area in which government tends to play a leading, but not exclusive, role in R&D funding. Environmental research is an area in which poorly defined property rights tend to create private incentives for firms to overuse the waste assimilation services of the environment and to underinvest in information about the effects of their actions on the environment.

A final justification for public sector support of R&D is uncertainty. The output of R&D, particularly basic research, cannot always be predicted from its input. This uncertainty can be reduced through futures markets, which reduce the risks to producers by spreading this risk over a large number of buyers and sellers. Insurance performs a similar function. However, as Arrow (1962) points out, shifting of risks in the real world is incomplete. Under these conditions, one would expect underinvestment in risky activities and that the magnitude of this underinvestment would increase with the level of risk. Since government expenditures on R&D are paid for through taxes, public sector investment in risky activities has the positive effect of spreading risk much more widely than would be expected by private market arrangements.

In summary, then, competitive market arrangements can be expected to result in underinvestment in R&D because information is frequently subject to indivisibilities in production, because the results of R&D are difficult to appropriate fully, and because R&D is inherently risky. The underinvestment in R&D will tend to be greatest in basic research, where these three problems tend to be most acute. Finally, even if a firm is able to capture all of the benefits that can be derived from an R&D investment, that information will tend to be monopolized by the firm and underutilized by society.

3.1.2 Objectives of Federal R&D

The above arguments are used to justify three different types of research objectives in the public sector:

- increasing the information base of society through basic research
- increasing social welfare through new technologies and lower costs
- reducing the uncertainty associated with policy decisions

As previously mentioned, firms in the private sector are more likely to underinvest in basic research than in applied research. While basic research can be widely used by numerous industries, once it has been produced, it is difficult for firms to convert this type of research into private profits without government support. This is not only because the benefits of basic research are the most difficult to appropriate, but also because of the substantially greater risks associated with this type of investment. In addition, government support of basic research usually ensures that the results are widely disseminated and not monopolized by a single firm.

A second objective of public sector research in the U.S. involves increasing the general welfare of society by developing new products or by lowering the production costs of existing products. This type of support for applied research usually takes one of two distinct forms. First, the federal government supports R&D to improve the performance or reduce the costs of goods and services used by the government itself. One of the best examples of this objective in practice is the funding of research on national defense. Since it is difficult to exclude individuals from the protection afforded by many investments in this area, national defense is typically regarded as a public, as opposed to private, responsibility. By funding investments in R&D in this area, the public sector plays a role in which private market incentives are limited, while at the same time reducing its own costs and directing R&D to serve its own needs. Second, government can decide to undertake the development and early commercialization of new technologies in a specific industry or sector of the economy. In the case of agricultural research, this type of research investment has traditionally been justified by the argument that firms in the industry are too small and specialized to undertake commercial development of new technologies (Evenson et al. 1979). More recently, federal support for the commercialization of new energy conservation technologies was based on the potential benefits to society of avoiding future, and potentially catastrophic, disruptions in the market for crude oil.

A final objective of public sector involvement in R&D, and one that is often ignored in the literature on this subject, is to provide better information for making public policy decisions. Two of the most recent examples of this type of investment involve federal government investments to learn more about the nature and the effects of CO_2 buildup and acid rain. In both cases, multi-agency research programs have been initiated to help reduce the uncertainty associated with these two phenomena and, thereby, to provide better information on which to base public policy decisions regarding the appropriate means, if any, for regulating the causes of these phenomena.

3.2 TECHNIQUES FOR EVALUATING PUBLIC SECTOR R&D

The purpose of this section of the report is to briefly review some of the different techniques that can be used to evaluate public sector R&D investments in a comparative framework both in an ex ante and ex post context. The approaches reviewed here include: 1) peer review; 2) bibliometric techniques, and 3) economic methods. The discussion of economic methods is intended to serve as an introduction to the more detailed treatment in Section 3.3 of the economic methodology used in this research.

3.2.1 Peer Review

A recent review (Logsdon and Rubin 1985) of methods used by the federal government to evaluate basic research investments found that most agencies base their research funding decisions on peer reviews rather than on economic or other quantitative indicators of expected or past performance. The first agency to implement the peer review process for funding basic research was the old Office of Naval Research (ONR), a research agency within the Department of Defense. The ONR practice was based on an earlier recommendation by Vannevar Bush (1945) that peer review by independent scientists, with no direct links to the federal government, would strengthen basic research by separating the research mission of federal agencies from their operational missions. The ONR peer review model consisted of a multi-level review process, involving both internal functional and external peer reviews. This model provided the basis for current-day peer review procedures at the National Science Foundation (NSF).

Other federal agencies and groups that rely heavily on the peer review process to evaluate basic science funding decisions include the National Institute of Health (NIH), the Department of Energy's Office of Basic Energy Sciences, and NASA's Office of Aeronautical and Space Technology. As a recent review of research evaluation methods by the U.S. Office of Technology

Assessment (OTA) notes, there is a high degree of confidence in the peer review process both in these agencies and in the scientific community (OTA 1986).

The peer review process can be used as a basis for funding research projects, for exercising managerial control over them and for making decisions regarding continuation of funding. Peer review has also been the traditional mechanism through which agencies have tried to justify their research to various oversight groups. Most agencies use traditional forms of peer review in which other scientists are asked to assess various attributes of a proposal or project using qualitative measures of performance. However, there have been efforts to make the peer review process more quantitative.

One of the best examples of quantitative peer review was an ex post assessment of its basic research program by DOE's Office of Energy Research (DOE 1982). The assessment plan involved a review of a 10 per cent stratified random sample of 129 basic energy science projects. Panels of experts were asked to rank nine different attributes of each project, such as scientific merit and productivity, on a scale of 0-10. These attribute scores were weighted to reflect the relative importance of each attribute to the assessment. The weighted attribute scores were then summed to provide a total project score. These scores were then used to rank projects and assess their contributions to basic energy science.

The peer review process has a number of strengths, perhaps the most important of which is that it has broad support. Both those who administer the peer review process and members of the scientific community whose research is the object of peer review support this process as the best method for making basic research funding decisions.

According to the OTA study cited above, there is far less agreement about the validity of using economic or bibliometric methods as a basis for deciding which research to fund. This lack of agreement can be explained in part by the fact that scientists in the same discipline participate in the peer review process both as reviewers and as proposers, whereas other forms of evaluation are more likely to be conducted by professionals outside the discipline of the proposer.

A second valuable aspect about the peer review process is that it helps give the research program a scientific credibility it might otherwise lack if research funding decisions were made without the advice and consent, so to speak, of the scientific community. The importance of consensus in funding decisions helps to explain the tremendous support for peer review within the scientific community. As mentioned above, most federal agencies that employ this method do not use highly quantitative peer review methods to score or rank research proposals or projects. Rather, these agencies depend heavily upon the weight of consensus among multiple reviewers. Thus, approval of a technical proposal or project through the peer review process generally signifies broad agreement within relevant disciplines.

Finally, peer review is an extremely flexible approach to evaluation when the outputs of a research proposal or project are highly abstract and not immediately related to a commercial application. As such, it is best employed in the evaluation of basic science. The application of this approach to basic research can be defended on the grounds that it yields decisions that are presumably consistent with the preferences of those who will make the most immediate use and derive the most immediate satisfaction from the results of the research. While no rigorous efforts have been undertaken by economists to determine the value of information for its own sake, discrepancies between academic and industry salaries in many disciplines certainly suggest that many scientists are willing to pay substantial amounts of money (i.e., foregone income) for the satisfaction afforded by intellectual pursuits. By contrast, the expected value of the research in its future commercial application is likely to be very small due to a combination of uncertainty about future uses and values and the impact of discounting into present value dollars earned in the very distant future.

Peer review methods have been criticized on at least four main grounds. The most common criticism directed at this approach is that peer review cannot be used to compare the value of federal research with other federal programs for the purpose of resource allocation. In fact, the most frequently used peer review methods do not even provide a single-valued metric for allocating scarce research expenditures to competing research proposals. This can lead not only to ambiguity about how limited resources are allocated to a number of technically exceptional proposals, but also to concerns about the nature of the criteria used to make these incremental decisions. A second concern is that the results of peer reviews tend to reflect only the preferences of the individual peer reviewers, along with their backgrounds, biases and objectives, whereas the results of the research might benefit a much broader group of people whose preferences are not taken into account.

A third criticism of the peer review approach is that it is essentially conservative in that it tends to promote what Thomas Kuhn (1962) terms "problem solving" in science rather than invention. This manifests itself in a tendency for peer reviewers to favor well-accepted research methods over more controversial approaches.

Finally, peer review methods can be criticized because they may be more subject to manipulation by agency administrators who may have a particular interest or research result that they want to achieve. These ends may be easier to achieve through peer review than through other evaluation methods because of the discretion allowed in selecting the reviewers and assigning the weights used to score different attributes of a proposal. However, while these and other questions about peer review persist, no major proposals for change have been convincing enough to overhaul the peer review system in the federal government.

3.2.2 Bibliometric Methods

Bibliometric methods attempt to measure the quantity and quality of the output of a research project, program or institution by counting the citations or cross-citations associated with it. The important assumption that underlies this approach is that new information is the key output of research and that the contribution of a project to the information base of society can be measured by the number and quality of publications that are produced from it. A recent variant of this approach combines bibliometric methods with peer review to try to assess the efficiency of research investments. Bibliometric methods, like peer review methods, have been criticized because it is difficult to use them to make resource allocation decisions involving comparisons between research and other federal programs.

Early efforts in the field of bibliometrics explored the feasibility of understanding science through its literature, independent of the scientists themselves. The first bibliometricians tended to use counts of citations as indicators of the directions in which science was moving. However, according to Chubin (1976, 1981) limitations associated with measuring and scaling these outputs soon led beyond the simple counting of citations toward more complicated statistical and mathematical techniques that would allow bibliometricians to describe, in quantitative terms, the structure of the information base reflected by the scientific literature and citations. Now that these tools have been developed, bibliometricians are attempting to use them to evaluate research projects and programs on an ex post basis.

Perhaps the best and also the most controversial use of bibliometric methods to evaluate scientific research is contained in a series of articles by Martin and Irvine (1983a, 1983b, 1984, 1985). They claim that citation evidence can be used in conjunction with ex post peer review to determine the productivity of basic research. Their approach involves obtaining counts of publications and citations associated with different research programs in a specific scientific field or topic and then normalizing the outputs from each program with respect to the scale of the research effort, using cost, person hours of effort, or some other obtainable input paramers. The normalized research outputs for each program are aggregated into a single indicator of research productivity and the research programs are ranked based on their productivity. Finally, an ex post peer review is conducted for each of the research programs and the citation rankings are compared with the rankings from the peer review. If the productivity analysis is consistent with the peer reviews, Martin and Irvine argue that these "converging partial indicators" can be used as a basis for shifting some resources from less efficient research programs to more efficient ones.

Martin and Irvine's work has been applied in an international context to laboratories engaged in high energy physics (1984) and the field of radio astronomy (1983b). Although, their method is still relatively controversial and has not been used by any agencies of the federal government to evaluate basic research, more general bibliometric studies have been used by federal agencies. Some of these studies are described in the next paragraphs.

In the United States, the earliest studies in bibliometrics were supported by NSF. However, most of the work in this area over the past decade has been sponsored by the Program Evaluation Branch of NIH. The first round of NIH bibliometric studies, conducted by Grace Carter (1974), analyzed over 800 research grants by NIH. She found that grants which were renewed had a higher publication rate than those which were terminated and that priority scores from peer reviews of grant applications were highly correlated with the number of subsequent publications. More recently, NIH has sponsored bibliometric studies to determine the effectiveness of alternative methods for supporting research and to evaluate biomedical manpower training programs (OTA 1986).

Bibliometric methods are valuable because they provide a means of measuring the output of a research project or program along several important dimensions. Publication counts, when appropriately adjusted for the quality of the journal in which they are published, give a rough measure of the information produced by a research project. Furthermore, as Martin and Irvine have shown, publication counts can be normalized on the basis of other research inputs to provide an indicator of the productivity or efficiency of a research project. These measures of output and efficiency can be compared in fields where publication practices and incentives are identical for ranking purposes. Similarly, citation counts are also a valid indicator of the impact that the results of a research project have had on the information base of a particular field. Taken together, these indicators can be used to help discriminate between research projects, programs or research groups based on their output, impact, and productivity.

However, there are at least three basic limitations with this approach when applied to research decision-making. First, bibliometric methods can be criticized because their measures of output and productivity are too narrow. This criticism rests on the multiple outputs of research units. Facilities, laboratories and scientific institutes have functions other than producing publications and citations, such as training and education, which are not taken into account by bibliometric methods. Measurements that do not account for these other functions will systematically understate the research productivity of the unit being evaluated. Second, while bibliometric methods may be able to demonstrate a high correlation between peer review scores and output, they have no inherent predictive capability. This limits the applicability of these methods to evaluate research on an ex ante basis. Finally, these methods, like peer review approaches, cannot be used to make resource allocation decisions involving tradeoffs between research and non-research activities. Indeed, some critics (Chubin 1981) of this approach contend that structural differences between research fields and disciplines in some cases make it impossible to compare even the most sophisticated bibliometric measures of research output from different research projects.

3.2.3 Economic Methods

The term economic methods, as used in this report, refers to a wide variety of approaches which, directly or indirectly, either attempt to measure the effect of changes in federal R&D investments on the productivity of particular industries or else try to determine the monetary value of the net benefits associated with that investment. In this section, we briefly review five different approaches that have been used by economists to evaluate the impacts of federal investments in R&D. For convenience, we have given them the following names:

- the production function approach
- the accounting method
- the residual imputation approach
- the human capital approach
- the economic surplus approach.

Production Function Approach

This represents the traditional approach to measuring the impact of federal R&D on productivity. It shares with all of the other methods to be discussed the idea that R&D can be described in terms of a production process. The process is characterized by a technology that converts inputs, such as capital, and labor, into outputs. In this particular framework, R&D expenditures are treated as an input to production, while the outputs of the R&D process can be thought of as new information, changes in product quality, or new technologies.

Although the description of the production process and, particularly, its outputs are somewhat stylized here, the application of the method is more straightforward. In practice, economists postulate an R&D production function that relates the output of goods and services by a particular sector to observable inputs, including R&D expenditures. Multiple regression methods are then used to estimate parameters of the production function. The form of the production function is chosen such that the regression model can be evaluated to determine the effect on the output of goods and services in the industry of a small change in R&D expenditures. This measure of the marginal productivity of R&D is then used to characterize the rate of return to the R&D investment.

This approach has generally been employed in a national economic or single industry setting. The results have been mixed. A recent study by Griliches and Lichtenberg (1984) estimated a 1.5 percent average rate of return to federal R&D in 27 industries for the period 1959-1976. The corresponding rate of return to private R&D in these same industries was almost 22 percent. Much higher rates of return to federal R&D have been noted, particularly in agriculture where rates of return have typically been estimated in excess of 25 percent (Evenson et al. 1979), well above the opportunity cost of capital in most private markets.

The low rates of return found by Griliches and Lichtenberg have been rationalized by Terleckyj (1974) who argues that this result is consistent with the behavior of a firm that is given a free good to use in production: the firm will use the good until additional amounts do not produce additional outputs.[a] A second explanation for apparently low rates of return is advanced by Mansfield (1984) who contends that federal R&D in many cases does not directly contribute to output growth, but tends to enhance the profitability of private R&D, instead. A third explanation is that a firm's rate of return on R&D is small because of R&D-induced decreases in the prices of goods and services. The benefits to consumers of this R&D, on the other hand, may be substantial, due to the same low prices. However, the production function approach generally does not measure benefits to consumers.

(a) Until its marginal product is zero.

Particularly in agriculture, the production function approach has proved to be a useful means of isolating the effect of R&D on productivity. However, this approach does suffer from a number of theoretical and practical limitations. From the standpoint of theory it is not clear, as Mansfield (1984) suggests, that R&D investment enters the production function in the same form as other inputs. A second theoretical limitation is that this method does not account for the effect of spillover effects on other industries, nor does it capture the benefits that R&D may create by lowering the cost of goods and services to other firms and consumers. Finally, there is the question of how the results of productivity analysis can be applied on an ex ante basis to compare individual federal investments. The application of productivity analysis to evaluate basic research is particularly problematic due to unknown or unintended results. On a broader scale, productivity analysis may provide some indication of which industries should receive continued support based on higher-than-average private market returns; however, it is not at all useful in deciding whether the federal government should allocate its resources to individual programs.

Accounting Methods

Accounting methods are among the simplest and most frequently used by firms in the private sector and, occasionally, by federal agencies, to measure the value of R&D projects on both an ex ante and ex post basis. The measures used most often include net present value (sometimes referred to as discounted cash flow), internal rate of return, and project payback. This method varies in each application, but generally involves the following steps. First, the expected effect (for ex ante analysis) or observed effect (for ex post analysis) of the project on the net revenues of the firm or market segment is calculated over time. This flow of future values is then discounted over time into present values to reflect the alternative earning opportunities of the R&D investment. Summing these discounted values over time yields the present value of project benefits. The same procedure is applied to R&D costs to determine the present value of project costs. The net present value of the R&D investment is calculated by subtracting the present value of project costs from the present value of project benefits. The internal rate of return is the discount rate that will exactly equate the present value of project benefits to project costs. Finally, the payback period of the investment is calculated as the amount of time it will take for the present value of the benefits to equal the present value of project costs.

As stated above, accounting methods are used more frequently in private industry for selecting R&D projects than in the federal sector. One example of the use of accounting methods to perform ex ante project selection involvec the screening of energy conservation programs by the Energy Development and Research Administration (ERDA) and later DOE (Roessner 1981). These agencies developed project selection models to calculate the payoff associated with research investments on different technologies and strategies for saving energy. While the nature of the inputs and outputs of these models varied, energy cost savings per barrel of oil, internal rate of return and length of project payback period were frequently used to compare these investments.

By providing a common set of metrics, accounting methods can be used on an ex ante basis to compare investments in R&D with other forms of investment by both the private and public sectors. Accounting methods are useful in measuring the net benefits of an R&D project when: 1) the project is narrowly focused on making a small improvement in an existing technology or reducing its cost; 2) the project does not substantially influence the market price of the technology; 3) the market for the technology is competitive, and 4) there are no spillovers into other markets. Under these conditions, accounting methods can be used to approximate the benefits to society of the R&D investment. The fact that these conditions rarely hold for R&D investments in basic research makes this type of approach particularly ill-suited for evaluating that kind of federal investment.

The Residual Imputation Approach

A traditional method for valuing the productivity of inputs that are hard to price or hard to measure is the residual imputation approach. In this approach, budgets showing input usage and costs are constructed for representative firms in the industry being investigated. These budgets are used to determine the costs[a] and quantities associated with each input used

(a) The appropriate costs used in the budgets should be opportunity costs (what is being foregone by using that input) and not its historical cost.

in production. These costs are totalled to determine what it will cost the firm to produce a unit of output at an appropriate scale of operation. This normally includes a profit margin, which is figured as a payment by the firm to its owner. Next, the marginal output of the firm is valued at its market price and the costs associated with this additional unit of output are subtracted from it. The remainder is then used to value the contribution of the unobserved, or hard to price, input to the value of output.

This approach has traditionally been employed in agricultural economics to determine the social value of inputs, such as water, which are not priced in competitive markets at their true opportunity cost. An interesting and less rigorous (but conceptually similar) approach has been used by Mowery (1985) to determine the benefits associated with federal R&D support of commercial aviation technology. In his study, Mowery used a relatively simple index of aircraft performance (number of available seats multiplied by air speed) to reflect changes in aircraft technology between 1940 and 1983. He then calculated the change in direct operating cost per passenger mile for the same period.

Mowery combined these two indices to show that the cost to society of using the 1940 technology to carry the volume of passenger traffic in the U.S. in 1983 would have been roughly $25 billion, as opposed to the actual cost of transporting this traffic which was about $6 billion. Thus, by imputing all of the increase in productivity and all of the decrease in cost to federal R&D, Mowery suggests that the $19 billion annual saving to society can be used to approximate the total benefits produced by federal R&D in this area. According to Mowery, this translates into a rate of return on federal R&D of about 24 percent, again substantially higher than the opportunity cost of capital in most alternative private investments.

This approach is best used as a preliminary method for evaluating R&D. It has virtually no ex ante application; it is not well-suited for valuing the benefits of a technology to consumers due to lower product prices; and it does not account for spillover effects into other industries. Moreover, the residual value that is imputed to R&D could just as easily come from other sources that are equally hard to observe and/or measure. However, in the absence of a great deal of data, approaches like those used by Mowery can prove useful in screening federal R&D programs for further, in-depth review.

Human Capital Approach

The methods we have discussed so far all rely on measures of market activity to evaluate federal R&D. However, there are many instances in which federal R&D is used to improve human welfare in ways that cannot be entirely captured through the use of market prices. This is true of investments in human health where markets do not exist for pricing the values of lives saved or of greater longevity. This is also true, in many cases, of R&D investments associated with environmental quality where market prices of complementary goods (such as pollution reduction technology) do not capture the social value associated with their use, or where there are no market prices at all to reflect environmental values.

One way that economists have tried to overcome this limitation in the health field is by valuing the impact of R&D on direct and indirect health costs to individuals. The so-called "human capital" approach is based on the assumption that changes in morbidity and mortality can be valued in terms of the opportunity cost of the resources used in treatment and the income foregone by sickness or premature death. This approach was used by Mushkin (1979) in conjunction with residual imputation to quantify the value of biomedical research during the period 1900-1975. She first calculated the direct costs associated with different chronic illnesses, including expenditures on hospitalization, physicians, drugs, etc. To this were added 1) the morbidity costs due to losses incurred by an individual when illness or disability results in absence, either temporary or permanent, from the work force and 2) mortality costs due to premature death. The latter was estimated by the net present value of an individual's earnings foregone due to premature death. These costs vary according to the occupational, age and sex composition of the population to which they are applied.

Mushkin used a combination of the production function and human capital approach to determine the effect of biomedical research on the reduction of mortality during the period. Indicators of technological change attributable to biomedical research could not be found. Consequently, any reduction in mortality that could not be attributed to other factors was attributed, as a residual effect, to advances in biomedical research. Using this approach, Mushkin estimated that a one percent increase in biomedical research during the period resulted in a 0.05 percent decrease in mortality. She also estimated biomedical research contributed to about 40 per cent of the reduction in days away from employment because of illness. Finally, Mushkin used the human capital cost estimates to calculate the value of premature deaths avoided and work years gained due to biomedical research. She found that these values, when combined, were approximately $150 billon in present value terms. This was consistent with an annual rate of return on investment of 46 percent.

While the human capital approach is specific to health-related fields, it represents one way to overcome a more general problem associated with the valuation of goods and resources that are not sold in markets (nonmarket goods). The theoretical advantage of placing a monetary value on the benefits of R&D that improves human health or on other nonmarket goods and services is that it enables explicit comparisons of the tradeoffs associated with alternative uses of federal funds. However, there are also theoretical problems with the human capital approach. Specifically, the use of expected future earnings as a measure of the value of life can be faulted on three grounds: 1) it implies a positive value for the death of someone whose expected contribution to Gross National Product (GNP) is negative; 2) it ignores the feelings of the potential victims, and 3) it assumes that the only contribution that a human life makes to society is to the GNP. Finally, as a practical matter, the approach used by Mushkin is primarily oriented toward ex post evaluation and cannot be used on an ex ante basis to make R&D decisions, unless one assumed that the average rate of return on past biomedical R&D equals the marginal rate of return on proposed biomedical research.

Economic Surplus Approach

An important weakness with most of the methods presented above is that they do not take into account the fact that technological breakthroughs as a result of R&D can cause changes in the market prices of relevant goods. These price changes make it difficult to value R&D benefits using traditional methods. For example, the so-called "Green Revolution" made it possible to grow high-yielding grain varieties in a number of different parts of the world.

This has been an important factor in the recent decline of world grain prices. The primary beneficiaries of the Green Revolution have been consumers worldwide, who now have access to much lower priced grain, and some producers in developing and lesser developed countries where lower production costs compensated for the decline in prices. Grain producers in the U.S., on the other hand, were hurt because they derived none of the benefits of the lower production costs afforded by the Green Revolution, but had to sell their grain on a world market in which prices were depressed, due in part to the higher production made possible elsewhere by the Green Revolution. To properly value the benefits of research related to the Green Revolution, we need a method for measuring benefits that takes into account the conflicting impact of research-induced price changes.

The economic surplus approach attempts to do this in two ways. First, the benefit measures that are used by this approach take into account the fact that consumers derive benefits from the consumption of a good when they are able to purchase the good for an amount less than the maximum amount they would be willing to pay for it. By the same token, a firm is benefitted by the production of a good when it is able to sell that good at a price greater than the minimum amount it costs to produce the good. In both of these cases, there is an economic surplus present. The concept of economic surplus and its utility for measuring the benefits of R&D will be dealt with more fully in Section 3.3; for the moment, what is important about this concept is that it provides a way of measuring benefits to consumers and producers in common units. Furthermore, it does this in a way that allows one to take into account the sometimes uneven impact of R&D-induced price changes on the benefits of both groups.

The second important aspect of the economic surplus approach is that it uses mathematical representations (i.e., models) of supply and demand curves in relevant markets as the basis for measuring these surplus changes. The parameters of these supply and demand curves are estimated statistically and the models are joined to simulate the economic behavior of buyers and sellers in relevant markets leading to the setting of "equilibrium" prices at which sellers and buyers agree to exchange money for goods. The economic surpluses of consumers and producers are calculated from information obtained directly from the supply and demand curves. R&D investments are generally modeled using a production function approach, such that a simulated increase in R&D funding lowers the marginal cost of producing relevant goods over a substantial range of output and makes these goods more attractive to consumers. The models then simulate the process of exchange with the new technology in place until market equilibrium is achieved and the consumer and producer surplus calculations are repeated. The periodic benefits of the R&D investment are calculated as the change in total economic surplus.

The above approach has been used with some success to evaluate the benefits of R&D in areas where the R&D investment can be traced directly to a new or improved type of market good. The best examples of this approach are to be found in the ex post evaluation of R&D in the agricultural sector. The first such major use of this approach was by Schultz (1953) who calculated the value of the inputs saved in agriculture due to improved, more efficient production techniques. Following Schultz, Griliches (1958) used this approach to estimate the loss in surplus to consumers that would occur if research on hybrid corn had not occurred. These early studies were methodologically flawed because of overly simplistic assumptions made by Schultz, who assumed that individual demands for agricultural commodities were not price-sensitive, and by Griliches, who alternately assumed that the supply of corn was totally price-insensitive or else that the price of corn was insensitive to changes in supply. Peterson (1967) dropped these assumptions in his study on poultry research in the U.S. and calculated the effect of this type of R&D on consumer and producer surpluses. He then compared these benefits with the costs of the R&D and estimated a rate of return of about 25 percent on this investment. Peterson's work is generally regarded as the standard against which methodological improvements are measured.

The economic surplus approach is general enough that it can be applied broadly to R&D impacts on both market and nonmarket goods, although some of the methods for deriving the demand curves for nonmarket goods are highly controversial. In either setting, however, this approach does have several important limitations. First, the data needed to estimate demand and supply curves are generally not available from published sources and are often difficult to obtain either for cost or proprietary reasons. Second, while spillovers into other markets can be modeled using this approach, the data problems, which are already severe, become much more serious. Third, this approach generally does not work well with basic research since it is extremely difficult to trace the effects of basic research to all of the goods that have been influenced by it. Finally, this approach can only be used fruitfully in an ex post evaluation setting. Uncertainties about the effects of basic research on the supply and demand functions of both market and nonmarket goods, coupled with its data intensiveness, make it a poor candidate for ex ante evaluation.

3.3 CONCEPTUAL BASIS FOR THIS RESEARCH

The main body of this report, Chapters 4 through 6, contains three case studies of OHER or OHER-related investments, in which benefit-cost analysis (BCA) was used as one method for evaluating the contribution of these investments to societal well-being. BCA uses the concepts of producer- and consumer-surplus as described in our discussion of the economic surplus approach. In undertaking this kind of approach we are in effect engaging in hypothetical experiments. Our purpose in each of these case studies is to try to estimate what the welfare of society would be with and without these investments. In that general context, the major objective of this section of the report is to provide the reader with a general understanding of how economists use BCA to measure changes in welfare and how these principles can be applied to the evaluation of R&D investments by the federal government.

3.3.1 Theoretical Foundations of Benefits-Cost Analysis

A basic principle underlying the use of BCA is that of economic efficiency. This principle is defined with respect to the allocation of available resources in a society to alternative productive opportunities. A resource allocation is said to be efficient when it is not possible to change it without making someone worse off. By contrast, a resource allocation is said to be inefficient if it is possible to reallocate resources and make at least one person better off without making any other individual worse off. This criterion of economic efficiency is called the Pareto criterion. If a particular resource allocation is efficient in the above sense, then it is called "Pareto optimal."

Under certain, highly idealized economic conditions the "invisible hand" of the market will automatically produce a Pareto optimal resource allocation. However, in many economies these conditions are not satisfied and, as a result of these so-called "market failures" (Bator 1958), the allocation of resources that prevails in such an economy will not be Pareto optimal. In the presence of market failures, government intervention in the economy can be justified on efficiency grounds as a means of guiding the economy toward a more efficient resource allocation. In that context, BCA represents a method for comparing alternative government actions from an efficiency standpoint and selecting those that contribute most to the goal of economic efficiency.

As a practical matter, the Pareto criterion for economic efficiency is difficult to apply because virtually any action by a government causes some injury or damage to at least one individual. As a result, a second criterion, known as the compensation criterion, has been adopted as a basis for judging whether a government action represents a contribution to economic efficiency. According to this criterion, a government action passes the efficiency test if those individuals who are benefitted by the action can compensate those who are injured by the action, and still be better off than they were before the action. There are, in fact, several different compensation criteria (Hueth, et al. 1982). However, the one most often used in the U.S., the so-called Kaldor Hicks criterion, does not require actual compensation to take place. Instead, a government action meets the Kaldor-Hicks criterion as long as the potential exists for the gainers from a government action to compensate the losers. In this context, BCA provides a method not only for determining whether the benefits from an action are greater than the costs associated with it, but also for identifying the distribution of gains and losses among different groups within society.

3.3.2 Measuring the Effects of R&D on Societal Well-Being

According to Arrow (1962), "the central economic fact about the process of invention and research is that they are devoted to the production of information." This view of R&D has been criticized in two recent reviews of the use of economic methods to measure the returns from federal R&D (OTA 1986; Finneran (1986) on theme in these two studies is that Arrow's view is too narrow because many of the results attributed to R&D are not produced in the same way as market goods and services, or else they cannot be valued in monetary units, such as dollars. Economists, in their own defense, would argue that economic theory is flexible enough to satisfy both of these criticisms, but that practical problems in applying the theory make it difficult in some cases to use BCA effectively to evaluate federal R&D investments. For the remainder of this section we will concentrate on the theoretical basis for measuring the benefits and costs of R&D. In Section 3.4, we will focus on the limitations of BCA to evaluate federal R&D investments, particularly in basic research.

Figure 3.1 presents a highly stylized diagram of the R&D process. The inputs to R&D include the services from the stock of information relevant to a particular project, the services provided by the capital facilities and equipment where the project is conducted, and finally, all of the different types of labor services provided by those working directly or indirectly on the project. These inputs are combined in the transformation or production function, labeled "R&D" in the center of the diagram, to produce the output of the project, which is information. In basic science, this information might take the form of a new hypothesis or the results of a test of an existing hypothesis. In applied research, this information might be represented by the results of an experimental method for producing electricity or by an experiment to determine the toxicity of a particular chemical. Finally, Figure 3.1 shows that the information produced by the R&D process can be used in one or more of four different ways. First, the information can be used as an input in other R&D projects. Second, it can be "consumed" by individual scientists for reasons of personal enjoyment and professional advancement. Third, it can be used by government to make policy decisions. Fourth, it can be used in private markets by firms to help reduce the costs of existing products or to develop new or improved products for sale in markets.

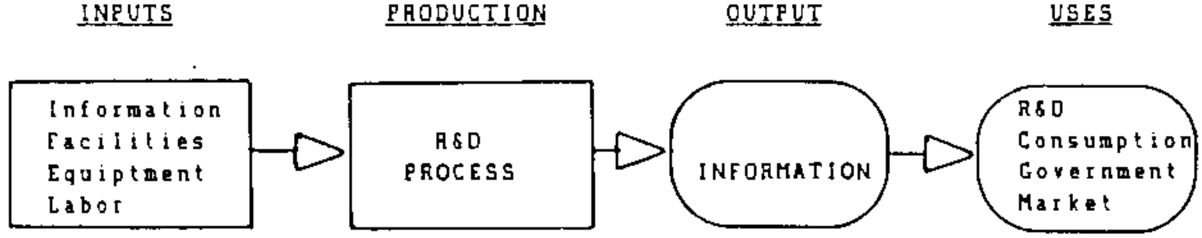

FIGURE 3.1. Schematic Diagram of R&D as a Production Process

All of these different types of uses of information represent potential sources of benefits which can, in theory, be measured using a common framework. This framework is based on the principle that a rational economic agent (i.e., an individual consumer or firm) is willing to pay some maximum amount of money as compensation for an increase in his personal welfare. The principle also suggests that there is a minimum--not necessarily the same--amount of money which a rational economic agent will accept as compensation to forego the same increase in welfare. In the large majority of cases involving BCA, the willingness-to-pay/accept compensation principle can be used to measure the net benefits that accrue to rational economic agents.

Measuring Net Benefits for Firms

One way that the information produced by R&D acquires value to society is through its effect on the ability of firms to supply goods in markets. This can occur through several different paths. The first and most direct route is through the effect of applied R&D on the production of market goods. A second possible route is through the effect which information has on a government policy decision that, in turn, influences the production of goods and services by a firm. For example, better information about the toxicity of a chemical could lead to a government decision to allow production of a chemical that had been banned on the basis of the best previous information. Finally, R&D can reach the market indirectly either through successive phases of R&D which eventually results in the production of information that can be used in the production of market goods and services, or through "spinoffs" to other technologies.

The appropriate measure for characterizing the change in the welfare of a firm due to the direct or indirect effects of R&D is producer (or, more generally, seller) surplus. As stated previously, producer surplus arises because there is often a difference between the price at which a firm can sell a good in a market and the minimum price it will accept for the good, rather than shut down. The change in this measure of net benefits is represented by the change in the difference between the gross receipts of the firm and the firm's total variable cost.[a] Finally, the reader should note that changes in gross receipts, revenues or other measures for the value of products sold by a firm do not constitute a legitimate welfare measure because these measures fail to account for the value of the resources used to produce goods. Since these resources could alternatively be used to produce other goods, the cost associated with not using them elsewhere in the economy must be deducted from gross receipts to obtain a legitimate welfare measure.

Figure 3.2 illustrates how the change in producer surplus of firms can be used to measure the effects of a government investment in R&D resulting in information that makes it possible to reduce the cost of providing a market good or service. The example we use here involves a hypothetical R&D

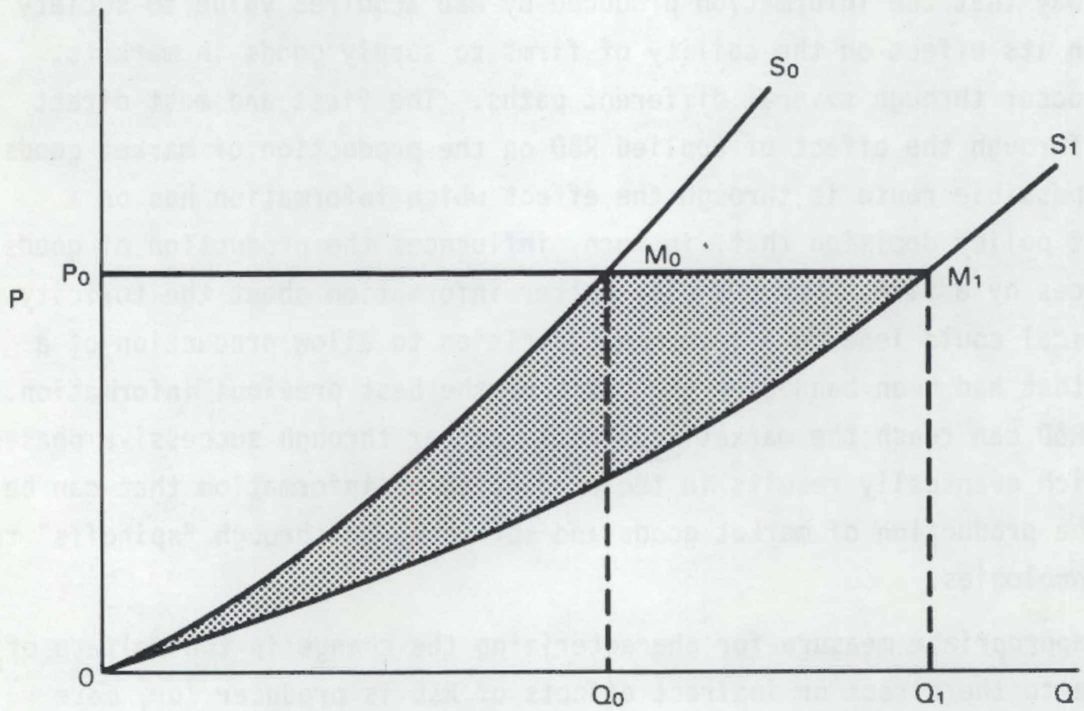

FIGURE 3.2. Net Benefits to Firms of a New Technology

(a) Economists often use the term quasi-rent, which measures the difference between the amount which the factors of a resource owner earn in their current occupation and the minimum sum he or she is willing to accept to keep them there, is often used interchangeably with the term producer surplus. Under most conditions the two measures are equivalent.

investment which results in a new technology for detecting a specific type of illness. Let us assume here for simplicity that the relevant market service affected by the R&D investment is a test to detect the illness. The initial market supply curve for the test is given by the line OS_0. This curve shows the total number of tests (Q) on the horizontal axis that firms are willing to offer in the market at each price (P) on the vertical axis. For simplicity, the market demand for the test is assumed to be perfectly price elastic: a change in the quantity of tests demanded in the market will have no influence on the market price for each test, P_0. Later this assumption will be dropped. Under these conditions, there is a unique market equilibrium at point M_0, such that firms sell and buyers take Q_0 tests from the market, given the price P_0. The gross receipts of firms from the sale of tests is P_0 times Q_0. This is represented by the area $OP_0M_0Q_0$. The total variable cost of all firms in the market is measured by the area under the supply curve up to M_0, which is OM_0Q_0. Producer surplus is measured by the difference between gross receipts and total variable costs, which is equal to the pie-shaped area $OPOM_0$.

Now suppose that the effect of the new technology is to reduce the variable cost of providing the test, no matter how many tests are given. The effect of this investment on the provision of tests in the market is shown by the new market supply curve for this service, represented by the line OS_1. This supply curve shows that firms are now willing to provide more tests in the market at the same price as the old test. The result is that, given the same perfectly elastic aggregate demand for tests, firms now sell and buyers take Q_1 tests from the market at a price of P_0 for each test. Following our previous calculations, producer surplus can now be measured by the area OP_0M_1. The net benefits of the R&D investment to firms in the market is measured by the shaded area in Figure 3.2, OM_0M_1. Conceptually, the change in producer surplus shown in Figure 3.2 is composed of two parts. The shaded area to the left of Q_0 represents the partial economic surplus due to the decrease in the variable cost of tests, holding the number of tests constant at the initial level. The shaded area to the right of Q_0 represents the partial economic surplus generated by the provision of new tests (i.e., $Q_1 - Q_0$), using the new technology.

Measuring Net Benefits of Individuals

A second way that the information produced by R&D can acquire value is through its impact on the welfare of individuals. This can occur in at least three different ways. First of all, individual welfare will generally be improved when R&D results in new or improved products or in a decrease in the price of an existing good or service. This can occur as a result of market or government uses of R&D (See Figure 3.1). For example, the decision to deregulate a specific chemical on the basis of new information might lower the costs of health care to consumers. Nor is this type of welfare improvement strictly limited to goods and services provided in markets. For example, information that results in less expensive pollution control technologies can improve the welfare of individuals who derive greater enjoyment from a cleaner environment. Second, the welfare of individual scientists can be improved through direct monetary compensation in the form of higher pay, additional grants, and indirectly through greater status in the profession. Finally, the welfare of individual scientists can also be improved through non-monetary compensation as a result of the enjoyment derived from research. This last point can be extended to non-scientists, as well. By definition, anyone who derives enjoyment from learning about the information provided by R&D is benefitted by it.

Measuring these types of welfare changes in dollar terms is more complicated for individuals than for firms. One possible measure is ordinary consumer (buyer) surplus, which is defined as the difference between the maximum amount a consumer is willing to pay for a good, rather than do without it, and the amount actually paid for the good. The primary advantage of this welfare measure is that it can be estimated using information obtained directly from the ordinary demand curves of consumers for goods. The chief disadvantage of this measure is that it may not always provide a unique measure of the net benefits to individuals associated with R&D investments. Fortunately, Willig (1976) has shown how information obtained from ordinary demand curves can be used in conjunction with consumer surplus to bound the errors associated with the non-uniqueness problem.

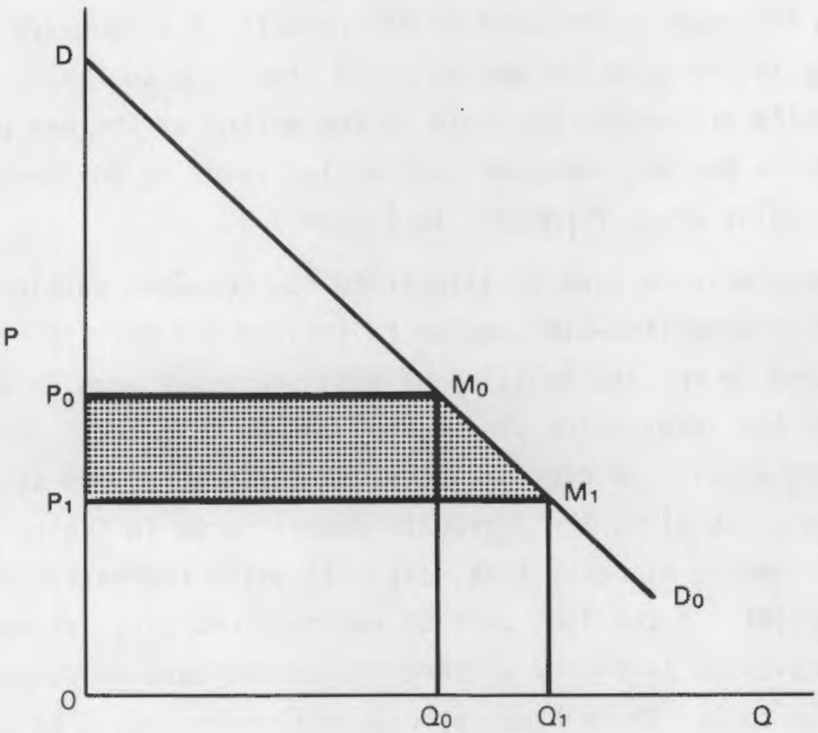

FIGURE 3.3. Net Benefits to Individuals of a Price Change

Figure 3.3 illustrates how ordinary consumer surplus can be used to measure the net benefits to individuals of an R&D investment which reduces the price of a market good from P_0 to P_1. In this case, we assume for simplicity that the market supply curve for the relevant good is perfectly price elastic. Later we will drop this assumption. Prior to the application of the information produced by the R&D investment, this supply curve is shown by the horizontal line P_0M_0. The ordinary market demand function for the good is shown by the line DD_0. Each point on this curve describes the total quantity of the good (Q) that buyers will take from the market when faced with a specific price (P). Under these conditions, the consumers take Q_0 units of the good from the market at a price of P_0 per unit. The consumer surplus associated with this market equilibrium can be calculated as follows. Some individuals are willing to pay as much as D for the first unit of Q rather than do without it. However, they only have to pay P_0, not D, to purchase it. Therefore, the consumer surplus associated with the first unit of Q is equal to D - P_0. Repeating this calculation for each additional unit of Q up to Q_0 results in a consumer surplus total which can be represented by the area under the demand curve and above the market price line at P_0. This area is equal to P_0DM_0. Now, suppose that the information produced by R&D results in a downward shift in the aggregate supply curve in the market for Q from P_0M_0 to P_1M_1. Under these conditions, Q_1 units are bought and sold in the market at the new price P_1. As a result of these changes consumer surplus increases by an amount equal to the shaded rectangular area, $P_1P_0M_0M_1$, in Figure 3.3.

Figure 3.3 can also be used to illustrate how consumer surplus can be used to measure the benefits which accrue to individuals as a result of an R&D-caused increase in the availability of some nonmarket good. Assume, for example, that the information produced by an R&D investment in pollution control technology results in cleaner water, as measured by its turbidity. In this case each point along the aggregate demand curve in Figure 3.3 would measure the total amount of money that, say, all water recreation users would be willing to pay (P) for the last unit of reduced turbidity, as measured at Q. Given a reduction in turbidity (literally, an increase in reduced turbidity) from Q_0 to Q_1, these hypothetical individuals would be willing to pay an amount of money equal to the total area under the aggregate demand curve for reduced turbidity between Q_0 and Q_1, or $Q_0M_0M_1Q_1$. If these turbidity reductions are provided to these individuals at no cost, then this area also corresponds to the change in consumer surplus. If, on the other hand, these services are optimally priced based on information both about the demand for clean water and the supply for clean water, using the pre- and post-technology change supply curves for turbidity reduction services (P_0M_0 and P_1M_1, respectively), then the shaded area in Figure 3.3 represents the change in consumer surplus associated with cleaner water.

Synthesis of Benefits

The concepts of producer surplus and ordinary consumer surplus are brought together explicitly in Figure 3.4. This figure shows how information obtained from ordinary demand curves for a market or nonmarket good can be used to approximate the net benefits of an R&D investment to both individuals and firms. The initial aggregate supply and demand curves for the good (Q) are shown by the lines DD_0 and OS_0. Market equilibrium occurs at the intersection of the supply and demand curves at M_0 and is characterized by the market clearing price and quantity combination of P_0, Q_0. At this point, ordinary consumer surplus is equal to the area P_0DM_0 and producer surplus is equal to the area OP_0M_0. The effect of new information on the production of Q is represented by a shift in the aggregate supply curve from OS_0 to OS_1, indicating that the variable cost of producing the good is smaller at all levels of output. As a result of this new information, a new market equilibrium is reached at point M_1. At this new equilibrium, the market price has fallen to P_1, while output and consumption have increased to Q_1. Consumer surplus is now given by the area P_1DM_1, while producer surplus is represented by the area OP_1M_1. The change in the sum of producer and consumer surplus as a result of the new information is equal to the shaded area OM_0M_1.

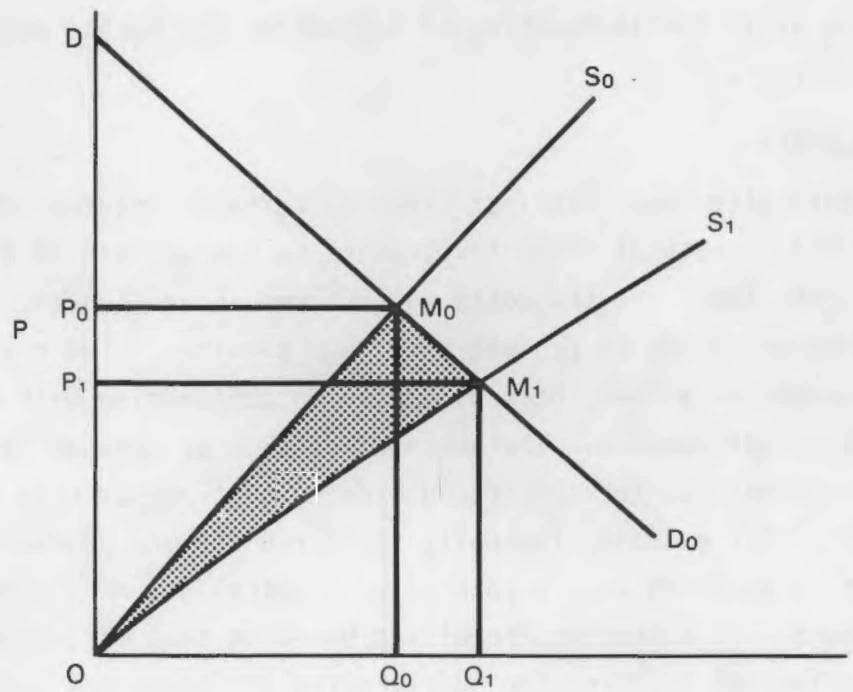

FIGURE 3.4. Measurement of the Net Benefits of Government Investments for Firms and Individuals

This area represents an approximation of the net benefits received by individuals and firms as a result of the new information in a single market in a single period. However, as we suggested earlier through Figure 3.1, the results of R&D have the potential to influence the welfare of firms and individuals in a variety of market and nonmarket situations. Changes in the sum of producer and consumer surplus in a single market are appropriate measures of the effects of new information on economic well-being in a partial equilibrium framework. These same measures are also appropriate in a general equilibrium framework in which markets are linked by the exchange of inputs and outputs, and the effects of new information in one market can spill over into others in the form of changes in price, output and consumption levels. In this more general case, however, aggregation of consumer and producer surpluses must be done with care. This is because an economic agent can be a buyer in one market and a seller in another. Consequently, the change in the sum of the buyer and seller surpluses in all markets will generally be greater than the change in the sum of the surpluses of all buyers and sellers (Hueth et al. 1982). To avoid double counting of surpluses, the second method of aggregation is correct.

Estimating Costs

There are basically three distinct kinds of costs associated with R&D investments and the effects of these investments on the welfare of firms and individuals. First, there are the costs which firms incur when they use new information and other inputs to produce goods and services. The treatment of these types of costs has already been discussed in conjunction with the measurement of producer surplus. The above discussion of consumer and producer surplus is also appropriate for the second type of cost--costs that represent negative benefits. For example, federally sponsored R&D may produce information that the toxicity associated with a particular chemical was more serious than originally believed. If a drug was regulated based on that information, this would have the effect of shifting the supply curve in Figure 3.4 to the left --for example from S_1 to S_0--causing a reduction in the sum of producer and consumer surplus in the market for that chemical. On the other hand, if the decision to regulate the chemical was made strictly on the basis of a benefit-cost analysis, this presumes that the decrease in total surplus in the market for the chemical would be offset by increases in consumer surplus due to reduced morbidity and mortality.

Finally, we need to account for costs that are incurred to finance an R&D project. The appropriate measure for this type of cost is the same as for the firm, the opportunity cost of the resources used in the process of producing information in the R&D process. The opportunity cost of these resources is a measure of what society must give up to fund an R&D project rather than use project resources in their next-best alternative use. These costs include all of the costs we normally associate with federally funded R&D efforts. For example, it includes the amount the government is billed for the research services provided by the grantee or vendor. It also includes costs that are not normally accounted for as R&D costs such as the value of the time spent by government officials who screen, evaluate and monitor an R&D project. Opportunity costs also include costs associated with the use of goods and services that may be provided "free" to a project. For example, some government laboratories provide materials and chemicals for experimental use by researchers in other labs at no charge to users. However, these goods are valuable to society, even if their only use is experimental, since the resources used to produce them could have been used elsewhere in society. Accordingly, free goods and services should be priced at their best alternative use, which in most cases is not zero.

3.4 PROBLEMS IN THE APPLICATION OF ECONOMIC METHODS

In the previous section we attempted to show that economic theory provides a basis for consistently measuring changes in benefits and costs associated with the production of new information through R&D investments. In addition, we tried to suggest that this framework was broad enough to measure changes in benefits and costs associated with a wide variety of uses to which new information could be put. This includes measurement of benefits associated with the enjoyment of science for its own sake by scientists and others, with changes in the health risks to which individuals are exposed, and with changes in environmental quality. Valuation of these so-called non-market goods and services is controversial both for methodological and normative reasons. In this section, we briefly examine the more important and very real methodological problems associated with valuing these benefits in an applied framework. These problems can be grouped under two headings: 1) those associated with attributing the benefits and costs of R&D, and 2) those related to estimating the benefits and costs of R&D. We do not deal with the normative issue of whether it is right or wrong to convert all values into monetary units.

3.4.1 Attribution of Benefits and Costs

As previously mentioned, the application of BCA to federal projects involves conducting a hypothetical experiment to determine what the net welfare of society would be with and without a specific research project. As such, one of the first steps in applying BCA consists of identifying all of the potential effects of the R&D investment, both favorable and unfavorable. It also involves identifying the market and nonmarket contexts in which these potential effects could occur and the economic agents (i.e., firms, consumers, factor owners) who will be influenced directly or indirectly in these markets. To see why attribution of benefits is a serious problem in the evaluation of federal R&D, let us first look at a case in which the problems are not as severe and then compare it with the several R&D-related examples.

Consider, first, the application of BCA to a decision to build a large irrigation project. The output of the project is irrigation water. The direct beneficiaries of the project are farmers on project lands, who will experience increases in producer surplus due to increased yields, lower variable costs, and the ability to grow more profitable crops. If this led to lower market prices for affected crops then consumers would also benefit through increases in consumer surplus. However, some of the effects of the project may be unfavorable. Lower market prices for affected crops could hurt farmers with higher production costs in other areas and cause them to experience a decrease in producer surplus. In addition, the project could adversely affect wildlife habitats, scenic values, and existing forms of recreation. These negative consequences of the project would be accompanied by decreases in the consumer surplus of individuals whose use of the environment would be impaired by the project. Finally, the project could also reduce the consumer surplus of individuals who feel unhappy about the environmental effects of the project even though they may not experience them directly through their use of the environment. Attribution of the benefits and costs (i.e., negative benefits) in the above case is relatively straightforward, with the possible exception of the final category of negative benefits. In almost all instances, we can identify the potential (not the actual) consequences of the project and relate these consequences to specific groups of economic agents. Furthermore, this is true whether the evaluation is conducted on an ex ante or ex post basis.

Now consider a near-polar case involving the application of BCA to a basic science research project in purely theoretical fields, such as the so-called "unified theory," which, among other things, tries to trace back all of the currently known physical forces to a single force that was present at the moment the universe was formed. The major problem with evaluating the most basic types of research is that the information produced by a project like this has no clear effect on any currently available technology. As such, there is simply no way to attribute market-related benefits to such a project without benefit of a hundred or more years of hindsight. A more immediate effect of such a project will be to increase the stock of knowledge available to other theoretical physicists. This would increase the consumer surplus of individuals, presumably scientists who enjoyed reading or knowing about the results of the project. Which scientists? Identifying the users of information which has not yet been produced may be a somewhat arbitrary exercise. Finally, if a basic research project is successful, it could lead indirectly to additional monetary compensation and professional recognition for the project team members. While these types of benefits are easier to attribute to individuals, most economists and scientists would be understandably reluctant to employ such a partial measure as the sole basis for evaluating a basic research project. Part of the problem in the above example lies in the ex ante nature of the evaluation. While the problem of attribution is made easier when BCA is applied on an ex post basis, it by no means disappears. In the case of basic research, the results of a research project may be a proof of a mathematical theorem whose only foreseeable use is as an input to other, equally abstract theorems.

The problem of attribution also arises in the context of more applied forms of research. Consider, for example, the problems associated with attributing the benefits and costs of R&D investments in nuclear medicine. In an ex ante evaluation framework, one faces problems of attribution similar to those associated with basic research: identifying potential market and nonmarket benefits. Even the market benefits of the most applied forms of R&D are difficult to predict in advance. This is because the link between R&D and its eventual commercial application frequently depends upon advances in other, seemingly peripheral, technologies. The same problem exists, to a degree, in ex post evaluations of applied R&D due to unrealized applications, yet to be commercialized. Perhaps more serious than this is the effect which different assumptions about the time when an R&D project began can have on the attribution of benefits and costs. For example, if one is attempting to calculate the benefits and costs of R&D in nuclear medicine in an ex post framework, must one include the cost of the Manhattan Project? Presumably, the results of such an investigation would be extremely sensitive to any such assumption.

The problems noted above can generally be traced to one of three sources. First, as mentioned previously, it is frequently very difficult for firms or individuals to fully appropriate the benefits from R&D in private markets. This is because ideas have an illusive quality which causes problems for the "owners" of these ideas to exclude other individuals even through legal protection from using the idea or information. Difficulties in establishing and enforcing ownership of information both translate into problems with attributing the benefits associated with that information to identifiable sources. Second, information, once it has been produced, takes the form of a "public good" in the sense that its availability to any member of society does not reduce the amount that could be made available to others. Consequently, the benefits of this information can be shared widely and equally by many different economic agents without any real way of tracking all of the benefits from a specific program to specific groups. Finally, it is often the case in the public sector that markets do not exist for trading and valuing the information produced by R&D. This further obscures the path of R&D from a research project to its many different uses.

3.4.2 Estimation of Benefits and Costs

Estimation of benefits and some types of costs in the framework provided in Section 3.3 is ideally accomplished in a three step process, as follows. Once the potential effects of R&D on individual economic agents have been identified, the first step involves constructing demand and supply curves for the relevant economic agents in the appropriate markets or nonmarket contexts. The second step consists of using these demand and supply curves to simulate the behavior of buyers and sellers, with and without R&D for a period of time appropriate to the specific case. Third, the results of the simulations are used to calculate the difference in the sum of producer and consumer surpluses due to R&D in each period. These surplus changes are discounted in each period back to the date of their origin and then summed to obtain a measure of the present value of the net benefits to society as a result of the R&D. The present value of project costs is calculated and subtracted from the present value of project benefits to obtain a measure of the net present value of the R&D society.

The execution of these steps is sometimes problematic. In cases involving ex ante and, in many cases, even ex post evaluations of basic research, the problems of predicting the long-term consequences of R&D and identifying markets for the information produced by R&D make it virtually impossible to construct demand curves for that information, except perhaps for scientists and others who value this research for its own sake--and this has never been attempted. Given these problems, it seems unlikely that BCA represents a practical tool for evaluating basic research projects, unless the effects of the project can be defined well enough to construct demand or supply curves, as required. In Chapter 5 we describe an approach that we feel may help value the outputs of basic research.

Construction of supply and demand curves is less difficult in cases where the information produced by R&D could influence, or actually has influenced, the production or consumption of market goods and services. Constructing market demand and supply curves is conceptually straightforward in cases where the major results of R&D have been to reduce the variable costs of producing an existing market good or service. In this case, the analysis of net benefits is consistent, conceptually, with the movement of the supply curve in Figure 3.4. Unfortunately, constructing these demand and supply curves may be limited by the proprietary nature of sales information in an industry or by prices which do not reflect the true social value of a good or service due to market distortions. In Chapter 6 we describe the problems with proprietary data that are encountered in valuing the benefits associated with a radiation detector. The case of goods and services provided by government defense contractors may represent the best example of problems caused by market distortions.

In other cases, where R&D has resulted in the production of a new good or the improvement of an existing good, different supply and demand curves must be constructed to reflect these changes. However, the data requirements associated with modeling the effects of quality changes on supply and demand curves are extensive and, in many cases, probably exceed the availability of information needed to conduct this type of analysis. In cases where lack of data makes it difficult to construct market supply and demand curves for the goods in question, economists may still be able to use available market data in conjunction with simplifying assumptions about the curvature of supply and demand curves to approximate changes in producer and consumer surplus due to the effects of R&D.

As previously mentioned, one of the major problems associated with identifying the benefits of federal R&D is that there may be no market in which to value some of the potential or actual effects of R&D. In these cases, construction of supply and demand curves for nonmarket goods and services has, until recently, been extremely difficult. Two traditional approaches to this problem have involved valuing these nonmarket effects as a residual, after the returns to all other inputs have been calculated, or else by valuing them based on the cost of inputs used to produce the effects in question. The human capital approach to valuation of nonmarket effects is an example of this latter approach. However, cost-based definitions of nonmarket values are not consistent with willingness-to-pay concepts and are particularly problematic in cases where the federal government is the only buyer in a particular market, such as in defense or space-related contracting.

More recently, two alternative approaches for measuring the benefits associated with the production and consumption of nonmarket goods have gained increasing favor among economists. The first such method uses surveys to elicit from individuals how they think they would behave in a hypothetical situation. Typically, this approach tries to determine how much an individual would be willing to pay for another unit of a nonmarket good. This information is then used to construct demand curves for the nonmarket good. The chief strengths of this approach are that it is well-grounded in economic theory and very flexible in application. On the other hand, the values elicited by this approach are potentially subject to a number of biases, which has made it extremely controversial.

The second of these approaches uses changes in market values--either the wage compensation of individuals or the value of property--to measure nonmarket effects. This approach is used in this report to value some of the effects of OHER's marine research program. The major advantage of this approach is that it relies on existing market information to estimate labor supply curves or property bid and offer curves, as relevant. This is an important advantage over the former method which asks people what they would spend in a hypothetical situation, but does not require them to part with their money. The main weakness of this approach is that it is less consistent with economic theory and requires fairly stringent assumptions about the structure of relevant property markets and the relationship between property values and the nonmarket effects in question. In spite of these problems, both of these approaches represent a substantial improvement over traditional approaches for measuring the benefits and costs associated with nonmarket effects.

A final problem area associated with the estimation of the benefits and costs of R&D involves the practice of discounting future monetary sums into present values. Two arguments are advanced to justify this practice. First, resources that are not used for immediate consumption can be employed in investment projects yielding a return in later periods. And second, society may regard consumption by future generations as somewhat more or less important than that of the present generation. The first argument generally supports the use of discount rates on federal investments which reflect rates of return on displaced spending in the private sector. The second argument is generally used to support lower discount rates to ensure that more wealth is passed along to future generations.

In short, there is no single approach to discounting, nor any single discount rate on which all economists and decision makers would agree. However, different discount rates can have a profound effect on the net present value calculated for a specific project. In general, higher discount rates make future costs and benefits worth less and tend to favor projects with immediate payoffs. As such, high discount rates would tend to hurt the relative standing of basic research investments vis-a-vis R&D investments that have near-term market applications.

3.4.3 Conclusions

Several fairly general conclusions can be drawn from our discussion of the problems associated with applying BCA to federal R&D investments. The first is that, except in cases where the primary effects of R&D are directed at identifiable market goods and services, use of BCA in ex ante applications is not apt to be very productive. This is due to the problems associated with predicting and tracing the effects of R&D from a specific project to all of its potential beneficiaries.

Second application of BCA to evaluate R&D in fundamental basic science is likely to be of limited use in assisting decision makers to allocate resources either in an ex ante or ex post framework. This is due, in part, to the same reasons given above, but perhaps more importantly to the fact that results of much fundamental basic science may have limited application, with the exception of the benefits it produces for scientists. We do not wish to discount the importance of these types of benefits. However, because they can be evaluated through less controversial peer review methods, it seems appropriate to use that approach until economists can demonstrate the worth of nonmarket methods in valuing how scientists feel about the research of their colleagues. In our discussion of the OHER Marine Research Program, we present an approach for valuing research somewhere along the continuum of basic and applied research. This approach seems likely to be most useful in valuing research that does not lead to direct applications but does reduce the cost of conducting future research.

Third, the fact that the major effects of an R&D project may not be measurable by market values is not a valid a priori reason for dismissing the use of BCA. Recent methodological developments in the field of nonmarket valuation make it possible to evaluate these effects in a BCA framework. The important requirements that must be met to do this are that the primary non-market effects of a project can be identified and traced from the project to specific groups of economic agents. The availability of data will then determine whether these nonmarket effects can be valued directly through observed changes in wage compensation or property values, or indirectly through the use of survey methods to elicit individual willingness-to-pay.

Finally, if the effects of R&D are to be evaluated on an ex post basis using monetary values (market or nonmarket), it is important for economists to place these effects in an appropriate context so that users of this information can gain a better understanding of how important these effects are in relation to others, which, for whatever reasons, have not been quantified. In addition, it is also important to clearly state the assumptions required to conduct the analysis, how sensitive the results of the analysis may be to changes in the assumptions, and whether these assumptions provide an upper or lower bound on the net benefits associated with the effects of R&D that have been measured.

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4.0 ACID DEPOSITION RESEARCH CASE STUDY

This case study will focus on evaluating the benefits and costs of research, conducted during the period 1980-1986, to improve methods for regulating the precursors to acid deposition. This case study differs from the others in this report in at least one important way. Specifically, the research to be evaluated was not funded directly by OHER but was instead the product of a multi-agency federal program in which DOE was a participant. OHER's interest in trying to evaluate the costs and benefits of acid deposition research stems from its longstanding role as a key actor in DOE's programs to evaluate the environmental impacts of energy resource development and utilization.

This chapter is organized into four sections. Section 4.1 provides background information about the causes and consequences of acid deposition and about the Congressional response to the acid deposition problem. Section 4.2 identifies the objectives of emission control research conducted by the federal government, describes the federal R&D process, and identifies the accomplishments of emission control research during the period 1982-1986. Finally in Section 4.2, we use the information from this discussion to select two advanced emission control technologies, duct injection and furnace sorbent injection, for further detailed analysis. Section 4.3 describes the models and methods used to evaluate the benefits and costs associated with the research conducted on these two technologies. Finally, the results of this analysis are presented in Section 4.4.

4.1 BACKGROUND

Although acid deposition is commonly referred to as "acid rain", the term actually encompasses both the wet and dry deposition of acidic substances. That is, acid deposition can take the form of rain, snow, or other "wet" precipitation, or it can be deposited as dustfall, impacted fine particulate aerosols, or by adsorption and absorption of gases. The acidity of such deposition is determined by a complex mixture of partially or completely disassociated acidic and alkaline substances.

Acid deposition is a global phenomenon, traceable to both natural sources (such as volcanic emission, biological activities and natural combustion) and man-made atmospheric pollutants. While a number of atmospheric chemicals have been identified as precursors to acid deposition, sulfur dioxide (SO_2) and the oxides of nitrogen (NO_x) are the principal substances linked with the phenomenon. On a global basis, about half of the sulfur in the atmosphere is attributed to natural sources (ITFAP 1982a). However, in those areas where acid deposition has aroused the most concern (such as the northeastern United States), man-made sources--pollutants associated with high levels of industrial activity--are considered to be the dominant cause (ITFAP 1982a). While scientists have been able to determine, to some extent, whether the sources are natural or man made in a given receptor region, opinion varies as to the relative contribution of close and distant sources of the precursors of acid deposition. Research to provide a better understanding of pollutant transport and transformation, and of the relationship between pollution concentrations at a source and those found in the receptor regions as acid deposition, is an important component of the federal program.

The complex atmospheric transport and cloud processes responsible for the transfer of atmospheric pollutants to the ground as acid deposition are not well understood. Compounding this uncertainty is the lack, until recently, of long-term monitoring networks that utilize comparable measurement techniques to document trends in precipitation acidity. It has, therefore, been difficult to establish the degree to which ecological damage has occurred as a result of acid deposition, or to establish the relationship between varying levels of local or long-range pollutants and subsequent acidic depositions in susceptible regions.

The best documented acid deposition effects at this time are those to aquatic ecosystems, particularly for lakes in New England, Canada and Scandinavia. Although aquatic ecosystems can often accommodate some rate of gradual acidification, dramatic damage (e.g., fish kills) has been noted in bodies of water where spring melting of acid-containing snow and ice causes major and rapid changes in the acidity and other properties of the receiving waters. Aquatic life is also damaged as a result of impaired reproductive capability due to increased levels of toxic metal ions (especially aluminum) released from the soil by acid precipitation (ITFAP 1982b).

Much less is known about the deleterious effects of acid deposition on crops, forests, and soils. Some laboratory and field studies indicate that damage can occur from excessive acid deposition, although little effect is noted from ambient conditions. It has also been hypothesized, however, that acid deposition may have a beneficial effect on plants by increasing sulfur and nitrogen in soils that are deficient in those nutrients, thereby stimulating growth.

In response to concerns about the actual and potential impacts of acid deposition on the environment, Congress passed, and the President signed into law, the Acid Precipitation Act of 1980 (Title VII of the Energy Security Act P. L. 96-294). This Act created the National Acid Precipitation Assessment Plan (NAPAP) and established the Interagency Task Force on Acid Precipitation (ITFAP) to develop and implement a long-term comprehensive national research program within the framework of NAPAP. The goal of NAPAP, stated in Operating Research Plan (NAPAP 1984) is to develop and progressively improve an objective and comprehensive information base on the causes and effects of acid deposition and its effective management. Since its inception, roughly $205 million in federal funding has been spent to achieve programmatic objectives.

Acid deposition research has resulted in at least three broad, and qualitatively different types of achievements which represent legitimate benefits of this research. First, acid deposition research has led to the development of more cost-effective technologies for reducing emissions of the precursors to acid deposition. Second, it has yielded improved estimates of the magnitude and various distributional effects of the physical and economic damages caused by acid deposition to key receptor systems at risk. Systems at risk for which improved damages estimates have been developed as a result of acid deposition research include aquatic and managed agricultural (i.e., crop) ecosystems and different types of exposed materials. Finally, this research has resulted in information which has made it possible to more accurately target the sources emissions responsible for different types of damages.

4.2 OVERVIEW OF CONTROL TECHNOLOGY RESEARCH

Our research focuses on estimating the benefits and costs associated with the first of the achievements discussed above, research on more cost-effective control technologies. This selection was based on the relatively small amount of data available for evaluating the benefits and costs associated with the other two broad types of achievements and, also, on the relatively greater levels of uncertainty associated with the research findings in these other areas. The remainder of this section of the chapter is intended to familiarize the lay reader with the progress that has occurred in the area of control technology research under the NAPAP program during the period 1982-1986.

4.2.1 Legislative and Regulatory Background

Federal research and development into the control of acid deposition precursor emissions did not begin in 1980. Much of the current R&D effort has its roots in the 1970s in response to the Clean Air Act of 1970 and the Clean Air Act Amendments of 1977. The Clean Air Act directed the Environmental Protection Agency (EPA) to establish national air quality standards. The EPA issued National Ambient Air Quality Control Standards in 1971 and in the same year, established New Source Performance Standards (NSPS) that controlled SO_2 and NO_x emissions from new power plants with a capacity of 73 MW or more. Under the NSPS, SO_2 emissions were limited to an average annual rate of 1.2 lbs/million Btu; NO_x emissions to 0.7 lbs/million Btu and particulates to 0.1 lbs/million Btu. The NSPS left the choice of emission control methods up to the utilities and the states [under the State Implementation Plans (SIPs) created under the Clean Air Act]. Among other things, this allowed the utilities to switch to low-sulfur coal as a usable option for meeting the emission standards. Also, no emission standards were specified for existing power plants. The basic strategy behind the NSPS was that existing power plants would be replaced within 20 or 30 years by new coal-fired units (which meet the NSPS) and nuclear units.

It was quickly demonstrated that this strategy would not work. The escalation in world oil prices increased the demand for coal-fired generation (because of higher oil and natural gas prices), while, at the same time, inflation in construction costs led to delays and cancellations for new coal-fired and nuclear capacity. The result was increased use of existing coal-fired capacity, capacity that did not meet emission control standards. Also, the prospect was for continued reliance on this existing capacity for many years into the future. Another problem was that the use of fuel-switching to meet NSPS threatened serious economic consequences for regions that produce high-sulfur coal. Finally, Congress acted to make the existing emission control requirements more stringent. The end-result was the Clean Air Act Amendments of 1977.

As implemented by EPA in 1979, these amendments required that new power plants reduce SO_2 emissions by 90 percent, in addition to meeting the 1.2 lbs/million Btu limit (although if emissions were 0.6 lbs/million Btu or less, then the percentage reduction was only 70 percent). These requirements were designated the Revised New Source Performance Standards (RNSPS). Other provisions of the Clean Air Act Amendments further tightened controls on emissions (including NO_x), but the essential point from the perspective of emission control technology R&D is that the RNSPS effectively required that all new coal-fired power plants have flue gas desulfurization devices (FGDs) and that the new FGDs meet more stringent emission control requirements.

The available FGD technology in 1979 was the wet lime/limestone scrubber. The scrubber uses a large tower in which the flue gas is sprayed with a lime or limestone slurry. The calcium in the slurry reacts with the SO_2 to form calcium sulfite and calcium sulfate, which are collected in solution at the bottom of the scrubber tower.

Several problems with this technology encouraged R&D efforts, both by the private sector and by the federal government. Wet scrubbers require frequent maintenance to avoid outages caused by calcium deposits that clog pipes and sprayers, use large quantities of water, produce large quantities of wet waste product ("sludge"), and become prohibitively expensive to operate above a 90 percent SO_2 removal rate.

The federal R&D effort in emission control technology was centered at this time in EPA and the Tennessee Valley Authority (TVA). EPA was a logical choice because it had the responsibility for issuing and enforcing environmental regulations. TVA was involved in this effort because, as an operating utility with substantial coal-fired generating capacity, it would be required to comply with the emission control requirements.

The objective of this R&D was to reduce the costs of meeting the Clean Air Act requirements, including the NSPS, RNSPS, SIPs, Prevention of Significant Damage (PSD), etc., that all utilities, including TVA, were required to meet. Control of acid deposition was not then a separate and specific objective.

In 1980, however, Congress passed the Acid Precipitation Act, which led to the creation of NAPAP. An important objective of NAPAP was to bring the various federal R&D programs involving acid deposition and emissions controls under a single coordinating body. Concern over acid deposition changed the direction and focus of emission control technology R&D in two ways. First, the concern over current emissions of acid deposition precursors raised the question of retrofiting existing coal-fired power plants with emission controls. Since retrofits of wet scrubbers were estimated to be between 10 and 40 percent more expensive than scrubbers at new installations (and in some cases as much as 100percent more expensive), the potential costs of such retrofits were high enough to warrant further research, both into the general area of acid deposition and specifically into alternatives to wet scrubbers. Second, NO_x emissions became a more important issue as a precursor to acid deposition than had been the case previously. The prospect of adding a second flue gas processing device to remove NO_x was enough to spur research into alternative methods of reducing NO_x emissions.

4.2.2 R&D Strategy for Emission Control Technologies

The requirements for emission controls, and therefore the best technology for achieving those controls, depend on the specific legal requirements set by Congress. To date, no additional legal requirements have been imposed, beyond those in the Clean Air Act, as amended in 1977. A number of acid deposition control laws have been proposed in every recent Congressional session, however. These proposals cover a wide range of emission control levels, control strategies, financing plans, etc. Because the implications of the various proposals differ significantly, there has been a great deal of uncertainty about what emission controls the utility industry will have to face. One result has been that R&D has been directed at a large number of different, and often competing, technologies.

Since Senator Mitchell first introduced legislation to control the precursors of acid deposition in the fall of 1981, almost 50 similar types of bills have addressed this problem in one way or another. The proposals to control emissions can be divided into two broad categories, based on how specific they are in defining the options available to the utility industry to meet emission control objectives. In one category, specific targets are set for emission reductions from individual power plants (most commonly identifying the 50 power plants with the highest level of SO_2 or NO_x emissions), and the utilities are left with few options for achieving these targets other than retrofitting the power plants with some form of flue gas processing equipment. In the second category, emission targets are based on total state or utility emissions, allowing the states or utilities to use a mix of control technologies based on their own cost calculations. Within each category, the proposals differ with respect to the required level of emission reductions, when emission reductions must be achieved, financial support (usually in the form of a tax or fee based on generation and/or emissions), and other detail.

For any given legislative proposal, and given the available technology, there is a least-cost compliance strategy. In some cases, even the least-cost strategy is still going to be very costly. There are incentives, therefore, to find ways of reducing these costs. If there was a specific emission control program enacted into law, then R&D could be directed at minimizing the compliance costs of that program. Since there are still many different proposals under consideration, R&D has been devoted to a number of different types of technologies.

One can identify at least five objectives associated with current research programs to control the precursors of acid deposition that would help reduce the costs of emission controls:

1. Reduction of Coal Cleaning Costs. Reducing the costs of removing pyritic sulfur and organic sulfur from coal would lessen the need for add-on emission control systems under low-impact emission controls (say 20 to 30 percent SO_2 removal), and could lower the costs of flue gas processors by reducing the amount of sulfur that has to be removed by the processors. Improved coal cleaning would also help protect the market for high-sulfur coal, which is threatened by emission control programs that allow fuel-switching.

2. Capital Cost Reduction of SO_2 Emission Controls. One of the more serious problems with retrofitting emission controls to existing power plants is the high capital costs of wet scrubbers. While the costs of installing scrubbers on a new generating unit can be spread over a 30-year book

life, the same scrubber installed on an older generating unit may be amortized over 10 or 15 years of remaining service life. In this case, there is a much more severe impact on electricity rates from the retrofit. Also, scrubber capital costs are higher per unit of capacity for smaller power plants than for larger ones. Again, this means a relatively greater increase in electricity rates for consumers. An emission control technology that has lower capital costs, even if operating costs are higher, could reduce the total cost of emission controls for older, smaller power plants with low utilization rates.

3. Reduction of NO_x Removal Costs. The "best" technology for removing NO_x from flue gas in 1980 appeared to be the selective catalytic reduction process (SCR), a type of scrubber designed for NO_x removal. The SCR process was estimated to cost about half of what a wet lime/limestone scrubber would cost, and this would be in addition to the cost of the wet scrubber. By developing either a low-cost NO_x control system for moderate NO_x removal (50 percent or so) or a lower cost process for high-level NO_x removal, considerable cost savings could occur.

4. Development of Combined SO_2 and NO_x Removal Processes. Wet scrubbers are able to operate efficiently at up to 90 percent SO_2 removal. Beyond that level, operating costs increase very rapidly. Although experience with SCR processes is limited to a few industrial applications, a similar situation seems likely. Since some emission control proposals may require some power plants to reduce SO_2 emissions by more than 90 percent or impose strict NO_x controls, development of new technologies for very high level control (above 90 percent emission reductions) and for simultaneous SO_2 and NO_x removal may offer significant cost savings.

5. Development of 50 percent SO_2 Removal Technologies. Conventional scrubbers are extremely expensive to install. Much recent legislation requires scrubbing to reduce emissions. However, achieving all emission reductions through conventional scrubbing may not be cost-effective. It may be cheaper to control more plants at lower SO_2 removal efficiencies, thereby diminishing the importance of conventional scrubbing in achieving large SO_2 reductions. This makes the lower cost 50 percent SO_2 removal technologies much more attractive than they were several years ago.

4.2.3 The Federal Research and Development Process

To better understand the progress that has been achieved through control technology research it will be helpful to identify the R&D stages through which a control technology passes on its way to commercialization. Generally speaking, the path of a successful control technology through the R&D process can be divided into five stages.

The first stage consists of theoretical analysis of an emission control technology. The second stage involves experimental (or "bench-scale") testing of the technology and initial estimates of the costs of control using the technology. In the third stage, pilot-scale testing is conducted to see if the bench-scale results apply in a scaled-down version of the technology as it would actually be used. Information from the pilot project is used to improve the technology, refine cost estimates, and design the next stage. Also, if the technology proves unsatisfactory or too costly, the project can be terminated. The fourth stage normally consists of commercial scale demonstration/evaluation using a full scale version of the technology in an operational environment. Typically, this means using an existing power plant and running the technology using utility personnel, using commercially available reagents (as opposed to laboratory grade reagents), and operating under utility requirements to meet loads. The technology is evaluated under various conditions (for example, using different coal types) and engineering technology and cost data are developed for use in designing commercial installations. Technology becomes commercially available to potential buyers in the fifth and final stage of R&D. Whether or not a control technology is used depends on its costs and effectiveness compared to competing technologies. In most cases, this depends on a number of specific factors that vary from power plant to power plant.

The federal R&D effort can occur in all stages, except commercial availability, depending on the specific technology under development. Exactly where the federal effort enters into the R&D process depends on the individual technology. In some cases, federal funding supports the basic research into the new technology. In others, federal funding supports commercial-scale demonstration of a technology developed by private industry. In the case of emission control technologies, many technologies have been developed and are in commercial use in industrial boilers or in power plants overseas (especially Japan and Germany). Before these technologies can be considered for use in U.S. power plants, it is often necessary to evaluate their cost and performance under utility operating conditions (which are usually more demanding than industrial operations) or when used with U.S. coals and boiler designs. Japan and Germany have different types of coal than those typically found in the United States and power plant boilers are usually designed to obtain optimal performance from available coals. A control technology that works with one type of boiler/coal combination may not work under other conditions. Also, there is a wide range of coal types found in this country and the costs and effectiveness of control technologies vary depending on coal types.

One important aspect of R&D, product improvement, is not usually a federal responsibility. For emission control technologies, this means that there is no federal R&D into improving existing scrubber technologies. This type of research is left to the private sector. The distinction is that the federal effort is not directed, for example, toward making wet limestone scrubbers work better, but toward finding alternatives to that technology. At the same time, this does not preclude demonstration of improved scrubbers as part of the federal R&D effort.

4.2.4 Achievements of Federal R&D

With the emergence of acid deposition as a critical issue in 1980, there was an informal division of labor among federal agencies, based on R&D in progress. The Tennessee Valley Authority (TVA) continued its interest (begun in response to the RNSPS) in testing and evaluating new scrubber designs and in providing test sites for TVA and DOE projects. TVA, as an operating utility, had a definite interest in technologies that would be practical and directly applicable to meeting emission control programs. Within DOE, the Office of Fossil Fuels undertook R&D in the areas of clean coal technology and new technologies for flue gas clean up. EPA looked at low-cost NO_x controls, boiler modifications as alternatives to flue gas processes, and economic evaluation of emission control technologies.

A brief discussion of the research programs undertaken by these agencies, the technologies targeted for research, and the accomplishments of this research under NAPAP follows below. The major control technologies for controlling the precursors to acid deposition are summarized in Table 4.1.

TVA Programs - Lime Spray Drying

As a result of the 1979 RSNPS, TVA was faced with complying with more stringent SO_2 emission limits from its coal-fired power plants. The objective was to find ways to reduce the costs of complying with these new emission control requirements. TVA did not actually undertake R&D to develop more efficient emission control technologies, or to make existing technologies more cost-effective. Instead, TVA set out to test and evaluate improved scrubbers and new technologies developed by others. Among the developments tested by TVA were

1. use of adipic acid enhancement to improve the performance of lime/limestone wet scrubbers

2. forced-oxidation of scrubber sludge to produce gypsum, either for sale or for disposal as a dry waste-product

3. the DOWA process, a Japanese FGD that uses an aluminum/limestone dual alkali process that produced gypsum as a by-product and reduced operating costs by reusing the limestone

4. the DRAVO process for disposing of scrubber waste-products

Around 1983, TVA sharpened the focus of its R&D effort toward potential acid deposition control legislation and how to reduce costs of major retrofit requirements. Emphasis was placed on adapting the lime spray dryer technology, or dry flue gas scrubber, to the high-sulfur coal used by TVA in most of its coal-fired power plants. Lime spray drying involves spraying the hot flue gas with a finely atomized lime slurry. The hot gas evaporates the water, leaving lime particulates that absorb the SO_2. In a wet scrubbing system, only a portion of the slurry gas water is evaporated. For this reason lime spray dryers are sometimes referred to as dry scrubbers. The particulates are then collected by the electrostatic precipitators (ESP) or fabric filters already installed for control of fly ash. Much of the development process has involved modifications of the ESP or filter system to handle the increased particulate loading created by the spray dryer. The lime spray dryer technology trades lower capital costs for higher operating costs (as compared to the lime/limestone wet scrubber) and is better suited for retrofits of older power plants. However, the maximum SO_2 removal with the spray dryer is 75 percent. Higher removal rates increase the need for lime and raise operating costs above acceptable levels. Spray dryer technology has been in commercial use since about 1980, but only for low-sulfur western coals.

In 1983 TVA initiated testing two 1-MW pilot lime spray dryers with ESPs at their Shawnee Test Facility to determine the applicability of this technology to the burning of high-sulfur coal. Preliminary tests indicated that SO_2 removal rates of up to 80 percent are technologically feasible with high-sulfur coal. As a result of this, TVA has constructed and begun to operate a 10-MW Spray

TABLE 4.1. Potential SO_2 and NO_x Control Technologies for Coal-Fired Boilers (NAPAP 1985, Table H-1)

Technology	Percent Emission Reduction SO_2	Percent Emission Reduction NO_x	Development Status	Potential For Retrofit Application
I. Precombustion				
Lower Sulfur coal	Variable (dependent on sulfur content of original and alternative coals)	Negligible	Commercial	Most boilers
Physical Coal Cleaning				Most boilers
Conventional	20-50	Negligible	Commercial	
Advanced	35-65	Negligible	Developmental (some near-commercial)	
Chemical Coal Cleaning	90	Negligible	Developmental (in pilot stage)	Most boilers
II. Combustion				
Low excess air	Negligible	15	Commercial	Most boilers
Overfire air	Negligible	30	Commercial	Most boilers
Low NO_x burners (LNB)	Negligible	50+	Commercial & near-commercial (depends on type)	Many large boilers (except cyclone boilers)
LNB + Reburning	15-25	80	Developmental	Same as LNB (SO_2 reduction from replacement of coal in re-burning step by natural gas)
LNB + Furnace Sorbent Injection (LIMB)	50-60	50-60	Developmental (commercial demonstration in 1987)	Same as LNB

TABLE 4.1 (cont'd).

Technology	Percent Emission Reduction SO_2	NO_x	Development Status	Potential For Retrofit Application
III. Post-Combustion				
Selective catalytic reduction	Negligible	80	Commercial (in Japan)	Most boilers
Lime/limestone flue gas desulfurization (FGD)	80-90	Negligible	Commercial	Most large utility boilers & large industrial boilers
Lime/limestone FGD with organic acid addition	90-95	Negligible	Commercial	Same as for conventional lime/limestone FGD
Lime spray drying	70-90	Negligible	Early commercial	Many boilers
Duct injection of sorbents	50-70	Negligible	Developmental; large (5 MW) pilot testing planned for 1987	Same as lime spray drying
Advanced SO_2/NO_x cleanup processes	90-95	90	Developmental; large (5 MW) testing currently underway	Many boilers; better for new applications
IV. Advanced Boiler/Power Generation Processes				
Atmospheric Fluidized Bed Combustion (AFBC)	90	60-70	Near-commercial	Most applicable in cases where boiler replacement or "repowering" is economically justified
Pressurized Fluidized Combustion (PFBC)	90	60-70	Developmental	Same as AFBC
Integrated Gasification Combined Cycle (IGCC)	99	90	Near-commercial (100 MW demonstration underway)	Same as AFBC

Dryer/ESP pilot plant. A full scale demonstration project of this technology is planned for the Shawnee Steam Plant, which already has the necessary bag house.

DOE Programs - Coal Cleaning, Combined SO_2/NO_x Removal, Duct Injection

As previously noted, DOE's R&D effort in this area is divided into two program areas, clean coal and flue gas clean up. Initially, the clean coal program aimed at producing coal-based substitutes for oil. This involved reducing the ash content of coal to produce clean-burning coal-oil and coal-water slurries. These slurries could then be used in oil-fired boilers, furnaces or even diesel engines. The cleaning process removed sulfur along with other impurities and was, therefore, potentially adaptable as an emission control technology.

There are actually two forms of coal cleaning, physical cleaning and chemical cleaning. Physical cleaning removes pyritic sulfur that clings to the surface of the coal particles. The process involves grinding the coal, then mixing it with water or other liquid and allowing the denser sulfur and other impurities to sink. Coal can be ground fine enough to release virtually all of the pyritic sulfur. The problem is in removing the cleaned coal from the mixture. At the maximum level of cleaning, up to 75 percent of the coal is lost. The R&D effort has been directed at increasing the recovery of the clean coal. Various processes, such as oil agglomeration, liquid CO_2 coalescence of fine coal, heavy liquid cycloning, etc., have been or are currently being developed and tested. Even at the maximum level of physical coal cleaning, on average only about 25 or 30 percent of SO_2 emissions can be eliminated because of the sulfur that remains.

Due to the low SO_2 removal efficiencies associated with physical coal cleaning, DOE initiated research on several advanced coal cleaning technologies that have shown the potential to remove more than 90 percent of pyritic sulfur and ash from a variety of coals. In 1984, DOE and EPRI agreed to undertake a joint program to test advanced fine-coal cleaning technologies at EPRI's Coal Cleaning Test Facility. The results from these tests led to the selection of two promising technologies, a dry electrostatic process and a microbubble technology, for further research. The feasibility of these technologies is currently being investigated in proof-of-concept scale plants at EPRI's test facility.

Chemical coal cleaning treats the coal with chemical reagents or processes to remove either pyritic sulfur or sulfur that is part of the coal matrix itself, or both. Chemical cleaning techniques have been developed and tested that remove up to 90 percent of the sulfur from coal. These techniques, however, are far too expensive to use at the present time. Federal R&D has involved basic research into such technologies as electrostatic separation and microbial sulfur removal, as well as supporting work on several technologies developed by the private sector, such as the Gravimelt process and a microwave process. At the current time, the Gravimelt process is being tested on a pilot scale by TRW. The remaining processes are still in the laboratory stage.

DOE's flue gas clean-up program is the most complex of the emission control technology R&D programs. Initially, the objective was to improve existing technologies (especially wet scrubbers). Congress, however, directed that the focus of the R&D should be basic research and the development of alternatives to conventional technologies. Particular emphasis was to be placed on simultaneous SO_2 and NO_x removal and on advancing some of the newer 50 percent removal technologies, such as lime spray drying, pressure hydrated lime injection, and duct injection of sorbents.

Much of the R&D effort was directed toward a better understanding of the chemistry and physics of emission control processes, including control of particulates (fly ash). This research was intended to provide information that other researchers could use to develop control technologies. Another objective was to test and evaluate various new and innovative technologies for removing both SO_2 and NO_x emissions. Most of these technologies were developed by either the private sector or universities with assistance from DOE. In addition to removing both SO_2 and NO_x, several of these technologies were designed to produce usable by-products (such as chemical feedstocks) and/or reusable reagents. However, a number of these technologies did not prove to be successful, either because they did not work or because they were too expensive.

Nonetheless, progress in advanced SO_2/NO_x removal technologies has been achieved in several areas. Starting in 1985, DOE has been conducting research to determine the technical feasibility of using spray dryers in conjunction with electron beam radiation to enhance SO_2 and NO_x removal from coal-fired boiler flue gas. Pilot-scale results from TVA's Shawnee plant indicated that 90 percent SO_2 and 80 percent NO_x removal efficiencies could be achieved through this process. Similar removal efficiencies were demonstrated for the DOE-sponsored ammonia injection/electron beam concept at the E.W. Stout plant using a 5-MW proof-of-concept pilot facility. In addition, DOE sponsored the initial testing of the fluidized bed copper oxide process for joint SO_2/NO_x removal. Based on the 90 percent removal efficiencies achieved in these tests for both SO_2 and NO_x, a proof-of-concept facility (5-MW) was constructed at Commonwealth Edison's Kinkaid Station, where testing continues.

In 1985, Congress changed the focus of the flue gas clean-up program to give more emphasis to the immediate problem of acid deposition. In particular, the thrust of NAPAP-related research was aimed at finding lower cost retrofitable technologies for older, smaller power plants. The flue gas clean-up program had previously included work on the lime spray dryer and the use of pressure hydrated lime furnace injection. Both of these technologies have the potential for commercial availability in the near future, unlike most of the other projects in this program. As mentioned above, the work on the lime spray dryer technology complemented TVA's effort by focusing on combined SO_2/NO_x reduction. Pressure hydrated lime furnace injection is a boiler modification type of technology similar to that being developed by EPA and will be discussed in the section on EPA's programs. These technologies are able to achieve moderate levels of emission control at moderate cost.

Beginning in 1985, DOE undertook to find even lower cost alternatives. The most promising of these, sorbent duct injection (duct injection for short), involve injecting sorbents (lime, limestone, pressure hydrated lime, etc.) into the flue gas ducts at a point where they leave the furnace. The concept is basically the same as spray drying, except that there is no separate spray dryer facility (reducing capital costs) and the process is less effective (50 percent maximum SO_2 removal on low-sulfur coal instead of 75 percent removal). Because of relatively low removal efficiencies for low-sulfur coal, duct injection probably could not replace conventional FGDs in new power plants in the eastern U.S. to meet the most stringent emission control programs. However, this type of process could reduce the costs of complying with some emission control programs in plants burning relatively low-sulfur coal or in retrofit applications, especially where the utilities are required by law to use some sort of scrubbing technology to achieve emission control levels. Starting in 1985, DOE began a program of pilot testing several duct injection processes at utility power plants. Results of tests at Ohio Valley Electric Cooperative's Muskingum River Station and at DOE's Coal Combustion Test Facility have demonstrated removal efficiencies for SO_2 up to 80 percent on low-sulfur coals. However, tests conducted at Ohio Edison's Toronto Station suggest that removal efficiencies of around 50 percent are more reasonable for the high-sulfur coals commonly burnt in the eastern United States. Based on current research it is expected that this technology could reach commercial development by the very early 1990s.

EPA Programs - Low-NO_x Burners, Furnace Sorbent Injection (LIMB)

EPA undertook to develop low-NO_x burners and to test similar burners developed by boiler manufacturers as a low cost alternative to the SCR technology. It was known well before 1980 that the simplest way to reduce NO_x emissions was to change the way boilers were fired by using a richer fuel mix to reduce the amount of combustion air to a minimum. This can be accomplished by minimizing excess air or by staged burning (overfire air) in which a fuel-rich burning stage is followed by an air-rich stage. Unfortunately, the NO_x reduction efficiencies of these technologies was not enough (15-30 percent) to meet proposed emission standards.

The next step was to explore ways to modify burners and develop new burners that would reduce NO_x formation during combustion. Among other factors, lower temperatures reduce NO_x formation and burners can be designed to provide adequate heat to the heat transfer mechanism while reducing the maximum temperature in the furnace. Such burners have been developed, both for new boilers and for retrofitting many existing boilers, and have been tested by EPA. With the exception of cyclone boilers and wall-fired boilers with cell burners, most existing utility boilers can be retrofitted with low-NO_x burners, at much less cost than the selective catalytic reduction technology or other

NO_x reduction technology. Many industrial boilers are already using low NO_x burners and newer, more effective burners are likely to be available soon. These burners remove about 50 percent of NO_x, which is sufficient to comply with existing NO_x emission standards and most proposed standards.

Evidence that NO_x may be a more important contributor to acid rain damages has stimulated interest in achieving even higher NO_x removal efficiencies. An in-furnace NO_x reduction technology, known as reburning, has been developed for use on boilers. This technology involves diverting 15 percent of the primary fuel to a location downstream of the primary burning zone to form a reducing zone. Exhaust gas is applied further downstream to complete the process. An alternative approach consists of using a substitute fuel, such as natural gas, to reburn the primary fuel prior to the application of exhaust gas. Results from developmental tests suggest that NO_x can be reduced by as much as 80-85 percent using these technologies.

EPA's principal R&D initiative in emission controls has been the development and testing of the dry sorbent furnace injection (furnace sorbent, for short) technology. Originally known as LIMB (Limestone Injection Multistage Burner), this technology combines low-NO_x burners (originally, multistage burners) and direct injection of sorbent material into the furnace. Since the R&D program with began in 1980, other sorbents beside limestone have been tested, such as lime, pressure hydrated lime, and certain sodium compounds, that appear to be more cost-effective than limestone. The sorbent material combines with the SO_2 in the furnace and is then collected by the particulate control system. The advantage of this technology is that the costs of installing the process is much less than the cost of a wet scrubber system. However, operating costs may be higher, because of higher demand for sorbent, and SO_2 removal is less (about 50 percent instead of 90 percent). This means that dry sorbent furnace injection like duct injection, is most suited for retrofit applications, not new facilities.

This technology is currently in the commercial demonstration stage, and could be commercialized by the early 1990s. Development and testing of furnace sorbent injection (including low-NO_x burners) has been under way since 1986 at a demonstration facility at Ohio Edgewater's 105-MW Number 4 plant. The Electric Power Research Institute (EPRI) has also been cooperating with EPA on this technology. Currently, EPA and EPRI are jointly demonstrating furnace sorbent injection on a 60-MW tangentially fired boiler at Richmond Power and Light's Whitewater Valley Station. In addition to the EPA effort, DOE has sponsored testing of furnace sorbent injection using pressure hydrated lime at a 50-MW lignite fired boiler. The results from early tests show that the use of hydrated lime, as opposed to limestone, has the potential to boost SO_2 removal from 20-30 percent to 50-60 percent.

4.2.5 Non-Federal R&D Programs

While the subject of this report is primarily devoted to federal R&D, it is important to recognize the contribution of the private sector to acid-rain-related emission control technologies. In particular, the private sector has been an important contributor to the development of control technologies that are most likely to be available in the near term, such as spray drying and furnace sorbent injection.

The electric utility industry is the principal non-federal participant in the emission control technology R&D effort. Since the electric utilities are the primary targets for emission control proposals, this is not surprising. The focal point for the electric utility industry's R&D efforts, including emission controls is EPRI. There has been considerable joint effort in the R&D programs, such as the use of EPRI's Homer City Coal Cleaning Test Facility for pilot testing of the coal cleaning processes under development at DOE's Pittsburgh Energy Technology Center. Also, EPRI has sponsored parallel projects on the spray dryer technology, sorbent furnace injection, coal cleaning, etc. There have been extensive exchanges of information, including joint conferences on dry scrubbing and other technologies. In general, it is reasonable to say that the final results of the emission control R&D effort will represent the combined contributions of the federal government and the private sector, especially EPRI and the electric utilities.

At the same time, while EPRI has not been involved in the type of basic research that DOE has supported as part of the clean coal and flue gas clean-up programs, it has supported R&D into several types of technology that have not been supported by the federal effort, such as dry scrubbing (which uses a dry sodium compound instead of a lime or limestone slurry). Also, EPRI has been extensively involved in testing and evaluating new types of wet scrubbers and NO_x controls, many of them developed and used in Japan or Germany.

4.2.6 Advanced Boiler/Power Generation Processes

Up to this point, the discussion of emission control technologies analyzed in this chapter has focused on technologies that are all add-ons to basic coal-fired steam-electric generating facilities. They are intended to reduce the emissions produced by the combustion of coal in any of several types of furnaces that have been in use for a number of years. There are, however, several new types of coal-based generating technologies under development that have inherently lower emissions. These include atmospheric fluidized bed combustion (AFBC), pressurized fluidized bed combustion (PFBC), integrated coal gasification combined-cycle (IGCC), and magnetohydrodynamics (MHD). These technologies represent potentially more cost-effective generation and/or ways to use coal economically in place of oil and natural gas in such applications as peaking and cycling. The development of these technologies is based on expected economic benefits, not reduced emissions. However, the nature of these technologies is such that lower emissions are either a direct consequence or can easily be achieved by minor modifications to the process. The lower emissions are achieved without requiring added emission controls.

These technologies have a significant advantage over add-on emission control technologies in that there is no need to add additional (and usually very expensive) equipment to the generating facility to meet emission control standards. At the same time, it is not always clear that the total costs of these technologies are less than conventional technologies with add-on emission controls. Two of these technologies, AFBC and IGCC, are in the commercial demonstration stage and appear to have enough economic benefits to be serious contenders for new fossil-fuel generating capacity in the 1990s. PFBC and MHD are farther away from commercial development and there remain questions about their use in electric power generation (although PFBC may have significant industrial applications).

The fact that AFBC and IGCC may be the next generation of new fossil-fuel generating capacity could make add-on emission control technologies redundant in the long term. Instead of building new coal-fired power plants with wet scrubbers or other conventional emission control devices, new power plants could be built without the need for any add-on control devices. This does leave the short-term problem of retrofits. It is likely that the IGCC technology is not suited for retrofits to existing coal-fired power plants because the major economic benefits of IGCC come from the phased construction that is possible with this type of power plant and reduced financial risk. These consideration do not apply to retrofits for emission control. The AFBC technology can be used to retrofit certain types of existing boilers and to repower others. However, as a pure emission control technology, the cost of retrofitting an existing boiler with AFBC is substantially higher than retrofits with wet scrubbers. Retrofits with AFBC are economically feasible if the retrofit is combined with a life-extension program and, possibly, upgrading the capacity of a power plant. That is, instead of building a new power plant (complete with emission control technology), an existing, older power plant (or single generating unit) can be rebuilt with AFBC and have 25 or 30 years of additional service life. In addition, as part of the same project, the capacity of the plant (or unit) can be increased. Current estimates strongly suggest that retrofits and life-extension are significantly cheaper than new construction.

4.2.7 Selection of Technologies for Evaluation

Evaluating the benefits and costs associated with the research conducted on all of the technologies discussed above is well beyond the scope of this report. Therefore, a decision was made to limit the scope of the analysis, initially, to those technologies that could reasonably be expected to be commercially available in the 1990s. This decision was based on the high degree of uncertainty associated with estimating the expected costs, at commercial operation, of technologies that are in very early stages of their development. In general, advanced processes and technologies currently in the laboratory or pilot stage are unlikely to be commercially available in the 1990s. One reason is that the electric utility industry will not gamble on any technology, especially one as expensive as emission control, until that technology has been thoroughly tested and evaluated under utility operating conditions. In many cases, technologies currently under development will not prove to be successful, or are still too far away from practical application to be considered for the 1990s. These include most of the most advanced concepts in DOE's flue gas clean-up and coal cleaning programs, as well as new generating technologies such as MHD. In the case of coal cleaning, even if all pyritic sulfur can be removed economically, additional emission controls would still be required to reduce emissions from the organic sulfur in the coal. Coal cleaning could be part of an emission control program, which combines coal cleaning with moderate emission control technologies. However, the level of cleaning needed to reduce sulfur content beyond the cleaning technologies currently available is not likely to be economical even in the 1990s, unless there is another major increase in world oil prices.

This essentially leaves the following technologies for further consideration:

1. conventional wet lime/limestone scrubbers
2. spray dryer FGDs
3. furnace sorbent injection
4. duct injection
5. fluidized bed combustion
6. coal gasification

Fluidized bed combustion and coal gasification are very important potential long-run solutions to the problem of power plant emissions. However, the emission control aspect of these technologies is, in effect, a by-product of the technologies, and their adoption by the utility industry will occur if the potential economic benefits are realized. For that reason, and the fact that neither technology is suitable for retrofit solely for emission controls, neither technology is included in the analysis. Also, none of the R&D effort in either technology were classified as part of the acid deposition control technology R&D program, until after 1986, when TVA's AFBC commercial demonstration project was brought under the acid deposition control program. Finally, there has been little federal support for R&D for the IGCC, which was largely developed by EPRI, the utilities, and Texaco, supplier of the coal gasification system.

For the purpose of assessing the benefits and costs of the federal emission control R&D effort, there remain four technologies: conventional wet scrubbers, spray dryer FGDs, duct injection, and furnace sorbent injection. Conventional wet scrubbers provide the base case against which the benefits of the R&D program can be measured. The three remaining technologies share several features in common: first, they are all targeted at SO_2 removal (although furnace sorbent injection can be used in conjunction with low-NO_x burners), and, second, they all have SO_2 removal efficiencies of about 50 percent when used with high-sulfur coal. In further reviewing the performance and estimated costs of these three technologies, it was found that furnace sorbent injection and spray dryers have similar applications as retrofits for small boilers and, thus, can be viewed as close substitutes in achieving 50 percent SO_2 removal on smaller boilers (i.e., 300-MW or less). We also found that the estimated annualized cost of spray driers, whether expressed in terms of mills/kwh or $/ton of SO_2 removed, fell between the corresponding costs for furnace sorbent injection (the most expensive) and duct injection (the least expensive). Therefore, it was decided to limit the evaluation of advanced technologies to duct injection and furnace sorbent injection, based on the belief that the results obtained from this analysis could be used to bracket the range of benefits due to the introduction of spray dryers.

4.3 METHODOLOGY

The purpose of this section of the paper is to describe the approach that was used to estimate the benefits and costs associated with the research on the two new technologies, duct injection and furnace sorbent injection to reduce SO_2 emissions. The economic theory underlying the technical approach is presented first. This is followed by a description of the models used to estimate the benefits of control technology research. We next discuss the data and economic assumptions used in the analysis. We conclude with a description of the various emission control scenarios used to evaluate the benefits of emission control research and a discussion of how these scenarios were implemented to perform this evaluation.

4.3.1 Theory

Following the discussion in Section 3.3 of this report, the research discussed above has the potential to create benefits for society due to decreases in the long-run annualized cost of emissions control. This results not only in an increase in the expected value of producer surplus associated with reducing emissions, but also an increase in consumer surplus due the decrease in the long-run marginal cost of reducing emissions. A lower bound estimate of these benefits is measured by the cost-saving which is generated by introducing a new technology, holding the level of emission reductions achieved by the new technology constant at the optimal level possible under the technology which it replaced.

The above benefits can be illustrated more easily with the aid of a diagram. In Figure 4.1 the marginal benefit function is represented by the curve DD_0. This function shows the marginal value of benefits per unit of emissions (on the vertical axis) that can be achieved by reducing precursor emissions by specified amounts (on the horizontal axis) from a base case condition. These marginal benefits approximate the amounts of money firms and individuals would be willing to pay for reduced environmental damages due to incremental reductions in the precursors to acid deposition rather than do without these services. The line OS_0 represents the supply curve for emissions reductions. It traces out the marginal resource costs per unit of reduced emissions associated with reduced precursor emissions from the base case.

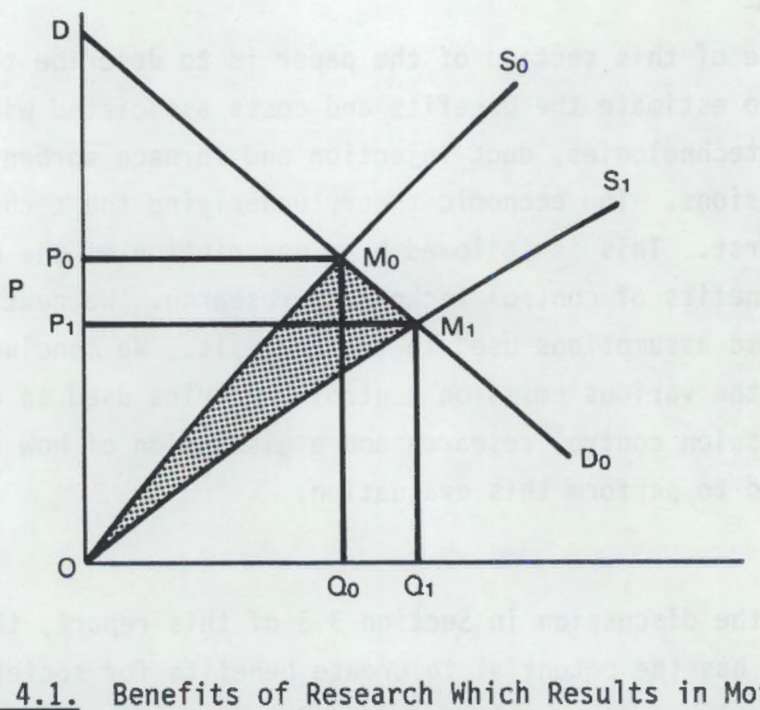

Figure 4.1. Benefits of Research Which Results in More Cost-Effective Control Technologies

To maximize society's welfare, the marginal cost of an emissions reduction policy should equal the marginal benefits of the policy. In Figure 4.1, this condition is satisfied at point M_0, which is consistent with marginal benefits equal to P_0 dollars and Q_0 units of reduced precursor emissions. Under these conditions, total benefits, as approximated by total willingness to pay, are equal to the area underneath the marginal benefit curve and to the left of the vertical line drawn from M_0 to Q_0. Total variable cost is equal to the area below the initial supply curve for reduced emissions and to the left of the vertical line from M_0 to Q_0. The net benefits of achieving the Q_0 emissions reduction level can be approximated by the difference between total willingness to pay and total variable cost, which is represented by the area ODM_0.

The introduction of a more cost-effective control technology is shown in Figure 4.1 by the new supply curve for reduced emissions, labeled OS_1. This curve lies entirely below the original supply curve, indicating that emissions can always be reduced at a cost below that which was possible under the old technology. With the new technology in place, the optimal level of emissions reductions increases from Q_0 to Q_1, while the marginal benefits and marginal cost both decrease from P_0 to P_1. Following previous logic, the net benefits associated with the new level of reduced emissions (Q_1) can be approximated by the area ODM_1. The net benefits due to the introduction of the new technology can be represented by the change in net benefits due to the new technology, or area ODM_1 - area ODM_0. This is approximated by the shaded area OM_0M_1 in Figure 4.1.

Following our previous discussion, we can decompose the benefit triangle in Figure 4.1 into two different parts. Conceptually, the first part is the cost saving which is generated strictly as a result of the introduction of the new technology, holding the level of emission reduction services constant at the pre-research level. This cost saving, which is a benefit to society, is measured in Figure 4.1 by the portion of the shaded benefit triangle which lies to the left of the line Q_0M_0. If the information at point M_0 is known, this cost saving can be used as a lower bound estimate of the benefits associated with introducing the new technology. The second part of the benefit triangle in Figure 4.1--the area to the right of the line Q_0M_0--can be traced to the output effect associated with the lower cost technology.

In some cases, and this is one of them, there is insufficient information about the effect of reduced emissions on environmental damages, and it is impossible to determine the location and shape of the marginal benefit function. In that case, the "optimal" level of reduced emissions and the corresponding marginal benefits and costs associated with that optimum will be unknown. A potential solution to the problem described above is to ignore the damages/benefits side of Figure 4.1 and focus on the cost savings achieved by new emission control technologies for given emissions reduction policies. This approach is illustrated in Figure 4.2 where a research-induced shift in the supply curve for reduced emissions from OS_0 to OS_1 results in a cost savings equal to the area a, given the policy consistent with reduced emissions of Q_0. For the policy Q_1, this cost savings increases in value from a to a + b. The obvious drawback to this approach is that research benefits can be made arbitrarily large, simply by increasing the magnitude of the emissions reduction target. Consequently, the cost savings measured using this approach would only represent a lower bound on acid deposition research if the emissions reduction target was optimal (taking into account the benefits of reduced emissions). In this case, the reasoned and experienced judgment of policy makers must be used in conjunction with sensitivity analysis to determine an appropriate range of societal benefits.

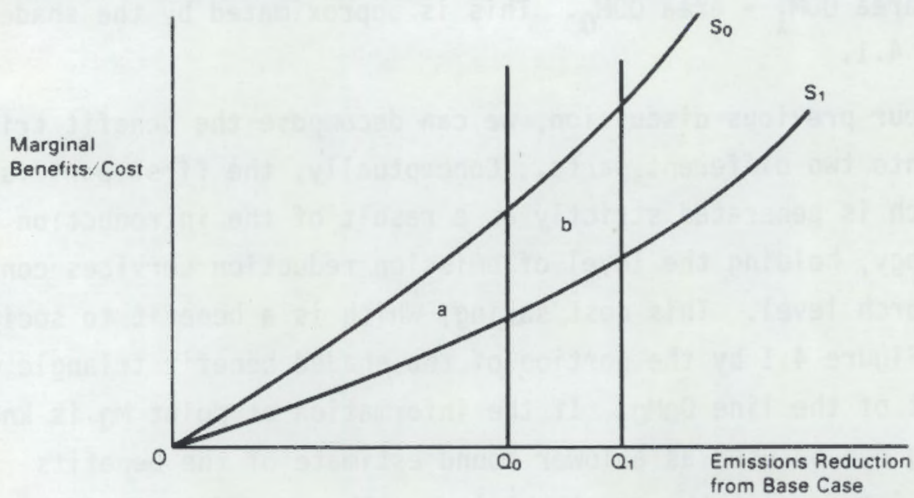

Figure 4.2. Cost Saving Due to More Cost-Effective Emission Reduction Technology

The benefits associated with emission control technology research, as illustrated in Figure 4.1 or 4.2, are shown only for a single time period. However, since optimal investment patterns in emissions control technology involve the gradual phasing in of new equipment over time (Stauffer 1985), the benefits associated with optimal emissions reductions levels must be estimated for each year the technology is in use over an appropriate time horizon, as determined by its expected usable lifetime. The periodic benefits illustrated in Figure 4.1 must then be discounted back to the point when the technology was adopted using an appropriate opportunity cost of capital or social rate of time preference (Lind 1982) and aggregated to produce an estimate of the present value of the research benefits. The net present value of the research is calculated by subtracting the present value of the research cost from 1980-1986 plus the expected development costs until commercialization from the present value of the benefits. If the estimated net present value of the research is positive, this indicates that the rate of return on the research investment was greater than the rate of return on the private sector spending and investment which was displaced by the taxes used to fund this research.

As previously mentioned, the information required to develop defensible marginal benefit functions for SO_2 and NO_x emission reductions has not yet been produced by NAPAP. Therefore, the analysis of the benefits of research on the two selected technologies--duct injection and furnace sorbent injection--will essentially duplicate the type of analysis depicted in Figure 4.2. Specifically, we employed sensitivity analysis to compare the costs associated with using only conventional wet scrubbers with the costs of using duct injection and furnace sorbent technologies in conjunction with conventional scrubbers at alternative emission reduction levels. The sensitivity analysis also involved looking at the cost savings associated with using these new technologies to achieve emission reductions as required under two, relatively new legislative proposals. The effects of alternative regulatory assumptions regarding the extent of fuel switching and emission trading allowed to meet alternative emission standards were also examined.

4.3.2 Description of Models

Projections of baseline SO_2 emissions, control costs, and the market penetration of conventional and the two advanced control technologies were developed using the ICARUS (Investigation of Costs and Reliability in Utility Systems) and AIRCOST models. These models were developed at Argonne National Laboratory (ANL) and have been used extensively in the past to determine the costs of meeting proposed emission standards (Streets, Vernet and Vaselka 1984; Streets and Vaselka 1984). The primary function of the ICARUS model is to project the number of coal, oil, gas, hydro, nuclear and pumped storage electrical generating systems required to meet projected electricity demands for the period, 1986-2010. A more detailed discussion of this model can be found in VanKuiken (1983). The conceptual basis of the AIRCOST model is presented in Silverman (1985), while a detailed treatment of the algorithms developed at ANL is discussed in Streets and Vaselka (1984).

An output file from ICARUS, which consists of a detailed inventory of electric generating units in the U.S., is used by the AIRCOST model. The unit inventory contains information about the location, operating characteristics, pollution control equipment, on-line and retirement dates, fuel cost and quality data, and capacity factors for each electric generating unit (both existing and projected) in the contiguous U.S. Based on this inventory, the AIRCOST system of models projects future baseline SO_2 emission levels and estimates the least-cost configuration of emission control measures to reduce emissions below the baseline.

For the purpose of this research, emission reduction methods included in the model were coal (fuel) switching and blending, installation of conventional wet scrubbers, duct injection and furnace sorbent injection. However, the internal structure of AIRCOST is such that new emission reduction technologies can be added to the model in a generic fashion. Given information on the costs and removal efficiencies of these technologies, the AIRCOST model performs a unit level analysis to determine the least-cost method of emission controls for each plant by comparing the total levelized costs of a set of alternative fuels and emission control technologies. When uncontrolled emissions from the combustion of a given type of coal exceed the unit's emission limit, AIRCOST selects the least-cost control method to limit emissions to compliance levels.

Once control technologies have been paired with coals that require emission controls, AIRCOST selects the coal/control-technology option with the lowest total levelized cost.

To simulate an areawide emission-reduction strategy, the AIRCOST model is run for several emission limits for each unit in the controlled area. The results of these simulations are then used to compute the marginal cost-effectiveness of reducing SO_2 emissions between successive emission limits at each unit. The controls are applied in order of decreasing cost-effectiveness (increasing marginal cost) until the SO_2 emission reduction goal is achieved. With the exception of the type and quantity of fuel consumed and the pollution-control devices used at a unit, all operating conditions remain static. The size and location of the emission control areas can be specified by the user. In analyzing most legislative proposals, the unit inventory is divided into state-level control regions with specific emission reduction targets. Alternatively, multi-state or even national control regions can be designated. In all of these cases, AIRCOST reduces emissions within each region wherever it is least costly to do so in ascending order of marginal control cost.

AIRCOST calculates the present value of the emission control costs (in 1985 dollars) for each plant in the inventory over a preselected time horizon. These costs are annualized. AIRCOST then aggregates the total annualized costs over all plants in each state or multi-state region to determine the total annualized emission control cost for each region. Finally, the regional emission control costs are summed to obtain a total annualized control cost for the nation. Total and marginal cost (i.e., supply) curves for emissions are constructed at the unit level by connecting the emission reduction/control cost points to define a convex hull cost frontier. These points are connected in a piece-wise linear fashion, the slopes of which represent the marginal cost of moving from a less restrictive control strategy to a more restrictive strategy. Points that lie above the cost frontier represent suboptimal strategies, since they are more costly in terms of SO_2 removed. All unit-level curves within a state or multi-state region are aggregated to produce a state-level cost versus emission reduction curve. This is achieved by ordering marginal cost curve segments from lowest to highest cost and adding the tons of SO_2 removed at each marginal cost level. The same ordering is used to aggregate total costs on each point of the total cost curve.

4.3.3 Data and Assumptions

In this section we describe the engineering cost functions that were developed for the two technologies and present the assumptions that were used in running the ICARUS and AIRCOST system of models.

Cost Data

Engineering cost equations were estimated for the capital costs, fixed O&M costs, and variable costs for both conventional technology and the two new technologies, duct and furnace sorbent injection. These cost equations were adapted by Energy Ventures Analysis, Inc., from studies prepared for the EPA Office of Research and Development by the Radian Corporation[a]. These studies examined the costs for the above technologies in both new and existing (i.e., retrofitted) plants at the 200- and 500-MW scale. The engineering cost equations for the three technologies are presented in Appendix B. Illustrative annualized technology costs for these technologies for different size plants are presented in Table 4.2.

As previously mentioned, the three technologies being analyzed are not interchangeable. Of the three, conventional FGD systems and duct injection are the closest substitutes in terms of their compatability in a wide variety of existing coal-fired plants, the major difference between the two being that conventional FGD systems can remove up to 90 percent of SO_2, while duct injection removes 50 percent of SO_2. However, the application of furnace sorbent injection systems is currently limited to small plants with wall-fired, opposed fired or tangentially fired boilers. These technology applicability constraints, which are presented in Table 4.3, were imposed on the unit inventory in the AIRCOST model.

Three important features about these cost estimates need to be stressed. First, the cost estimates for the two new technologies are not based on information obtained from commercial plants. As previously mentioned, these

(a) Energy Ventures Analysis Inc. 1986. Draft Report, Selection Criteria and Preliminary Ranking of Large Power Plant Candidates for an Emission Reduction Retrofit Demonstration Program. Arlington, Virginia

TABLE 4.2. Illustrative Annualized Technology Costs for Conventional FGD Furnace Sorbent and Limestone Duct Injection (1985 Dollars per Ton of SO_2 Removed) Unit Characteristics

Capacity (Mw)	Coal Sulfur (percent)	Conventional FGD	Furnace Sorbent Injection	Limestone Duct Injection
100	2.0	$700	$700	$410
250	2.0	570	620	380
500	2.0	500	N/A	350
100	3.0	540	630	380
250	3.0	450	560	350
500	3.0	390	N/A	330
100	5.0	410	570	360
250	5.0	350	520	330
500	5.0	310	N/A	320

Source: E.H. Pechan and Associates, Inc. 1987. New Technologies and Utility Emissions. Springfield, Virginia.

technologies are both in pre-commercial phases of development. Duct injection is currently in the conceptual design phase, while furnace sorbent is in the demonstration stage of development. As such, the cost estimates for these technologies should not only be viewed as preliminary, but also as potentially sensitive to future research developments. Second, the cost equations for the two advanced technologies may reflect research accomplishments that extend beyond the scope of NAPAP funding. While these two technologies were selected precisely because research on them could be traced almost entirely to the NAPAP program, attributing all of the costs and benefits back to the NAPAP program is probably not appropriate since the advanced technologies have not been commercialized. Third, retrofit costs for all of these technologies vary considerably from plant to plant, depending on a variety of factors which are not adequately captured in the engineering cost functions used in this analysis. However, adding this type of detail to the unit inventory and the AIRCOST system of models would dramatically increase the computation costs of analyses performed with the models.

TABLE 4.3. Technology Applicability Constraints

Technology	Applicability
Conventional Scrubbing	No Limits
Limestone Duct Injection	No Limits
Furnace Sorbent Injection	Applies to units <300 MW with wall, opposed, tangential, or undetermined firing

Assumptions

The following assumptions were made when running the ICARUS and AIRCOST models:

- 2.7 percent growth in electric demands, consistent with current National Energy Policy projections.
- Controls are applied only to coal-fired electric utility boilers.
- 50 year retirement age for coal-fired units.
- New technologies are available by 1990.
- All units meet existing regulations by 1990.
- New Source Performance Standards will not be made more stringent.
- Real coal prices remain constant at 1986 levels.
- 6.1 percent real interest rate used for discounting/annualizing.
- Capital costs are amortized over a 20-year period.

4.3.4 Description of Scenarios

We employed sensitivity analysis to estimate a range of benefits associated with research on duct injection and furnace sorbent injection, taking into account several sources of uncertainty that could influence these benefits. For convenience, the analysis can be divided into two parts. The first part of the analysis consisted of developing total and marginal cost curves with and without the advanced control technologies. The second part involved analyzing the costs of complying with two of the most recent legislative proposals to reduce emissions of the precursors of acid deposition with and without the advanced technologies. Table 4.4 outlines the scenarios that were constructed for both parts of the analysis.

In the first part of the analysis, the total and marginal cost curves were developed under two alternative scenarios--one in which utilities were permitted to switch fuels as one method of reducing SO_2 and a second in which fuel switching was not allowed and all SO_2 reductions had to be achieved through control technologies (i.e., forced scrubbing). All these simulations were conducted under the assumption that emissions reductions could be achieved wherever it was least costly to do so in the contiguous U.S. (i.e., interstate emission trading). Thus, two total and marginal cost curves were produced for the base case.

In the second part of the analysis we examined the costs of complying with two recent legislative proposals. Both of these bills have been proposed as amendments to the Clean Air Act. They are S.316, whose chief sponsor is Senator Proxmire, and S.321, which was introduced by Senator Mitchell. The state-level emission reductions required by the two bills are shown in Table 4.5. As in the previous set of simulations, the costs of complying with these limits were analyzed under alternative scenarios regarding fuel switching. In addition, the sensitivity of compliance costs to both intra- and interstate emissions trading was examined. Thus, for each legislative proposal, a total of four different base case cost estimates was produced.

TABLE 4.4. Description of Scenarios to Analyze the Costs of Emission Reductions

Analysis	Fuel Switching	Forced Scrubbing	Emissions Trading Intrastate	Emissions Trading Interstate
Cost Curve	x	x		x
Legislative Compliance	x	x	x	x

TABLE 4.5. SO_2 Emissions and Required Reductions for the Electric Utility Industry

State	1996 Baseline SO2 Emissions (1000 Tons/Yr)	Emission Reductions Required By Bill (1000 Tons/Yr) Proxmire	Mitchell
AL	550.3	244.72	383.43
AZ	109.6	0.00	34.50
AR	83.0	0.00	66.90
CA	97.7	0.00	49.10
CO	109.2	0.00	29.00
CT	61.6	0.00	0.00
DE	57.9	1.05	19.97
DC	10.1	0.00	0.00
FL	574.5	66.71	168.70
GA	866.7	285.43	697.02
IL	887.0	490.00	589.09
IN	1533.5	812.61	1358.27
IA	242.4	93.77	169.51
KS	91.1	0.00	0.00
KY	831.9	444.78	681.26
LA	86.7	0.00	68.70
ME	27.5	0.00	6.85
MD	271.0	84.87	161.79
MA	289.3	64.75	56.31
MI	512.9	0.00	249.76
MN	206.0	37.76	110.01
MS	106.7	21.11	15.53
MO	1011.4	596.54	916.39
MT	65.3	0.00	65.47
NE	80.4	0.00	40.99
NV	60.0	0.00	21.10
NH	73.4	38.70	42.76
NJ	121.8	0.00	11.90
NM	78.6	0.00	0.00
NY	578.4	33.86	0.00
NC	388.7	29.01	144.59
ND	96.6	0.00	59.90
OH	2122.1	1248.45	1732.30
OK	147.4	0.00	143.40
OR	11.6	0.00	11.00
PA	1078.8	490.55	630.05
RI	5.3	0.00	0.00
SC	246.8	54.04	168.76
SD	19.5	0.00	4.41
TN	784.0	480.31	686.91
TX	937.7	0.00	909.40
UT	25.5	0.00	5.00
VT	7.7	0.48	5.68
VA	184.8	4.68	91.40
WA	75.6	0.00	44.08

TABLE 4.5. (cont.)

State	1996 Baseline SO2 Emissions (1000 Tons/Yr)	Emission Reductions Required By Bill (1000 Tons/Yr) Proxmire	Mitchell
WV	865.7	420.82	606.20
WI	399.2	183.40	322.68
WY	98.1	0.00	0.00
TOTALS	17171.2	6328.4	11580.1

The Proxmire Bill applies to the 31 states that are east of, or border, the Mississippi River and the District of Columbia. Under this proposal, emissions reductions go through a two-phase approach. In phase one, annual statewide average emission rates of SO_2 are limited to 2.0 lbs per MMBtu by January 1, 1993. In the second phase, these rates must be reduced to 1.2 MMBtu by December 31, 1997. Under this bill, the following emission reduction measures are allowed: least emissions dispatching, early retirement of plants, energy conservation, fuel cleaning and both intra- and interstate trading of emissions. The Mitchell Bill is generally more stringent than the Proxmire bill. First of all, it applies to all of the states. Second, states must achieve the more stringent of the following SO_2 reduction goals: annual average statewide emission rates of 0.9 lbs per MMBtu, or a pro-rated share of a 12 million ton emission reduction goal as specified in the act. In addition, the Mitchell bill does not allow fuel switching or interstate emission trading.

4.3.5 Overview of Simulations

The benefits associated with research on duct injection and furnace sorbent technologies were estimated in six steps. First, the engineering cost equations, the technology applicability constraints and the major assumptions identified above were entered into the ICARUS and AIRCOST models as appropriate. Second, base case costs were estimated for the two different sets of simulations for the period 1985-2010. For the cost curve analysis, the models were run at alternative emission reduction levels to develop reference total and marginal cost curves for reduced emissions of SO_2 using conventional scrubbers as the primary control technology options. Base case cost curves were developed for both the fuel switching and forced scrubbing scenarios using conventional scrubbers. Base case compliance costs, using conventional scrubbers as the only technology for reducing emissions, were also estimated for each of the legislative proposals using the two models. For this portion of the analysis base cost estimates were developed for each of the fuel switching and emissions trading options.

In the third step, the ICARUS and AIRCOST system of models were rerun under the same conditions as those which existed in the base case analysis, except that both conventional scrubbers and the advanced technologies were allowed to be used to reduce emissions in both sets of simulations. For a given scenario, both the base case and advanced technology simulations provided estimates of the annualized cost of meeting emission reduction levels. The fourth step involved estimating the annualized cost saving associated with a particular scenario. This was done by subtracting the annualized base case emission reduction cost estimate from the corresponding annualized cost estimate obtained from the relevant advanced technology simulation.

4.4 RESULTS AND CONCLUSIONS

This section presents the major results of the simulations described above and discusses the conclusions that can be drawn from them. The quantitative information presented here is based on more detailed results contained in Appendix C.

4.4.1 Cost Curve Analysis

The major results of the cost curve analysis are summarized in Tables 4.6 and 4.7. Table 4.6 shows the annualized cost saving for the two advanced technologies at alternative emission reduction levels, assuming interstate emissions trading and fuel switching. Table 4.7 presents the corresponding cost saving for each of the two advanced technologies if fuel switching is prevented and all states are forced to employ control technologies to reduce SO_2 emissions. The base case control costs for conventional scrubbers (FGDs) for the two scenarios are shown in the second column of each table for cross comparison purposes.

The two tables show that both duct injection and furnace sorbent injection have the potential to be more cost-effective than conventional scrubbing,

TABLE 4.6. Annualized Cost Savings of Duct Injection and Furnace Sorbent Technologies of Alternative Emission Reduction Levels with Interstate Emission Trading and Fuel Switching

SO_2 Emission Reductions (10E6 Tons/Yr)	Conventional FGD Control (10E6 1985 $/Yr)	Duct Injection Cost Saving (10E6 1985 $/Yr)	Furnace Sorbent Cost Saving (10E6 1985 $/Yr)
2.0	252.9	0.0	0.0
4.0	710.1	0.0	0.0
6.0	1431.4	0.3	0.0
8.0	2702.1	28.1	0.0
10.0	5477.5	186.8	24.1
11.2[a]	7913.5	290.7	-
12.0	10237.0	416.8	214.7
12.1[b]	10599.8	-	234.3
12.8[c]	14294.0	0.0	0.0

(a) Emission reductions at which maximum penetration of duct injection occurs
(b) Emission reductions at which maximum penetration of furnace sorbent occurs
(c) Emission reductions where new technologies are not technically feasible

TABLE 4.7. Annualized Cost Savings of Duct Injection and Furnace Sorbent Technologies at Alternative Emission Reduction Levels with Interstate Emission Trading and Forced Scrubbing

SO_2 Emission Reductions (10E6 Tons/Yr)	Conventional FGD Control (10E6 1985 $/Yr)	Duct Injection Cost Saving (10E6 1985 $/Yr)	Furnace Sorbent Cost Saving (10E6 1985 $/Yr)
2.0	812.8	18.2	0.0
4.0	1922.3	38.2	0.0
6.0	3366.8	109.5	12.1
8.0	5236.9	294.0	68.5
10.0	7959.4	382.5	151.8
10.3[a]	8399.6	372.0	-
10.9[b]	9488.3	-	138.0
12.0	12428.5	284.7	167.7
12.4[c]	14713.0	0.0	0.0

(a) Emission reductions at which maximum penetration of duct injection occurs
(b) Emission reductions at which maximum penetration of furnace sorbent occurs
(c) Emission reductions where new technologies are not technically feasible

depending on the size of the emission reduction and the nature of the regulatory requirements regarding fuel switching. For example, our analysis shows that the commercial introduction of duct injection technology could save an average of about $187 million a year in helping to achieve a 10 million ton SO_2 reduction without forced scrubbing and around $382 million a year in meeting the same emission reduction target with forced scrubbing. The corresponding cost savings (at the 10 million ton reduction level) for furnace sorbent injection are about $24 and $152 million, respectively. Underlying the penetration of these new technologies, but not shown here (see, instead, the results in Appendix C), is a pattern in which it is optimal to control emissions at more plants than in the base case, but at lower removal efficiencies.

Of the two advanced technologies, duct injection is not only the more cost-effective, it also becomes more competitive with conventional scrubbers at lower emission reduction levels than does furnace sorbent injection. This is due, in part, to lower removal costs per ton of SO_2 for duct injection, as shown previously in Table 4.2, and, in part, to the fact that furnace sorbent technology is restricted in its application, as shown in Table 4.3. This latter characteristic is evidenced (see Appendix C) by the fact that, while the simulated maximum penetration of duct injunction was achieved at 302 plants (11.2 million ton emission reduction with fuel switching), the corresponding maximum penetration of furnace sorbent injection was achieved at a level of only 208 plants (12.1 million ton emission reduction with fuel switching).

As expected, the two advanced technologies play a more important role and save more money when states are forced to achieve emissions reductions by technological means (forced scrubbing) than when they are allowed to switch fuels. For example, in the 8 million ton reduction case with fuel switching, duct injection was installed on 42 plants (see Appendix C) and saved society an average of about $28 million annually, while furnace sorbent injection was not installed on any plants. However, under a forced scrubbing scenario, duct injection was installed on 211 plants, resulting in an annualized cost saving of $294 million. Under the same conditions, furnace sorbent injection was installed on 96 plants, resulting in an annualized cost saving of about $69 million.

While the relatively greater importance of the advanced technologies in the forced scrubbing scenarios is not surprising, given the results of previous studies, it does tend to suggest that the policy objectives of the acid deposition research initiative on control technologies have, in fact, been fulfilled through research investments on these two technologies. In short, the above results support the conclusion that the objective of creating lower cost alternatives to conventional FGDs to meet more stringent regulatory proposals--many of which excluded fuel switching--has been met by recent investments in duct injection and furnace sorbent injection.

4.4.2 Analysis of Compliance With Proposed Legislation

The major results of the portion of the analysis which examined the effects of introducing duct injection and furnace sorbent injection on the costs of complying with the proposed Proxmire and Mitchell bills are summarized in Table 4.8. This table shows the annualized cost saving associated with each of the two advanced technologies for eight different scenarios. These scenarios vary according to 1) which legislative proposal is being analyzed; 2) whether emissions trading is allowed between states (interstate) or only within states (intrastate); and 3) whether the proposed emission reduction can be achieved through fuel switching or not (i.e., forced scrubbing). The relevant SO_2 reductions (6.3 tons for the proxmire bill and 10.6 tons for the Mitchell bill) are shown in the third column of this table. Finally, the base case control costs using conventional FGDs are shown for each scenario in column four.

In general, the results of this part of the analysis are consistent with those in the previous tables on three counts. First, the introduction of the two advanced technologies reduces the annualized cost of complying with the two bills. These cost savings range from a low of just over $1 million per year to comply with the Proxmire bill (with fuel switching and intrastate emissions trading) using conventional FGDs in conjunction with furnace sorbent injection, up to about $375 million a year to comply with the Mitchell bill (with forced scrubbing and interstate emissions trading) using a combination of conventional scrubbers and duct injection.

TABLE 4.8. Annualized Cost Savings of Duct Injection and Furnace Sorbent Technologies Under Proxmire and Mitchell Emission Reduction Proposals for Different Emission Trading and Fuel Switching Scenarios

Proposal	Emission Trading	SO2 Emission Reductions (10E6 Tons/Yr)	Conventional FGD Control Costs (10E6 1985 $/Yr)	Duct Injection Cost Saving (10E6 1985 $/Yr)	Furnace Sorbent Cost Saving (10E6 1985 $/Yr)
			FUEL SWITCHING		
Proxmire	Interstate	6.3	1912.8	4.4	1.5
Proxmire	Intrastate	6.3	2202.4	16.6	1.1
Mitchell	Interstate	10.6	6580.4	250.8	40.9
Mitchell	Intrastate	10.6	8317.4	277.0	115.2
			FORCED SCRUBBING		
Proxmire	Interstate	6.3	4008.5	211.7	51.1
Proxmire	Intrastate	6.3	4239.6	236.3	64.5
Mitchell	Interstate	10.6	8989.0	378.6	152.5
Mitchell	Intrastate	10.6	10058.6	359.0	152.0

Second, for each scenario the cost savings achieved through the introduction of duct injection are always higher than those associated with the introduction of furnace sorbent injection. In the most extreme case, which involved complying with the Mitchell bill under the assumptions of forced scrubbing and interstate emission trading, the annualized cost saving associated with using duct injection as opposed to furnace sorbent injection was about $225 million. Third, in most cases, the more severe the constraints associated with the emissions reduction scenario, the more expensive it was to meet that standard and, correspondingly, the greater the cost savings associated with introducing a new technology. Thus, holding other variables constant, 1) the Mitchell bill was always the most costly piece of legislation with which to comply, but generated the largest cost savings; 2) forced scrubbing scenarios created the highest compliance costs and largest cost savings; and 3) in all cases, intrastate emissions trading was a more costly compliance alternative than interstate trading and in most cases it also generated the largest cost savings.

Finally, the reader may recall that the Proxmire bill allows both interstate emissions trading and fuel switching to reduce emissions, while the Mitchell bill does not. For the scenarios which most closely reflect these differences, the maximum annualized cost saving associated with the introduction of a new technology is $4.4 million for the Proxmire bill and $359 million for the Mitchell bill. Thus, if the Mitchell bill is adopted in its current form, the benefits of control technology research conducted during the NAPAP era on these two technologies are considerably greater than if the Proxmire bill is adopted. This result is entirely consistent with DOE research objectives in that it reflects the concerns which policy makers had in the mid-1980s, and still share to some extent today, about the high cost of meeting very restrictive acid rain legislation. Viewed from this perspective, research on the so called "50 percent" technologies may be viewed as a kind of insurance policy against potentially very costly legislative proposals like the early Waxman-Sikorsky and the current Mitchell bills.

4.4.3 Comparison of Benefits With Research Costs

Our analysis has shown that the introduction of duct injection to achieve a 10 million ton per year SO_2 reduction could result in an annualized cost saving of nearly $400 million with forced scrubbing and slightly less than $200 million a year when fuel switching is allowed. The corresponding annualized cost savings for furnace sorbent injection are about $152 and $24 million, respectively. In light of the substantial value of the annualized benefits associated with the introduction of these technologies, the question we now seek to address is whether these benefits are large enough to offset the resource cost associated with their creation.

In traditional BCA this question is typically answered by comparing the present value of benefits with the present value of costs. If benefits are in excess of costs, then the associated investment must have a rate of return which is greater than the rate of return reflected in the discount rate. Unfortunately, the AIRCOST model calculates total annualized compliance costs as the sum of the annualized compliance costs for each plant in the inventory, instead of on the basis of total net present value for all plants. Since the number of periods over which AIRCOST calculates emission control costs varies from plant to plant, the sum of the annualized cost savings for each plant does not equal the annualized net present value of the cost saving for all plants. This convention in AIRCOST is not incorrect. However, it does not allow us to convert the annualized cost savings for all plants back into the total net present value of these cost savings.

Unfortunately, there is no quick solution to this problem, other than altering the costing algorithms within the AIRCOST model. This effort was believed to be beyond the scope of this individual project. Therefore, a partial, but not altogether satisfactory, solution to this problem was adopted. The approach adopted consisted of three steps. First, we computed the present value of the research costs associated with the two technologies, including the expected research costs to commercialize these technologies by 1990. Second, using the same capital recovery factor and amortization period as in the AIRCOST model, we calculated the minimum value of the annualized cost saving required to just offset this research cost for each of the advanced technologies. Third, we compared the annualized cost savings computed in the previous step with the research benefits shown as annualized cost savings in Tables 4.6 through 4.8. If the annualized value of the benefits (i.e., cost savings) in a particular scenario exceeded the minimum annualized cost saving calculated in the second step, then the net present value of research benefits was assumed to be positive for that scenario.

We estimated the present value of the research cost associated with the expected commercialization of duct injection and furnace sorbent injection in the following manner. Duct injection research costs prior to 1987 were estimated from a draft of the 1987 Congressional Budget for Fossil Energy. Furnace sorbent research costs through FY 1986 were estimated from Martin (1986) and EPRI (1986). The present value of the research cost for these two technologies was computed using the assumed AIRCOST real discount rate of 6.1 percent. Using this method, the present value of the research cost for duct injection was estimated at $9.7 million, while the corresponding cost for furnace sorbent injection was $39 million.

Given the assumption that both technologies would be commercialized in 1990, we estimated the present value of the expected research costs for each technology based on the average annual research cost over previous years. For duct injection this figure was $3.6 million/yr and $8.4 million/yr for furnace sorbent injection. The present value of the expected research costs were estimated using the same discount rate as in the previous part of the analysis for the period 1988-1990 for duct injection and 1987-1990 for furnace sorbent injection. Inclusion of these costs raised the estimated present value of R&D costs on the two technologies to $17.9 million for duct injection and $59.5 million for furnace sorbent injection. These costs were assumed to represent the present value of the resources foregone by society to develop the two technologies using primarily federal R&D funds.

To compute the annualized cost saving required to just cover these research costs, we used a capital recovery factor (CRF) of $0.061/(1-(1.061)^{-20}) = 0.088$. Applying this CRF to the present value of the research costs estimated above, we find that the minimum annualized cost saving required to just equalize the present value of project benefits with the present value of project costs is $1.57 (0.088*17.9) million for duct injection and $5.25 million (0.088*59.5) for furnace sorbent injection. If the annualized cost saving for a particular scenario in Tables 4.6 - 4.8 is greater than the minimum research cost for the relevant technology, this is a strong indication that the net present value of the research benefits associated with that technology is positive.

Turning back to the results of the cost curve analyses in Tables 4.6 and 4.7, we find that duct injection passes this test at all emission reduction levels above 2 million tons/yr when scrubbing is required (Table 4.7). Under fuel switching, the annualized value of the cost savings associated with the research on duct injection exceeds the minimum cost figure at the 8 million tons/yr emission reduction level. For furnace sorbent injection, the annualized value of estimated research benefits exceeds the minimum cost threshold at the 6 million ton/yr emission reduction level under forced scrubbing and at the 10 million ton level when fuel switching is allowed.

The same general pattern of estimated research benefits in excess of research costs is true for the legislative analyses shown in Table 4.8. For these scenarios, the annualized cost saving associated with research on duct injection is always greater than the threshold cost figure. The results for furnace sorbent injection are not so strong. For this technology, annualized benefits are below threshold costs for the scenarios involving compliance with the Proxmire bill when fuel switching is allowed. For all other scenarios, however, the value of annualized research benefits associated with furnace sorbent injection do exceed the minimum cost threshold.

4.4.4 Conclusions

At least three broad conclusions can be drawn based on the results contained in sections 4.4.1 through 4.4.3. First, both technologies appear to show benefits in excess of research costs over a wide range of emission reductions and regulatory conditions. Second, net research benefits associated with the introduction of duct injection appear to be substantially greater than those for furnace sorbent injection even though we were not able to make comparisons based on such totals. Given the substantial benefits associated with research on this technology, it is unlikely that changes in estimated research costs or other important parameters would affect this conclusion. This is not only because of lower research costs on duct injection, but also because this technology is more efficient at reducing emissions and can be applied to a wider variety of boilers. Third, the pattern of positive net research benefits for both technologies is consistent with a primary objective of the NAPAP research program to develop lower cost alternatives for meeting very stringent acid-rain-oriented emission reduction bills. Finally, the estimated values and conclusions in this study should be interpreted with appropriate regard for the uncertainties associated with the commercial performance of the two technologies, future R&D costs and the assumptions required to conduct the economic analysis.

4.5 REFERENCES FOR CHAPTER 4.0

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5.0 MARINE RESEARCH PROGRAM CASE STUDY

OHER's Marine Research Program represents a broad research effort directed towards understanding the oceanic transport of particulates. Since the ocean is a necessary feature of so many energy exploitation and development activities--including offshore oil drilling, oil transport, and nuclear testing--this understanding of basic oceanic processes has been the subject of focused and continuing research. Indeed, DOE and its antecedent agencies have been funding this program for nearly 40 years.

Two key factors define the unique contribution of OHER's Marine Research Program. One is the continuity of the support. Because most oceanic processes are measured in years and decades, reliable data or fundamental processes are not easily gathered or understood from short-term studies. The DOE programs have recognized this and have typically committed resources to research projects for a longer period of time than have other agencies. Secondly, the research tends to be of both a basic and an applied nature. OHER has directed much of its funding to multidisciplinary activities that have greater potential to result in fundamental breakthroughs. These activities often have unanticipated applications and lead to unpredicted scientific advances.

The character of this research makes it difficult to quantify the economic value of the research. Basic research does not easily translate into observable, economically measurable results. Instead, the results shade ideas, provoke additional research and are, therefore, hard to trace to a marketed good.

Because it would be impossible to evaluate all marine projects, we have selected three of the OHER's Marine Research projects for review. They include an evaluation of the benefit of OHER research 1) to support policy making for off-shore oil and gas leasing of the Georges Bank, 2) to reduce the cost of future oceanographic research and 3) to reduce the cost of oil spill cleanup operations. These three were selected as representative examples of the breadth of OHER's Marine Research Program.

In this chapter, we first present an overview of the Marine Research Program and indicate which agencies cooperate with DOE in funding the federal government's overall oceanographic research agenda. We describe techniques we would use to evaluate the benefits in three specific cases, and report the actual implementation of a case study. Appendix A contains a more technical discussion of the statistical analysis supporting our benefit estimates. The final section provides a discussion of the problems encountered, lessons learned, and potential remedies available to DOE.

5.1 MARINE PROGRAM OVERVIEW

The DOE Marine Program was originally separated into four regional oceanography programs:

- Atlantic Northeast
- Atlantic Southeast
- Pacific Northwest
- Southwest

With the exception of the Pacific Northwest, these regional programs still exist. Each of the regions has an agenda that fits its geographical constraints and opportunities. As might be expected, research activities vary considerably among the regions; however, they are unified by their attempts to understand oceanographic transport of particulates.

The basic research generic to the OHER marine program has led to a number of applications and contributions that have cut across the specific regional programs. Most often, these are spillover benefits of better understanding the ocean.

Five such benefits have been identified across the four regional programs:

- reduced costs of oil spill cleanup
- reduced costs of search and rescue operations
- increased ability to predict the fate of waste dumped at sea
- identification of critical habitat for marine life
- development of a pool of trained, experienced researchers.

The first three relate simply to a better understanding of the ocean's currents. Being able to predict the movement of an oil slick allows for more efficient, cheaper cleanup. Understanding ocean currents has also reduced the cost of search and rescue operations such as finding drifting ships that have lost power and locating wreckage from the Challenger disaster to predict the fate of waste dumped at sea allows the best disposal site to be chosen, and allows rational choices about whether ocean dumping is the best alternative in the first place.

By studying the biology of the sea, researchers have been able to locate habitats critical to different commercial and recreational species. One benefit of this result has been to lower the cost of using the critical habitat criterion to evaluate the siting of potential nuclear power plants.

Finally, an important result of the research has been to develop a pool of trained, experienced researchers who are able to respond quickly and more economically to ocean research needs. This pool provides immediate expertise in time of need.

These broad accomplishments cut across geographic boundaries. All of the regional programs have contributed to the research that has resulted in the five benefits described above. In the following sections the specific accomplishments of each regional program are discussed.

5.1.1 Atlantic Northeast Regional Oceanographic Program

The Atlantic Northeast Regional Oceanographic program has been particularly active in supporting the development of governmental policy. Some of the research in this area has been focused on highly visible policy decisions. One such decision was whether the Georges Bank area ought to be leased for offshore oil development. Another study was directed toward understanding the oceanographic forces that contributed to the New York Bight floatables incident of 1978. The impact of both of these incidents on society was large.

The Georges Bank leasing decision was the result of careful study by several governmental agencies, including the Minerals Management Service, the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA) and OHER. The value of this research is analyzed in Section 5.5 of this chapter. Information generated by OHER's research was important to making the best decision possible regarding if, when, and where to lease potentially rich offshore oil tracts.

The New York Bight floatables incident occurred in the summer of 1978 when a large quantity of sewage and garbage floated ashore along the beaches of Long Island. OHER research, undertaken in coordination with the NOAA, the National Marine Fisheries Service and the EPA, helped establish the causes and precautions that could be taken to protect against a repeated occurrence. The most visible result was a change in policy that required waste be dumped 112 miles from shore rather than 6 miles.

5.1.2 Atlantic Southeast Regional Oceanographic Program

The Atlantic Southeast Regional Program is the newest of the four regional programs. Research focused on the interaction of the Gulf Stream and the mid- and outer-continental shelf waters has led to directly useful discoveries, the most immediate of which is the identification of previously undiscovered fisheries off the coasts of Georgia and South Carolina.

Research into coastal shelf dynamics such as temperature, fronts and upwelling helps to locate fish. Another facet of the research is to identify those areas where the currents are weak enough to allow effective fishing. This fishery research, as well as many other studies in this regional program, has been supported jointly by NOAA, the National Science Foundation and OHER.

5.1.3 Pacific Northwest Regional Oceanographic Program

This program is the oldest of the four. Its beginnings lay in the first attempts to understand the paths radionuclides traveled following atomic testing in the Pacific Ocean. Subsequent research has focused on the Columbia River and the Puget Sound. Studies in all three ecosystems have yielded significant research results.

One of the important, directly applicable results of the OHER research has been a better understanding of the circulation of currents in the Puget Sound. Only when these currents were understood was it possible to model different sewage outfall locations. The ability to accurately simulate how tidal forces flush Puget Sound made it possible to choose outfall locations that do not encourage the accumulation of waste. This should have the effect of minimizing degradation of the Sound.

5.1.4 Southwest Regional Oceanographic Program

Much of the work of the Southwest Regional Oceanographic Program has focused on the Southern California Bight, specifically, the food chain dynamics of the bight and on basic chemical and geochemical research. Together these lines of research have generated an important base of knowledge that is directly applicable to understanding the biological effects of pollutants released during petroleum and natural gas exploitation.

One application of this research has been to develop industrial emission guidelines. In California these have included chlorine emission standards. Understanding coastal processes permitted calculation of a reasonable standard. If the OHER research had not been available, either another group would have had to perform the research or unnecessarily restrictive standards might have been implemented. The extension of the basic OHER research to these two areas of application facilitated more timely, responsible decisions.

5.2 ASSESSMENT STRATEGIES FOR MARINE PROGRAM BENEFITS

As the overview has indicated, research topics funded under the auspices of the Marine Program have been quite varied and wide-ranging. Undoubtedly, its benefits could be traced to virtually everyone in the United States in one fashion or another. Such an exercise will not be performed here. Instead, we will evaluate three identifiable benefits that are the result of the Marine Program's research efforts. These "case study" benefits of the Marine Program were selected from a number of potential program benefits.

Selecting a case study approach to valuing the Marine Program's research benefits has several virtues. First, use of case studies will permit us to investigate and report on several very different techniques for valuing research benefits. A fuller menu of options of benefit measurement techniques is available for comparison. Second, by looking at specific benefits in some detail the link between a benefit, its funding and the source of its funding can be more easily forged. Without this link there is a real danger of identifying phantom benefits that do not actually exist. Third, from a pragmatic point of view, case studies reduce the sheer quantity of researchers and projects that must be identified and understood. Case studies tend to be more tractable.

The three types of benefits from OHER research are discussed in this chapter:

- those accruing from a better understanding of potential environmental damages from off-shore oil drilling. The benefits of this information are assessed for the Outer Continental Shelf oil and gas leasing conducted by the federal government.
- those accruing from reducing the costs of conducting subsequent oceanographic research. This is an important aspect of OHER's research on fundamental oceanographic questions.
- those accruing from improved ability to predict the behavior of oil spills. This reduces the costs incurred in cleaning up after oil spills.

Each of these benefits was initially evaluated to judge its potential for further analysis and quantification of benefits. We finally decided to concentrate on quantitative estimates of the benefits from OHER research that accrue to oil and gas leasing. This was done for two reasons. First, we believed the benefits from OHER research in oil and gas leasing could be substantial. To date, bonuses paid to the federal government from oil and gas leases total $51 billion. Second, a considerable amount of data is available on oil and gas leases that will provide the basis to estimate benefits. The value of OHER research in reducing the cost of subsequent oceanographic research was not chosen because of the difficulty in applying the conceptual model within the scope and time constraints of the project. Although we decided not to pursue quantifying the benefits of OHER research on subsequent research, a National Science Foundation researcher has proposed nearly the same approach (Averch 1987) and we feel the approach is worth further investigation. Similarly, we decided not to pursue estimating the value of benefits of cost reductions associated with oil spills. Generally, the data were not available within the scope of our effort to estimate these benefits.

We have included an overview of our initial approach for each of these three OHER Marine Program benefits. Later in the chapter, we present our quantitative estimates of the benefits of OHER research to federal oil and gas leasing.

5.2.1 Marine Research and Offshore Oil Leasing

The OHER Marine Program has generated a substantial amount of information about the movement of ocean currents in areas that have been leased for offshore oil and gas development. Offshore oil and gas development is a risky proposition with potentially high gains and losses to both the companies involved and to society. Benefits to society from locating oil or gas are straightforward. The benefit is the net value of the found resource. Losses come in two categories: 1) the cost of looking for oil and gas and not finding it, and 2) the environmental damage associated with oils and gas spills or leaks where the resource has been found. The size of the losses from environmental damages can be catastrophic. Understanding ocean currents is critical in evaluating the risks associated with development of the Outer Continental Shelf (OCS).

Estimating the value of OHER's contribution to enhancing OCS oil and gas development requires a clear understanding of the leasing process and the role of environmental considerations. There are three stages to the leasing process. These three stages begin with designation of an area available for lease and finish up with each tract either leased, or withdrawn from exploration and development.

In the first stage the Minerals Management Service (MMS) of the Department of Interior assesses the environmental sensitivity of each of the tracts, and, taking into account the potential resources and damage, determines which tracts will be available for bid. Equation (5.1) shows such a relationship.

$$\text{Prob(offer)} = F(E, O, C) \qquad (5.1)$$

where

E = expected environmental damage

O = estimated oil reserves

C = cost of extraction

As indicated in Equation 5.1, the probability that a tract will be offered depends principally on the expected environmental damage (E), the estimated oil reserves (O) and the costs of extraction (C).

The quality of the environmental information on a tract is a critical factor in determining the ability of the MMS to perform its role effectively. If the quality of the environmental information is biased towards underestimating the potential environmental damage, then tracts that ought not to have been developed but were (through a mistaken notion of the danger involved) will sustain too much environmental damage. On the other hand, if the tracts are not offered for lease, there will be losses associated with foregoing oil which ought to have been extracted but was not because of an excessively conservative appraisal or overstatement of the potential environmental damages. OHER contributes to improving the process by helping MMS assess more precisely the environmental damage associated with a tract.

Once the MMS has decided which of the tracts are suitable for potential development, then the oil and gas industry has the opportunity to bid on them. The oil and gas industry also has access to the results of OHER's research and must decide which of the available tracts it wishes to bid upon. Since the individual companies will have legal liability for damages caused by spills, they will want to weigh these potential costs when choosing where to bid. It is entirely conceivable that the industries' appraisal of the risks associated with individual tracts will differ from MMS's appraisal. Equation (5.2) indicates this relationship.

$$\text{Prob(bidding)} = G(E,O,C) \tag{5.2}$$

where

E = expected environmental damage

O = estimated oil reserves

C = cost of extraction

The information about expected environmental damage and ocean currents works in the same way at this level as it did in Equation (5.1). Equation (5.2) shows the industry's probability of bidding where Equation (5.1) shows the probability that MMS will offer a tract. The issue is whether or not undue risk is taken or avoided.

In the final step, given that the tract is offered and bid upon, the firm must decide on the level of its bid. Several factors play an important role at this level. The environmental risk associated with a tract is one of the considerations, along with individual firm financial information, costs, and oil and gas potential. The more likely a firm is to incur costs from environmental damages, the lower the bid ought to be, all else constant. There has been a considerable amount of research into the determinants of high bids in OCS leasing. Equation (5.3) shows a typical relationship.

$$\text{High Bid} = K(O,B,C,E,J,F) \qquad (5.3)$$

where

O = expected oil reserves

B = number of bidders

C = cost of drilling

E = expected environmental damage

J = if a joint or solo bid

F = measures of the bidders' current financial situation

One sale that was specifically supported by OHER research was Sale 42, the Georges Bank sale. This sale potentially exposed valuable shoreline, wildlife habitat, and fisheries to damage from oil and gas leaks. OHER supported some of the important pieces of research that allowed the risk of developing the different tracts to be estimated.

The value of OHER research would be the difference between actions taken by MMS and industry and action that would have been taken if MMS and industry not had access to the research. An approach that allows the value of this research to be estimated has three stages. The first is to econometrically model each major step in the leasing process. This provides a statistical model of how the various actors responded in the actual event. The second, is to simulate the projected response given differing levels and kinds of information. The final step is to calculate the losses accruing to the different kinds of errors that are possible without research. This approach allows us to illustrate the losses from either excessively over- or underestimating potential environmental damage. Later in this chapter we follow these three steps to estimate the value of OHER research in OCS oil and gas leasing.

5.2.2 The Effect of OHER Research in Reducing Costs of Subsequent Research Programs

An important aspect of OHER's Marine Research Program is that it is one component among the federal government's oceanographic research. As noted earlier, the OHER contribution to this research effort has some important and unique aspects--specifically its stability and the basic nature of the research it supports. Reductions in the scale, or a termination of OHER research, would entail giving up more than just the direct results of OHER research projects; it would also raise the costs of all other ocean research efforts. This represents a real, tangible benefit of OHER research.

To provide a framework for evaluating the research cost reductions generated by OHER research, we begin by considering a completed, published piece of OHER research. In related subsequent research efforts (generally referred to as "applied research"), irrespective of funding source, the completed OHER work will form a part of the research that will not need to be repeated. For example, once an ocean floor has been mapped, it will not need to be mapped again in support of another task. Without the completed OHER research, an additional increment of funding would be needed to perform the new (applied) research. This increment is the value of OHER research to the next project down the line. Our conceptual approach to estimating the value of this research is described below.

Our approach is to consider applied or secondary research funding as a competitive market. We consider research funding as a competitive market in order to trace the effects that OHER's research has on a subsequent product (applied research). Many researchers compete for funding among a variety of sponsors. The funded proposals and the funding level reveal the price-quantity equilibrium in this market. From this perspective the funding reveals the price and the research output is the quantity.

Defining and measuring research output is difficult. In this case both a research input quantity and a research output quantity need to be defined and measured. An output quantity is suggested by the bibliometric literature. As described in Chapter 3.0, many agencies already use a publication or citation count as a measure of research output. A straightforward extension of this approach is to rank the journals and then compile a quality-adjusted page or word count of research output. This would provide a measure of applied research output.

Basic research supplied by OHER that is used as an applied research input also needs to be measured. One approach would be to simply rank the importance of the OHER original basic research to the applied article, on an article-by-article basis. These could then be grouped to create an ordinal quantification. This would be adequate to estimate the benefits associated with broad categories of OHER research.

Within this framework, basic research is one of the factors in producing applied research. Economists refer to this relationship, between outputs and production inputs as a "production function." There are other inputs, such as physical facilities, quality of staff and other research results. Equation (5.4) shows a general applied research production function with these elements.

$$Q = F(O,S,F,W) \qquad (5.4)$$

where

Q = quantity of applied research

O = original basic research

S = staff

F = physical facilities

W = other research results

In a recent article Averch (1987) econometrically estimated a relationship similar to Equation (5.3) for National Science Foundation grants. He found statistically significant relationships between research output, measured as citations per funded research dollar, and measures of staff and institution attributes. As Averch points out (p. 357) this approach does not make full use of the state-of-the-art in either econometrics or bibliometrics.

In the remainder of the section an approach that is closer to the state-of-the-art than Averch's is briefly described. Our approach, while more demanding of data and statistical theory, comes closer to realizing the goal of evaluating the benefits of basic research to the scientific community.

The production relationship described by Equation (5.3) shows how much "research output" can be obtained from predetermined levels of inputs. An analogous question is, given that X amount of "research output" must be produced, what is the cheapest mix of inputs to produce it? This relationship is termed a "cost function."

The cost function relates a predetermined level of output and the costs of inputs. A slightly different formulation of the cost function is to relate the cost of a given output to a predetermined level of output, the quantities of some inputs, and the prices of others. This formulation is generally referred to as a restricted cost function.

A restricted cost function consistent with Equation (5.4) would be Equation (5.5).

$$C = C(Q^*, Q^o, P^s, P^f, P^w) \tag{5.5}$$

where

Q^* = fixed quantity of output

Q^o = quantity of original research

P^s = cost of staff

P^f = cost of physical facilities

P^w = cost of other research results

In this formulation the cost of production is a function of the quantity of research output, the quantity of basic research, and the cost of other inputs.

There are two benefits of formulating the problem in this version rather than as Equation 5.4. One benefit is that the producers and consumers surpluses, which were described in Chapter 3, are obtainable directly from this specification.[a]

(a) To locate the surpluses, and so find the benefits of research, note that the demand for basic research is found by differentiating the restricted cost function with respect to Q^o. The total value of the basic research to the next generation of research is the area under the demand curve (consumer's and producer's surplus).

A second attraction of this formulation is that it requires observation of data which, in principle, are available. These data include secondary funding levels, quantities of outputs, quantities of original research and prices of other inputs. Prices of other inputs might include charge rates for support services, ship time, research assistance and researcher support.

This approach, while attractive from the point of view of "do-ability," is not well-suited for estimating the benefits of path-breaking research endeavors. Nor will it capture the benefits which might accrue to a sudden realization that something done twenty years ago is the missing link in a scientific puzzle. While acknowledging these shortcomings, it must also be acknowledged that most research, even fairly basic research, does not fall into these catagories.

Most research is designed to be a small step forward in a particular direction. To obtain funding, principal investigators generally need to specify what types of research output they intend to produce, and what kinds of inputs they are going to use to get there. If, when reviewed, their peers believe this is reasonable, funding is forthcoming. Our proposed methodology was designed to incorporate this funding process and to value projects that are fairly predictable additions to the store of knowledge. Although we decided not to attempt to use this approach in this research project, we feel it represents an innovative advance in the approaches for valuing basic research.

5.2.3 Oil Spill Cleanup Cost Reductions

One of the indirect applications of the basic ocean current research funded by OHER during the last ten years has been improved ability to predict the behavior of oil slicks. Improved understanding of ocean currents allows for better, more cost-effective cleanup of oil or chemical spills.

Estimating the value of this application involves first estimating a clean-up cost function that explains the determinants of clean-up costs. One of the inputs into the function includes the degree to which ocean currents are understood in the spill area. Other inputs might include the amount of foam, absorbent bales, labor, and ship time. The benefits are the savings in clean-up cost that accrue to understanding the ocean currents. This clean-up cost function can be simulated to assess the cost savings attributable to OHER research.

There are approximately 1200 substantial oil spills per year in the United States. The costs of cleaning up an oil spill depend on the time and place of the spill, with large spills requiring more resources to clean up than smaller spills. Given that most spills are smaller, with only a few catastrophic spills happening each year, and that the very large spills would be expected to be unique, there does not seem to be any strong a priori reason to believe that a statistical representation would be better than a case-by-case examination for these very large spills. However, the smaller spills are too numerous to examine on a case-by-case basis. Smaller spills are also more likely to provoke a standard response; that is, a small spill will not require innovative techniques or unusual efforts in its cleanup. These features suggest that a statistical representation of the cleanup costs for the smaller spills is reasonable.

A simple representation of the relationship between the costs of cleanup and various determining factors is given in Equation (5.6).

$$\text{Costs} = F[i,w,k,l,s] \quad (5.6)$$

where

i = quantity of ocean current information

w = weather information

k = price of capital

l = price of labor

s = size of spill

This relationship can be estimated using simple cost relationships (Cohen 1986). This provides us with an idea of the contribution of ocean current information to the cleanup of smaller oil spills.[a] The equation was estimated without specifying the source of the current information.

Once the cost equation has been estimated, the effect of OHER information on clean-up costs remains to be determined. The equation was estimated without specifying the source of the current information. The preferable course of evaluation would be to calculate the quantity of ocean current information available both before and after OHER research took place. This would allow a computation of the proper marginal contribution of OHER research to a reduction in clean-up costs. From an operational point of view, this approach requires far more detail than can reasonably be expected to be gathered.

Therefore, a simplifying assumption about the relationship between the timing of OHER research and other sources of oceanographic research is helpful. If OHER and all other sources are considered as a single source, then the proportion of total funding associated with OHER will be the proportion of benefits accruing to OHER. However, we felt it would be difficult to apply this approach within the scope of this research. The next section discusses our resolution of which of the possible benefits to estimate.

5.2.4 Summary of Assessment Strategies

This section has outlined three strategies for assessing three distinct social benefits associated with OHER marine environmental research. Each of the assessment strategies has different strengths and weaknesses. Their relative merit depends on scope, goals, and resources of the assessment project.

One of the approaches, valuation of basic research, attempts to measure the usefulness of OHER Marine Program research to other researchers. It focuses on developing a economic relationship between researchers, their equipment and training, existing OHER research, funding levels and the final

(a) The per spill factor demand is found by differentiating Equation (5.6) with respect to the quantity of ocean current information. The area under this demand curve gives the benefits of ocean current information. If the quantity of information is measured qualitatively rather than continuously, the demand curve will be a step function with a step corresponding to each quantity level.

research results. Recently, Averch (1987) conducted a study for the National Science Foundation that statistically related citations per research dollar to levels of these project attributes. Averch notes that the simple statistical model he presents does not represent the state-of-the-art in econometrics or bibliometrics. To fully exploit this approach requires the sort of data collection effort outlined in section 5.2.1. The execution of the research plan implied by section 5.2.1 was simply beyond the scope of the time frame and funding level of this task. The approach does, however, appear to hold promise for future use to develop and evaluate research funding guidelines for administrators.

Two other approaches, evaluating OCS leasing decisions and the extent to which the costs of cleaning up oil spills has been reduced, are attempts to estimate a portion of the benefits of OHER marine research. These benefits miss some, possibly most, of the social benefits. To get a grip on something closer to full social benefits, there must be a closer examination of other uses of the OHER research and data. The advantage of assessing these benefits is that they can be closely linked to readier sources and types of data than the first approach. These two are more straightforward economic applications.

The reduced cost of oil spill cleanup is a social benefit. At issue in the actual implementation of the research plan was the role of environmental damage when estimating the cost of cleanup. Essentially, the issue revolved around whether or not level of cleanliness achieved by cleanup was approximately equal across spills. If it were not, and the differences were not controlled for, then the statistical relationship of Equation (5.6) would not be meaningful. Following a review of the research concept, the decision was made to not attempt this task. Given time and funding constraints in addition to the quite real possibility that the effectiveness of cleanup would vary across the country in an unknown way, quantification of the benefits of reduced oil spills was dropped.

The final assessment task, OCS leasing, was chosen for actual implementation. It had several important advantages. First, OCS leasing has already been the subject of considerable research. The mechanics of the process are well understood and well documented. Secondly, the role of OHER research in defining the environmental risk associated with different courses of action is understood. Finally, the size of the potential benefits was enormous. During the last 15 years approximately $50 billion has been collected in OCS auctions. In the remainder of the chapter the benefits associated with OHER research associated with OCS leasing will be examined.

5.3. OFFSHORE OIL LEASING DECISIONS AND ENVIRONMENTAL INFORMATION

Approximately half of the nation's energy consumption, about 30 quads (quadrillion Btu) is in the form of petroleum energy. Generally, about one-third to three-fifths of that energy resource is imported because of the shortfall of domestic production. The largest remaining area for hydrocarbon production potential in the United States is the OCS. It has been estimated that more than three-quarters of future additions to domestic reserves will come from OCS exploration and development (Niering 1983).

Cumulative production of oil in the OCS (as of the end of 1983) totaled 6.18 billion barrels--about 36 quads. OCS production of natural gas was 62.7 trillion cubic feet. Through October 17, 1984, 85 lease sales have been conducted, and as a result, 38 million acres have been leased. This is a small fraction of the overall OCS acreage. For the leasing of OCS lands, the government has received bonuses totaling approximately $50 billion. Another $25 billion has been generated in payments from oil and gas royalties.

The above statistics make clear the historical importance of the OCS leasing program to domestic oil supplies and federal revenues. The most recent five-year plan includes potential offerings of 750 million acres, with expected additions to reserves of about 37 billion barrels of oil (equivalent). This section discusses offshore oil leasing and how environmental information is used in the leasing process.

5.3.1. Federal Leasing of Offshore Lands for Hydrocarbons

The leasing of federal lands in the OCS for oil and gas exploration, development, and production is a major function of the U.S. Department of the Interior. Offshore areas known as OCS lands range from 3 to 200 miles from shore. The entire OCS has been subdivided into 4 major planning regions: Atlantic, Gulf of Mexico, Pacific, and Alaska. It has been further subdivided into 26 planning areas. Examples of planning areas are the North Atlantic, Mid-Atlantic, and South Atlantic.

Many changes have occurred in the leasing process since leasing began in 1954, following the adoption of the Outer Continental Shelf Lands Act of 1953 (U.S.C. 1953). The Act was amended in 1978, after significant criticisms of leasing were voiced in the 1960s and mid-1970s. The Amendments also resulted in changes, but a general process can be described.

The Minerals Management Service (MMS) of the Department of Interior begins the leasing process by identifying (with the help of the U.S. Geological Survey) areas with oil and gas potential. The first formal action by MMS is a call for information and nominations. Firms, states, and others comment on areas, stating whether or not they are interested in a given location to be leased. From this, MMS delineates an area within which one or more lease sales may take place and which will be analyzed in an environmental impact statement (EIS). At this step, certain areas may have been excluded for environmental reasons or because of insufficient industry interest. Next, MMS issues a draft EIS. A final EIS follows the comment period.

The next step is the issuance of a proposed notice of sale. This notice gives specific information about a proposed sale within the area covered by the EIS, including blocks to be offered, special stipulations, and lease terms. The governors of the states involved then have 60 days to comment on the proposed sale. On the basis of these comments, the MMS recommends whether to proceed with the sale.

5.3.2. Environmental Research and the Leasing Process

Because of the importance of the hydrocarbons in the OCS, and the importance of environmental considerations associated with OCS development, a considerable amount of environment-related research is conducted each year. Although much of this research is funded directly by MMS for the purpose of developing an EIS, considerable research funding from other federal and state agencies--including DOE--is relevant to OCS/environmental issues.

Direct environmental studies conducted with OCS leasing issues in mind have been divided into 6 major categories (U.S. DOI, 1983.): 1) environmental inventory and assessment, 2) benchmark/baseline, 3) geologic and physical processes, 4) biologic, 5) endangered species, and 6) socioeconomic.

Studies concerning ocean currents, circulation, and particles transport --such as those funded by OHER's Marine Research Program--would fall into the geologic and physical process category. Information about ocean currents and transport is vital in determining likely paths of oil spills and normal discharges from operations. When combined with information about oil spill frequencies, likely wind velocities, and environmental resources likely to be damaged, the link from ocean current studies and potential OCS block offerings and leasing can be understood.

MMS typically analyzes the oil spill risk for a proposed lease sale, Such a study is designed to examine the oil spill risk associated with development of the proposed sale area. The study for Sale No. 42 in the North Atlantic involving Georges Bank Basin ". . . analyzed probability of spill occurrence, likely paths of pollutants from spills, and locations in space and time of recreational and biological resources likely to be vulnerable" (U.S. Geological Survey 1976).

Of particular interest for the purposes of the present study is the oil spill trajectory simulation and its linkup with environmental resources. In a 1983 study of the North Atlantic, locations of environmental "targets" are digitized to be compatible with trajectory simulations. Targets include the full range of environmental resources potentially affected by an oil spill, each given a monthly sensitivity. Examples of targets would be coastal waterbird colonies (March-November), bald eagle nesting areas (January-June), inshore lobster grounds (year-round), coastal marshes (year-round), and state wildlife and natural areas (year-round). This ensures that migrating birds, as an example, could be affected by an oil spill only if it occurred when the birds are passing through that environment. (U.S. DOI, 1983.)

Oil spill trajectory estimates are obtained by incorporating trend and variation in ocean surface currents and winds into a probabilistic model that is simulated by Monte Carlo methods. Monthly surface current velocity fields are required by the model. Current information may by incorporated into the analysis both directly as input, and indirectly, affecting, to some extent, the model structure.[a] Current information is combined with wind speed and wind drift angles to generate simulated trajectories for oil spills.

The oil spill risk analysis modeling takes note of the number of times a simulated oil spill intersects with a given environmental resource in a month when that target is sensitive. The number of intersections is coupled with oil spill frequency estimates, and probabilities of environmental impact for each target are obtained. By varying the launch points in the trajectory simulation, the different impacts of leasing in various subareas within a planned sale area are estimated.

Impacts of Environmental Information on Leasing

Environmental information has both formal and informal impacts. Formal impacts are, of course, the easiest to observe. The most obvious application of environmental information is in the development of alternatives to the planned sale. The EIS generally presents a number of alternatives to the planned and recommended option. Alternatives may include not holding any sale, delaying or accelerating the sale as described, and adding/subtracting blocks from the sale offering. The latter alternative most clearly reflects the use of environmental information. Often, an alternative will suggest deleting a cluster of blocks from the recommended sale, usually on environmental grounds. The consequences of such a deletion are sometimes stated in terms of the oil and gas resources that are foregone, as well as the environmental damage averted. When the Secretary of the Interior prepares a final notice of sale, he/she has usually responded to comments and suggestions based in part on the environmental consequences of alternatives examined in the EIS.

Other, less obvious, impacts exist as well. The environmental estimates seem to be well known to all participants in the process, including the oil and gas companies preparing bids for the blocks. Quite often, special stipulations are published in the sale notice telling potential bidders that one or more special tests, precautions, or drilling methods will be required in the lease. Considerable flexibility may be built into these stipulations

(a) Personal communication, Jim Lane, Atlantic OCS Regional Office, MMS, April 30, 1986.

so that they can be applied differentially to the various blocks as conditions warrant. Each of these considerations translates into costs for the winning bidder.

Even if MMS did not apply explicit restrictions to the lease operator, liability rules for spills would influence the firm's behavior in the lease auction. Two blocks with identical hydrocarbon potential, but with vastly different potentials for seriously damaging the environment, are not likely to be valued the same. From this, the informal effects of environmental information can be postulated. Each potential bidder's decision whether to bid on a block will be affected, as will the level of the bid. This further translates into changes in the winning bid because of environmental information.

The five-year leasing plan released in April of this year is another example of the impact of environmental information. Interior has eliminated 46 percent of the 1.4 billion acres of the OCS from consideration, and will undoubtedly withdraw more acreage as sales approach. But some areas in the 750-million-acre offering plan, including 81.5 million acres in the Bering Sea off Alaska, contain considerably <u>more</u> acreage to be offered than oil companies had agreed to in informal negotiations with environmental groups last year. The pact among oil companies and environmental and conservation groups was put together under the auspices of the Institute for Resource Management. According to the <u>Wall Street Journal</u> (April 28, 1987, "Drilling Plan for Bering Sea Off Alaska May Sink Hard-Won Conservation Pact"),

> "Pragmatic environmentalists ... argued that such a truce would lower litigation costs while preserving the most environmentally sensitive area. And oil companies saw the plan as a way of adding some certainty to a process in which drilling plans were often disrupted because of lawsuits filed after leases had been issued."

Regardless of the extent to which cleaning birds, fish, and beaches damaged by oil spills is paid directly by oil companies, the associated lawsuits filed as a result of the oil spills are clearly costly.

5.3.3. <u>Economic Analyses Related to Offshore Leasing</u>

A considerable body of literature relates to the general area of offshore oil and gas leasing. Although no exhaustive literature review is provided here, relevant prior published work is briefly discussed so as to place the present work in context.

Prior Economic Evaluations of Leasing: General

The early economic research focused on the economics of alternative leasing methods, i.e., whether cash bonus bidding systems are to be preferred to other alternatives. Commonly discussed major alternatives include royalty bidding, (net) profit share bidding, and work commitment bidding. Royalty bidding involves firms bidding a specific fraction of the hydrocarbons recovered from the block. Profit share bids are those where the firm bids a fraction of its (net) profit from operations on that block. Work commitment bids are where firms pledge to engage in a certain amount of drilling and development work. The literature addressing alternative leasing methods generally involves the application of standard static microeconomic concepts; relatively little empirical support is provided because of the lack of significant experimentation by the Interior Department. Examples include Gardner (1967); Mead (1969); Leland and Norgaard (1974); Logue, Sweeney, and Willett (1975); Jones, Mead, and Sorensen (1980); McDonald (1979); Ramsey (1980); McDonald (1981); and Mead, Moseidjord, and Muraoka (1984). A good recent summary of the general economic research associated with offshore oil and alternative leasing systems may be found in Mead, Moseidjord, Muraoka, and Sorensen (1985).

Theoretical and simulational modeling relating specifically to the leasing system, OCS bidding behavior, and firm behavior post-lease can be found in Kalter, Stevens, and Bloom (1975); Kalter, Tyner, and Hughes (1975); Attanasi and Johnson (1976); Reese (1978); Reese (1979); Teisberg (1980), and Hyde and Markusen (1982); Klan (1987).

Empirical studies of note using actual leasing behavior in an econometric framework include the Jones, Mead, and Sorensen (1980) article cited above, as well as Markham (1970); Sullivan and Kobrin (1980); Gilley and Karels (1981); Gilley and Karels, (1983); Mead, Moseidjord, and Sorensen (1983); Gilley and Klan (1986); and Mead, Moseidjord, and Sorensen (1986). Empirical topics include the rates of return earned by lessees and bidding behavior in an auction (including joint bidding)--both the bid/no bid decision by firms and the amount of the bid.

Environmental Information in Economic Leasing Studies

It is safe to say that the role of environmental issues in economic analyses of the OCS leasing process has been almost entirely ignored to date. Not only does no prior work exist that helps link ocean current research to the tangible benefits of OCS leasing, but no prior work exists that clarifies the increasingly vital role of environmental information generally.

Generally, both theoretical and empirical leasing studies work with the value of the block in terms of its net hydrocarbon value, abstracting from cost issues. When the cost of exploiting a block is explicitly considered, it is cast in terms of the direct physical cost of drilling and development. The implicit environmental liability accruing to firms engaged in offshore operations is abstracted away. The explicit costs of special stipulations in a lease--such as the requirement for costly directional drilling to protect an environmental resource--are ignored. In empirical studies, where costs are explicitly included, they are generally proxied only by water depth, or (less often) distance to shore.

Another way in which environmental impacts on the leasing process are ignored is in constructing the sample to be analyzed empirically. It appears that all prior empirical studies work with OCS blocks that have been offered in sales, and omit consideration of those that have been withdrawn. Further, most studies analyze only those blocks that were, in fact, bid upon and leased.

There appear to be four reasons for ignoring environmental information in prior leasing studies. First, the logical unit of observation in OCS leasing often appears to be the sale, and much (although not all) of the impacts of environmental information have already been expressed through the withdrawal of tracts. Thus, the environmental effect can be hard to see because of the built-in bias in selecting the sample. Second, specific data useful in an economic analysis that incorporates environmental information are considerably harder to obtain than the sale data provided on tapes by MMS. Third, in the early years of OCS leasing the hydrocarbon values tended to swamp the potential environmental damages. It is at least arguable that for the first 20 years or so of the leasing process, environmental costs were relatively unimportant, even from a social perspective. Economic theory requires that the highest hydrocarbon blocks and areas with the largest net value be leased first.

Fourth, analysts tend to think of the costs of hydrocarbon exploitation in physical terms relating to the individual stages of exploration, development, and production. Economic costs associated with delay because of environmentally inspired litigation, or due to implied liability for an oil spill that has not yet occurred, are simply not part of the analytic tradition.

5.4. OFFSHORE OIL LEASING CONCEPTUAL MODEL: THREE STAGES

To illustrate the influence of environmental information on OCS leasing and to estimate its effects, a three-stage conceptual model was estimated.

The key, formal steps of the leasing process along with the actions of the leasing parties are organized into a simplified decision tree shown in Figure 5.1. The model is structured to give some idea of the importance of environmental information in each stage. The model has three stages, which are discussed in the following sections. Specific model runs are presented in Appendix A.

5.4.1. First Stage: Minerals Management Service Decision to Offer or Withdraw Blocks

As shown in the diagram, the leasing process begins with a set of blocks planned for a sale. The MMS and the Secretary of the Interior must decide which blocks to finally offer in the sale and which to withdraw. The withdrawal decision is usually linked to environmental concerns, but other issues such as transnational boundary disputes may also be involved. As noted earlier, the Secretary must be sensitive to the concerns voiced by state governors when making the final decision. The enabling OCS leasing legislation requires that a balance be struck between hydrocarbon potential and potential environmental damage.

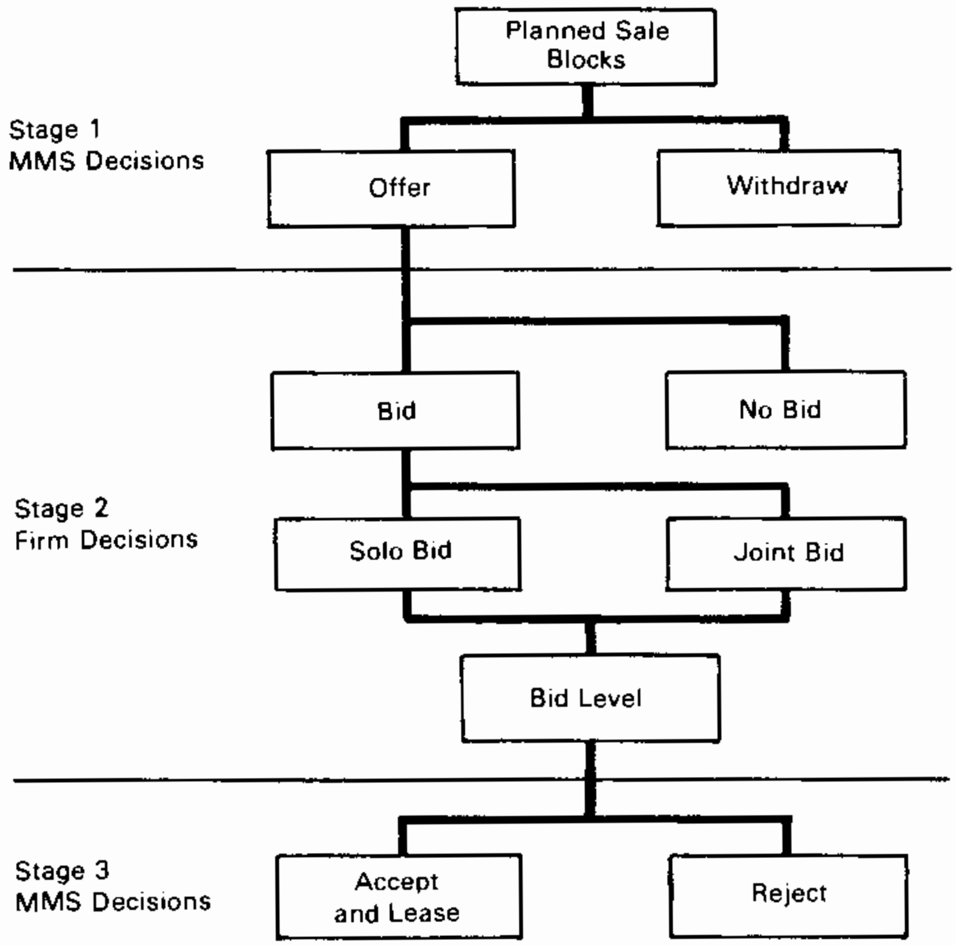

FIGURE 5.1. Decision Tree for Outer Continental Shelf

In principle, then, the MMS decision to offer or not to offer a block may be modeled as a binary choice model. The probability with which a particular block will be offered is functionally related to the block's

- expected hydrocarbon potential, net of extraction costs
- potential for environmental damage associated with exploration, development, and production activity
- location (state), and the attitude of that state's officers to its potential leasing.

5.4.2. Second Stage: Industry Bid/No Bid Decision on Offered Blocks

Returning to the decision tree in Figure 5.1, we can see that the next decision is made by industry. If a block is offered in a lease sale, individual firms must decide whether or not to submit a bid for it. From the aggregate perspective, industry decides whether any bid will be made or not. Quite often in a sale--especially since 1983 when large areas have been offered in any given sale--a block will not receive a single bid from industry. That block may, of course, be re-offered in a later sale and ultimately bid upon and leased.

At the same time it decides to bid, industry must make two other decisions: 1) whether to bid as a single company, or in combination with others, and 2) how much to bid. The solo/joint bidding decision is not treated explicitly here, as it is off the main track of inquiry. [See Gilley and Karels (1983) for factors influencing joint bidding.] The bid level decision is discussed later.

Again, a binary framework is appropriate to model the industry decision of whether or not to submit a bid. The probability that a bid will be submitted may be functionally related to a block's

- expected hydrocarbon potential, net of extraction costs
- expected environmental damage from operations, and costs associated with environmental concerns (such as required surveys and litigation, etc.)
- lease terms (e.g., type of bid required).

Note the differences from the first decision model described above. Environmental issues now enter in several ways. The type of bid becomes important--whether profit share, cash bonus with fixed royalty, cash bonus with sliding scale royalty, royalty bid, etc.. Other aspects of the lease can also vary, such as the initial term of the lease, or the minimum bid required. Minimum bids, for example, have sometimes been set by MMS at $25 per acre; at other times, the minimum has been $150 per acre. This sixfold difference can be a significant factor for the bid/no bid decision on marginal tracts. The location, state in which a block is located, should no longer be directly important, although indirect effects transmitted through different environmental and permitting attitudes can still exist.

5.4.3. Third Stage: Winning Firm's Bid Level Decision

If the individual firm decides to bid, it must then decide how much to bid (refer to Figure 5.1). Mead, Moseidjord, and Sorensen (1986) postulate a regression model for winning bids that takes into account the expected value of the lease, the competitive structure of the lease market, and factors characterizing the information available to bidders. A similar approach is taken here, with two major differences. First, since the sale to be examined contains only wildcat blocks (blocks on or near which no previous successful development has taken place), no information relating to productivity of neighboring blocks is employed here. Second, environmental information and the role it plays in influencing bid levels is included.

The level of the winning bid is postulated to be functionally related to the same general set of factors as the bid/no bid model, plus three additional factors. The first new factor is the winning firm's financial capability to bid, as expressed through a measure such as current assets. Bidding companies typically face an internal sale budget, which constrains both the amount of their bids and the number of bids made. Larger budgets tend to imply larger winning bids, other things equal.

The second new factor is the winning firm's attitude toward risk. Lease bidding is very risky business. OCS leasing and development have been generally less profitable than other industry activities in the United States, in part (perhaps) because of the so-called winner's curse. The winner's curse says that if you win a block, you are cursed, because your firm is the firm that most overestimated the block's value. Firms that are more risk-averse tend to have lower winning bids.

The third new factor is whether the winning bidder is a single firm or part of a consortium. The influence of joint bidding has received considerable attention in the literature. The consensus seems to be that joint winning bids tend to be slightly higher than solo winning bids, other things equal. This is a fairly complex phenomenon, since joint bidding also appears to increase the number of bidders for a block, and increased competition reduces an individual bidder's bid. The winning bid, nonetheless, is increased, because of the distributional aspects of increased numbers of bids.

The ordinary least squares (OLS) regression technique can be used to estimate the influence of the explanatory factors on the bid level, as long as the minimum bid restriction by the MMS is not too high. In cases where the minimum bid restriction is high enough, actual bids are fewer than desired, and the sample of bid levels is considered to be censored. When this happens, the tobit technique is probably more appropriate than OLS.

5.4.4. Minerals Management Service Acceptance/Rejection Decision

The tree diagram in Figure 5.1 has an additional decision branch that has not yet been discussed. This is the acceptance/rejection decision made by MMS for a given high bid on a block. Not all high bids are accepted. Very roughly, only those high bids that are received on blocks for which many bids are submitted, or that exceed MMS's estimate of the value of the tract will be accepted. No model has been developed for this decision, since no postulated role for environmental information and research could be seen.

5.5 OFFSHORE OIL: NORTH ATLANTIC CASE STUDY (GEORGES BANK SALE)

One OCS lease sale has been selected for detailed investigation: OCS Sale No. 42 in the North Atlantic, held December 18, 1979. This sale was selected, in part, because considerable environmental research--including OHER ocean current research--has been conducted in the Georges Bank Basin, which is part of the leased area.

The North Atlantic planning area consists of the Georges Bank Basin, the Gulf of Maine, and deep waters seaward of Georges Bank. A map of the area is shown in Figure 5.2. The Georges Bank Basin is the most promising hydrocarbon area in the North Atlantic. Conditional mean probability estimates of hydrocarbons in the North Atlantic are 350 million barrels of oil and 7.14 trillion cubic feet of natural gas. Two stratigraphic test wells were drilled in the Basin in 1976, and eight exploratory wells were drilled in 1981-1982. All were dry holes. (See Rudolph and Havran 1985.)

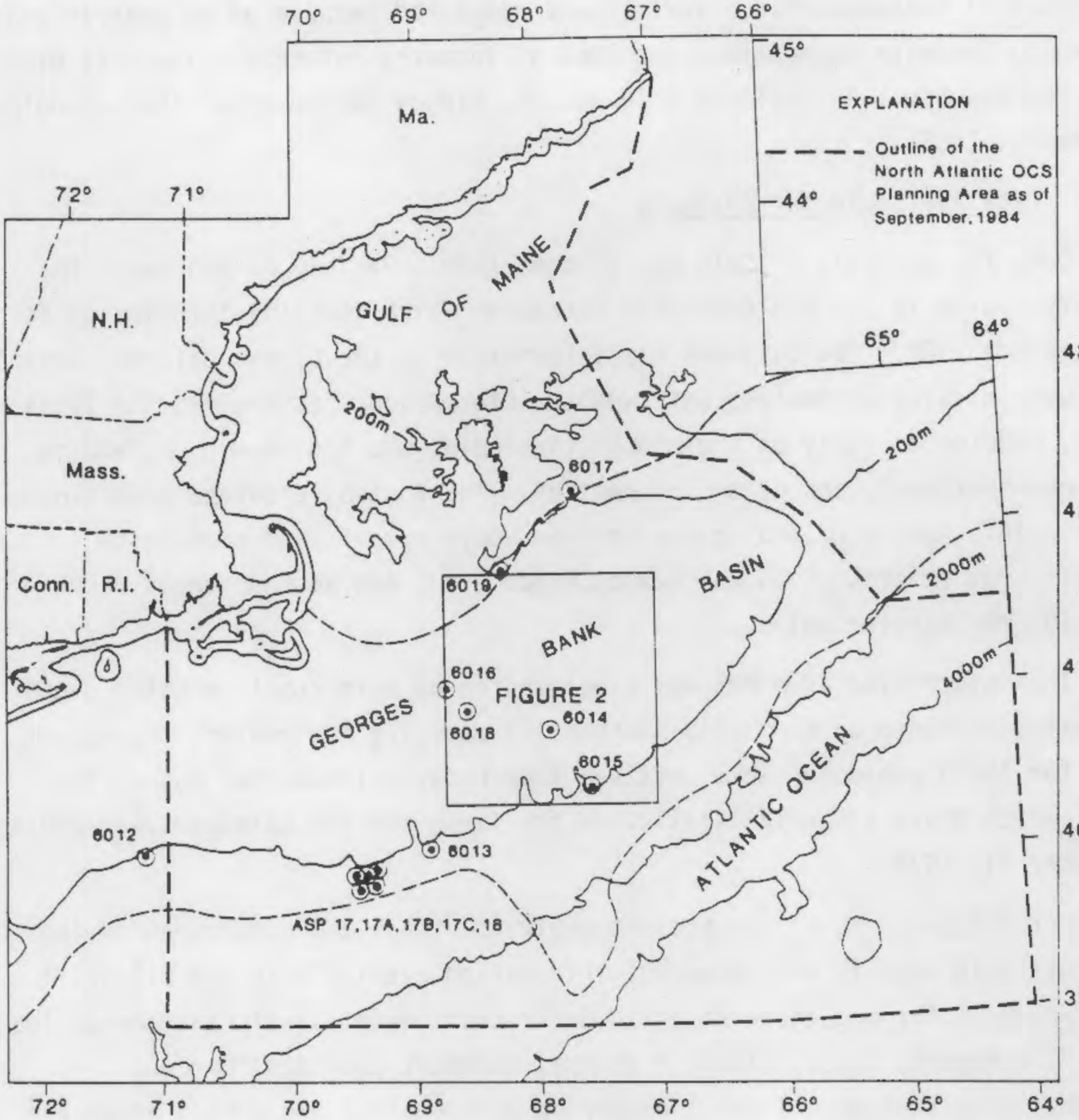

FIGURE 5.2. North Atlantic Outer Continental Shelf Planning Area

The only lease sale to date in the North Atlantic is Sale No. 42, held December 18, 1979, after a two-year delay because of litigation. Two other sales have been scheduled for the region and subsequently cancelled. Sale No. 52 was cancelled November 21, 1983, primarily because of prolonged litigation surrounding the EIS. Sale No. 82, Part I, was cancelled September 25, 1984; Part II of the sale was cancelled December 21, 1984. Part I was also cancelled because of strong environmental opposition and legal action by the state of Massachusetts. Part II was cancelled because of an adverse ruling regarding Canadian boundaries, and lack of industry interest. The next proposed sale for the North Atlantic is Sale No. 96, slated for November 1987 (Rudolph and Havran 1985).

5.5.1 Data Available for Analysis

Data for analysis of Sale No. 42 come from a variety of sources. The primary source is the MMS Post-Sale Database, which contains information for sales since 1978. The database has information on the blocks offered, presale hydrocarbon value estimates, water-depth information, facts about the lease terms, bidding activity on the blocks (including who bid, how much, and in what combinations), and other information. The Post-Sale Database does not contain information regarding exploration, development, and production activity, as is present in the Lease, Production, and Revenue tapes (LPR-5/10/19) for earlier sales.

The information from MMS was supplemented by more complete water-depth estimates obtained by examining bathymetric maps for the region. Financial data for the highbidders were obtained from Moody's Industrial Manual for 1980, which gives financial statistics for firms for the calendar year ending December 31, 1979.

For the purposes of the present analysis, the vital supplement to the MMS Post-Sale data is environmental information available in "An Oil Spill Risk Analysis for the North Atlantic Outer Continental Shelf Lease Area" (USGS Open File Report, 1976). Table 2 of that document provides "percent probabilities that an oil spill occurring at potential production areas and along anticipated transport routes . . . would impact important biological resources and recreation areas." The 206 blocks planned for the sale were clustered into 13 production areas. The probabilities range from less than 0.005 that production in area 12 would impact grey seal whelping areas, to 0.52 that production in that area would impact cod and haddock spawning areas. The data from this document appear to have been widely available at the time the sale was held.

5.5.2 Analysis Results

Three offshore leasing stages for the 1979 OCS sale for the Georges Bank Basin in the North Atlantic were statistically modeled and estimated. The first stage is the MMS decision whether to offer a particular block in the sale. The second stage is the oil and gas industry's decision whether to bid upon a block which has been offered in the sale. The third stage is the high bidder's decision concerning how much to bid for a block. Models for stages one and two were estimated statistically using a common technique for representing binary choices. In stage one MMS chooses whether or not to offer a bid; in the second stage the choice is by the company whether or not to bid. The third stage model was estimated using ordinary least squares regression. Details of the estimation procedure and results may be found in Appendix A.

In 97 percent of the cases the estimated model for the offering decision correctly predicts whether a block was offered. All of the explanatory variables have the expected effects; all but one are statistically significant. The model as a whole is highly significant, making it extremely unlikely that these results are due to random chance. A higher probability of an oil spill reaching shore is associated with a significantly lower probability of the block being offered in the sale. Thus, the statistical analysis provides evidence that the MMS considers possible environmental damages in its decision to offer a block for bids.

The model for the bidding decision by firms correctly predicts 68 percent of the cases. That is, over 2/3 of the time the model can correctly predict which blocks receive bids. The main variables of interest in the model have the expected effects and are statistically significant. Overall, the estimated model is statistically significant. A block with possible environmental damage has an impact on bidding behavior. A higher probability of an oil spill reaching shore is associated with a substantially lower probability of the block receiving one or more bids.

The bid level model is estimated for the cases in which the expected value of hydrocarbons is above the minimum. Additional environmental variables are included to estimate the influence of oil spills potentially reaching herring, cod, and hake spawning grounds, as well as the nearest beach. The proportion of explained variation in the bid level variable (i.e., the corrected R^2) is 0.58. Although most of the explanatory variables have the expected effects in the estimated model, several are statistically insignificant. For the variables representing herring, cod, hake, and beach, a higher probability of an oil spill impacting these resources is associated with a lower bid in the OCS lease sale.

The sensitivity of the block offering decision and the block bid decision to a range of probabilities for a oil spill reaching shore is shown in Table 5.1. Both the offering decision and the bid decision results are separated into two cases: 1) a moderate amount of hydrocarbons is expected and 2) the expected value of hydrocarbons is low. The "low" case is quite common in the Georges Bank lease sale, representing about 2/3 of the blocks.

Consider the offering of blocks as illustrated in Table 5.1. For a block where a moderate amount of oil (and gas) are expected, and where other key variables are pegged at their average values, the probability of MMS offering the block approaches one. This is true regardless of the probability of an oil spill reaching shore (over reasonable ranges). For those blocks with smaller amounts of oil expected, the oil spill impact probabilities become important. If such a block is located where distance, ocean currents, and winds place the likelihood of an oil spill reaching shore at about 0.25, the block is withdrawn from the sale.

The influence of environmental factors appears even greater in the industry decision whether to bid on a block which is offered in a lease sale. A block with a moderate amount of expected oil ranges from 0.84 to 0.07 in probability of receiving a bid, depending on the likelihood of a

TABLE 5.1. Oil Spill Probabilities and the Offering and Bidding of Blocks

Probability of MMS Offering Block	Overall Probability of an Oil Spill Reaching Shore 0	0.05	0.1	0.15	0.2	0.25
Medium Oil Estimate[(a)]	1.00	1.00	1.00	1.00	1.00	1.00
Low Oil Estimate[(b)]	1.00	1.00	1.00	0.95	0.60	0.12
Probability of Bid on Block						
Medium Oil Estimate[(a)]	0.84	0.69	0.49	0.28	0.14	0.07
Low Oil Estimate[(b)]	0.82	0.63	0.42	0.23	0.11	0.05

(a) These calculations employ the arithmetic means of the hydrocarbon value estimates for the sets of blocks analyzed, as well as the means for the other explanatory variables. The hydrocarbon value mean for the set of blocks involved in Interior's offering decision is $2.54M. The hydrocarbon value mean for the set of blocks involved in industry's block bidding decision is $2.04M.

(b) These calculations reflect the hydrocarbon value estimates for blocks valued at the minimum acceptable bid level of $25 per acre (or about $143,000), and the arithmetic means for other explanatory variables on these sets of tracts.

spill reaching shore. If the probability of an oil spill reaches even 0.1, the block will not be bid upon. The blocks with lower oil estimates have lower corresponding bid probabilities, since the payoff is now smaller for the oil companies.

The table graphically illustrates the relevance of environmental issues to the offering and bidding of blocks in an OCS lease sale. The probability estimates are derived from the statistical models developed for each decision. Concern about oil spills is evident in the behavior of both the oil and gas companies involved in leasing, as well the Department of the Interior in its role as manager of the federal lands.

5.5.3 Implications Regarding Environmental Research

Econometric evidence based on the data for a single sale in the North Atlantic supports the procedural and anecdotal evidence that environmental issues play an important role in several of the key stages of OCS leasing. A block with a higher probability of an oil spill reaching shore is substantially less likely to be offered in a sale, other things equal. For blocks offered by MMS in a sale, those with higher probabilities of oil spills reaching shore are substantially less likely to be bid upon. And finally, those blocks with higher oil spill impact probabilities are likely to receive lower bids, although the evidence is less compelling here.

The econometric results could not and do not stand alone. They are just one of several factors that emphasize the importance of environmental issues. The first is the intent of the law. The second is the amount of environmental investigation associated with the leasing EIS process. The third is the amount of environment-related press and litigation. The fourth is special drilling and operating restrictions placed on leaseholders because of environmental concerns, resulting in real and substantive costs. Finding econometric evidence to substantiate the importance of environmental information in the OCS leasing process is thus not a surprise.

In the process of finding the role of environmental information in OCS leasing, the contribution of OHER (and other) ocean current studies was also found. That contribution is in the development of the oil spill impact estimates that appear to be developed for every planned sale. The trajectory of the oil spill is modeled based upon what is known about ocean currents and wind speeds at and near the launch point. A cursory examination of the estimated probabilities shows that they are quite different than a naive approach (such as raw distance from shore) would suggest. This difference can only be attributed to what is known about wind and currents.

5.5.4 Extension of Case Study to Entire Outer Continental Shelf

Ideally, the models estimated for Sale No. 42 should only be used to value the role of environmental research (including OHER research) for the Georges Bank area covered by that sale, and only for 1979. A fully supported valuation for the entire U.S. OCS requires an analysis of each planning area, if not of all the prior sales.

But some idea of the overall impact of OHER research can be obtained by extrapolation of the estimated results. The valuation of OHER ocean current research for the North Atlantic Sale No. 42 case study, and the valuation of OHER ocean current research generally, is the topic of the next subsection.

5.6 VALUE OF ENVIRONMENTAL RESEARCH FOR OFFSHORE OIL LEASING

Exploitation of exhaustible resources invariably results in some impact upon the environment. Coal, oil, and mineral mining each result in tailings or spills that cause environmental damage. Understanding the degree of potential damage prior to development allows the appropriate decisions about when, where and how to develop these resources.

Environmental information also allows some quantification of the risk involved in developing these resources. The role environmental information plays in OCS oil development has been discussed at length in previous sections. This section will use the estimated relationships to examine what the course of events might have been with less environmental information.

The social value of the information is net benefit associated with an improved course of action attributable to the additional information. In the case of OCS leasing, two separate benefits or costs can be identified. The first is additional oil tracts that can be leased because the information has revealed they are less dangerous than previously thought. In this case, the benefit is the additional oil bid revenues. The second is the withdrawal of tracts that are more dangerous than was previously believed. In this case, the benefit is the reduction in environmental damage.

As has been discussed in Section 5.4, the administrative steps that correspond to these benefits are the offering and bidding. The benefits show up as the MMS decision to offer/not offer a tract and as the oil industry decision to bid/not bid on a tract. These effects can be simulated given the estimated statistical model for the respective decision. A complete description of the statistical models developed for the simulation is in Appendix A.

5.6.1. Simulation Procedure

Simulation of the econometric model of bidding-leasing behavior described in the previous sections requires that an alternative scenario be postulated. This alternative needs to consider what would have happened if OHER's research were not available. This is quite challenging. A vast quantity of imponderable elements would need to be sorted before the precise change in information attributable to OHER research could be identified. It is doubtful that a meaningful measure could be developed. Therefore, an alternative approach will be adopted to illustrate the value of the environmental information, and through it, the benefits of OHER Marine Program research.

Rather than attempt to fully understand the state of information, the alternative scenario will be developed as deviations from the actual MMS estimates of risk that oil will reach shore. These deviations will be measured as percentage changes from the actual MMS estimates of the likelihood of oil ashore.

In this simple model it is assumed that decision makers believe the likelihood of oil contacting the shore is inversely proportional to the distance to shore. For example, a 10 percent increase in the perceived likelihood of oil ashore means that if the MMS thought that the likelihood was 7 percent then the alternative scenario is a 7.7 percent probability. These decisions can then be simulated using the econometric model discussed in Appendix A.

Benefits to information can be found by investigating the choices if the conventional wisdom had been different without the research. Clearly, there are two possible cases. Either a tract could have been thought safer or more dangerous than subsequent information revealed. Depending on the case, the measurement and type of benefits of research will vary.

If the tract was thought safer, then the benefit accruing to the information is the averted environmental damage. The literature on valuing environmental damage from oil spills is voluminous. Given the level of aggregation in this study and the diversity of environmental attributes that could be damaged, a simple dollar aggregation of the value of the averted damage is beyond the scope of this study. However, the bid level equation does suggest which environmental attributes are most at risk from a marginal change in leasing behavior due to reduced information. These include: beaches, silver and red hake, sea herring and cod.

The increased risk to these environmental attributes that is associated with reduced information is estimated by tracing reduced overall damage probabilities through the offer and bid mode decision nodes. For simplicity, these two nodes are assumed to be independent, and therefore the likelihood of a bid actually being forthcoming is simply the two probabilities multiplied together. The per tract increased environmental risk associated with a naive, overly safe view of the tract is the change in probability that the tract will be offered times the probability of environmental damage. This calculation can be carried out for each of the four environmental goods of interest as well as for various degrees of naivete. One possibility is that in the absence of OHER research people would overestimate the environment safety associated with an OCS lease. Figure 5.3 shows how the environmental damages would increase if individual's mistakenly thought OCS was safer than actually the case.

As can be seen from the figure, the additional risk borne by these selected resources increases as the deviation from Sale 42 actions increases. Hake is the most sensitive, with cod, beach and herring following.

For the purposes of this study, deviations larger than 20 percent are likely to be inappropriate. This is because the net contribution of OHER is likely to be small in relation to the total understanding of ocean currents in the area. It seems implausible that OHER research refined the estimates of the likelihood of environmental damage more than 20 percent. This corresponds to shifting the expected likelihood of oil ashore from a tract from 6.25 percent to 7.5 percent. However, if the effect of OHER research was to refine the estimates a full 60 percent, from 4.69 percent to 7.5 percent, then the increased environmental risk would be between 50 percent and 60 percent greater than the actual Sale 42 conditions. There exists considerable latitude for error in the estimation of potential risk to environmental resources.

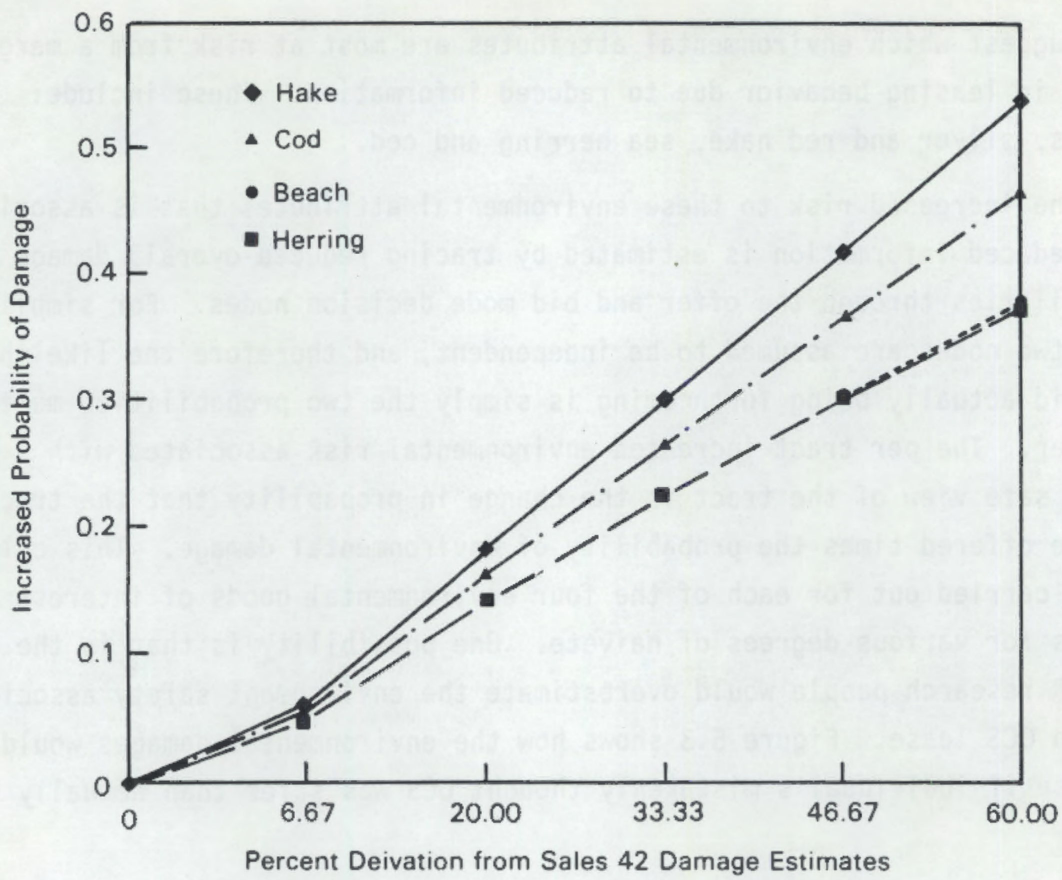

FIGURE 5.3. Relationship Between Environmental Risk and the Perceived Safety of Leasing Area

The second mistake that can be made is to underestimate the safety with which a given tract can be exploited. In this case, the benefit of the additional information to correct this underestimate is the additional oil that can be extracted. The effect of underestimating the safety of a tract is found in a procedure analogous to the overestimation case. In this case the compound probability is multiplied by the oil estimate for each tract instead of the damage probability. Total benefits for the sale are found by summing up differences between the Sale 42 oil reserves sold and the predicted oil reserves sold. Table 5.2 shows the total oil sale benefits for changes in likelihood of a tract being leased.

As can be seen from the table, a 6 percent increase in the perceived probabilities that leasing a tract will incur oil-related environmental damage costs $55 million in foregone oil reserves. This is a considerable foregone value. If the difference in perceived risk was increased by 20 percent, the foregone oil is valued at $163 million. Again, a deviation greater than 20 percent is not likely to be observed, but, if research did have dramatic impacts on the ability to accurately predict the movement of oil, the table clearly indicates that the losses associated with being unreasonably conservative are considerable.

The above discussion has centered generally around the losses resulting from inaccurate estimates of the relative risk of developing different tracts in the ocean. Moving from the general level to OHER's contribution to an increase in the precision of risk estimates is problematic. The largest difficulty stems from the inability to specify either the complete outcome of the OHER research or the proportion of all knowledge about the ocean currents in the area that is attributable to OHER-funded work. As a result, precise evidence regarding the contribution of OHER to this process is not forthcoming.

However, it is reasonable, and entirely feasible, to examine plausible ranges of benefits that would accrue to a research effort the size of OHER. An estimate with some prima facie plausibility is that OHER contributed 5 percent to the knowledge of ocean currents in the area. Extrapolating from this number to an estimate of benefits indicates that, with a 6 percent deviation from Sale 42 actual estimates, $2.75 million of benefits might be attributed to OHER's research due to keeping the MMS and industry from being unreasonably cautious about potential oil damage. A similar calculation with regard to the environmental damage caused by being unknowingly reckless shows that a 0.3 percent chance of beach damage, a 0.25 percent chance of herring damage, a 0.25 percent chance of hake damage, and a 0.3 percent chance of cod damage was averted by OHER research. The total benefit includes both the benefits of the value of additional oil and reduced environmental damage.

TABLE 5.2. Sale 42 Oil Benefits Estimates

Percent Deviation from Sale 42	Oil Value (millions)
6	$55
20	$163
33	$272
46	$381
60	$489

5.6.2. Value of Environmental Research to Outer Continental Shelf Leasing in General

The tempting course of action at this point is to try to extend the benefits to the entire OCS leasing program. Indeed the OHER Marine Program has been instrumental in understanding the ocean currents associated with much of the OCS area that has been offered for lease in the last fifteen years. Several problems preclude even an illustrative calculation of the complete benefits number.

First, each area will have unique environmental attributes. The particular fisheries, their value, and the aesthetic values associated with different parts of the coastline are not easily compared using the very limited results of this research. Secondly, there are likely to be differences in the conditions of the sales, and this will change the value of the offered tracts.

However, it is possible to make an order-of-magnitude approximation estimate for the value of not being unreasonably cautious about potential environmental damage. If OHER's level of participation were about the same in other sales as it was in Sale 42, a simple proportion would indicate the order of magnitude. Using $2.75 million (the 6 percent deviation benefit estimate) as a baseline puts the benefits of OHER marine research at 0.34 percent of leasing revenues. Over the last 15 years OCS leasing revenues have been $49.17 billion. Simple multiplication indicates that OHER's research would have generated $165.6 million of benefits. This estimate is not a sophisticated analysis, but does indicate the order of magnitude of benefits that are possibly accruing to marine research in this one area alone.

5.7 CONCLUSIONS AND RECOMMENDATIONS FOR MARINE PROGRAM ASSESSMENT

This study of the marine program has examined several ways through which the research results could be valued. Clearly, a program as wide-ranging and diverse as this one has a wide variety of benefits. Attempts to value each one brings its own analytical difficulties. An attempt to completely examine the program is not possible at this time. An alternative is to take the case study approach as was done here. In this case, the OCS leasing program was selected for careful review.

The first level of the analysis was to demonstrate, empirically, that OHER's research plays an important role in the OCS leasing decision process. Secondly, once the relationships between OHER research and OCS leasing were defined, the benefits implied by this relationship were estimated. Individually, each step has a role in the evaluation of a program. Together they provide direct and supporting evidence of the importance of OHER's work in the functioning of private and public decision making.

Estimation of the role of environmental information in the decision making of the federal government and the oil industry is a new undertaking. Given that this relationship has never been quantified before, it is not surprising that its effect is largely regarded as, at best, on par with other anecdotal evidence. This study clearly places the role of environmental information in the forefront of OCS leasing decisions. OHER is one of the prime developers of this information. OHER's basic research about currents and oceanic activity forms the basis for the environmental risk modeling.

The actual benefit estimates provided are also new. Unfortunately, they serve more to illustrate the order of magnitude of potential benefits rather than a definitive estimate of them. But these order-of-magnitude estimates are useful. Indeed, even if the most conservative case is taken, and it is high by an entire order of magnitude, the benefits accruing to improved OCS leasing decisions alone are a considerable portion of the marine program budget for the period under consideration. Illustrative though the actual number reported may be, it is tightly linked both to the decisions of the federal government and of industry and to the social well-being of the country.

5.8 REFERENCES FOR CHAPTER 5.0

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6.0 GERMANIUM RESEARCH CASE STUDY

The gamma-ray spectrometer is a device for detecting, characterizing and monitoring gamma radiation.[a] The energies of gamma rays are always characteristic of the radioisotope under analysis. The gamma-ray spectrometer, by measuring the gamma-ray energies of a source (as well as the level of activity), is thus able to measure and identify the radioisotopes present.

A number of separate components make up a spectroscopy system. A commonly used and fairly recent gamma-ray spectroscopy system is shown in block diagram form in Figure 6.1. This chapter is concerned with one particular type of detector, the high-purity germanium [Ge(HP)] detector, the development of which was funded by OHER. The detector "reads" the gamma-ray emissions from a sample by outputting a signal pulse whose magnitude is proportional to the energy of the gamma ray. Electronic techniques are then used to amplify, analyze, and identify the signal pulse. The computer is used in this analysis and identification process and to display pulse height spectrums, which represent the true energy distribution of gamma-ray emissions striking the detector.

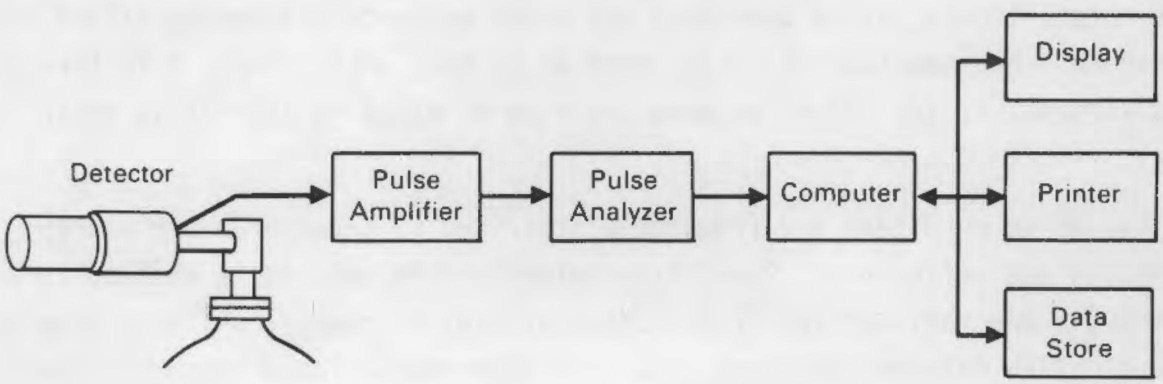

FIGURE 6.1. Block Diagram of a Gamma-Ray Spectrometry System

(a) A gamma ray is electromagnetic radiation emitted by radioactive decay.

Gamma-ray spectrometers with Ge(HP) detectors are used in a number of different applications usually involving gamma radiation monitoring and elemental analysis of radioactive or neutron-activated substances. Not only have Ge(HP) detectors replaced other types of detectors in existing applications, they have created entirely new applications, such as in astrophysical research. A brief description of some of these applications will help to indicate the number of ways Ge(HP) detectors are used.

Ge(HP) detectors are used in nuclear power plants to monitor the plant environment and the content of effluents and to measure the condition of the reactor fuel elements; Ge(HP) detectors are also used to monitor the radiation levels of staff working in or around the reactors. Resource exploration companies use the detectors in aerial and ground surveillance, mapping and well-hole logging. Laboratories (national, university, commercial) use them to monitor environmental conditions of the laboratory itself and to conduct elemental analysis and astrophysical research. Environmental monitoring organizations, such as state environmental protection agencies, use Ge(HP) detectors to record levels of radiation being emitted into the environment. Ge(HP) detectors were used in Europe to analyze food samples for any radioactive content following the Chernobyl accident. In criminology, the composition of paint chips, fibers, blood specimens and other evidence can be identified and matched to other samples. Finally, medical centers employ these detectors to image internal organs and to measure the flow of blood to and within these organs.

Radiation detectors are frequently described in terms of their energy resolution and efficiency. Resolution refers to the detector's ability to distinguish one radionuclide from another of similar energy, which is done by discriminating between gamma-ray peaks. A high-resolution detector is one that can discriminate between the gamma-ray peaks of a large number of radionuclides. In a low-resolution detector, the signals of emissions of similar energy blurr together to form a "broad peak." Resolution is described by the width of a peak at a particular energy level.

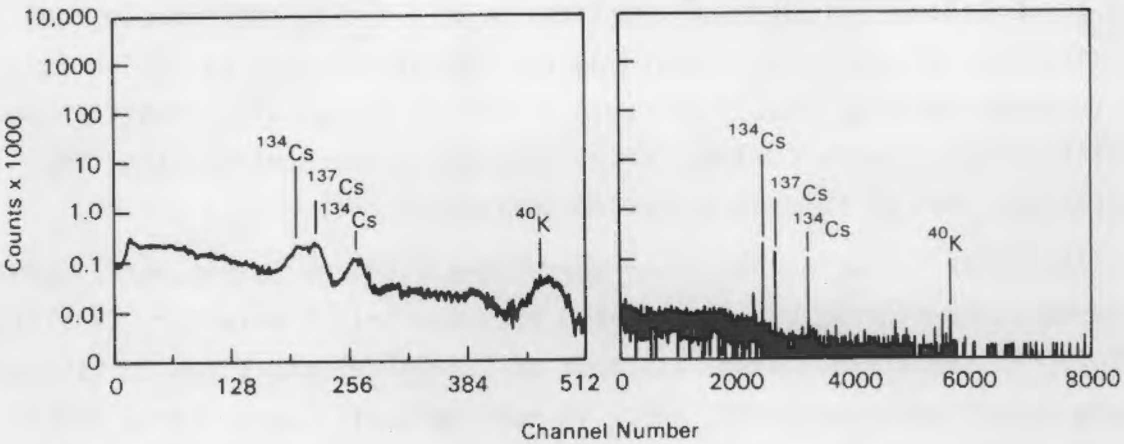

FIGURE 6.2. Comparison of Resolution: Pulse Height Spectrums From a Scintillator and Ge(HP) Detector

Figure 6.2 shows pulse height spectrums for a spectrometer using a scintillation detector (scintillator) and one using a Ge(HP) detector; these spectrums are composed of gamma-ray peaks and valleys. The germanium detector is superior in resolution to the scintillator because its peaks are much narrower. This enables it to discriminate clearly between two isotopes of cesium. In contrast, the scintillator generates one wide peak containing both cesium-134 and cesium-137; it is difficult to distinguish the individual isotopes.

Efficiency refers to the detector's ability to absorb and count radiation emissions per unit of time. A high-efficiency detector is one that can quickly measure the amount of radiation being emitted from a source. A high-efficiency, low-resolution detector can quickly identify how radioactive a source is, but may not be able to identify the radionuclide causing the radioactivity. An example of this kind of detector is the scintillator.

OHER funded research into the development of the Ge(HP) detector to improve upon the lithium-drifted germanium [Ge(Li)] detector, which was itself developed because of a need for higher resolution detectors in physical and biological basic research. The development of both germanium detectors was supported by OHER. Higher resolution detectors are important in quickly identifying the type of radiation being analyzed.

The substantially higher resolution of the Ge(Li) detector helped to revolutionize the field of gamma-ray spectroscopy. However, the detector also has drawbacks in terms of practical use. To cite one example, the Ge(Li) detector must at all times (including periods of non-use) be cooled to very low temperatures with liquid nitrogen or costly damage will result. The Ge(HP) detector only requires cooling during operation, hence eliminating the maintenance cost of keeping it cooled during storage.

The Ge(HP) detector has other advantages over the Ge(Li). The Ge(HP) detector is considerably more portable than the Ge(Li) detector, facilitating analysis in the field. Also, a number of Ge(HP) detectors can be "stacked" to create a multidetector array, which is much more efficient than a single Ge(HP) detector; Ge(Li) detectors cannot easily be stacked, due to the requirement that they be cooled at all times. With advantages such as these, the Ge(HP) detector has facilitated many of the existing applications for detectors and opened up entirely new applications.

The first Ge(HP) detectors were sold commercially by GE in 1974. Currently, there are three major manufacturers: EG&G Ortec, Princeton Gamma Tech and Canberra Industries. Industry estimates of the worldwide market for Ge(HP) detectors range from $18 million to $25 million annually. The Ge(HP) itself costs between $10-20/gram. According to 1987 price lists supplied by the manufacturers, the price of Ge(HP) detectors runs between $9,000 and $37,000, depending on the accompanying features.

Section 6.1 describes the research history and development of the Ge(HP) detector. Section 6.2 describes the principal improvements in the detector. Section 6.3 describes the commercial development of the Ge(HP) detector and Section 6.4 a number of applications of the detector.

Section 6.5 describes how the benefits of OHER research into the development of the Ge(HP) detector were estimated. The conceptual framework within which the benefits of this detector were estimated, the empirical estimation of those benefits and the limitations of the estimation are provided. Caveats that should be taken into account in interpreting the results are also discussed. Section 6.5 provides a sensitivity analysis by changing some of the underlying assumptions used in the benefit estimation.

Finally, Section 6.6 presents the conclusions of this analysis of the benefits of the OHER-funded Ge(HP) detector.

6.1 RESEARCH HISTORY

The scintillator was the detector most commonly used for ray spectrometry up until 1970. The scintillator is a sodium iodide crystal that detects gamma rays by emitting light when excited. Development of the scintillator was funded by OHER's predecessor agencies between 1952 and 1962. The scintillator was an efficient detector of gamma-rays, but its resolution was not fine enough to discriminate between gamma-rays of very similar energies, and thus, between various emitting isotopes. Basic research needs for a detector with higher resolution provided the impetus for the development of the Ge(Li) detector.

Until 1963, research into the development of the Ge(Li) detector was funded by federal (non-OHER) agencies, private companies and foreign sources. The first Ge(Li) detector was made in 1962 but it was inferior to the scintillator in both resolution and efficiency; the primary development of this detector was performed at Chalk River Laboratories in Montreal. Tavendale and Ewan were among the key investigators at Chalk River.

In 1963, the AEC (the predecessor to DOE) began funding research to improve the Ge(Li) detector. Funding supplied by AEC to Lawrence Berkeley Laboratory (LBL), Brookhaven National Laboratory (BNL) and Oak Ridge National Laboratory (ORNL) totaled about $100,000 per year between 1963 and 1971.

As a result of this funding, two improvements in the detector were made. First, its resolution was increased through an improved process of drifting the germanium crystal with lithium to fill impurities in the germanium.

Second, the signal processing system associated with the detector was improved so that the resolution of the detector was not destroyed by the processor. The end result was a detector that surpassed the scintillator in resolving power by orders of magnitude, although it was still inferior in efficiency.

The importance of the Ge(Li) detector was recognized in 1967 by the American Nuclear Society, which presented its first Radiation Industry award to two Chalk River Laboratory researchers for their work in developing large volume Ge(Li) detectors. The citation reads in part: "This work has revolutionized the field of gamma-ray detection and has had a profound effect on nuclear physics and spectroscopy, activation analyses, biomedical applications of radioisotopes and other fields where the availability of high-resolution gamma-ray detectors is of importance. The immediate widespread acceptance of these detectors is a tribute to their superiority over previous gamma-ray detection systems and to the vital importance of this development." (McKenzie, 1979).

Despite this laudatory citation the Ge(Li) detector still suffered from an important drawback. To prevent damage to the detector, the Ge(Li) had to be cooled to very low (cryogenic) temperatures with liquid nitrogen during manufacture, use and storage. This made work with the detector difficult, especially in field work where portability was important, because the detector had to be equipped with a large cryostat for storing the necessary liquid nitrogen. A typical cryostat and some of its components are shown in Figure 6.3. The Dewar in which the liquid nitrogen is stored may be 70 cm in height and 50 cm in diameter. Storage was also a problem because if the cryostat was not carefully monitored and refilled, the detector would be destroyed.

A superior detector was still needed, and continuing research eventually led to a detector that used pure germanium (or intrinsic) crystals instead of lithium-drifted ones. Research into the development of pure germanium crystals began at GE Research Labs. In 1967 Hall at GE reported the possibility of manufacturing Ge(HP). Subsequently, the first Ge(HP) crystals were grown at GE under contract to AEC. The AEC, and later OHER, was involved in supporting almost all further scientific and applied advances in the development of a Ge(HP) detector. In 1970, the first Ge(HP) detector was made at GE by Tavendale, Beartsch and Hall.

From 1970 to 1975, OHER and its predecessor provided $100,000 per year to LBL and GE to further develop the Ge(HP) detector; since 1971, LBL researchers such as Goulding, Hansen and Pehl have dominated advancements in the Ge(HP) detector.

In 1974, GE sold the first commercial Ge(HP) detectors. Unlike the Ge(Li) detectors, these Ge(HP) detectors only required cooling during operation and not during manufacture and storage. These detectors also had about twice the efficiency of Ge(Li) detectors, although their efficiency was still inferior to the scintillator.

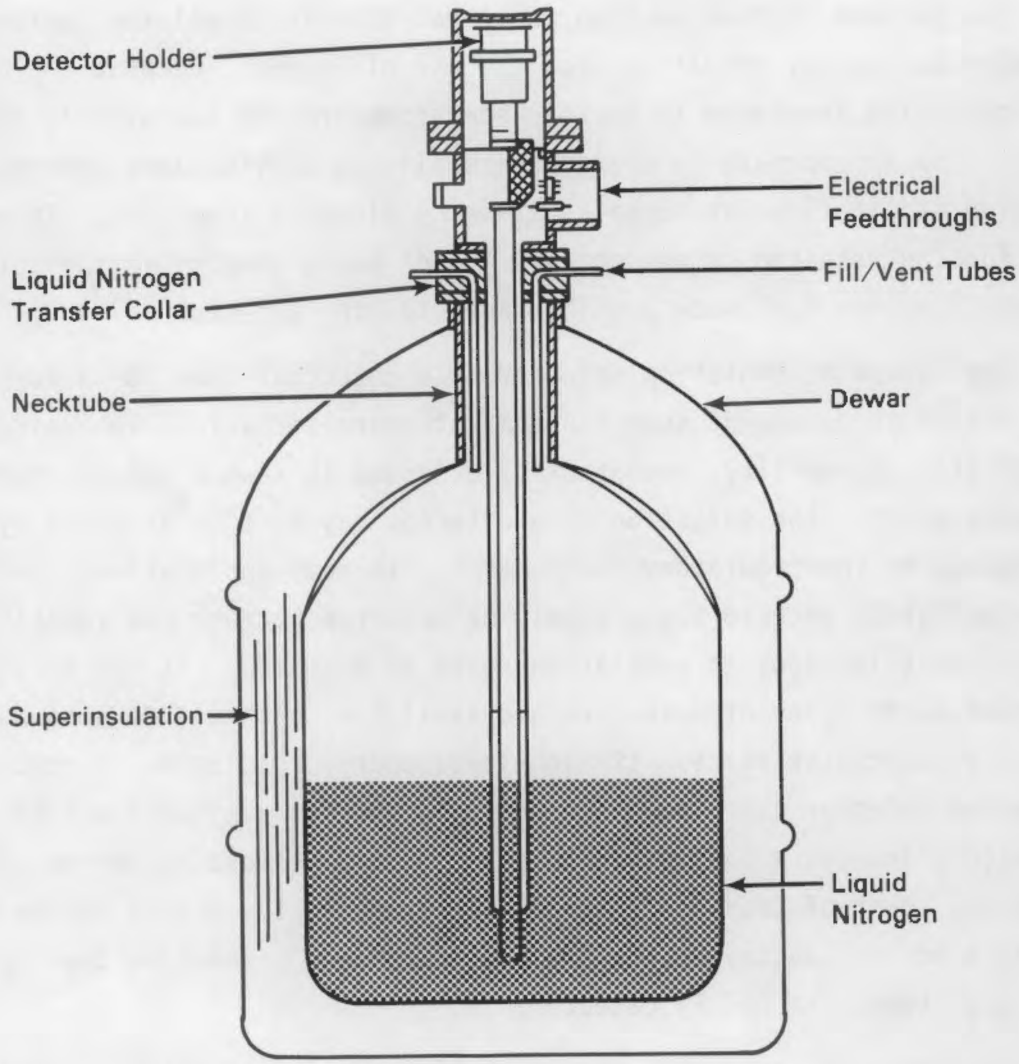

FIGURE 6.3. Detail of a Typical Cryostat

The ability to work with Ge(HP) at room temperature also permitted the construction of multi-detector systems. Multi-detector systems connect as many as ten Ge(HP) detectors to one processing unit; the advantage is efficiency increased to the level of the scintillator detector with no loss in resolution. OHER has provided $25,000 per year to LBL for the development of these multi-detector systems. OHER continues to fund improvements in Ge(HP) detectors at LBL.

6.2 IMPROVEMENTS IN DETECTOR TECHNOLOGY WITH HIGH-PURITY GERMANIUM

The purpose of this section is to describe in detail the improvements in detector technology resulting from the use of Ge(HP). Because the development of high-purity germanium to improve spectrometers was exclusively funded by OHER, it is appropriate to characterize all new applications and improved existing applications as benefits stemming directly from OHER. In essence, OHER funding resulted in an improved "good" being offered in the detector marketplace, one that made possible new uses for detectors.

The choice of radiation detector by a potential user for a particular application is dependent upon a number of characteristics, including cost, portability, durability, amount of time needed to scan a sample, efficiency and resolution. The selection of a detector may also be dictated by the stringency of the regulatory environment. In some applications, for example, high-resolution detectors may simply be required because the identification of different isotopes at similar energies is mandated. At the present time at least seven types of detectors are available, each with a somewhat different bundle of characteristics. If high-level energy resolution is required by a radiation detector user, however, the only choices available are the Ge(Li) and Ge(HP) detectors and radiochemical analysis because no others offer the resolving power of these detectors. For example, the scintillation detector, widely used in industry and health physics, has a resolution that is 50 times less than that of a Ge(HP) detector.

Radiochemical analysis, the other high-resolution option, requires from one-half day to several days to perform the same analysis that a Ge(HP) detector can do in 1000 seconds or less. In addition, radiochemical analysis requires a laboratory environment. Thus, it is difficult to use for work in the field, such as the monitoring of foodstuffs for radiation. If resolution, testing speed, portability, and ease of use are important criteria in the choice of detection, then it is clear that the choice is between the two Ge detectors. On the other hand, if efficiency is the paramount factor then the scintillator detector would likely be selected due to its higher efficiency (unless the user were willing to incur the substantially higher cost of purchasing an array of Ge(HP) detectors with equal efficiency.)

A description of some of the requirements of the Ge(Li) detector and a comparison to the Ge(HP) detector will indicate some of the OHER-funded improvements in the detector field. The Ge(Li) detector must be manufactured, operated and stored at very low (cryogenic) temperatures. This constant cooling is accomplished with a cryostat filled with liquid nitrogen. If the detector is overlooked and warms to ambient temperature, it will be severely damaged and perhaps destroyed. Recognizing that this characteristic of Ge(Li) detectors is a serious drawback, one detector manufacturer offers one free redrifting of the Ge(Li) crystal if its Ge(Li) detector is ever accidentally warmed.

The cooling requirement of the Ge(Li) detector has at least three distinct drawbacks. First, the detector is not easy to store and care for because it requires constant monitoring and replenishment of the liquid nitrogen supply. Second, the constant cooling requires a rather large cryostat (a smaller one would require proportionately more refilling and monitoring). This requirement limits portability, due to weight and unwieldiness, and ease of access for some applications due to the sheer size of the cryostat. (A typical cryostat and some of its features are shown in Figure 6.3.) The Dewar in which the liquid nitrogen is stored may be as large as 70 cm in height and 50 cm in diameter. Third, the necessity for constant cooling, even when not in operation, prevents the possibility of efficiency improvements via the construction of multidetector arrays, since such arrays are only easy to assemble when the detectors can be worked with at room temperature. Multidetector arrays are important because they increase detector efficiency without loss of resolution.

The development of high-purity germanium circumvented the above three drawbacks. First, although Ge(HP) detectors must be operated at cryogenic temperatures, they do not have to be manufactured or stored that way. This reduces both the manufacturing and operating costs (e.g., less liquid nitrogen is required), and the danger of damaging the detector during storage through neglect is eliminated. Second, the Ge(HP) detector, by requiring a smaller cryostat than its lithium counterpart, is both more portable and more accessible in some uses due to its smaller weight and size. Hand-held, portable detectors, often weighing no more than 12 pounds, have been developed as a result of Ge(HP). These detectors are ideal in field use. Figure 6.4

shows a portable, hand-held detector relative to a detector with a typical cryostat. The difference in size is obvious. Third, because Ge(HP) can be worked with at room temperature, unlike Ge(Li), up to ten detectors can be connected to one processing unit to construct multidetector arrays. This development ameliorated the Ge detector's primary disadvantage, low efficiency, with no loss of resolution.

Another advantage of the Ge(HP) detector is that it can be used and re-used indefinitely in spite of damage from radiation incurred during experimentation because it can be successfully annealed by the user. This distinguishes it from another type of detector, the silicon detector, which cannot be re-used indefinitely.

In summary, the Ge(HP) detector possesses the following superior features:

- cyrogenic cooling not required during manufacture and storage
- portability and ease of use due to the smaller size of the cryostat required
- increases in efficiency possible through the construction of multidetector arrays, with no loss in resolution
- indefinite re-use possible, in spite of radiation damage, because annealing can be done.

6.3 COMMERCIAL DEVELOPMENT

The information in this section was compiled primarily from brochures and price lists supplied by these detector manufacturers. Some additional information was acquired through a visit to the facilities of the principal manufacturers and through discussions with executives of these manufacturers. The type of information presented here is not uniform across the companies because the companies each supplied different types of information.

The three principal manufacturers of the Ge(HP) detector are EG&G Ortec, Princeton Gamma Tech (PGT), and Canberra Packard. These companies dominate the Ge(HP) detector market, accounting for 90 percent of total sales[a]. The

(a) Personal communication with industry representatives.

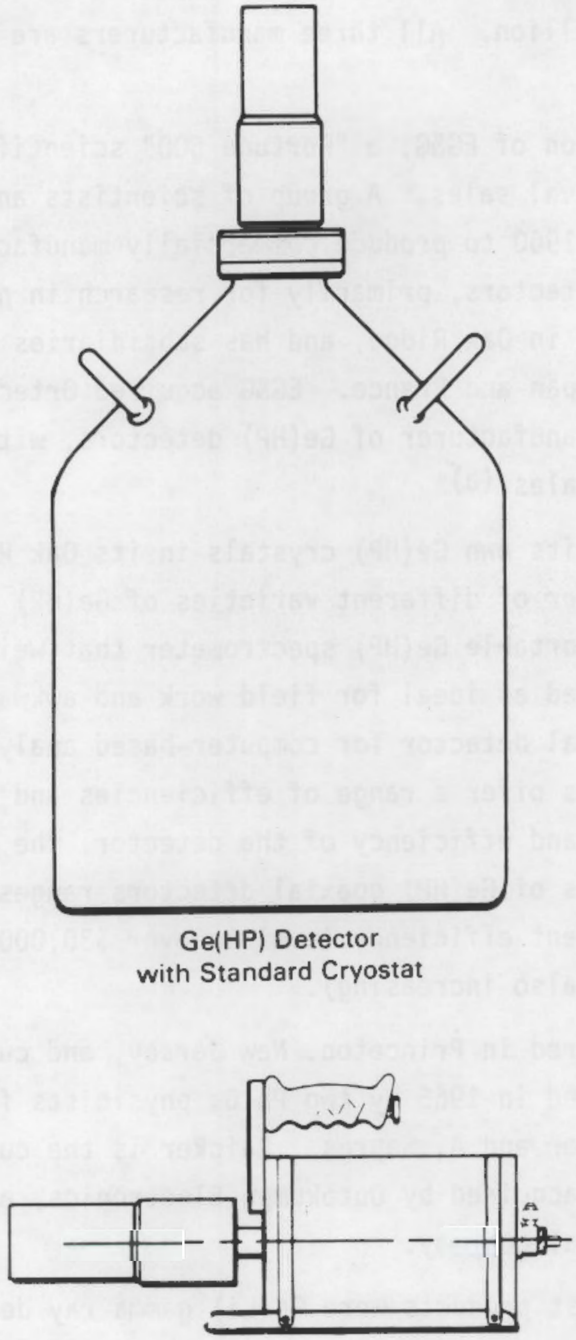

FIGURE 6.4. Size Comparison: Ge(HP) Detector with Standard Cryostat and Portable Ge(HP) Detector.

annual current worldwide market for Ge(HP) detectors is estimated to be between $18 million and $25 million. All three manufacturers are headquartered in the U.S.

Ortec is a division of EG&G, a "Fortune 500" scientific company with some $1 billion in annual sales. A group of scientists and engineers from ORNL founded ORTEC in 1960 to produce commercially manufactured, research-grade semiconductor detectors, primarily for research in nuclear physics. Ortec is headquartered in Oak Ridge, and has subsidiaries in eight foreign countries including Japan and France. EG&G acquired Ortec in the late 1960s. Ortec is the largest manufacturer of Ge(HP) detectors, with around 40 to 50 percent of worldwide sales.[a]

EG&G Ortec grows its own Ge(HP) crystals in its Oak Ridge laboratory. It manufactures a number of different varieties of Ge(HP) detector. For example, it offers a portable Ge(HP) spectrometer that weighs less than 11 pounds and is advertised as ideal for field work and awkward locations, as well as a Ge(HP) coaxial detector for computer-based analysis of complex spectra. The detectors offer a range of efficiencies and resolutions. The higher the resolution and efficiency of the detector, the higher the price. For example, one series of Ge(HP) coaxial detectors ranges in price from under $10,000 at the 10 percent efficiency level to over $30,000 at the 50 percent level(with resolution also increasing).

PGT is headquartered in Princeton, New Jersey, and currently employs 170 people. PGT was founded in 1965 by two Ph.D. physicists from Columbia University, J.A. Baicker and A. Sayres. Baicker is the current president of PGT. In 1985 PGT was acquired by Outokumpu Electronics, a large diversified Finnish mining and metal company.

The company's first products were Ge(Li) gamma ray detectors. According to its brochures, PGT was the first company to successfully manufacture large volume Ge(Li) detectors. These detectors were sold mainly to nuclear research laboratories.

(a) Personnel communication with industry representatives.

PGT also claims it was the first company, by several years, to make Ge(HP) detectors. PGT has constructed special Ge(HP) detector arrays for a large number of uses, from in vivo lung monitoring to space probes. PGT has currently developed a portable Ge(HP) detector that is electrically cooled this is likely a very significant advance. Primary buyers of PGT detectors presently include university and industrial laboratories, national laboratories, defense establishments, and nuclear power plants. PGT holds approximately 20 to 25 percent of the Ge(HP) detector market.[a] According to PGT, Ge detectors represent about 1/3 of its sales, but account for a large proportion of the total company profits.

PGT grows its own Ge(HP) crystals in a laboratory in Princeton. To produce these crystals involves three basic steps. PGT acquires "intrinsic grade" germanium that is 0.999999999 or "9 nines" pure. Using various specialized techniques, PGT further purifies the material. Large single germanium crystals are grown to a purity of 0.9999999999999 or "13 nines." This degree of purity is analogous to a single grain of sugar hidden in a railway car of salt. The crystal of germanium may be as large as 65 mm in diameter and 12 cm long. These crystals are then used in the manufacture of Ge(HP) detectors in Princeton and also in West Germany. The same level of crystal purity is required of all Ge(HP) detector manufacturers.

Canberra Industries, headquartered in Meriden, Connecticut, has over 1000 employees. Canberra, like PGT, holds about 20 to 25 percent of the worldwide Ge(HP) detector market. Canberra has a network of 14 subsidiaries in Europe, Australia and Japan to support its products. Over 50 percent of Canberra's revenues are generated from foreign sales. This high percentage of export sales to total sales was recognized by President Reagan when Canberra was given an award for Excellence in Export Sales. Canberra manufactures Ge(HP) detectors in Belgium for sale to the European market and in Connecticut for sale to the non-European market.

Canberra's sales and earnings growth has been 18 percent (at a compounded rate) and its average return on equity has been 19 percent. Over the past

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(a) Personal communication with industry representatives.

several years, research spending by Canberra has averaged close to 10 percent of sales.

Like its competitors, Canberra manufactures a number of different detectors for different applications. According to the company, it is the leading supplier of whole body counting systems [which employ Ge(HP) detectors] used for internal dosimetry and personnel radiation safety. It also offers a portable Ge(HP) detector system. Prices for Canberra detectors appear to be comparable to the prices of EG&G Ortec and PGT.

6.4 SPECIFIC APPLICATIONS OF HIGH-PURITY GERMANIUM DETECTORS

In this section a number of specific uses of Ge(HP) detectors will be described. This description of applications does not attempt to be exhaustive but does help to reveal the range of uses and potential uses for the detector. The information in this section was culled from technical papers and journal articles, from literature supplied by the three principal manufacturers, and from discussions with detector users at PNL and the Washington Public Power Supply System (WPPSS).

6.4.1 Nuclear Plant Monitoring Applications

Ge(HP) detectors are used in nuclear power plants to monitor the environment of the plant and to monitor the effluents discharged from the plant. In the first application, the detectors are used to monitor areas of the plant for the existence of radiation and to analyze samples and smears called "swipe smears" taken from plant equipment. Personnel safety is the primary reason behind such analyses. The Ge(HP) detectors are preferred to the scintillators in this work because regulatory and safety considerations often make it essential to identify the specific isotope source of any contamination. Also, lightweight Ge(HP) detectors are more portable and easier to maintain than large cryostat Ge(Li) detectors. These hand-held Ge(HP) detectors can monitor hard-to-reach areas within the plant, such as behind equipment and in large pipes. The portable detectors can also be easily used by staff who must "suit up" in cumbersome protective clothing before entering restricted areas of the plant.

Effluent monitoring is another key use for Ge(HP) detectors. The detectors are frequently used to monitor the radionuclide content of the effluents released into the air from cooling stacks at nuclear power plants. Regulatory requirements again dictate that it is essential to know the type of radiation being released into the environment.

The advantages of the Ge(HP) over the Ge(Li) detector in both effluent and plant monitoring were emphasized by a source at WPPSS Nuclear Plant 2.[a] He said that of the five germanium detectors used in the plant, three were Ge(HP) and two were Ge(Li), and that the Ge(Li)s would be upgraded to Ge(HP)s as soon as financial resources permitted due to the superior capabilities of the latter.

A third use in nuclear plants is in actual plant operations. To identify isotopes present in the reactor core, Ge(HP) detectors are frequently attached to pipes carrying cooling water. Failures and inefficiencies in the reactor can be detected and then corrected by adjusting the reaction process or shutting down the reactor. Accidents can be prevented through the information provided by Ge detectors (both Li and HP). For example, the accident at Three Mile Island, where a Ge detector was not in use, might have been avoided had a Ge detector been installed. This accident apparently provided the impetus for the use of Ge detectors at all nuclear power plants in the U.S.

6.4.2 Health Physics Applications

Another application of Ge(HP) detectors is in the field of radiation protection monitoring. Staff who work in potentially radioactive areas such as nuclear power plants are routinely checked for radioactive contamination, especially contamination through the inhalation of americium and plutonium. This is done with whole body counters, which use detectors to determine if radiation health safety standards are being met. Whole body counters utilize both scintillators and Ge detectors. Figure 6.5 provides three examples of how whole body counters are used; the illustrations are from Canberra literature advertising the features of their Ge(HP) whole body counter. As the illustrations show, the whole body counter can be used for total body

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(a) Personal communication with Al Davis, senior radiochemist, 5/28/87.

scans, to test specific parts of the body such as the lung and thyroid, and to assay samples.

In whole body counting, scintillators have the advantage, because of their superior efficiency, of determining in a short period of time if someone is contaminated. Their efficiency also permits quick testing of many staff. However, the scintillator may not be able to identify the culpable isotope, and Ge whole body counters are used when it is important to identify the isotope source of the contamination. According to one source, scintillator whole body counters are ideally used to determine if staff are radioactive; if an individual tests positive, the Ge whole body counter is then used to identify the radionuclide.

To increase the efficiency of whole body counting, multiple Ge(HP) detectors can be mounted in a single cryostat, with no loss in resolution. Sometimes as many as six to eight Ge(HP) detectors are combined in an array. The result is a device that represents "the state of the art for the measurement of inhaled radionuclides" (Falk et al. 1978). The cost of such a multidetector array system is considerable. In 1977, an array of eight Ge(HP) detectors cost $74,000.

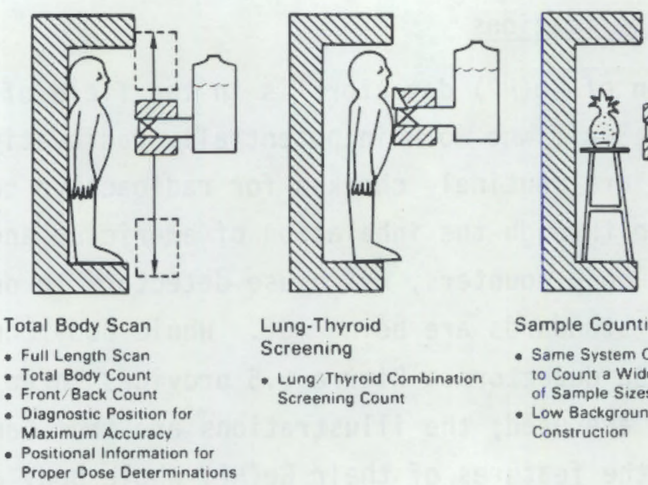

FIGURE 6.5. Three Applications of a Whole Body Counter.

6.4.3 Radiation Monitoring of Foodstuffs

Although radioactivity is and always has been present in all foodstuffs to some extent, concern about such radioactivity increased dramatically following the Chernobyl reactor accident in 1986. Many governments introduced regulations to prevent the importation and distribution of food which exceeded levels of contamination that were considered harmful. Of particular concern were foodstuffs contaminated with two isotopes of cesium, since these isotopes take a long time to decay and to decrease their activity levels. Following Chernobyl, for example, West German officials discovered 150 railroad cars full of radioactive powdered milk; the radioactivity was from the grass that Bavarian cows grazed on in alpine pastures contaminated by fallout of cesium isotopes from Chernobyl. The radioactivity substantially exceeded the maximum permitted level of radiation for milk products.

Ge(HP) detectors are used extensively to detect and identify radioactivity in foodstuffs. In fact, EG&G Ortec manufactures a spectroscopy system with Ge(HP) detectors called FOODGUARD2 for the specific purpose of monitoring foodstuffs. According to EG&G Ortec, FOODGUARD2 was designed for the analysis of food samples primarily as a result of the Chernobyl accident. Detectors such as this one are used by many countries to determine if the contamination in imported foodstuffs is within regulatory limits; if such limits are exceeded, the shipments are rejected. Some countries, such as Malaysia, even require certificates of activity levels to accompany the shipment, while others, such as Singapore, have very low acceptable limits for radioactivity. Such requirements create a demand for radiation detectors, particularly those with the resolution to identify many radionuclides.

6.4.4 Nuclear Medical Applications

Cardiovascular research widely employs the radioactive microsphere technique as a means of measuring regional blood flow in animals. The microspheres are made of polystyrene and have a radionuclide incorporated within. They are injected into the bloodstream of animals and are distributed to organs and regions within organs in proportion to the blood flow at that time. The microspheres are then assayed with a radiation detector. Before the development of the Ge(HP) detector, the scintillator detector was used in this work. The disadvantage of the scintillator was that only five to six different radionuclides per animal could be used, due to its poor resolution, which is inefficient in both time and money. More animals had to be used, requiring between-animal comparisons to be made when within-animal comparisons were desired. With its high resolving power, the Ge(HP) detector overcomes this limitation by distinguishing between radionuclides. This means that more radionuclides can be used per animal. As a result the Ge(HP) detector will "increase the research utility of the microsphere technique in a cost effective manner." (Kaufman et al. 1981).

Another use of Ge(HP) detectors is in the clinical Ge(HP) camera. This device was developed to image the human brain, thyroid, kidney, liver, heart, and other organs. The greater resolving power of Ge(HP) detectors accounts for their high diagnostic power and makes them more useful than scintillators in nuclear medicine.

6.4.5 Nuclear and Astrophysics Applications

The Indiana University Cyclotron Facility, in collaboration with the radiation detector group at LBL, developed a detector telescope system with good resolution for the detection of intermediate energy light ions. "The advent of high-purity detectors...made the development of this system possible." (Pehl, Luke and Friesel. 1985). Because the complexities of their handling and storage made them incompatible with typical nuclear research scattering chambers, Ge(Li) detectors were limited in application to charged particle detection. Ge(HP) detectors eliminated many of these difficulties.

Another use of Ge(HP) detectors is in the balloon-borne observation of astrophysical phenomena. According to one source, spectroscopy is one of the most important techniques available to astronomers for understanding of the universe. (Paciesas et al. 1983). NASA, for example, has attempted to measure gamma-ray emissions from solar flares with a Ge(HP) spectrometer carried on a long balloon flight. Information from these emissions is fundamental to an understanding of the flare process; the measurement of these emissions requires the fine resolution offered by germanium detectors.

Ge(HP) detector arrays have been used by other groups besides NASA for astrophysical research in high-altitude balloon flights. In its advertising literature, PGT notes that it has sold arrays of Ge(HP) detectors for high-altitude balloon probes to the Jet Propulsion Laboratory, Imperial College in England, and the Max-Planck Institute in West Germany.

Ge(HP) detectors are also being included as instrumentation in satellites for the observation and analysis of astrophysical phenomena. For example, some time in 1988-1989 a Mars-Orbiter satellite will be launched from a NASA space shuttle. Part of the instrumentation on that satellite will include a gamma-ray spectroscopy system, a central component of which will be an array of Ge(HP) detectors.

Ge(HP) detectors have also been employed to analyze the elemental composition of the moon rocks brought back by NASA's lunar missions. This analysis was performed at national laboratories and other locations.

6.4.6 Resource Exploration

Ge(HP) detectors are used in the search for radioactive and nonradioactive resources. For example, oil pools are typically surrounded by high concentrations of radioactive elements. Flyovers with Ge(HP) detectors can reveal the locations and outlines of these pools. The depth of the oil deposit is then determined by digging a log hole and lowering a Ge(HP) detector into the hole.

6.4.7 Radioactive Waste Site Monitoring

Ge(HP) detectors are used by state and federal environmental inspection agencies to identify the isotope source of radioactive waste at burial sites, and to insure that radiation levels are within regulatory limits. Portable Ge(HP) detectors facilitate such onsite analysis. In addition, the detectors are used by the burial sites to identify the particular isotope contaminations of the waste intended for burial. This is important because the burial and treatment procedures, and the accompanying costs, differ for different types of contaminated waste.

6.4.8 Some Other Applications

In criminology, the elemental composition of paint chips, tire tracks, fibers and blood specimens can be identified by Ge(HP) detectors, and then matched to another sample. Art forgeries can also be identified with detectors. The military employs Ge(HP) detectors in a number of ways, some of which are classified. It is known that PGT developed a small, portable Ge(HP) detector for use aboard naval submarines. A distinguishing characteristic of this particular detector is that it can be cooled with any power source and does not require liquid, nitrogen enabling it to be used where liquid nitrogen is not available.

6.5 ESTIMATING THE BENEFITS OF GERMANIUM DETECTOR RESEARCH

OHER's research into developing the Ge(HP) detector has not only resulted in many distinct, new applications for radiation detectors but has reduced the costs of achieving other applications. Each of these two benefits, a new or qualitatively different way of providing a good or service and a less costly way of providing an existing good or service, requires a different approach to obtain an estimate of its benefits.

This section of the chapter first briefly reviews the different conceptual approaches for these two types of benefits. Next, we present qualitative and quantitative information on the benefits associated with Ge(HP) detectors. This information was gathered from users and producers of the detector as well as from the scientific literature. Finally, we discuss the uncertainties associated with our estimates and the sensitivity of our results to alternative assumptions. We are able to provide only order-of-magnitude estimates because of the proprietary nature of much of the data that are needed to obtain benefit estimates.

6.5.1 Conceptual Basis for Estimating the Benefits of Germanium Detector Research

As discussed in Chapter 3.0, economists and others have developed techniques based on economic theory that can be used to estimate the benefits derived from basic and applied research. These techniques attempt to estimate the dollar value to society of new products or a superior way of providing an existing product. The dollar estimates reflect gains to consumers (consumer surplus) or to producers (producer surplus). This section briefly reviews the benefit estimation techniques used by economists and discusses their application to estimating the benefits of Ge(HP) detectors. The differences between the data needed to support the conceptual approach and the data actually available are also discussed.

If the benefit is best characterized as a totally different product, i.e., the product has no close substitutes, then the sale of this new product can be assumed to reduce the sale of a myriad of other products only slightly. In this case, the losses in consumer and producer surplus from the myriad of other products are negligible, since the losses occur only at the margins. The net societal benefit from the new product is equal to the sum of its own consumer and producer surplus, as shown by the areas CP_1B and CP_1A, respectively, in Figure 6.6.

Figure 6.6 shows the demand schedule, D, for the new product and the industry supply schedule S. The equilibrium price is P_1. The total societal benefits are approximated by the area ABC, which is the sum of consumer surplus (CP_1B) and producer surplus (CP_1A). To measure these areas, it is necessary to estimate the demand and industry supply functions associated with the new product.

Statistical estimation of these functions is not a trivial exercise and depends on reasonable amounts of data on a number of variables. Variables other than price and quantity must be present in the estimating equations to

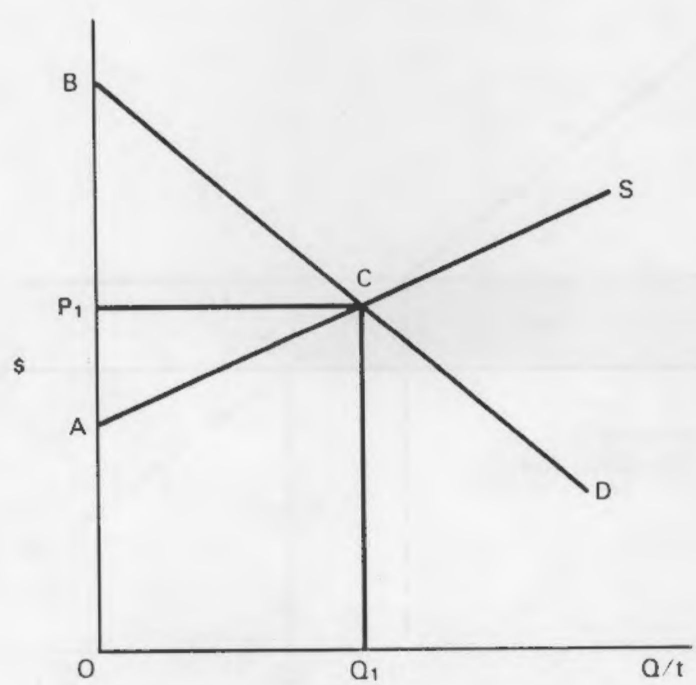

FIGURE 6.6. Benefit of a Totally New Product

avoid statistical problems associated with estimating simultaneous relationships. Often, some of the needed information is proprietary or is not readily available. For example, if the product is new (or rapidly changing), it may not be possible to obtain sufficient data to estimate the required demand and supply schedules. If adequate data cannot be obtained, the estimate must be based on nonstatistical techniques, e.g., on impressionistic information.

If one of the benefits of the OHER Ge(HP) research program is best characterized as a less costly or superior process for producing an existing good or service, then the change in consumer surplus and producer surplus, as shown in Figure 6.7, is the proper measure of the benefit. This figure shows demand schedule, D, and supply schedule S_1. The research is assumed to lower the production costs from S_1 to the new supply curve S_2. Note that we have assumed a flat cost curve indicating constant production costs over all

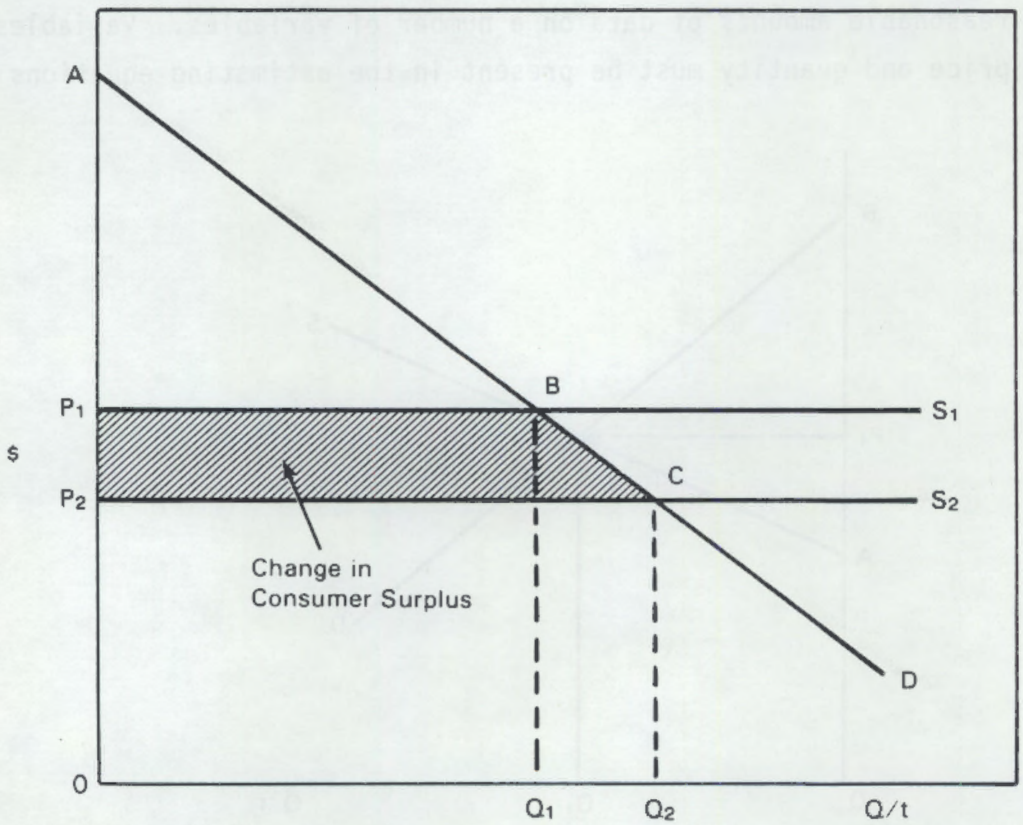

FIGURE 6.7. Benefit of a Less Costly Process

production ranges. The effect of the reduced production costs is to reduce the price from P_1 to P_2 and to increase the amount produced and sold from Q_1 to Q_2.

Consumer surplus increases under the lower production costs from ABP_1 to ACP_2. The net increase in consumer surplus is the trapezoid bounded by P_1P_2BC. The area of this trapezoid, which reflects the net societal benefits since there is no producer surplus, can be approximated by $(P_1 - P_2) \times Q_1$ or $(P_1 - P_2)\ Q_2$. Multiplying by Q_1 provides an underestimate of the change in consumer surplus while multiplying by Q_2 provides an overestimate. Note also that $P_1 - P_2$ is the amount that production costs are reduced by the research. Thus, to estimate the net societal benefits, one must know the per unit change in costs $(P_1 - P_2)$ and either the initial (Q_1) or final (Q_2) amounts sold.

In summary, Figures 6.6 and 6.7 show relatively uncomplicated examples of supply and demand curves. The actual shapes could be curvilinear rather than straight lines. The supply curve in Figure 6.7 reflects a constant cost of producing the good, and the change $(P_1 - P_2)$ indicates production costs are lowered by the same amount over all relevant production costs. These simplifications do not necessarily imply that estimates based on these assumptions are imprecise. The assumptions may be very close to realistic over the relevant portion of the demand or supply curves especially for relatively small changes.

However, even the relatively simple curves shown in Figure 6.6 indicate that it may be difficult to estimate the benefit to society when the benefits result in new applications. This is the case with several of the germanium detector applications. Because of these difficulties, we were only partially successful at estimating the benefits of Ge(HP) detectors. The next section discusses the benefits qualitatively and presents our quantitative estimates of their size.

6.5.2 Empirical Estimates

In general, the data needed to estimate the benefits of the entire spectrum of improvements and additional applications made possible by the development of the Ge(HP) detector were not available. Also, the project's time and resource constraints precluded additional analyses. We were able to estimate the value associated with cost saving in applications where the high-purity detector performs the task in significantly less time. We also verified previous estimates of these benefits obtained for OHER (Ecosometrics 1982). A number of users and the producers of the detector indicate that these cost savings are a small component of the Ge(HP) detector's benefits. The new applications of the Ge(HP) detector are seen as a much larger benefit. We did not estimate these values.

Summary of the Advantages of the High-Purity Germanium Detector.

As mentioned earlier in this chapter, the Ge(HP) detector overcame a number of problems seen in previous types of radiation detectors. In particular the following would seem to be the principal advantages of the Ge(HP) detector:

- The Ge(HP) detector does not require constant cooling during manufacture and storage. This advantage reduces detector down-time and expense that result from the failure to maintain the cryostat.
- The Ge(HP) detector is significantly more portable and convenient for operations away from a laboratory. This advantage is particularly important in environmental monitoring.
- The Ge(HP) detectors are capable of comparatively high resolution; the most recent models are able to accomplish the high resolution without significant loss of efficiency.

Principally because of the first two advantages, very few firms are continuing to manufacture Ge(Li) detectors, the principal competitor of Ge(HP) detectors. This fact indicates that consumers of the two products feel the Ge(HP) detector provides more service and value for the cost.

Estimate of Cost Savings Associated with Using the High-Purity Detector.

Estimating the cost savings associated with the Ge(HP) detector requires that the costs of conducting a certain task with the germanium detector be evaluated and compared with the cost of using the next best alternative to conduct the same task. Under certain conditions discussed below, these cost savings can be used as an estimate of some of the benefits of the germanium detector. There are several problems with this apparently straightforward task.

First, the quality of the results obtained by the two alternatives must be roughly comparable. For example, if the quality of results from the Ge(HP) detector in accomplishing the task is significantly higher than the quality of results from the alternative, the comparison will be misleading. The quality of the results, in terms of errors or other attributes, must be considered in the cost comparison.

Second, the appropriate alternative to using the Ge(HP) detector must be accurately identified. This becomes particularly important if there is a variety of instruments for performing a similar task. For the Ge(HP) detector, alternatives considered might include Ge(Li) detectors, sodium iodine scintillation detectors, or, in some cases, chemical separation analysis. Which of these is the appropriate alternative depends on the particular task.

Finally, there is an important caveat to the entire procedure. New products that substantially lower the costs of performing a particular task will often lead users to perform substantially more of that task than they would have with the older, more expensive products. In the case of gamma-ray spectrometers with Ge(HP) detectors, a user may be inclined to conduct more tests than if forced to use a slower, more costly radiation detection technique. Estimating the cost savings associated with the number of times the Ge(HP) detector is used is then somewhat misleading since some of these tests would not have occurred in the absence of the Ge(HP) detector. The conceptually correct way to estimate these benefits would be to segment the estimation process into an estimate of cost savings for the tests that would have occurred in the absence of the Ge(HP) detector and then add the consumer and producer surplus that result from the additional tests. However, if there are only a few additional tests or if there are data problems in estimating the additional producer and consumer surplus, a reasonable, pragmatic approach to estimating cost savings is to assume that all tests would have occurred in the absence of the Ge(HP) detector.

We focused our estimates of the cost savings associated with Ge(HP) on its applications for monitoring and operating within nuclear power plants. The detectors are used extensively within power plants, for example, to monitor fuel cells, liquid and gas discharges, and to analyze coolants. Many, or most, of these tests would be performed if the Ge(HP) or possibly the Ge(Li) detector were not available; however, the alternative in most cases would be the more expensive and time-consuming process of chemical analysis.

Estimates of the cost savings associated with germanium detectors were available from two sources. A study completed for DOE by Ecosometrics (1982) contains a fairly detailed comparison of the cost differences between using germanium detectors in nuclear power plants rather than performing chemical separations. Our second source of information is estimates made by users of the germanium detector.

The Ecosometric report differs from ours in that it looks at the benefits of both Ge(HP) and Ge(Li) detectors. We used the Ecosometric estimate of the number of Ge(Li) detectors in use as an approximation of the number of Ge(HP) presently used in nuclear power plants. Thus, we are assuming that as either type of detector wears out or becomes obsolete, it is replaced by a Ge(HP) detector. This is based on our information that the market for Ge(HP) detectors has grown very rapidly compared with the Ge(Li) detector market. This is not unrealistic since several of the major detector manufacturers no longer produce Ge(Li) detectors and none of the users contacted reported purchasing a Ge(Li) detector in several years. While this approximation of the number of Ge(HP) detectors is somewhat inaccurate for estimating the benefits of Ge(HP), it is almost certainly an underestimate for the benefits of both Ge(HP) and Ge(Li) detectors. The development of both germanium detectors can be traced to the research support of OHER (DOE 1986). Thus, our estimates of the benefits of detectors presented in this section, whether properly attributed to Ge(HP) or Ge(Li), are the result of OHER support.

Ecosometrics' estimates of the cost savings attributable to Ge detectors are built from a number of assumptions and estimates of the costs and usage of Ge detectors and their alternatives. In this case, the alternative to the Ge detectors is to use chemical separations to analyze much of the environmental discharges and Na(I) scintillation spectometers to monitor nuclear cores. Table 6.1 shows the cost comparison of Ge detectors and the alternatives for conducting environmental measurements at nuclear power plants.

TABLE 6.1. Cost Comparisons for Conducting Nuclear Power Plant Measurements Ecosometrics 1982

Measurement Technology	Cost/Plant/Year
Ge detectors	\$18,000
Chemical Separations and Na(I) Scintillation	\$200,000

To obtain annual estimates of the cost savings, Ecosometrics then multiplies the annual cost savings per plant per year, approximately \$182,000, by the number of nuclear power plants operating in the U.S. annually. These estimates are converted to 1982 dollars. Ecosometrics' estimate of the total cost savings when the alternatives are chemical separations and Na(I) scintillation is approximately \$175 million.[a] If we escalate to 1986 dollars using the GNP deflator we obtain an estimate of just over \$200 million.

There are two ways that the Ecosometric estimates could be updated. First, we can add to their data base of operating nuclear power plants those plants coming on-line since 1982. Table 6.2 shows the number of U.S. nuclear power plants coming on-line between 1983 and 1986. We use this information to add the additional benefits resulting from greater use of Ge(HP) detectors. Second, there are benefits resulting from use of Ge detectors in power plants outside the United States. While we have information from detector manufacturers that they make sales to non-U.S. power plants, we cannot be sure of the level. Therefore, in order to be conservative, we do not include any benefits from the use of Ge detectors outside the United States.

(a) Ecosometrics adds the cost savings from Ge detectors to an estimate of the benefits of Ge detectors when no alternatives are feasible to obtain a total estimate of \$184 million. For reasons described later we calculated only the cost savings portions.

TABLE 6.2. U.S. Nuclear Power Plants Beginning Commercial Operation: 1983-1986. (Nuclear News 1987)

Year	Number of New Plants
1983	2
1984	5
1985	8
1986	7

In Table 6.3 we use the Ecosometric estimate of the cost savings due to use of Ge detectors of approximately $180,000 (1982 dollars) to estimate the additional cost savings resulting from detector use at new power plants.

The total savings from the use of Ge detectors in U.S. nuclear plants beginning commercial operation after 1983 is $8.38 million (1982 dollars) or approximately $9.5 million in 1986 dollars. The total benefits, then, of the use of Ge detectors in U.S. nuclear power plants is their original estimate of $200 plus $9.5 million or about $210 million.

We verified the Ecosometrics cost-saving estimate through discussions with users of the detectors. One user estimated $100 as reasonable figure for the cost of an analysis using the germanium detector, while approximately $1000 to $4000 would be required for a chemical analysis[a]. The range of figures reflects whether the chemical analysis is for one particular chemical or for multichemical analysis. These estimates indicate that the costs of performing analysis with chemical separation would be about 10 to 40 times the cost of performing the same analysis with a germanium detector. The same ratio for the Ecosometrics estimates is approximately 11 or 12, indicating that both Ecosometrics and PNL estimates of the cost savings using germanium detectors to perform radiation tests produce similar estimates of the overall benefits of using germanium detectors.

(a) Personal communication with Ron Brodzinski, Battelle, Pacific Northwest Laboratory.

TABLE 6.3. Cost Savings From U.S. Nuclear Power Plants Beginning Commercial Operation 1983-1986.

Year	Cumulative Number of New Plants	Annual Savings (Millions 1982)
1983	2	.36
1984	7	1.26
1985	15	2.70
1986	22	3.96
		8.28

The above estimates indicate the cost savings associated with Ge detectors in nuclear power plants to be on the order of $200 million. We cannot further split those benefits associated with Ge(HP) detectors from those associated with the Ge(Li) detectors. However, both were developed through OHER support and, in any case, the benefits are orders of magnitude greater than the entire costs of developing both products.

6.6 SUMMARY OF OHER ACHIEVEMENTS

OHER achievements in the field of radiation detector technology have been substantial. The scintillator was widely used in gamma-ray spectroscopy and possessed excellent efficiency, but its poor resolution limited its usefulness in many applications. The need for a detector with improved resolution was apparent. Largely as a result of OHER funding, a detector with excellent resolution was developed, namely, the Ge(Li) detector. This Ge(Li) detector revolutionized the detector field, improving existing applications and creating new ones. However, the Ge(Li) detector had an important deficiency: it required cooling with liquid nitrogen at all times, even when not in use.

Continued OHER funding in Ge detector technology resulted in the development of the Ge(HP) detector. Unlike its predecessor, the Ge(HP) detector requires cooling only during operation. This improvement allowed multidetector arrays to be constructed (also OHER funded), which raised the efficiency of Ge(HP) detectors to the level of the scintillator with no loss in resolution. The fact that the Ge(HP) detector does not have to be cooled when not in use also permitted the development of portable detectors. By allowing increases in efficiency and permitting portability, the Ge(HP) detector opened up new applications for detectors in scientific research, health physics and other fields, as well as improving upon existing applications. Both the Ge(Li) and Ge(HP) detector are in use worldwide.

The development of the Ge(Li) and Ge(HP) detectors via OHER funding has created economic opportunities for private sector firms. The current worldwide market for Ge(HP) detectors, for example, is between $18 million and 25 million per year, with three manufacturers dominating production.

Our estimates of the benefits of Ge(HP) detectors were limited to updating and verifying previous estimates. The reason for this is the proprietary nature of the cost of producing Ge(HP) detectors and the research needed to estimate the benefits associated with numerous applications. However, our estimates indicate the cost savings associated with using both Ge(HP) and Ge(Li) detectors at U.S. nuclear power plants was approximately $200 million. This estimate, orders of magnitude larger than research and development support for both Ge(HP) and Ge(Li) detectors, does not include most of the societal benefits resulting from the Ge(HP) detector.

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APPENDIX A

MODEL ESTIMATION AND INTERPRETATION

APPENDIX A

MODEL ESTIMATION AND INTERPRETATION

A.1 ECONOMETRIC MODEL

The administrative process which characterizes the Outer Continental Shelf (OCS) leasing actions can be modeled as a series of independent binary choices. At each stage, except the amount of the final bid, the appropriate actor makes a yes-no decision. The choices available to the decision-maker at that time depend on what choices the other actors have made in prior steps. Two widely accepted techniques are available to econometrically model these kinds of situations. These are the logit and probit regression models.

These two approaches, logit and probit regression, are very closely linked. The difference between the two is the underlying distribution upon which they are based. Probit regression is based on the normal distribution. Logit regression is based on the logistic distribution. A number of studies have shown the two to be virtually indistinguishable in empirical applications[a]. The logit, however, is the easiest to compute and is analytically much more tractable. Therefore it will be the technique used in this study.

The logit regression model is based on the cumulative logistic probability function:

$$P_i = 1 / [1 + e^{-(a + b_i * x_i)}] \qquad \text{A.2}$$

where P_i represents the probability of observation i falling into a particular category given its values of x_i. The parameter b_i represent the incremental change in the likelihood of falling into a category given an additional unit of x_i.

The relationship actually estimated is given in equation (A.3).

$$Y_i = b_0 + b_i * x_i \qquad \text{A.3}$$

(a) See Amemiya, T. (1981). 'Qualitative Response Models: A Survey" Journal of Economic Literature 19(4):483-536.

where Y_i is one if the observation continues in the selection process and zero if it does not. Since the observations are individual OCS blocks in this application, equation (A.3) is estimated using maximum likelihood methods.

Once the logit equation has been estimated the predicted probability that the event will occur can be found by substituting the observation's value for the independent variables into the estimated equation.

A.2 DATA AND RELATED DIFFICULTIES

Data available for estimation were generally quite good with one exception. This was the information on hydrocarbon potential. Environmental information was provided through documentation by the USGS. Information about water depth was provided by NOAA maps. The final, and critical, information consisted of the MMS Post-Sale Data Base computer tapes which contained bidding information for North Atlantic Sale 42.

The USGS provided summary tables of estimated probability of environmental damage on both a resource-by-resource and an aggregate basis. The resources which were involved included:

- Beaches and recreation areas
- Wildlife sanctuaries
- Coastal bird breeding areas
- Pelagic bird wintering areas
- Cod and Haddock spawning areas
- Silver and red hake spawning areas
- Sea herring spawning areas
- Shellfish areas
- Grey seal whelping areas
- Salt marshes

The primary difficulty was the absence of hydrocarbon potential data for any tract which was not identified as highly likely to contain a great deal of hydrocarbons by the MMS. This created a second problem in the final stage of analysis. In the bid level equation there appeared to be collinearity between independent variables when observations without hydrocarbon potential were omitted from the analysis. Each of these problems are discussed more fully in the remainder of the section.

To estimate the conceptual model appropriately estimates of hydrocarbon potential on a block by block basis are needed. Unfortunately much of the sale had poor hydrocarbon data.

About two-thirds of the blocks in the planned sale have nominal(minimum) values associated with them. Since all blocks in this sale are the same size (approximately 5,710 acres), the $25 per acre minimum translates into a minimum bid of about $142,850. Thus, the information available to proxy hydrocarbon potential in the analyses is fairly thin. Geological data sources and a tractable approach for estimating hydrocarbon potential were identified in the course of this work. This approach would provide, while not as accurate as industry's assessments of the potential, an unbiased estimate of the hydrocarbon potential. These would allow hydrocarbon potential to be statistically controlled for in the analysis. Neither time nor funding were sufficient to incorporate these data into the analysis, however.

The $142,850 figure represents the maximum value of a block as estimated by MMS; the actual estimated value could range anywhere between nothing and $142,850.[a] Because of this, it was assumed that the hydrocarbon value variable was uniformly distributed between $0 and $142,850. Then, the mean for that distribution (or $71,425) was used in place of the maximum. The estimated results were robust to the alternative assumption of a log-normal distribution on values.

A.3. ESTIMATION OF THE BLOCK OFFERING MODEL (STAGE 1)

As discussed in the text, the MMS decides which blocks to offer in a particular lease sale. One common reason that blocks are withdrawn is

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(a) In fact, it is impossible that a negative block value is estimated, since the MMS attempts to take drilling costs into account. However, when then estimated hydrocarbon potential was regressed on water depth, a common proxy for direct cost of drilling, the coefficient was small and had a very large standard error. This suggests that the adjustment for costs maybe minimal.

environmental concern. For the block offering model the independent variables include:

- block value estimate (millions of dollars)[a] (soil2)
- water depth in fathoms (fathoms)
- water depth squared (fatsq)
- overall probability of an oil spill reaching shore (overall)
- dummy variable for Massachusetts blocks (mass).

All blocks are either assigned to Massachusetts or New York. Fathoms and fathoms squared are used in all models to pick up curvature in the water depth relationship. Expected hydrocarbon potential should be positively related to the probability of offering. Costs of exploration and development should be negatively related. Expected environmental damage should be negatively related to the offering probability. Locational effects cannot be predicted *a priori*.

Results of the offer/withdraw model estimation are shown in Table A.1.

The hydrocarbon value (soil2) has a positive sign as expected, but is insignificantly different from zero with a very low t-statistic. Fathoms of water depth has a negative and significant coefficient, and the quadratic term (fatsq) is significant as well. The overall probability of a spill to shore variable has a negative and significant coefficient, as does the Massachusetts dummy. The "predictive" power of the estimated equation is very high.

(a) The value estimate variable is the revised (but not final value estimate) reported on the post-sale data base tape. This is the estimate most likely available at the time when blocks were withdrawn--September and November 1979.

TABLE A.1. Logit Estimates for the Minerals Management Service Block Offer Decision

Logit Estimation
Dependent Variable - Offer

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
cons	68.03225	27.80529	2.44674
overall	-0.48961	0.19665	-2.48979
fathoms	-1.71973	0.69191	-2.48547
fatsq	0.106338	.00452	2.34975
soil2	20.08660	113.99600	0.17620
mass	-20.23950	7.83950	-2.58173

auxiliary statistics	at convergence	initial
log likelihood	-10.45671	-104.66522
number of observations	151	
percent correctly predicted	96.68874	

The most interesting results relate to the environmental variable and the state variable. While it is clear from the large significant constant that the MMS begins with the notion of offering, the data clearly support the notion that potential for environmental damage is important in the offer/withdraw decision. Blocks assigned to Massachusetts were also much more likely to be withdrawn than New York tracts. This probably reflects greater effort by Massachusetts to affect the process. All of the withdrawn blocks had nominal hydrocarbon potential values, and thus the relative lack of variation precluded a good estimate of the effect of hydrocarbon potential[a]. The estimated equation given in Table A.1 was used in the simulation reported in Section 5.4.2.

A.4. ESTIMATION OF BID DECISION MODEL (STAGE 2)

Industry bid on 73 of the 116 blocks offered; 43 blocks did not receive bids. Two different bidding schemes were used by MMS on these 116 blocks.

(a) Ordinary least squares regressions did, however, show a positive significant relationship between MMS offering decisions and hydrocarbon potential. While logit is a much preferred technique in this situation, the results are intriguing, and suggest that a fuller set of hydrocarbon potential or proxies, such as geologic information, might lead to a fruitful estimation of the effect of hydrocarbon potential on offering decisions.

The MMs decides before the sale which bidding scheme will be used on which blocks. The majority of blocks were bid under the usual cash bonus and fixed royalty system, with the royalty pegged at 16.67% of production. Some tracts were bid using a cash bonus and sliding scale royalty system, with the royalty rate to be adjusted to increase with increased quarterly production, and decrease with decreased quarterly production. Given two identical tracts, whether the cash bonus associated with the fixed royalty would be larger or smaller than that associated with a sliding royalty depends on the expected time path of production. No clear prediction is available. Nonetheless, a dummy variable for the sliding scale blocks (bid3) is included in this specification to determine if a consistent industry response was made to the sliding scale system.

Other than the addition of the sliding scale dummy (bid3), the set of explanatory variables remains the same as in the offer equation.[a] As stated earlier, the effect of Massachusetts dummy is less likely to be strong here as compared to the offer/withdrawal stage. It is conceivable and perhaps even likely that in its bid decision industry was more sensitive to environmental factors than is indicated by the "overall" variable. No clear effect of the individual resource variables could be statistically discerned, however.

The results for the initial industry bid decision model are given in Table A.2.

In this model, the hydrocarbon coefficient is now positive and significant. This change may be due to the industry's keener concern for the precise level of hydrocarbon potential. It may also reflect the greater precision associated with later estimates of hydrocarbon potential. Water depth retains the same signs but is no longer significant. Overall has the expected sign, and is significant at 90% level, two-tailed test. The Massachusetts dummy variable is no longer significant. Nor is the sliding scale dummy. The equation has fairly good predictive power, predicting 69% of the cases correctly.

(a) The hydrocarbon value estimate used is the one prepared just prior to the December sale, known as the revised mean range of value estimate. The scaled variable is denoted here as "soil3". The results are very robust to the choice of value estimates.

TABLE A.2. Initial Logit Estimates for Industry Bid Decision Model
Logit Estimation
Dependent Variable - modebi (bid=1)

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
cons	-1.46164	2.36632	-0.61768
soil3	0.14505	0.07519	1.92898
mass	0.09128	0.72031	0.12673
overall	-0.17343	0.00977	-1.77459
fathoms	0.08976	0.10806	0.83072
fatsq	-0.00054	0.00119	-0.45098
bid3	0.20771	0.51796	0.40101

auxiliary statistics	at convergence	initial
log likelihood	-66.35201	-80.40507
number of observations	116	
percent correctly predicted	68.96552	

Because this stage of modeling never shows any significance for either the sliding scale dummy (bid3) or the Massachusetts dummy, they were dropped from the equation. Several explanations for the absence of significance can be offered for either variable. One possible explanation for the surprising lack of effect the sliding scale dummy is that the MMS used an unknown rule for deciding which tracts required a sliding scale bid. If this were true then the effect of the rule could be to negate the econometric evidence. A second explanation is that the kind of bid, or stream of payments required, does not effect the industry wide bid decision. Rather, the effect of the bidding rule is to change the size of the bid. Similarly, the Massachusetts dummy may not be effecting the industry wide decision while still effecting the size of individual companies bids. The results of the logit estimation without these two variables are given in Table A.3.

There are two main things to note about the logit estimates for the reduced model (denoted "Final"). One is that the hydrocarbon and environmental coefficient estimates are quite stable, although their t-statistics are larger. The second is that a 1% increase in the likelihood of oil hitting shore reduces the probability of the oil and gas industry bidding more than an increase of $1,000,000 in hydrocarbon potential increases it. Note also that the water depth estimates have changed considerably, and in the right direction, but still have low t-statistics. This equation was used in the simulations.

TABLE A.3. Final Logit Estimates for Industry Bid Decision Model

Logit Estimation

Dependent Variable - modebi (bid=1)

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
cons	-1.80293	2.09679	-0.85985
soil3	0.15028	7.49776e-002	2.00429
overall	-0.17299	9.57431e-002	-1.80677
fathoms	0.10862	9.42296e-002	1.15267
fatsq	-7.24585e-004	1.09825e-003	-0.65976

auxiliary statistics	at convergence	initial
log likelihood	-66.44974	-80.40507
number of observations	116	
percent correctly predicted	68.10345	

A.5. ESTIMATION OF HIGH BIO LEVEL MODEL (STAGE 3)

Of the 116 blocks which were offered, 73 received bids. For those blocks, a winning firm bid-level equation can be specified. Unfortunately, the lack of variation in the hydrocarbon estimate data makes the equation estimated on the full set of 73 blocks work very poorly. Only 22 of the 73 blocks have value estimates different than the $25 per acre minimum. This would be a fairly serious problem if it only represented truncation of the data set. But more serious problems are present. Many of the blocks that MMS pegged at minimum value attracted very high bids. Obviously, the pre-sale estimates of the oil companies were not particularly close to those of MMS. Although the value estimate data appear to be good enough to predict whether any bid would be submitted (previous subsection), it does not appear good enough to help predict the level of the bid.

Because of this data problem, only those 22 blocks with non-nominal hydrocarbon value estimates are used in the estimation of the bid-level equation. The water depth, value estimate, and sliding scale royalty variables are the same as in the bid decision model. Financial variables have been added: combined total current assets (ctca), and the ratio of cash to assets (x100) (cratio). When the winning bidder is a joint venture, the total current assets of each participating firm are summed, representing the combined assets of the bidding consortium.[a] No joint venture dummy variable is included due to its extreme collinearity with several variables, especially environmental ones. The number of bids on the block (bids) is included as a measure of the competition for the block. In previous regressions a variable representing overall probability of a spill reaching the shore was used. In the bid level regression this has been replaced with a set of more specific environmental variables. These are the probability of an oil spill reaching and impacting

1) a beach or recreation area (beach)

2) a cod and haddock spawning area (cod)

3) a silver and red hake spawning area (hake)

4) a sea herring spawning area (herring)

The results of OLS regression with the bid amount (in millions of dollars) asthedependentvariablearegiveninTableA.4.

TABLE A.4. OLS Estimates of Full Winning Bid Level Model

Dependent Variable: sbidhi (high bid in $millions)

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
cons	1.39119e+003	8.22775e+002	1.69084
fathoms	-0.59927	2.23764	-0.26781
fatsq	9.42760e-003	2.37653e-002	0.39670
soil3	0.25218	0.33076	0.76244
herring	-27.14456	20.23853	-1.34123
beach	-32.78626	18.77923	-1.74588
hake	-22.43852	13.35252	-1.68047
cod	-24.63871	13.38930	-1.84018
bids	3.29341	2.39725	1.37383
bid3	2.80109	3.85065	0.72743
sctca	0.49028	0.30276	1.61936
cratio	-0.31920	0.51382	-0.62123

Number of Observations	22
R-squared	0.81706
Corrected R-squared	0.61583
Sum of Squared Residuals	3.98762e+002
Standard Error of the Regression	6.31476
Durbin-Watson Statistic	2.33204
Mean of Dependent Variable	8.32260

(a) Another option would be to weight the summed assets according the percentage participation in the bid.

The adjusted R^2 is fairly good for cross-sectional data (0.62). Where a predicted sign is available, the signs are as expected, but the variables rarely have high t-statistics. The environmental variables all appear to be correlated with lower winning bid levels, with beach having the largest effect in magnitude,and hake the smallest. These results are consistent with a properly specified theoretical model, but one which is estimated on too few observations to obtain good resolution on individual parameters.

Scatter plots and correlation matrices revealed that, not surprisingly, the number of bids is highly collinear with the hydrocarbon value estimate. The more hydrocarbon potential, the more interested bidders. As a result it is not possible to obtain a good individual estimate of both the hydrocarbon potential and the number of bidders on the size of the winning bid. In Table A.5 the number of bidders variable was dropped. Care should be taken to interpret the hydrocarbon parameter as including the effect of competition. A second variable which is generally included in high bid models, the sliding scale royalty variable is never significant, nor was it clearly correlated with any other variable. It, too, was dropped from the regression reported in Table A.5. These results are shown in Table A.5.

As would be expected, the t-statistic value for the hydrocarbon value estimate is increased, as are most of the variables except for the water depth variables. The adjusted R^2 has fallen slightly to 0.58. Herring continues to have a low t-statistic, while the other environmental variables perform as expected.

The results reported in Table A.5 suggest that bidding firms are fairly cognizant, and sophisticated, regarding specific environmental resources. The analysis also provides a list of the environmental variables which seem to influence industry bidders.

TABLE A.5. Illustrative OLS Estimates for Constrained Bid Level Model

ORDINARY LEAST SQUARES ESTIMATION

Dependent Variable: sbidhi (high bid in $million)

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
cons	1.54323e+003	8.28135e+002	1.86350
fathoms	-0.34958	2.32870	-0.15012
fatsq	7.96514e-003	2.47177e-002	0.32224
soil3	0.57958	0.23235	2.49443
herring	-27.86924	19.98448	-1.39454
beach	-40.76176	18.97244	-2.14847
hake	-24.82668	13.40557	-1.85197
cod	-27.34371	13.45249	-2.03261
sctca	0.79703	0.25610	3.11215
cratio	-0.64606	0.49729	-1.29915

Number of Observations	22
R-squared	0.76114
Corrected R-squared	0.58199
Sum of Squared Residuals	5.20672e+002
Standard Error of the Regression	6.58706
Durbin-Watson Statistic	2.35034
Mean of Dependent Variable	8.32260

A.6. SUMMARY

Each stage of the three-stage modeling procedure was estimated. The MMS decision to offer or withdraw blocks from a sale was estimated with a logit estimation technique, with meaningful results. A large proportion of the decisions can be accurately predicted, and the variables performed largely as expected. The industry decision to bid (or not) on a block, was also estimated via logit. Over two-thirds of the decisions are accurately predicted, with explanatory variables generally working well. The winning firm's decision regarding a bid level has been modeled less successfully. However, the results are close to those obtained by other researchers under the circumstances of very limited data in a micro-level cross-sectional framework. With an adjusted R^2 of 0.62, the model does fit the data fairly well, and provides evidence that the underlying theoretical models are appropriate to the data.

The multistage framework used in this study, incorporating the offer/withdraw decision appears to be unique. The inclusion of environmental information in bid decision and bid level models is also unique. While the importance of research to understand environmental effects is generally acknowledged, the manner in which it enters the decision process, and the scale of its impact have never been examined before.

APPENDIX B

COST EQUATIONS

APPENDIX B

COST EQUATIONS

This appendix contains the cost functions for conventional scrubbers, duct injection and furnace sorbent injection technologies used in Chapter 4. For each technology, equations in Tables B.1-B.3 provide estimates of capital, fixed Operating and Maintenance (O&M), and, variable O & M and costs. Variable names are xxxCAP for capital, xxxFOM for fixed O & M, and xxxVOM for variable O & M where xxx is a three character technology code for either conventional scrubbers (BFG), limestone duct injection (LDI) and furnace Sorbent Injection (FSI). Other variables used in the equations are:

CSUL - coal sulfur in percent;

FGDRETRO - unit-specific scrubber retrofit factor which incorporates economies of scale (size) and site-specific characteristics;

SZE - unit capacity in megawatts; and

FSIDR - Capacity Derate for furnace sorbent injectin.

TABLE B.1. Cost Equations for Conventional Scrubber (BFG)

$$BFGCAP\ (\$/kw) = 167 + (CSUL-2) * 23 * FGDRETRO$$

$$BFGFOM\ (\$/kw/yr) = .0645 * BFGCAP$$

$$BFGVOM\ (mills/kwh) = 3.2 * \left(\frac{CSUL}{3.5} \right)$$

TABLE B.2. Cost Equations for Limestone Duct Injection (LDI)

$$LDICAP\ (\$/kw) = 35 + (CSUL-2) * 7.36 * \left(\frac{SZE}{500} \right)^{-.28}$$

$$LDIFOM\ (\$/kw/yr) = .0645 * LDICAP$$

$$LDIVOM\ (mills/kwh) = 3.665 * \left(\frac{CSUL}{3.5} \right)$$

TABLE B.3. Cost Equations for Furnace Sorbent Injection (FSI)

$$FSICAP\ (\$/kw) = 76.5 + (CSUL-2) * 16 * \left(\frac{SZE}{500} \right)^{-.28}$$

$$FSIFOM\ (\$/kw/yr) = .0645 * FSICAP$$

$$FSIVOM\ (mills/kwh) = 4.993 * \left(\frac{CSUL}{3.5} \right)$$

$$FSIDR\ (\%) = 1.0$$

APPENDIX C

DETAILED SIMULATION RESULTS

APPENDIX C

This appendix contains the detailed results of the simulations conducted for Chapter 4.0. Tables C.1.1 - C.1.4 show the results of the cost curve analysis. Table C.2 presents the results of the legislative compliance scenarios for those cases involving interstate trading. Tables C.3.1 - C.3.12 contain the results of the legislative compliance scenarios for those curves in which emissions trading was restricted on an intrastate basis.

TABLE C.1 SO_2 Emission Reductions and Control Costs for Interstate Trading Under a Conventional FGD Scenario and a Duct Injection

SO2 Emission Reductions (106 Tons/Yr)	Conventional FGD Scenario: Control Costs (106 1985 $/Yr)	Conventional FGD Scenario: Conventional FGDs No.	Conventional FGD Scenario: Conventional FGDs Capacity (MW)	Duct Injection Scenario: Control Costs (106 1985 $/Yr)	Duct Injection Scenario: Conventional FGDs No.	Duct Injection Scenario: Conventional FGDs Capacity (MW)	Duct Injection Scenario: Duct Injection No.	Duct Injection Scenario: Duct Injection Capacity (MW)
2.0	812.8	42	18296	794.6	41	17410	9	1245
4.0	1922.3	92	39405	1884.1	80	34294	52	6723
6.0	3366.8	153	62944	3257.3	124	52588	123	18349
8.0	5236.9	253	87976	4942.9	173	68913	211	36996
10.0	7959.4	406	128419	7576.9	310	112290	250	40434
10.3[a]	8399.6	423	136350	8027.6	332	120841	259	42295
12.0	12423.5	671	208649	12143.8	600	197222	165	19032

[a] Emission reductions at which maximum penetration of duct injection technology occurs.

TABLE C.2 SO_2 Emission Reductions and Control Costs for Interstate Trading Under a Conventional FGD Scenario and a Furnace Sorbent Scenario. (Forced Scrubbing)

SO2 Emission Reductions (106 Tons/Yr)	Conventional FGD Scenario: Control Costs (106 1985 $/Yr)	Conventional FGD Scenario: Conventional FGDs No.	Conventional FGD Scenario: Conventional FGDs Capacity (MW)	Duct Injection Scenario: Control Costs (106 1985 $/Yr)	Duct Injection Scenario: Conventional FGDs No.	Duct Injection Scenario: Conventional FGDs Capacity (MW)	Duct Injection Scenario: Furnace Sorbent No.	Duct Injection Scenario: Furnace Sorbent Capacity (MW)
2.0	812.8	42	18296	812.8	42	18296	0	0
4.0	1922.3	92	39405	1922.3	92	39171	0	0
6.0	3366.8	153	62944	3354.7	149	60985	32	2359
8.0	5236.9	253	87976	5168.4	217	80981	96	10333
10.0	7959.4	406	128419	7807.6	349	120846	137	15033
10.9[a]	9403.3	429	155278	9319.5	429	147967	149	17552
12.0	12423.5	671	208649	12230.8	609	199697	137	14619

[a] Emission reductions at which maximum penetration of furnace sorbent technology occurs.

TABLE C.3 SO_2 Emission Reductions and Control Costs for Interstate Trading Under a Conventional FGD Scenario and a Duct Injection Scenario. (Fuel Switching Allowed)

SO2 Emission Reductions (106 Tons/Yr)	Conventional FGD Scenario			Duct Injection Scenario				
	Control Costs (106 1985 $/Yr)	Conventional FGDs		Control Costs (106 1985 $/Yr)	Conventional FGDs		Duct Injection	
		No.	Capacity (MW)		No.	Capacity (MW)	No.	Capacity (MW)
2.0	252.9	17	2296	252.9	16	2066	0	0
4.0	710.1	17	2296	710.1	16	2066	0	0
6.0	1431.4	17	2296	1431.1	16	2066	2	380
8.0	2702.1	33	10767	2674.0	29	9595	42	8684
10.0	5477.5	148	68662	5290.7	96	45339	221	54446
11.2[a]	7913.5	272	122334	7622.8	196	92978	302	65963
12.0	10237.0	433	171814	9820.2	344	153143	267	39017

[a] Emission reductions at which maximum penetration of duct injection technology occurs.

TABLE C.4. SO_2 Emission Reductions and Control Costs for Interstate Trading Under a Conventional FGD Scenario and a Furnace Sorbent Scenario. (Fuel Switching Allowed)

SO2 Emission Reductions (106 Tons/Yr)	Conventional FGD Scenario			Duct Injection Scenario				
	Control Costs (106 1985 $/Yr)	Conventional FGDs		Control Costs (106 1985 $/Yr)	Conventional FGDs		Furnace Sorbent	
		No.	Capacity (MW)		No.	Capacity (MW)	No.	Capacity (MW)
2.0	252.9	17	2296	252.9	17	2296	0	0
4.0	710.1	17	2296	710.1	17	2296	0	0
6.0	1431.4	17	2296	1431.4	17	2296	0	0
8.0	2702.1	33	10767	2702.1	33	10767	0	0
10.0	5477.5	148	68662	5453.4	139	65158	54	5669
12.0	10237.0	433	171814	10022.3	368	159294	194	24984
12.1[a]	10599.8	462	178857	10365.5	389	165932	208	27331

TABLE C.5. SO_2 Emission Reductions, Control Costs, and Control Technologies For Emission Reduction Strategies (Interstate Trading)

SCEN.	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES NO.	ADVANCED TECHNOLOGIES CAP (MW)
1	6329.10	4008.50	1014.452	633.344	203	66628	0	0
2	6325.20	3795.80	894.226	600.265	144	55098	150	23979
3	6323.10	3957.40	991.983	625.864	176	62502	62	6724
4	6327.90	1912.80	709.754	302.280	23	6199	0	0
5	6334.30	1903.40	702.096	301.220	23	6199	16	2582
6	6326.10	1911.30	708.727	302.129	23	6199	1	116
7	10593.60	8989.00	1851.267	848.579	461	147422	0	0
8	10591.90	8610.40	1837.775	812.920	336	131874	243	39624
9	10591.50	8836.50	1850.996	834.300	401	140182	147	16538
10	10596.70	6580.40	1962.565	620.906	200	94983	0	0
11	10595.60	6329.60	1869.344	597.380	138	67797	252	62909
12	10595.70	6539.50	1922.062	617.184	188	90814	77	8740

SCENARIO KEY

1 - PROXMIRE BILL S.316 - FORCED SCRUBBING NO ADVANCED TECHNOLOGIES
2 - PROXMIRE BILL S.316 - FORCED SCRUBBING DUCT INJECTION
3 - PROXMIRE BILL S.316 - FORCED SCRUBBING FURNACE SORBENT
4 - PROXMIRE BILL S.316 - FUEL SWITCHING NO ADVANCED TECHNOLOGIES
5 - PROXMIRE BILL S.316 - FUEL SWITCHING DUCT INJECTION
6 - PROXMIRE BILL S.316 - FUEL SWITCHING FURNACE SORBENT
7 - MITCHELL BILL S.321 - FORCED SCRUBBING NO ADVANCED TECHNOLOGIES
8 - MITCHELL BILL S.321 - FORCED SCRUBBING DUCT INJECTION
9 - MITCHELL BILL S.321 - FORCED SCRUBBING FURNACE SORBENT
10 - MITCHELL BILL S.321 - FUEL SWITCHING NO ADVANCED TECHNOLOGIES
11 - MITCHELL BILL S.321 - FUEL SWITCHING DUCT INJECTION
12 - MITCHELL BILL S.321 - FUEL SWITCHING FURNACE SORBENT

TABLE C.6. SO_2 Emission Reductions and Control Costs for Mitchell Bill S.321 Intrastate Trading (Fuel Switching)

STATE	EMISSION REDUCTION (103 TONS/YR)	CONTROL COSTS (106 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES None NO.	ADVANCED TECHNOLOGIES None CAP (MW)
AL	383.43	232.49	3014.056	606.317	10	4615	0	0
AZ	34.50	79.52	2384.191	2304.123	5	1787	0	0
AR	47.51	111.70	4593.931	2350.955	5	2973	0	0
CA	2.39	14.50	6864.563	6063.394	2	115	0	0
CO	29.00	64.60	2622.002	2224.697	4	1157	0	0
DE	19.97	33.44	2000.223	1674.110	2	468	0	0
FL	168.70	45.27	430.300	267.578	0	0	0	0
GA	697.02	570.05	4223.505	817.833	22	10246	0	0
IL	589.09	146.85	706.957	249.278	1	151	0	0
IN	1353.27	1009.90	5556.038	743.516	42	12078	0	0
IA	169.51	89.40	2102.630	526.232	3	1536	0	0
KY	681.26	420.01	2717.820	616.520	19	5778	0	0
LA	49.44	88.20	1924.858	1783.916	4	2160	0	0
ME	0.91	5.90	30765.839	6492.077	1	9	0	0
MD	161.79	144.52	1354.037	893.152	6	2210	0	0
MA	56.31	75.01	2024.425	1331.965	4	1268	0	0
MI	249.76	409.56	2668.070	1639.810	14	6517	0	0
MN	110.01	101.69	1532.200	924.368	5	1824	0	0
MS	15.53	1.89	103.157	104.656	0	0	0	0
MO	874.33	550.50	40212.027	629.624	31	9197	0	0
MT	47.33	99.00	36805.328	2091.838	4	1417	0	0
NE	40.99	71.77	2973.464	1741.773	3	1231	0	0
NV	21.10	40.43	1915.177	1916.028	2	1137	0	0
NH	42.76	31.75	1428.456	740.852	2	423	0	0
NJ	11.90	6.22	524.625	522.972	0	0	0	0
NC	144.59	222.69	1003.417	1539.519	9	5080	0	0
ND	59.90	77.38	2273.175	1288.618	5	1384	0	0
OH	1732.30	755.75	2838.128	436.268	23	11182	0	0
OK	59.74	173.30	14030.178	2900.816	10	4334	0	0
OR	6.70	19.90	2978.227	2971.125	1	530	0	0
PA	630.05	412.13	808.406	654.069	21	7558	0	0
SC	138.82	270.40	7608.691	1947.842	20	3487	0	0
SD	4.41	0.21	35.049	33.423	0	0	0	0
TN	686.91	497.08	2050.814	723.640	9	4017	0	0
TX	189.81	401.90	3679.984	2117.408	19	9904	0	0
UT	5.00	14.86	2765.426	2758.789	1	386	0	0
VT	5.20	8.40	3273.005	1614.143	1	52	0	0
VA	91.40	254.12	5579.054	2779.564	19	3724	0	0
WA	44.08	43.43	986.091	985.185	2	1220	0	0
WV	606.20	379.63	1707.340	626.115	8	6179	0	0
WI	322.68	342.03	6659.192	1059.930	24	5209	0	0
TOTAL	10590.60	8317.37		785.354	363	132593	0	0

TABLE C.7. SO_2 Emission Reductions and Control Costs for Mitchell Bill S.321 Intrastate Trading (Fuel Switching) Duct Injection

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (DUCT INJECTION) NO.	ADVANCED TECHNOLOGIES (DUCT INJECTION) CAP (MW)
AL	383.43	213.94	2050.539	557.968	4	2654	14	3237
AZ	34.50	67.21	2837.026	1945.382	2	980	4	1511
AR	47.51	111.70	4593.983	2350.955	5	2973	0	0
CA	2.39	14.50	11957.814	6363.394	2	115	0	0
CO	29.00	55.71	2817.760	1919.517	2	764	4	780
DE	19.97	26.65	1852.274	1320.953	1	209	6	829
FL	163.70	45.27	430.302	267.578	0	0	0	0
GA	697.02	546.41	6041.143	783.913	20	10118	9	904
IL	509.09	146.85	706.963	249.273	1	151	0	0
IN	1353.27	1009.90	5556.107	743.517	41	12077	1	12
IA	169.51	79.64	2101.365	469.359	1	425	4	2279
KY	681.26	402.97	2221.709	591.440	13	3705	17	3481
LA	49.44	88.20	2633.607	1783.916	4	2160	0	0
ME	0.91	5.90	47142.098	6492.077	1	9	0	0
MD	161.79	137.31	1629.056	848.451	4	1904	6	1018
MA	56.31	67.80	2911.840	1203.451	2	929	4	656
MI	249.76	369.18	2631.279	1477.870	10	5629	32	3334
MN	110.01	98.67	1590.139	895.174	3	1318	6	1291
MS	15.53	1.89	103.166	104.656	0	0	0	0
MO	874.33	550.50	40212.039	629.624	31	9197	0	0
MT	47.33	99.00	36805.340	2091.838	4	1417	0	0
NE	40.99	68.19	2935.710	1654.935	2	1007	3	257
NV	21.10	39.31	1914.976	1858.697	1	947	3	470
NH	42.76	31.53	1435.648	735.983	1	414	1	41
NJ	11.90	6.22	524.633	522.972	0	0	0	0
NC	144.59	222.69	1803.430	1539.519	8	5079	0	0
ND	59.90	74.96	2270.485	1251.037	2	847	3	1363
OH	1732.30	696.93	2225.039	402.316	9	6840	36	7048
OK	59.74	173.30	23786.299	2900.816	10	4334	0	0
OR	6.70	19.90	2978.249	2971.125	1	530	0	0
PA	630.05	394.03	841.882	625.367	17	6431	16	3347
SC	130.82	270.40	9803.365	1947.842	20	3487	0	0
SD	4.41	0.21	35.066	33.423	0	0	0	0
TN	686.91	484.96	2451.632	705.990	9	4052	8	2077
TX	189.81	401.90	3680.010	2117.408	19	9904	0	0
UT	5.00	14.86	2765.450	2758.789	1	385	0	0
VT	5.20	8.40	6493.851	1614.143	1	52	0	0
VA	91.40	236.62	6393.776	2508.793	16	3362	3	490
WA	44.08	40.92	1192.908	922.307	1	541	1	738
WV	606.20	375.07	1754.554	618.651	6	5382	5	2336
WI	322.68	340.76	6862.725	1056.016	22	5151	2	124
TOTAL	10590.60	8040.38			297	115479	188	38123

TABLE C.8. SO_2 Emission Reductions and Control Costs for Mitchell Bill S.321 Intrastate Trading (Fuel Switching) Furnace Sorbent

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (FURNACE SORBENT) NO.	ADVANCED TECHNOLOGIES (FURNACE SORBENT) CAP (MW)
AL	333.43	224.91	2420.960	586.573	6	3816	6	1117
AZ	34.50	77.38	2384.049	2241.947	4	1621	1	242
AR	47.51	111.70	4593.932	2350.955	5	2973	0	0
CA	2.39	14.50	11675.113	6063.394	2	115	0	0
CO	29.00	59.90	2533.015	2060.047	2	906	3	445
DE	19.97	30.07	1733.126	1505.667	1	412	4	338
FL	168.70	45.27	430.301	267.573	0	0	0	0
GA	697.02	552.44	5633.368	792.565	20	10118	9	904
IL	509.09	143.85	706.959	249.278	1	151	0	0
IN	1333.27	1009.90	5556.091	743.516	41	12077	0	0
IA	169.51	88.65	2032.860	521.897	2	1433	1	260
KY	681.26	417.19	2520.823	612.364	18	5316	6	633
LA	49.44	88.20	1924.862	1783.916	4	2160	0	0
ME	0.91	5.90	46951.195	6492.077	1	9	0	0
MD	161.79	142.29	1501.526	879.301	5	2090	2	362
MA	56.31	71.21	2503.474	1264.407	3	1122	2	336
MI	249.76	390.15	2659.811	1561.965	11	6002	26	3049
MN	110.01	101.59	1530.858	923.121	3	1796	2	92
MS	15.53	1.89	103.161	104.656	0	0	0	0
MO	874.33	550.50	40212.031	629.624	31	9197	0	0
MT	47.33	99.00	36805.332	2091.838	4	1417	0	0
NE	40.99	68.76	2939.593	1668.236	2	1041	2	185
NV	21.10	40.12	1915.118	1899.818	1	1079	1	110
NH	42.76	31.75	1428.462	740.852	1	422	0	0
NJ	11.90	6.22	524.631	522.972	0	0	0	0
NC	144.59	222.69	1803.424	1539.519	8	5079	0	0
ND	59.90	77.38	2273.183	1288.618	4	1333	0	0
OH	1732.30	723.52	2303.233	417.658	13	8916	22	2892
OK	59.74	173.30	23546.990	2900.816	10	4334	0	0
OR	6.70	19.90	2978.240	2971.125	1	530	0	0
PA	630.05	412.08	900.016	654.011	20	7450	1	136
SC	138.82	270.40	9259.345	1947.842	20	3487	0	0
SD	4.41	0.21	35.059	33.423	0	0	0	0
TN	686.91	496.78	2050.829	723.204	9	4017	2	576
TX	189.81	401.90	3679.998	2117.408	19	9904	0	0
UT	5.00	14.86	2765.439	2758.789	1	385	0	0
VT	5.20	8.40	6165.039	1614.143	1	52	0	0
VA	91.40	240.43	6297.169	2630.491	16	3362	3	490
WA	44.03	43.43	936.107	935.185	1	1219	0	0
WV	666.20	379.63	1707.355	626.115	7	6178	0	0
WI	322.68	340.93	6683.259	1056.521	22	5163	1	40
TOTAL	10590.60	8202.20			320	126737	94	12257

TABLE C.9. SO_2 Emission Reductions and Control Costs for Mitchell Bill S.321 Intrastate Trading (Forced Scrubbing) Base Case

STATE	EMISSION REDUCTION (103 TONS/YR)	CONTROL COSTS (106 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (NONE) NO.	ADVANCED TECHNOLOGIES (NONE) CAP (MW)
AL	333.43	391.64	1476.849	1021.260	18	5742	0	0
AZ	34.50	80.81	2384.202	2341.997	4	1806	0	0
AR	47.51	111.70	4593.976	2350.955	5	2973	0	0
CA	2.39	14.50	6364.557	6063.394	2	115	0	0
CO	29.00	71.57	2615.036	2466.435	4	1485	0	0
DE	19.97	34.04	2097.803	1703.010	3	600	0	0
FL	168.70	97.12	643.777	575.442	4	1992	0	0
GA	691.37	691.00	38556.520	999.463	31	11066	0	0
IL	539.09	317.43	1200.341	538.837	18	4841	0	0
IN	1295.95	1008.10	11728.735	777.808	52	13905	0	0
IA	169.51	210.13	2151.756	1239.829	13	3605	0	0
KY	681.26	475.82	1250.479	698.418	27	6816	0	0
LA	49.54	91.10	1875.328	1839.000	4	2160	0	0
ME	0.91	5.90	13494.049	6492.077	1	9	0	0
MD	161.79	150.07	1371.674	927.527	8	2590	0	0
MA	56.31	87.74	2242.967	1556.960	5	1454	0	0
MI	249.76	451.67	3160.771	1808.238	25	8154	0	0
MN	110.01	132.38	1398.667	1203.174	7	3048	0	0
MS	15.53	8.61	199.989	199.666	1	184	0	0
MO	826.26	580.80	11167.869	702.418	31	9197	0	0
MT	47.33	125.80	822786.063	2657.945	5	1568	0	0
NE	40.99	92.74	2925.857	2258.343	7	1519	0	0
NV	21.10	40.43	1915.121	1916.028	1	1136	0	0
NM	42.76	32.43	910.700	756.159	1	445	0	0
NJ	11.90	9.47	746.011	746.896	1	119	0	0
NC	144.59	237.55	1795.004	1642.753	10	6786	0	0
ND	59.90	90.26	1850.940	1506.745	4	1797	0	0
OH	1732.30	1265.89	1673.494	730.746	61	17940	0	0
OK	59.78	175.20	14030.097	2930.560	10	4334	0	0
OR	6.70	19.90	2978.147	2971.125	1	530	0	0
PA	630.05	455.79	981.239	723.417	27	10477	0	0
SC	133.82	270.40	7608.606	1947.842	20	3487	0	0
SD	4.41	6.03	420.101	420.858	1	134	0	0
TN	636.91	612.73	2352.901	891.992	27	8197	0	0
TX	195.13	427.50	3679.894	2190.792	19	9904	0	0
UT	5.00	14.86	2765.343	2758.789	1	385	0	0
VT	5.20	8.40	2351.854	1614.143	1	52	0	0
VA	91.40	255.19	5122.629	2791.239	18	3746	0	0
WA	44.08	43.43	986.000	985.185	1	1219	0	0
WV	606.20	475.22	1450.839	783.811	17	9998	0	0
WI	322.68	387.14	4290.415	1199.761	25	5409	0	0
TOTAL	10480.63	10058.55			521	170924	0	0

TABLE C.10. SO_2 Emission Reductions and Control Costs for Mitchell Bill S.321 Intrastate Trading (Forced Scrubbing) Duct Injection

STATE	EMISSION REDUCTION (103 TONS/YR)	CONTROL COSTS (106 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (DUCT INJECTION) NO.	ADVANCED TECHNOLOGIES (DUCT INJECTION) CAP (MW)
AL	333.43	362.59	1671.678	945.629	13	4999	13	2046
AZ	34.50	63.76	2959.533	1990.602	2	1021	4	1470
AR	47.51	111.70	4593.979	2350.955	5	2973	0	0
CA	2.39	14.50	11757.809	6063.394	2	115	0	0
CO	29.00	61.22	2638.775	2108.435	2	784	7	1439
DE	19.97	26.65	1352.268	1320.953	1	209	6	829
FL	163.70	96.65	637.507	572.883	4	1611	2	578
GA	691.37	691.00	38556.523	999.463	31	11066	0	0
IL	589.09	309.56	1229.763	525.465	14	4551	6	796
IN	1295.95	1008.10	11728.744	777.823	52	13995	0	0
IA	169.51	139.64	2570.550	1118.697	9	2347	10	2124
KY	631.26	413.91	1656.173	650.911	21	6242	12	1908
LA	49.54	91.10	1375.342	1839.000	4	2160	0	0
ME	0.91	5.90	13494.062	6492.977	1	9	0	0
MD	161.79	140.16	1746.295	866.103	5	2144	5	778
MA	56.31	81.62	2333.224	1449.449	3	1267	3	318
MI	249.76	388.56	2977.957	1555.573	14	6638	29	3299
MN	110.01	122.44	1548.621	1111.734	3	1756	12	2033
MS	15.53	3.61	199.995	199.666	1	104	0	0
MO	823.86	530.80	11167.887	702.418	31	9197	0	0
MT	47.33	125.30	904482.063	2657.945	5	1568	0	0
NE	40.59	86.26	2920.979	2100.983	5	1255	6	537
NV	21.10	40.22	1915.075	1905.034	1	1079	1	110
NH	42.76	31.94	1219.759	744.245	1	435	1	20
NJ	11.90	7.11	629.810	598.907	0	0	1	216
NC	144.59	236.65	1789.918	1636.670	9	6597	2	316
ND	59.90	82.42	1967.387	1375.161	2	1026	5	1781
OH	1732.30	1226.79	2195.502	708.188	53	16971	14	1933
OK	59.78	175.20	23786.221	2930.560	10	4334	0	0
PA	630.05	426.99	972.709	677.687	21	8343	19	3927
SC	138.82	270.40	7608.633	1947.842	20	3487	0	0
SD	4.41	4.27	571.259	573.621	0	0	1	259
TN	686.91	595.28	2533.722	866.578	24	7712	8	1465
TX	195.13	427.50	3707.674	2190.791	19	9904	0	0
UT	5.00	14.86	2765.370	2758.789	1	385	0	0
VT	5.20	8.40	2795.744	1614.143	1	52	0	0
VA	91.40	239.97	6142.990	2625.365	17	3590	2	262
WA	44.08	40.92	1192.901	922.307	1	541	1	738
WV	605.20	468.81	1418.534	773.290	16	9650	3	292
WI	322.68	381.34	7003.016	1181.764	24	5256	4	246
TOTAL	10473.93	9699.58			448	155163	177	29770

TABLE C.11. SO_2 Emission Reductions and Control Costs for Mitchell Bill S.321 Intrastate Trading (Forced Scrubbing) Furnace Sorbent

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (FURNACE SORBENT) NO.	ADVANCED TECHNOLOGIES (FURNACE SORBENT) CAP (MW)
AL	333.43	378.37	1780.290	986.810	15	5542	7	1017
AZ	34.50	78.68	2304.061	2279.756	4	1641	1	242
AR	47.51	111.70	4593.978	2350.955	5	2973	0	0
CA	2.39	14.50	11675.107	6063.394	2	115	0	0
CO	29.00	66.95	2536.135	2306.043	3	1232	3	445
DE	19.97	30.07	1733.120	1505.667	1	412	4	308
FL	168.70	97.12	643.780	575.442	4	1992	0	0
GA	691.37	691.00	30556.523	999.463	31	11065	0	0
IL	589.09	315.17	1397.039	535.007	16	4703	2	138
IN	1295.95	1008.10	11723.741	777.823	52	13905	0	0
IA	169.51	201.19	2140.041	1185.204	10	3078	8	937
KY	681.26	463.51	1410.975	654.774	23	6323	6	936
LA	49.54	91.10	1875.338	1839.003	4	2160	0	0
ME	0.91	5.90	13494.059	6492.077	1	9	0	0
MD	161.79	146.33	1479.819	904.694	5	2212	4	620
MA	56.31	84.43	2121.673	1499.347	3	1267	3	318
MI	249.76	409.86	2974.119	1640.955	14	6435	25	3118
MN	110.01	128.55	1347.894	1168.331	6	2964	7	418
MS	15.53	8.61	199.994	199.666	1	124	0	0
MO	826.86	580.80	11137.803	702.418	31	9197	0	0
MT	47.33	125.80	822812.063	2657.945	5	1568	0	0
NE	40.99	88.39	2096.941	2156.189	5	1251	4	363
NV	21.10	40.43	1915.135	1916.023	1	1136	0	0
NH	42.76	32.22	1047.972	751.847	1	435	1	20
NJ	11.90	9.33	783.036	776.417	1	69	1	77
NC	144.59	237.55	1795.020	1642.753	10	6786	0	0
ND	59.90	88.50	1858.585	1475.287	4	1745	2	249
OH	1732.30	1247.34	1944.735	720.049	53	17107	12	1580
OK	59.78	175.20	23546.916	2930.560	10	4334	0	0
OR	6.70	19.90	2978.166	2971.125	1	530	0	0
PA	630.05	452.27	957.165	717.827	26	9908	7	1208
SC	138.82	270.40	7608.627	1947.843	20	3487	0	0
SD	4.41	6.03	420.108	420.853	1	134	0	0
TN	636.91	605.92	2872.855	832.094	25	7786	7	1221
TX	195.13	427.50	3679.917	2190.792	19	9704	0	0
UT	5.09	14.85	2765.364	2758.789	1	335	0	0
VT	5.20	8.40	2536.027	1614.143	1	52	0	0
VA	91.40	242.86	5715.010	2657.026	17	3570	2	252
WA	44.03	43.43	986.024	985.185	1	1219	0	0
WV	606.20	472.52	1418.526	779.411	16	9650	3	292
WI	322.68	382.64	6616.777	1185.817	24	5320	3	156
TOTAL	10480.63	9906.51			473	163896	113	14065

TABLE C.12. SO_2 Emission Reductions and Control Costs for Proxmire Bill S.316 Intrastate Trading (Fuel Switching): Base Case

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (NONE) NO.	ADVANCED TECHNOLOGIES (NONE) CAP (MW)
AL	244.72	211.37	1205.871	863.485	8	3220	0	0
DE	1.05	2.14	603.802	605.103	1	26	0	0
FL	66.71	33.64	525.335	501.276	1	715	0	0
GA	235.43	209.52	1304.020	733.892	8	3983	0	0
IL	490.00	237.20	923.659	484.053	12	3939	0	0
IN	812.61	521.40	1036.387	641.626	28	6777	0	0
IA	93.77	71.90	1015.995	766.326	6	811	0	0
KY	444.78	237.23	941.881	533.321	14	4073	0	0
MD	84.87	65.61	853.865	771.266	2	1302	0	0
MA	64.30	119.20	4681.937	1853.917	7	1586	0	0
MN	37.76	46.51	1350.009	1231.157	4	1126	0	0
MS	21.11	11.77	274.126	274.417	1	252	0	0
MO	596.54	303.13	1005.521	516.489	14	5135	0	0
NH	33.70	29.07	866.536	743.314	1	416	0	0
NY	133.86	177.18	2026.422	1323.458	12	1536	0	0
NC	29.01	43.60	1503.635	1502.856	1	1220	0	0
OH	1248.45	815.59	1093.772	653.272	36	11318	0	0
PA	490.55	327.63	897.961	667.876	22	8721	0	0
SC	54.04	77.68	1645.904	1436.894	4	1553	0	0
TN	420.31	274.20	912.736	570.777	9	4566	0	0
VA	4.68	6.90	392.203	392.218	1	174	0	0
WV	420.82	265.06	833.736	629.734	10	5596	0	0
WI	133.40	147.07	1160.150	801.644	8	2058	0	0
TOTAL	6327.47	4239.59			210	70158	0	0

TABLE C.13. SO_2 Emission Reductions and Control Costs for Proxmire Bill S.316 Intrastate Trading (Fuel Switching) Duct Injection

STATE	EMISSION REDUCTION (103 TONS/YR)	CONTROL COSTS (106 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (FURNACE SORBENT) NO.	ADVANCED TECHNOLOGIES (FURNACE SORBENT) CAP (MW)
AL	244.72	37.92	336.525	154.924	0	0	0	0
DE	1.05	1.47	682.606	681.830	0	0	1	43
FL	66.71	10.99	182.343	164.206	0	0	0	0
GA	235.43	70.49	444.668	246.703	0	0	0	0
IL	490.00	102.48	459.937	209.139	1	151	0	0
IN	812.61	337.23	600.404	414.939	0	0	0	0
IA	93.77	12.17	233.941	129.531	0	0	0	0
KY	444.73	162.03	627.940	334.372	5	832	0	0
MD	84.87	65.22	637.974	733.445	2	1162	0	0
MA	64.30	117.40	9009.604	1825.922	7	1596	0	0
MI	37.75	17.93	1390.722	474.918	1	67	0	0
MS	21.11	2.63	135.142	124.279	0	0	0	0
MO	596.54	124.36	245.193	238.449	0	0	0	0
NH	38.70	26.25	1013.337	678.171	1	337	0	0
NY	133.86	123.08	1031.955	919.135	2	452	3	185
NC	29.01	34.84	1472.460	1177.621	1	421	0	0
OH	1243.45	263.89	705.569	211.331	0	0	0	0
PA	490.55	304.67	793.065	620.998	18	6853	0	0
SC	54.04	43.17	1392.059	790.651	0	0	0	0
TN	430.31	191.49	736.204	373.649	0	0	0	0
VA	4.68	6.90	1553.611	1436.507	1	83	1	102
WV	420.22	113.83	722.640	282.330	0	0	0	0
WI	163.40	25.90	953.452	141.229	0	0	0	0
TOTAL	6327.47	2201.30			39	11954	5	330

TABLE C.14. SO_2 Emission Reductions and Control Costs for Proxmire Bill S.316 Intrastate Trading (Fuel Switching) Furnace Sorbent

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (FURNACE SORBENT) NO.	ADVANCED TECHNOLOGIES (FURNACE SORBENT) CAP (MW)
AL	244.72	37.92	336.525	154.924	0	0	0	0
DE	1.05	1.47	682.626	681.830	0	0	1	43
FL	66.71	10.99	182.343	164.206	0	0	0	0
GA	235.43	70.49	444.468	236.783	0	0	0	0
IL	490.00	102.48	459.937	209.139	1	151	0	0
IN	812.61	337.23	600.484	414.939	0	0	0	0
IA	93.77	12.17	233.941	129.531	0	0	0	0
KY	444.73	162.03	627.940	364.372	5	832	0	0
MD	84.87	65.22	637.974	763.445	2	1162	0	0
MA	64.30	117.40	9009.694	1825.922	7	1536	0	0
MI	37.76	17.93	1290.722	474.918	1	67	0	0
MS	21.11	2.63	135.142	124.279	0	0	0	0
MO	596.54	124.36	245.193	208.449	0	0	0	0
NH	38.70	26.25	1013.337	678.171	1	337	0	0
NY	133.86	123.08	1031.985	919.135	2	452	3	185
NC	29.01	34.84	1472.460	1177.621	1	421	0	0
OH	1243.45	263.89	705.569	211.331	0	0	0	0
PA	493.55	304.67	793.065	620.998	18	6858	0	0
SC	54.04	43.17	1302.059	793.654	0	0	0	0
TN	480.31	191.49	736.204	378.649	0	0	0	0
VA	4.68	6.30	1453.611	1436.307	1	83	1	102
WV	420.82	113.83	722.648	202.300	0	0	0	0
WI	103.40	25.90	953.452	141.229	0	0	0	0
TOTAL	6327.47	2201.30			39	11954	5	330

TABLE C.15. SO_2 Emission Reductions and Control Costs for Proxmire Bill S.316 Intrastate Trading (Forced Scrubbing) Base Case

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (NONE) NO.	ADVANCED TECHNOLOGIES (NONE) CAP (MW)
AL	244.72	211.37	1205.871	863.485	8	3220	0	0
DE	1.05	2.14	603.802	605.123	1	26	0	0
FL	66.71	33.64	505.335	501.276	1	715	0	0
GA	285.43	209.52	1034.020	733.892	8	3983	0	0
IL	450.00	237.20	923.659	404.053	12	3939	0	0
IN	812.61	521.40	1036.387	641.626	28	6777	0	0
IA	93.77	71.90	1015.996	766.326	6	811	0	0
KY	444.78	237.23	941.881	533.321	14	4073	0	0
MD	84.87	65.61	853.866	771.266	2	1302	0	0
MA	64.30	119.20	4081.937	1853.917	7	1526	0	0
MN	37.76	46.51	1350.009	1231.157	4	1126	0	0
MS	21.11	11.77	274.126	274.417	1	252	0	0
MO	586.54	303.13	1005.521	516.489	14	5135	0	0
NH	33.70	29.07	866.536	743.314	1	416	0	0
NY	133.86	177.18	2026.422	1323.453	12	1536	0	0
NC	29.01	43.60	1503.635	1502.856	1	1220	0	0
OH	1248.45	815.59	1093.772	653.272	36	11318	0	0
PA	490.55	327.63	897.061	667.876	22	8721	0	0
SC	54.04	77.68	1645.904	1436.894	4	1553	0	0
TN	480.31	274.20	912.736	570.777	9	4566	0	0
VA	4.63	6.90	392.203	392.218	1	174	0	0
WV	420.82	265.06	833.736	629.734	10	5596	0	0
WI	133.40	147.07	1160.150	801.644	8	2058	0	0
TOTAL	6327.47	4239.59			210	70158	0	0

TABLE C.16. SO_2 Emission Reductions and Control Costs for Proxmire Bill S.316 Intrastate Trading (Forced Scrubbing) Duct Injection

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (DUCT INJECTION) NO.	ADVANCED TECHNOLOGIES (DUCT INJECTION) CAP (MW)
AL	244.72	189.32	1070.553	773.283	2	1925	17	3224
DE	1.05	1.12	532.570	522.736	0	0	1	43
FL	66.71	33.64	525.337	501.276	1	715	0	0
GA	285.43	204.15	919.795	715.238	6	3396	6	1214
IL	490.00	224.53	887.150	453.167	9	3553	6	607
IN	812.61	498.20	837.625	613.037	24	6234	12	1109
IA	93.77	64.31	1141.477	685.053	3	669	7	560
KY	444.78	221.43	847.706	497.778	8	2527	15	2013
MD	84.87	63.58	764.104	749.030	2	1162	1	661
MA	64.30	119.20	5263.997	1853.917	7	1536	0	0
MI	37.76	37.99	1523.940	1001.731	1	201	9	1564
MS	21.11	11.77	274.133	274.417	1	252	0	0
MO	596.54	304.80	949.515	510.939	13	4915	3	823
NH	38.70	27.08	921.160	695.233	1	373	1	82
NY	133.85	153.03	1957.390	1143.163	7	1109	7	668
NC	29.01	43.60	1503.649	1502.835	1	1223	0	0
OH	1243.45	769.40	905.634	613.202	26	9428	26	4573
PA	490.55	314.23	752.572	641.750	17	6347	12	2710
SC	54.04	53.80	1500.953	1020.995	1	204	15	2290
TN	400.31	267.52	770.174	556.932	7	4187	5	927
VA	4.68	5.30	1025.532	1135.227	0	0	2	207
WV	420.82	263.13	605.215	625.333	10	5194	2	784
WI	183.40	126.07	827.306	687.393	4	1050	11	1655
TOTAL	6327.47	4003.25			151	56993	158	25714

TABLE C.17. SO_2 Emission Reductions and Control Costs for Proxmire Bill S.316 Intrastate Trading (Forced Scrubbing) Advanced Sorbent

STATE	EMISSION REDUCTION (10^3 TONS/YR)	CONTROL COSTS (10^6 1985 $/YR)	MARGINAL CONTROL COSTS (1985 $/YR)	AVERAGE CONTROL COSTS (1985 $/TON)	FLUE GAS DESULFURIZATION SYSTEM: CONVENTIONAL TECHNOLOGIES NO.	CONVENTIONAL TECHNOLOGIES CAP (MW)	ADVANCED TECHNOLOGIES (FURNACE SORBENT) NO.	ADVANCED TECHNOLOGIES (FURNACE SORBENT) CAP (MW)
AL	244.72	209.46	1193.050	855.854	7	2861	4	610
DE	1.05	1.47	632.603	681.830	0	0	1	43
FL	65.71	33.64	525.337	501.276	1	715	0	0
GA	285.43	203.05	907.872	728.828	8	3906	1	165
IL	490.00	233.80	802.216	477.135	10	3665	5	499
IN	812.61	512.90	995.325	631.177	24	6234	10	819
IA	93.77	63.56	1030.165	730.626	4	725	3	250
KY	444.78	231.59	853.212	520.282	12	3513	5	408
MD	84.87	65.61	853.874	771.266	2	1302	0	0
MA	64.30	119.20	4870.116	1053.917	7	1586	0	0
MI	37.76	43.42	1302.980	1144.820	2	901	5	316
MS	21.11	11.77	274.132	274.417	0	252	0	0
MO	596.54	303.13	1005.532	516.489	14	5155	0	0
NH	33.70	28.19	897.531	725.593	1	373	1	82
NY	133.86	164.73	1711.924	1230.545	7	1206	7	571
NC	29.01	43.60	1503.647	1502.856	1	1220	0	0
OH	1248.45	808.04	1042.980	647.233	32	10340	12	1573
PA	490.55	327.52	894.092	667.540	21	8579	1	174
SC	54.04	70.03	1635.521	1295.673	2	720	9	1191
TN	480.31	272.97	833.720	568.306	9	4515	1	231
VA	4.63	6.80	1453.541	1436.537	1	83	1	102
WV	420.82	265.06	833.756	629.734	10	5596	0	0
WI	183.40	140.55	1050.249	765.653	5	1539	8	803
TOTAL	6327.47	4175.08			180	65076	74	7837

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