ESTIMATING EXTERNALITIES OF NATURAL GAS FUEL CYCLES

OAK RIDGE NATIONAL LABORATORY
AND
RESOURCES FOR THE FUTURE

Report No. 4 on the
EXTERNAL COSTS AND BENEFITS OF FUEL CYCLES:
A Study By The
U.S. Department of Energy
And The
Commission of the European Communities

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Preface

This report describes methods for estimating the external costs (and possibly benefits) to human health and the environment that result from natural gas fuel cycles. Although the concept of externalities is far from simple or precise, it generally refers to effects on individuals' well being, that result from a production or market activity in which the individuals do not participate, or are not fully compensated. In the past two years, the methodological approach that this report describes has quickly become a worldwide standard for estimating externalities of fuel cycles. The approach is generally applicable to any fuel cycle in which a resource, such as coal, hydro, or biomass, is used to generate electric power. This particular report focuses on the production activities, pollution, and impacts when natural gas is used to generate electric power. In the 1990s, natural gas technologies have become, in many countries, the least expensive to build and operate.

The scope of this report is on how to estimate the value of externalities -- where value is defined as individuals' willingness to pay for beneficial effects, or to avoid undesirable ones. This report is about the methodologies to estimate these externalities, not about how to internalize them through regulations or other public policies. Notwithstanding this limit in scope, consideration of externalities can not be done without considering regulatory, insurance, and other considerations because these institutional factors affect whether costs (and benefits) are in fact external, or whether they are already somehow internalized within the electric power market. Although this report considers such factors to some extent, much analysis yet remains to assess the extent to which estimated costs are indeed external.

This report is one of a series of reports on estimating the externalities of fuel cycles. The other reports are on the coal, oil, biomass, hydro, and nuclear fuel cycles, and on general methodology. We thank Liz Hannon and McGraw-Hill/Utility Data Institute for their interest in this series of reports, and for publishing them to make them available to a wide audience. Bob Shelton, Randy Curlee, and Charles Kerley at Oak Ridge National Laboratory helped to push this report through to completion.

The study that produced these reports is known as the U.S.-European Commission Study on the External Costs of Fuel Cycles. The European Commission has issued a separate series of reports, detailing the results of its analyses. The numerical results in the two sets of reports differ because of different assumptions concerning the technologies and their emissions, as well as the geographical locations of the power plants; but the general methodological approach was developed jointly. We on the U.S. side benefitted and enjoyed

immensely our collaboration with our European counterparts. The European participation in this joint study was championed and sponsored by Pierre Valette, director of Directorate General XII of the European Commission.

As with the other reports in this series, the Fuel Cycle Peer Review Panel of the U.S. Secretary of Energy's Advisory Board provided a very detailed, useful review of a preliminary draft this report. The panel was chaired by Christopher Bernabo. The report has also benefitted from review comments provided by Hilary Smith and other staff of the Department of Energy (DOE). We thank Vito Stagliano and Sue Tierney, both formerly with the U.S. DOE policy office, for providing U.S. DOE financial support for the U.S. study. Of course, the authors assume sole responsibility for the contents of this report. Last, but certainly not least, we thank friends and family who steadfastly supported us in this endeavor over the years.

Russell Lee January 31, 1998

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EXECUTIVE SUMMARY

ES.1 INTRODUCTION

Social accounting is a concept, largely developed by economists, to account for all of the costs of production and consumption. These costs are both monetary and non-monetary in nature. Social accounting is of interest to many institutions in the world as a means of assisting in energy and environmental decision making. Social accounts have two components: private costs such as capital, operating and maintenance costs; and costs and benefits that are not reflected in market transactions. The latter are called *external* costs and benefits — or externalities. They include environmental quality, health, and non-environmental considerations.

It is well recognized (for example, DOE 1991) that the lack of high-quality information about external costs and benefits is a handicap to making good decisions about energy. To address this problem, the U. S. Department of Energy (DOE) and the Commission of the European Communities (EC) committed in 1991 to "develop a comparative analytical methodology and to develop the best range of estimates of costs from secondary sources" for eight fuel cycles and four conservation options for electricity generation. This report documents results for one of these fuel cycles, the natural gas fuel cycle, in which natural gas is used to generate electricity.

ES.2 PURPOSE OF STUDY

The purpose of this report is to demonstrate how to apply scientific information to estimate external costs and benefits from natural gas fuel cycles. The specific objectives of this study are:

(1) to implement the methodological concepts which were developed in the Background Document (ORNL/RFF 1992) as a means of estimating external costs and benefits of fuel cycles, and by so doing, to demonstrate their application to the natural gas fuel cycle;

(2) to use existing data and other information to develop, given the time and resources, a range of estimates of the marginal (i.e., the additional or incremental) damages and benefits associated with some of the important

impacts of a new gas-fired power plant, at two reference sites in the United States; and

(3) to assess the state of the information that is available to support the estimation of externalities and energy decision making, in which natural gas is an option; and by so doing, to assist in identifying gaps in knowledge and in setting future research agendas.

It is important to realize that the primary purpose of this study is *not* to develop externality values, per se. As will be made clear in this report, for any given type of fuel cycle, these values can vary considerably. Thus, the most important objective of this study is to demonstrate the methods, modeling procedures, and use of scientific information to estimate externalities. The report provides an illustrative example for those who will, in the future, undertake "actual" studies of "real" options at "real" sites. While data are used in the numerical examples in this study, the reference sites are only hypothetically considered as sites for the power plants. They are used to demonstrate the methodology. The specific numerical results are ***not*** generic. However, many of the basic exposure-response functions, models, and other analytical methods are. Thus, a significant result of the study is the compilation of analytical methods, as well as representative data, that can ultimately be used in a modeling and information system for computing externalities.

There are several reasons why ***it is not appropriate to apply directly the numerical results of this study to compare different fuel cycles:***

(1) All of the potentially important impacts are not addressed because of limitations in the state of quantitative knowledge or in the time and budget for this study.

(2) Impacts are project-specific. Different power plant specifications will change the magnitude of the residual damages and benefits.

(3) Impacts are generally site-specific. It would be erroneous to extrapolate, without appropriate analysis, the numerical estimates for the two sites analyzed in this study to other sites. In particular, the two sites are not intended to be representative of all sites in the country, nor even to be economically viable alternatives. Rather, the sites are selected so as to compare individual impacts across fuel cycles using a common environmental baseline. The sites are plausible from a physical standpoint, though not necessarily from an economic or regulatory one.

(4) Limitations in knowledge preclude quantitative estimates of many ecological impacts. The effect of these limitations on the ability to derive quantitative estimates may vary for different fuel cycles.

(5) Aggregation errors may arise from adding estimates of damages that are estimated separately for individual impacts.

ES.3 METHOD OF ANALYSIS

The fuel cycle that is considered in this study involves the construction and operation of a new gas-fired power plant. The fuel cycle also includes associated requisite activities, such as natural gas extraction and transportation. The source of the gas, pipeline transportation, gas processing, and other infrastructure that would be required to supply the power plant are assumed to already exist. Other planning options such as adding units to an existing plant, purchasing power from other power producers, or integrated resource planning to meet system-wide or region-wide needs are not addressed.

The Damage Function Approach (DFA) is the methodology used to estimate the social costs and benefits of the natural gas fuel cycle. The DFA combines natural science and economics to estimate the changes in both environmental and nonenvironmental conditions which stem from an incremental investment (to build and operate a gas-fired power plant).

Figure ES-1 is a flowchart that illustrates the DFA. It begins with an identification of the total fuel cycle and considers: (1) estimates of the more significant emissions and other residuals from each fuel-cycle activity; (2) the transport, deposition, or chemical transformations of these emissions, and the resulting change in the geographical concentrations of these pollutants; (3) the changes in ecological, human, and social resources which are caused by the changes in concentrations; (4) social costs and benefits, or the economic value, of these impacts; and (5) the distinction between the social costs and benefits that are internalized within the market, and those that remain as externalities.

The concept of impact-pathways is used within the context of the DFA to define a sequence of physical cause-and-effect linkages. An impact-pathway begins with a given activity or process of the fuel cycle (such as electricity generation). The impact-pathway is then defined in terms of a particular emission or discharge from this activity; the transport and the possible chemical and physical transformation of this discharge; the resulting change in its concentration in the

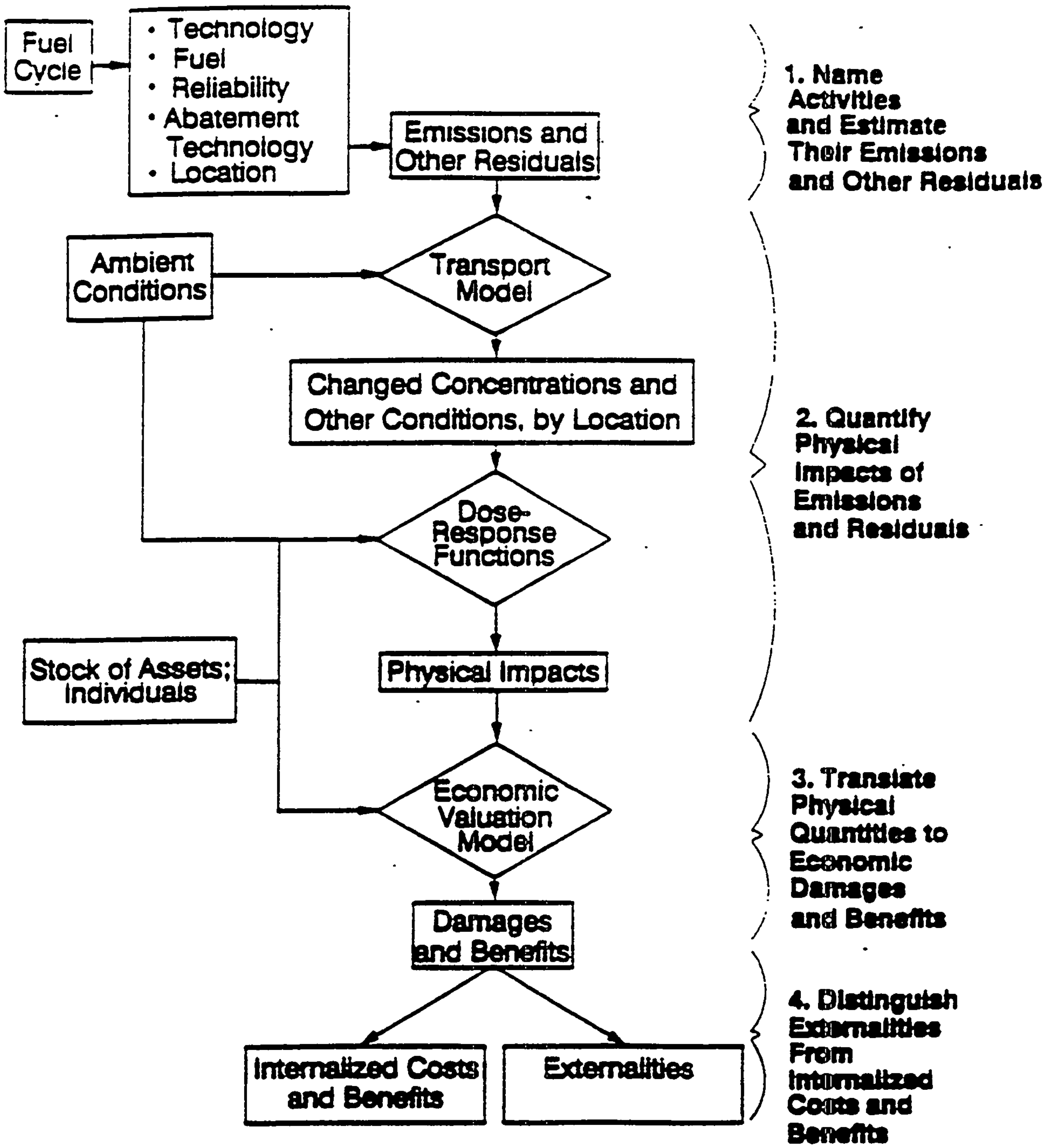


Fig. ES-1. Impact-pathway implementation of damage function approach environment; and the effect of that change, which results in a specific ecological impact or effect on health. This impact is the endpoint of the pathway and the starting point for estimating the economic value of that impact.

Economic value is the extent that individuals are willing to pay to avoid negative impacts or to obtain positive impacts -- the so-called willingness to pay (WTP) concept in economics that underlies modern benefit-cost analysis. Emissions or other residuals from the gas fuel cycle result in health, environmental, and other impacts. In this study, the valuation of these impacts generally utilizes the results of past economic studies that have estimated the WTP to avoid different types of impacts.

ES.4 NATURAL GAS TECHNOLOGIES AND EMISSIONS

The benchmark technology that is used in the analysis of the natural gas fuel cycle is a combined-cycle gas-fired electric generating plant. The analysis in this study focuses on the impacts and damages (and benefits) associated with this fuel cycle.

A representative baseload technology was selected for analysis on the basis of data on existing gas-fired plants in the U.S. A 500 MW combined-cycle gas-fired power plant built in 1990 having a lifetime of 40 years was selected for each of the two reference sites examined. We assume an 74.5% capacity factor for this power system which would generate 3.3 billion kWh per year. A 41% conversion efficiency was used, in the analysis, resulting in a daily consumption of approximately 72.9 million cubic feet of natural gas or 26.6 billion cubic feet per year.

The power plants are built to meet or exceed environmental standards for both the 1990 and 2010 time frames. The primary pollutants emitted by the power plants are particulate matter (PM), NO_x and CO. For the power plants built in 1990, we assume steam injection to be the primary emissions control technology.

For the power plants built in 2010, the same emission control technology as 1990 - steam injection. Table ES.4-1 contains some of the primary air emissions data used in the analysis. EPA's AIRS emissions factors are used to calculate both uncontrolled and controlled emissions per million cubic feet of natural gas input for a gas-fired power plant with gas turbine technology. The controlled emissions for 1990 are represented by emission factors for gas turbines for electricity generation from EPA AP-42. Controlled emissions for the 2010 gas-fired power plant are obtained from test results of GE's H technology advanced combined-cycle power plant.

Table ES.4-1. Emission Factors for electric utility turbines (lbs/million cubic feet of natural gas)

	NO_x	HC	CO	PM
1990 EMISSIONS				
Uncontrolled emissions: 1990 (AIRS/AP-42)	449.2	24.5	112.3	19.7
Controlled emissions - steam injection	122.5	NT[a]	82.0	5.1
2010 EMISSIONS				
Controlled emissions:	44.1*	neg.	82.0	5.1

*The emission values for the 2010 gas turbine were reported in units of ppmvd @15% O_2. We did not have sufficient technical parameters of GE's H series technology advanced combined-cycle power plant to calculate NO_x emission values in terms of lb/mmcf or lb/mmBtu, therefore our estimates were made considering the reduction of NO_x in terms of ppm.

[a]Not tested

The emission factors for 1990 (revised AP-42 data) consist of current technology for gas turbine units purchased by electric utilities. The 2010 emission factors assume the use of dry low NO_x technology for control of NO_x of 9 ppm and CO of 10 ppm.

ES.5 SELECTED IMPACT-PATHWAYS

Total fuel cycle externalities include those associated with the gas-fired electric power plant itself, the "upstream" activities that take place to supply natural gas to the plant, and the secondary activities that must take place for the gas-fired power plant to be built. Secondary activities are associated with the manufacturing of the materials and components used by the plant. Previous analysis showed that the emissions from secondary activities are about two orders of magnitude smaller than the direct emissions of coal-fired power plants (ORNL/RFF 1994b). As such, secondary emissions were not included in the detailed impact-pathway analysis for the natural gas fuel cycle.

There are many activities, processes, and emissions associated with the natural gas fuel cycle. Due to limitations in scientific knowledge, as well as time and resource constraints, only a subset can be addressed in any detail. Three major factors guided this setting of priorities: (a) impacts that are considered to be most important in terms of their potential damages or benefits (based on the existing literature and informed assessments); (b) impacts that span a number of the fuel cycles; (c) and impacts and damages (or benefits) that are more likely to be quantified. The existing literature and preliminary screening analysis were used to suggest impacts and damages that are important and likely to be quantified. The following impact-pathways were selected for more detailed analysis.

Impact-pathways given priority in this study

Stage of Fuel Cycle	Impact
Gas extraction and treatment	■ Effects on organisms due to wastewaters from drilling ■ Impacts on coastal wetlands from production and support activities ■ Deaths and injuries from offshore production activities
Gas processing	■ Ecological and health effects of emissions and other wastes from the processing plants
Gas transportation	■ Effects on plants and wildlife due to leakage of methane from pipelines ■ Deaths, injuries, and property damage due to pipeline accidents
Electricity generation	■ Decreased crop yield from exposure to ozone formed from emissions of HC and NO_X ■ Morbidity and mortality from ozone formation from emissions of HC and NO_X ■ Morbidity and mortality from air emissions of particulate matter ■ Net new employment benefits from construction and operation

Impacts are generally site- (as well as project-) specific. In this study, impacts are considered in different regional reference environments, reflecting the importance of how differences in location affect estimates of damages and benefits. For the United States, the Southeast and Southwest regions are selected as case study environments. Figure ES-2 is a map to show the locations of the two reference sites used in the analysis.

ES.6 MARGINAL ECOLOGICAL IMPACTS OF A NATURAL GAS FUEL CYCLE

Although quantitative information is limited on many of the potential environmental impacts of the natural gas fuel cycle, the approach to quantifying impacts and some general qualitative conclusions can be made based on available field and laboratory data. In most cases data useful for modeling impacts are not available. Impacts from the production stage of the fuel cycle include effects of wastewater emissions on aquatic resources at both offshore and onshore sites and effects of construction activities and navigation channeling on wetlands. Impacts at the power plant site include the potential changes in crop yield from ozone formation from power plant emissions of hydrocarbons and NO_x [though recent technological improvement greatly reduces NO_x emissions (refer to Table ES 4-1)]. Information and models to characterize the impact of methane emissions from pipelines, air emissions from drilling equipment and pipeline compressors, and air and wastewater emissions from refinery sites are lacking. Also, the impacts associated with global climate change from CO_2 and other greenhouse gas emissions are uncertain.

Commercial fishing in the Gulf of Mexico is an important economic component of the United States. Commercial landings of all fisheries in the Gulf of Mexico have decreased since the development of oil and gas resources. However, this decrease has been attributed to overfishing rather than to oil and gas development. Nevertheless, discharges of produced water, drilling fluids, and drill cuttings from drilling platforms add solid material, hydrocarbons, and metals to the sediments and hydrocarbons to the water column over the life of the well. These materials are diluted in the water, but can potentially produce sublethal effects on sensitive organisms. The contribution of these pollutants should be of concern in an area experiencing decreased fisheries landings and increased oil and gas development, but the severity of their impacts is uncertain.

At onshore drilling sites in coastal areas, wastewaters may be discharged to tidally-affected surface waters. These discharges can endanger commercial fisheries and destroy natural wetland areas. Inland, accidently discharged wastewaters may migrate to and impact freshwater streams. Produced water and drilling fluid constituents can leach from reserve pits and storage reservoirs to groundwater.

The contribution of nitrogen oxide and hydrocarbon emissions from the power plant to ambient ozone concentrations is modeled for the Southeast Reference site. Losses in crop production caused by ozone increases (above ambient concentrations) are calculated for the counties surrounding the reference power plant. Data and models were insufficient to predict the regional impacts of ozone and acid deposition on forests, crops and wildlife.

ES.7 MARGINAL EFFECTS OF A NATURAL GAS FUEL CYCLE ON HEALTH

The emissions and impact-pathways that are evaluated in this study probably represent the greatest proportion of the identified adverse health effects related to the natural gas fuel cycle. Notwithstanding, these impact-pathways represent a partial listing of potentially important sources of adverse impacts. For human health impacts, only the air inhalation pathway is considered. Consideration in the future should be given to transport through the environment to and through the food chain. Likewise, effluent releases to the aquatic pathway are not fully addressed because of the lack of a sufficient knowledge base. Finally, occupational disease and accident rates are not specific to the technology except for transmission pipeline accidents. Estimates of accident rates for offshore accidents must be considered as being tentative.

The emissions examined are chosen either to demonstrate a particular facet of the methodology, to highlight a technology stage, or to capture a sizeable fraction of the anticipated health effects. Data presented in Table 12.4-1 indicate that a small proportion of both health and ecological impacts are rated as having a high quality of information about them. Future efforts will, no doubt, demonstrate similar conditions with other residuals and pathways. Some of these would include characterization of the hydrocarbons, broken down at least into toxicological classes, and characterization of the food-chain and aquatic pathways.

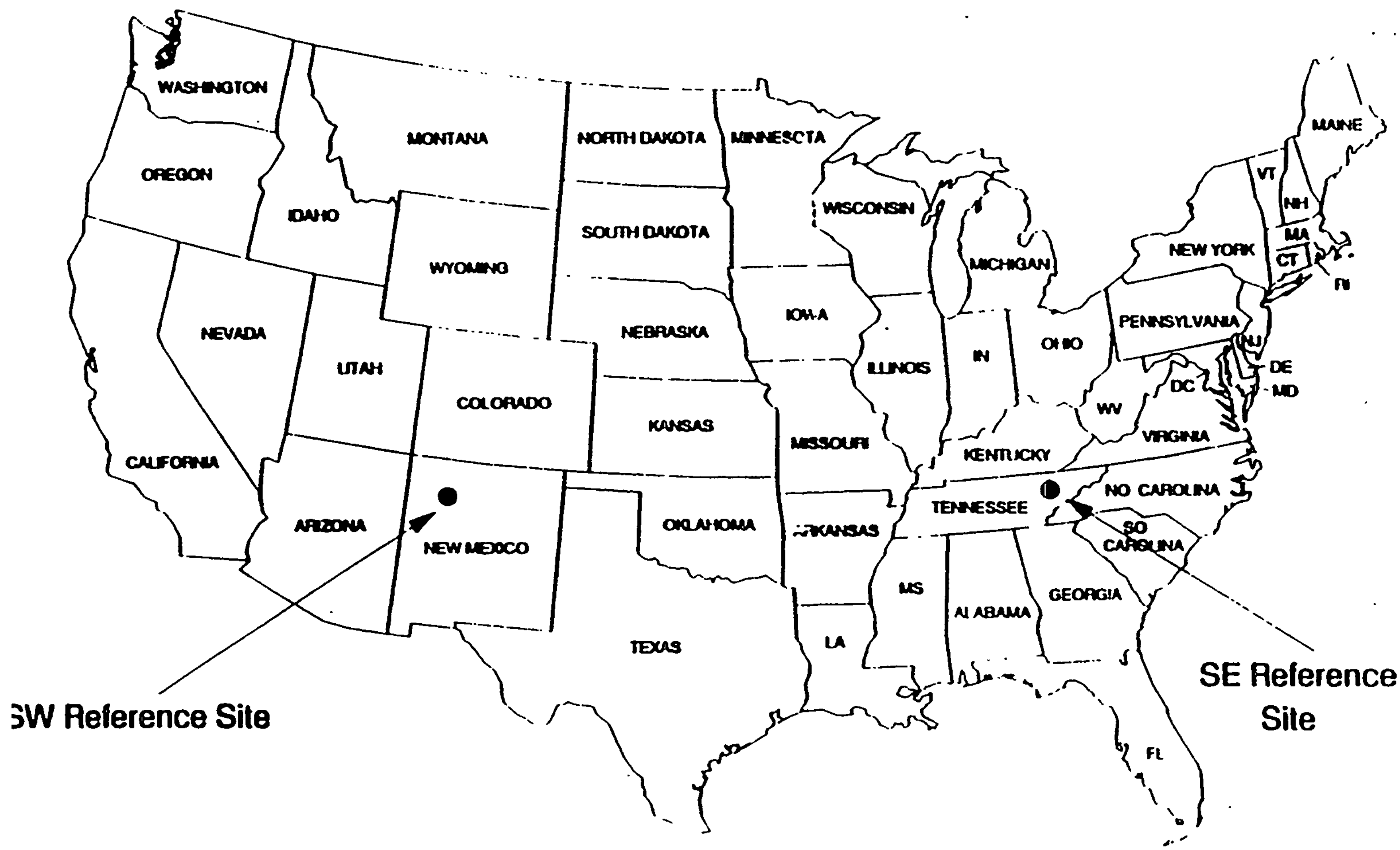


Fig. ES-2 Map of reference sites

ES.8 CONCLUSIONS

ES.8.1 Scope of the Study

The main goal of the study was to demonstrate methods for estimating damages and benefits. Thus far, selected damages and benefits have been addressed. The numerical results are in no respect definitive, generic estimates. The sites considered were for illustrative purposes. They are not representative of all, or even likely, sites in the U.S. The idea of the study was not to estimate damages and benefits that could be applied through the U.S., or even to other sites in the same region. Nor are these sites actual options. They are so numerous and different in their site characteristics that no single study could encompass all options.

In practice, analysis of every fuel-cycle activity, emission, and impact is impossible. Practical implementation of the damage function approach requires selecting some, but not all, of the impacts for detailed analysis. This selection is based on an informed a priori assessment of the more important impacts in terms of the magnitude of their damages or benefits. Not all impacts are addressed. However, since the primary objective of the study was to demonstrate methodology, whenever time or resource constraints required a tradeoff between analyzing more impact-pathways, but for only one site, versus fewer impact-pathways assessed for both sites, a decision was frequently made to consider more impact-pathways, but for only one site.

ES.8.2 Usefulness of the Damage Function Approach

This study has demonstrated that the damage function approach is an operational method for estimating many of the damages and benefits of a natural gas fuel cycle. Also, as more studies are done using this approach, it will be easier and less costly to implement. Insofar as many countries are considering ways of internalizing the external damages of fuel cycles, it seems all the more important to invest in thorough assessments. Regulatory burdens imposed on utilities and others can be very costly. They should be justified by thorough study. By the same token, the external damages to health and to the environment should be accounted for and reflected in energy prices. The method demonstrated in this study represents an important step in this direction. Thus, ***in spite of its limitations and the gaps in the base of scientific knowledge, the results gained from studies using this approach would add to the base of knowledge*** to support informed decisions about energy, and specifically about natural gas options. Such results extend beyond numerical estimates. They include estimates of the uncertainty and quality of the estimates; the identification of various analytical tools, dose-response functions, and valuation functions; and information about impacts that are not quantified.

ES.8.3 Marginal Damages and Benefits

Of the impacts that were quantified, the ***major sources of damage from the natural gas fuel cycle are ozone and particulate matter.*** Based on inspection of data on ambient ozone concentrations in the rural Southeast, high ozone concentrations are not uncommon. High ozone concentrations are associated with elevated rates of respiratory illnesses. Estimated damage to the population in the vicinity of the benchmark plant at the Southeast Reference site was 0.068 mills/kWh from morbidity. Ozone-related crop damage was estimated to be 0.06 mills/kWh. Damage attributed to an expected increase in morbidity from exposure to particulate matter was estimated to be 0.038 mills/kWh at the Southeast site, assuming a health-effects threshold of 30 $\mu g/m^3$. The value of the expected increase in *mortality* associated with particulate matter exposure was estimated to be 0.033 mills/kWh at the Southeast site (again, assuming a threshold of 30 $\mu g/m^3$). Other health effects were at least an order of magnitude less than the damages from ozone and particulate matter. Because of the negligible SO_2 emissions, exposure to secondary particulate matter is not expected to be a significant concern.

Since most of the quantified damages were health-related, if the power plant were situated in a region with 10 million people nearby, rather than only one million, as in the Southeast Reference site, then the quantified damages would be significantly greater -- assuming that meteorological conditions, topography, population density, and demographic characteristics are comparable at the two sites. In general, the ***size of the nearby population is a major determinant of the level of damages from the natural gas plant.*** Simply put, the greater the number of people exposed to a pollutant, the greater the expected health impacts.

Global climate change results from CO_2 emissions and other greenhouse gasses. But their damage is uncertain. Estimates in the literature are imprecise and not very reliable. Notwithstanding these caveats, it is interesting to note that estimates of the cost of global climate change, which are based on literature that is representative of much of the current thinking (in 1996), are about 2.9 - 3.9 mills/kWh. This estimate is based on greenhouse gas emissions from the power plant, which would comprise most of the greenhouse gas emissions from natural gas fuel cycles in the U.S. Leakages of methane from gas pipelines are minimal in the U.S., but may be very significant in other countries. Thus, even though CO_2 emissions from natural gas fuel cycles are the least (on a per kWh basis) among fossil fuel technologies, these emissions may nevertheless lead to significant externalities.

Estimates of damages are highly uncertain, and are project- and site-specific. The estimates should not be summed and then compared, either between the two regions or technologies, or among alternative fuel cycles. There was generally a lack of quantitative information on ecological exposure-response functions. Also, some impacts were quantified at one site, but not at the other. The same differences are true among the different fuel cycle studies (e.g. oil, biomass, and coal). It is, however, informative to compare **individual** impact-pathways -- between sites, technologies, or fuel cycles.

Finally, note that the relative size of damages in these various categories may not be indicative of the relative size of the externalities associated with these damages. In most cases, the damages estimated in this study are externalities. But detailed analysis is required to conclusively make this determination with due regard for the policy setting, tax rates, and other factors particular to the pollutant or activity generating the damage or benefit and its location (see Freeman, Burtraw, Harrington, and Krupnick 1992 for a full discussion). Numerical estimates should never be used in policy making and planning decisions without assessing the underlying assumptions and study context.

ES.8.4 Information Needs

A major conclusion of this study is that while the scientific base of knowledge is reasonably good in some areas, it is certainly lacking in others. The paucity of quantitative estimates of ecological impacts is particularly striking, all the more so for regional and global impacts that extend well beyond the local site of a natural gas power plant. The many interacting factors in ecological systems make it difficult to identify well-defined functions describing the impacts of changes in pollutant concentrations on ecosystems. ***Given the current state of knowledge, it will generally be very difficult to develop quantitative estimates of ecological damages caused by fuel cycles.***

In the health effects area, the air inhalation pathway was considered in some detail. However, some of the more important health-effects estimates rely on a few or sometimes individual studies. The ***lack of health-effects studies is an obvious weakness which can be overcome with additional research.*** The lack of information about the effects of effluents on aquatic ecosystems and effects related to solid wastes have not been addressed. The ingestion of pollutants through the food-chain is another area where the knowledge base is lacking. Also, priorities should be established to ***develop better long-range atmospheric transport models*** that are reasonably accurate and that are also inexpensive to use in terms of their demands on data.

In economics, a major issue in this area of research is the accuracy and precision of estimates of individuals' willingness to pay (WTP) to avoid certain ecological impacts or health risks. In using estimates of ***WTP, significant issues arise in the transferability issue*** — the application of results obtained in one location or context to another. Other major issues are aggregation and non-use value. Aggregation refers to the practice of how to best add damages and benefits to obtain an overall measure. Non-use value refers to individuals' willingness to pay for certain environmental conditions, even though the individuals may never experience those conditions themselves.

Finally, all of the caveats regarding the interpretation of the numerical results bear repeating:

- The analyses were performed on a number—but not all—of the possible effluents and impacts.
- Limitations in the knowledge base precluded quantitative estimates on most ecological impacts.
- The analyses are project- and site-specific.
- Because of these and related limitations in the analyses, the numerical results in this report should not be used in any definitive comparison of externalities from alternative sources of energy.

1. INTRODUCTION

1.1 BACKGROUND

The social accounting concept is of interest to many institutions in the United States and elsewhere as a means of assisting in energy and environmental decision making. Social accounting seeks to make explicit all the social costs and benefits resulting from production and consumption decisions.[1] Ideally, a system of social accounts reflects two components: private costs (e.g., capital, operating, and maintenance costs); and externalities (incremental costs and benefits that, for various reasons, are not explicitly reflected in electricity-market transactions but that, nevertheless, have value). External costs and benefits include environmental quality, health, as well as nonenvironmental considerations.

Estimating the externalities of energy production and consumption requires information about many complex factors. Information is needed about: (1) the total *fuel cycle* for each energy source, which is defined in this study as beginning with the development and extraction of the energy resource and ending with the disposal of its wastes; (2) the production processes and technologies at each stage of the fuel cycle, particularly about *emissions* and other residuals; (3) changed *concentrations* and deposition in the environment that result from the emissions and residuals; (4) the incremental consequences, or *impacts*, that result from these changed concentrations, or from other physical changes, in the environment; (5) the magnitude to which these impacts are valued by individuals as economic *damages,* or as *benefits*; and (6) factors to distinguish between *externalities* and the costs and benefits that are already "internalized" within market prices. This series of information needs corresponds to the identification of *"impact-pathways,"* in which the effect of an emission is traced from its source to its ultimate damage or benefits. The term emission is used here to mean any residual or altered chemical or physical condition. Further discussion on these concepts is provided in the Background Document for this study (ORNL/RFF 1992).

This impetus for this study was the U.S. Department of Energy's National Energy Strategy (DOE 1991), which was published as a guide for the United

[1]The term "social costs and benefits" refers to conditions that have economic value to individuals. These conditions may be environmental, health-related, socioeconomic, or any other nature.

States' energy future. It stated that "analysis is needed to account for the full costs and benefits of energy production and fuel consumption, especially taking into consideration environmental, public health, and safety concerns" (DOE 1991 p. 145). It recognized that the lack of high-quality information about external costs and benefits was a handicap to making good decisions about energy. This problem was apparent both at the federal level, in terms of allocating energy research and development budgets, and (at the time of the beginning of this study) at the state Public Utility Commission (PUC) level, in terms of conservation, fuel cycle, and technology choices. Both sets of decisions have large implications for the nation's energy future. Consequently, DOE launched a major initiative to provide a foundation for sound decision making. The European Commission (EC) had come to much the same realization—that the external costs and benefits of fuel usage could not be understood, estimated, and correctly applied given the current state of knowledge. Thus was born this joint U.S.-EC study of fuel cycle externalities.

More recently, state regulation of electric power in the U.S. has been undergoing a revolutionary restructuring. This restructuring will deregulate most of the industry and, hopefully, will reduce costs to consumers. A direct consequence of this restructuring, however, is that externalities will *not* be formally considered in the electric power planning process. Nevertheless, concern remains about the environmental and health effects of fuel cycles, particularly in countries other than the U.S.

This report documents the U.S. research team's analysis of the natural gas fuel cycle, in which natural gas is extracted and used to generate electricity. This report is essentially self-contained so that some if its material overlaps with that in the reports on the other fuel cycles.

1.2 STUDY PRIORITIES AND CAVEATS

The major objectives of this study were three-fold:

(1) to implement the methodological concepts which were developed in the Background Document (ORNL/RFF 1992) as a means of estimating the external costs and benefits of fuel cycles, and by so doing, to demonstrate their application to natural gas fuel cycles;

(2) to develop, given the time and resources, a range of estimates of marginal (i.e., the additional or incremental) damages and benefits associated with selected impact-pathways from a new natural gas-fired power plant, using

a representative benchmark technology, at two reference sites in the United States; and

(3) to assess the state of the information available to support energy decision making and the estimation of externalities, and by so doing, to assist in identifying gaps in knowledge and in setting future research agendas.

The demonstration of methods, modeling procedures, and use of scientific information was the most important objective of this study. It provides an illustrative example for those who will, in the future, undertake "actual" studies of "real" power-plant options at "real" sites.

As in most studies, a more comprehensive analysis could have been completed had time and budget constraints not been as severe. Particularly affected were the air and water transport modeling, estimation of ecological impacts, and economic valuation.[2] However, the most important objective of the study was to demonstrate methods, as a detailed example for future studies. Thus, having severe time and budget constraints was appropriate from the standpoint that these studies could also face similar time and budget constraints. Consequently, a more important result of the study is an indication of what can be done in such studies, rather than the specific numerical estimates themselves.

Obviously, is not appropriate to apply blindly the numerical results of this study to compare different fuel cycles:

(1) All of the potentially important impacts were not necessarily addressed because of limitations in the state of scientific and economic knowledge or because of study priorities and inevitable time and budget constraints.

(2) Impacts are project-specific. Different power plant specifications will change the magnitude of the residual damages and benefits.

(3) Impacts are generally site-specific. It would be erroneous to extrapolate, without appropriate analysis, the numerical estimates for the two sites analyzed in this study to other sites. In particular, the two sites are not intended to be representative of all sites in the country, nor even to be economically viable alternatives. Rather, the sites were selected so as to compare individual impacts across fuel cycles using a common

[2]While the phrase "economic valuation" is redundant to economists, it is used in this study to be clear that residual damages and benefits are valued in economic terms.

environmental baseline. The sites are plausible from a physical standpoint, though not necessarily from an economic or regulatory one.

(4) Limitations in knowledge preclude quantitative estimates of many ecological impacts. The effect of these limitations on the ability to derive quantitative estimates may vary for different fuel cycles.

(5) Aggregation errors may arise from adding estimates of damages that are estimated separately for individual impacts.

(6) While the damages and benefits that were estimated are candidates for externalities, a comprehensive study has not yet been completed to take into account regulatory, taxation, and other factors that may internalize some portion of those damages.

(7) This study is primarily a demonstration of methods, rather than a conclusive comparison of alternative energy technologies.

1.3 SCOPE OF THE STUDY

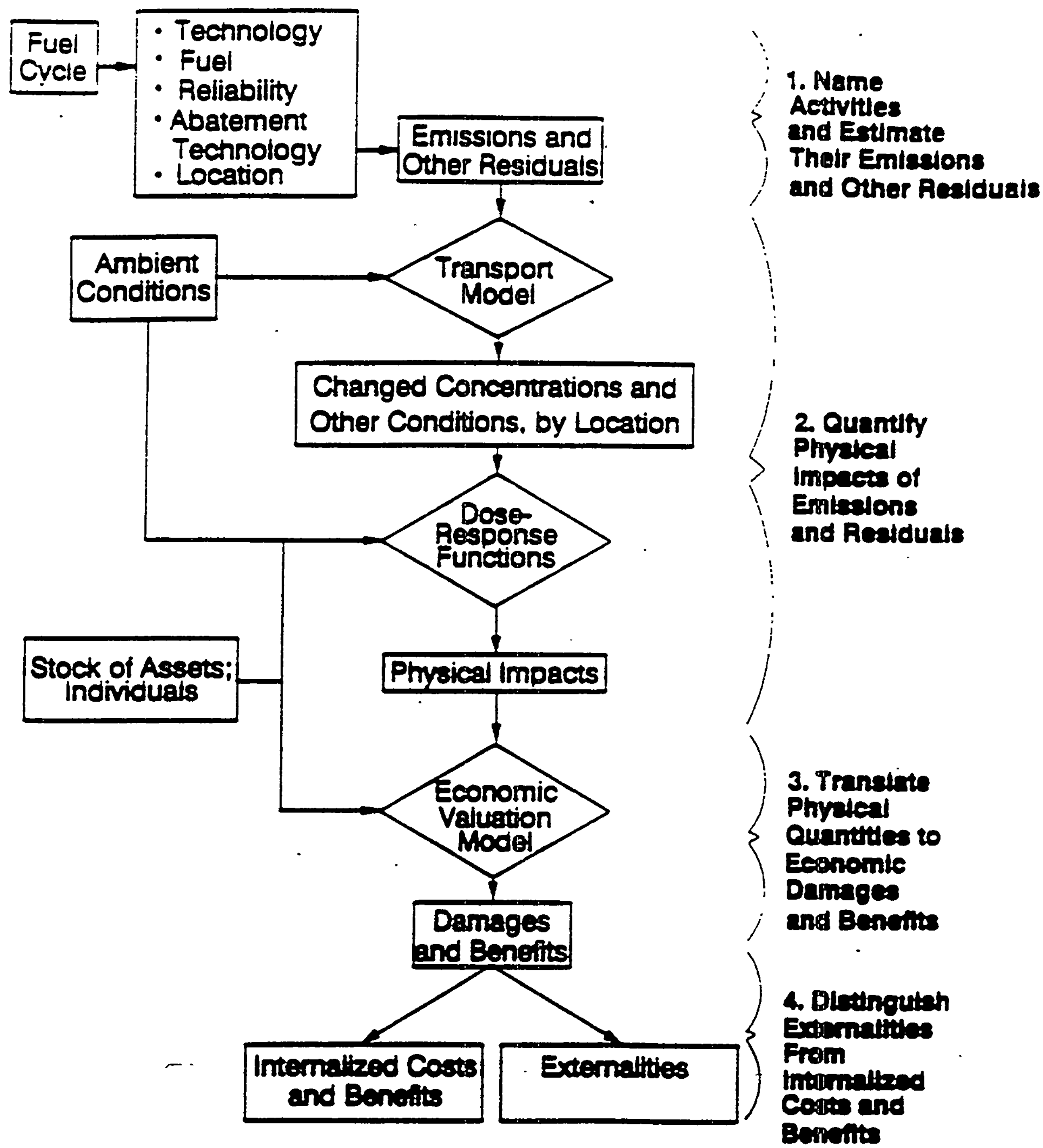
This study established a set of priorities in order to best reach its objectives. All studies must decide how much of the world is critically necessary to include and how much can be held fixed or beyond the scope of the study. Given the relatively unexplored territory faced by this study, many choices had to be made. These are summarized in the remaining part of this section.

Study Approach:

- The Damage Function Approach (DFA) was selected by the study teams as the basic methodology. The DFA combines natural science and economics to identify the changed conditions that stem from an incremental investment. In our study the investment is building and operating a natural gas-fired power plant. Figure 1.2-1 shows a flow chart that illustrates the DFA. It consists of a sequence of analyses in which (1) the major processes, activities, technologies and stages of a fuel cycle are identified; (2) their emissions and other residuals are characterized and estimated; (3) changes in ambient concentrations are estimated using atmospheric transport or other models; (4) ecological, health, or other impacts are quantified using dose-response relationships; (5) these impacts are translated into economic damages or benefits; and (6) these values are distinguished as being externalities or already internalized in market transactions. The DFA is described further in Section 1.3 and in the Background Document (ORNL/RFF 1992).

- A major departure from other approaches, which provide information about residual emissions and impacts, is the use of economic valuation approaches to monetize the physical impacts. Resources or impacts have economic value only because they affect ***individual welfare***, not because they represent so many energy units, labor units, or land units or even health or the ecology *per se*. The assessment of damages and benefits, as defined by the theory of welfare economics, reflects both location-specific impacts and the monetary *value* of these impacts.

Figure 1.2-1. Impact-pathway for damage function approach



- Given the extreme challenges posed by dynamic modeling at the given level of knowledge, in terms of both data and the understanding of the physical and economic processes, the U.S. and EC teams chose to develop a static set of data and relationships. The term "static" describes the lack of feedback and other interactive channels that would normally be active in any systems approach for a given incremental change in generating capacity. For instance, we ignore the effect of more impaired health on wage rates and on demand for commodities.

Fuel-Cycle Assumptions:

- The U.S.-EC studies are based on the fuel cycle concept, which includes fuel extraction, transport, and conversion (or more broadly in the context of certain renewable energy sources, resource use) for the generation of electricity.

- By definition, fuel cycle stages encompass all of the activities involved in: (1) primary resource extraction, transport, and refining into petroleum or other products; (2) transport and storage of products and materials; (3) electricity generation from fuel; (4) distribution of electricity or products; and (5) disposal of wastes. End-use activities are highly varied and should be addressed in future study.

- For the natural gas fuel cycle, the study focused on the following stages of activities: natural gas drilling, extraction and treatment, natural gas processing, the transportation of fuel to the power plant, and electric power generation.

- The scenario considered in this study was the construction and operation of a new generating plant located at a particular site. The natural gas is assumed to be from plausible domestic sources close to processing plants, which themselves are assumed to be nearby the power plant. Natural gas extraction, treatment, processing, transportation, and other infrastructure required to supply the power plant with fuel were assumed to exist already unless they were unlikely to exist without the natural gas plant. Other options—such as adding units to an existing plant, purchasing power from other power producers, or integrated resource planning to meet system-wide or region-wide needs—were not addressed in this study.

- The U.S. and EC teams adopted an incremental investment view of the problem, leaving the operations view to be applied in further extensions of this work. Investment and operation activities are not mutually exclusive but involve a substantially different perspective on the information required to examine pollution emissions and other effects. The operations view requires a complete characterization of the existing production system's activities to capture the change in emissions and other effects from an increase in electricity output associated with bringing a new plant on line. The investment view limits the analysis to characterizing emissions, impacts, and damages associated with the increment to output, holding the rest of the power system constant.

- Similarly, it is more consistent with existing literature to frame the incremental needs of a new power plant than those of a new extraction process. Thus, incremental activities performed within other stages are assumed to reduce under-utilized capacity, unless that activity is dedicated to the new plant.

Scenario Assumptions:

- A benchmark technology was considered. One technology represents a current (i.e. 1990) technology. The other technology represents a future technology, one available in the year 2010. For the current timeframe, we assume that the natural gas-fired power plants built in 1990 use the combined-cycle gas turbine technology. We assume that the natural gas-fired plant built in 2010 will also utilize an advanced high-efficiency combined-cycle gas turbine but will also employ a new combustion concept called "premix lean" to achieve significantly lower NO_x values. Since impacts are project specific, however, different power plant specifications will change the magnitude of the residual damages and benefits. Illustrative calculations using the methodology are reported for the 1990 scenario. Analogous calculations can be carried out for the 2010, or for any other, scenario.

- Power plants come in many sizes, which influence their use in an existing electricity system. A review of current United States utility expansion plans suggested that, for commercial feasibility, coal, nuclear, oil, and gas plants corresponded to medium- to large-scale investment needs; and that hydro, biomass, photovoltaic and wind might satisfy smaller-scale needs. Medium to large scale is 300 megawatts electric (MWe) or larger, while smaller scale is under 50 MWe.[4]

[4] Of course, some plants, particularly gas-fired ones, are in the range 50 to 500 MWe.

The scale set for the benchmark natural gas plant for both timeframes (1990 and 2010) was a 500 MWe capacity. This benchmark plant was assumed to achieve a 74.5% capacity factor producing 3.26 billion kWh per year for 40 years.

Since impacts may have varied temporal distributions, the corresponding damages and benefits must reflect their placement in time: conventionally, this is done either by using a discount rate to derive present values or by using an interest rate for "levelization." The levelized cost is the amount which, when summed annually in equal annual amounts, equals the total present value of the cost over the life of the natural gas plant. This study used a 5% real discount rate, which falls within the commonly considered range of 2% to 10%; and puts all damages and benefits in levelized terms, that is, in mills/kWh.

Impact Scope:

- The scope of impacts includes local, regional, and global consequences. The U.S. and EC teams agreed to examine local and regional impacts first. While there is considerable interest in the association between fuel cycles and the problem of global warming, there is considerable uncertainty and scientific disagreement about the linkage between emissions and measurable physical changes. Thus, this study summarizes a range of CO_2-related damages, based on other studies; and does not recommend any one specific value.

- Impacts are generally site specific (as well as project specific). In this study, impacts were considered in two different regional reference environments reflecting the importance of how differences in location affect impact and damages. For the natural gas fuel cycle analysis, regional reference environments were defined for the Southeast (Clinch River site, Tennessee) and Southwest (Farmington, New Mexico area). See Chapter 4 for a description of the regional reference environments.

1.4 OVERVIEW OF IMPACT-PATHWAYS DAMAGE-FUNCTION APPROACH

The general methodological approach consists of three related concepts: total fuel cycles, the damage function approach, and impact-pathways.

The first concept, the total fuel cycle, refers to the approach in which all stages of the fuel cycle are explicitly considered, beginning with the development and extraction of a resource, and ending with the disposal of all wastes or residuals.

The second key concept is the damage function approach (DFA). This approach uses the existing scientific literature on ecological and health impacts associated with the fuel cycle to identify impact categories, exposure processes that link emissions to impact endpoints, dose-response information to quantify endpoint changes, and various measurement and quantification issues. A detailed discussion of the literature supporting the analysis of ecological impacts from the natural gas fuel cycle can be found in Appendix D. Some of the health impacts are discussed in Appendix E of the Coal Document (ORNL/RFF 1992).

For estimates of incremental damages, the DFA considers each major fuel cycle activity and estimates: (1) the residual emissions or the altered physical conditions; (2) the transport, deposition, or chemical transformations of these emissions and other residuals, and the resulting change in the concentrations of the pollutants and other materials; (3) the physical response of ecological, human, and social resources to these changes in concentrations; (4) the value that is placed on these impacts by the individuals affected; and (5) the distinction between externalities and social costs and benefits which are internalized within the market.

In practice, analysis of every fuel-cycle activity, emission, and impact is impossible. Practical implementation of the damage function approach requires that the more important impacts be selected for detailed analysis.

These more important impacts are analyzed using the third key concept, impact-pathways. This concept is used to define the sequence of linkages or "mappings" for a given activity or process of the fuel cycle (such as electricity generation). Defining an impact-pathway begins with an emission or other residual from an activity, the transport and/or chemical and physical transformation of that emission, the resulting changes in its concentration in the environment, and the effect of that change that results in a specific ecological impact or health effect. This impact is the endpoint of the pathway and the start point for an economic valuation of the impact, what we call a damage, or benefit of that impact. Table 1.3-1 illustrates some general impact and valuation pathway mappings, both at the broad level and at the more specific level.

Table 1.3-1. Impact-pathway mappings

	Broad-Level Mappings	
Fuel cycle stages	→	activities
Activities	→	emissions and other residuals
Emissions	→	transport and change concentration
Transport and changed concentration	→	physical impacts
Impacts	→	economic damages and benefits
Damages and benefits	→	External costs and external benefits
	More Specific Mappings	
Emissions	→	source terms
Source Terms	→	concentrations
Exposures	→	doses
Doses	→	responses
Responses	→	physical impact endpoints
Impact endpoints	→	valuation start points
Valuation start points	→	damages and benefits
Damages and benefits	→	external costs and external benefits

1.5 ECONOMIC VALUATION

Value is intimately connected to opportunity costs: the concept that there is no free lunch, that something must be given up to gain something else. Thus, values are determined in the context of constraints, be they money, time, health, or something else that is valued. These constraints imply that *something has value to the extent that individuals are willing to pay for it* - the so-called willingness to pay criterion in economics that underlies modern benefit-cost analysis. Emissions or other burdens imposed by the natural gas fuel cycle result in health and environmental impacts (which may be positive or negative). These impacts have a monetary counterpart in that people may be willing to pay to avoid such negative impacts (or to obtain positive impacts). Whether these "marginal damages" (or benefits) are counted as a social cost of the fuel cycle external to (and therefore additive to) the private costs of delivering electricity from natural gas depends on the type of policy in place to address these impacts and even on details of its design (see Freeman, Burtraw, Harrington, and Krupnick 1992).

The practical and conceptual problems of economic valuation are discussed fully in the Background Document (ORNL/RFF 1992). However, some general remarks about the valuation process are worth noting here:

- The concept of value is based on decades of research in neoclassical microeconomic analysis. At the core of this notion is consumer sovereignty—i.e., that each individual in society is the best judge of his or her value for a good or resource.

- When damages show up in non-marketed commodities, values are estimated as the individual's willingness to pay (WTP) for an improvement in the state of nature (in terms of reductions in pollution or its physical consequences) or by the individual's willingness to accept (WTA) compensation to tolerate a worsening of the state of nature.

- Standard economic methods to valuing changes in welfare may be used when damages show up in marketed products, such as using demand and supply models to derive price and quantity changes, which, in turn, provide the basis for damages.

When impacts occur in non-marketed commodities, two broad approaches have been developed to estimate damages: the contingent value (CV) and indirect approaches. Both of these approaches have been developed over decades and continue to evolve and improve, although significant problems remain and significant types of impacts have yet to be credibly valued.

Even with all of this research activity, effort has been unevenly distributed among the benefit categories. The most effort has clearly gone into the theory and estimation of recreation and mortality benefits. Mortality benefit studies have derived values for reducing risks of accidental death that are quite consistent with one another. However, very few studies have obtained values for reducing mortality risks arising from environmental improvements. Substantial research has also addressed the valuation of pollution effects on health, visibility, and economic production, particularly on the effects of ozone exposure on field crops. Valuation of damages to materials and to ecosystems (including endangered species) is largely unexplored, although much effort has recently been placed on the natural resources damage assessment process particularly applied to the Exxon Valdez oil spill.

The CV methods involve asking individuals either open- or closed ended questions to elicit their willingness to pay in response to hypothetical scenarios involving reductions in health or environmental risks or effects.[5] The major advantages of these approaches are that they can be designed for *ex ante* situations,[6] the good being valued can be specified exactly to match other information available to the analyst (such as the endpoint specified in a dose-response function), and the survey can be administered to a sample appropriate for the good being valued (whether representative of the general population or of some other group, such as older people). Further, for some types of values, such as existence values, there are no other means of obtaining values. On the other hand, the hypothetical and often complicated nature of the scenarios raises serious concerns about whether individuals can process the information provided and have enough motivation and familiarity with the "goods" being valued to respond as if they were in a real situation. Concern over strategic bias[7] appears to have been overcome and much recent research has attempted to systematize and standardize the development and conduct of these surveys (Mitchell and Carson 1989; Cummings, Brookshire, and Schulze 1986), in terms of payment vehicle, treatment of risk in the scenarios, open versus closed-ended questions, and other issues such as how questions are phrased. Additional research has attempted to compare values elicited from CV surveys to

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[5]Open-ended questions ask individuals for their WTP, either in a bid format, on a payment card, or some other method that seeks a best estimate from the individual. Closed-ended questions involve asking individuals whether they would be willing to pay as much or more than a given amount. This latter approach is less demanding of individuals, while still permitting recovery of values for the group.

[6]This means that WTP for some future change in the state of nature can be elicited. This is the appropriate perspective for valuation. In contrast, other methods must rely on realized (or *ex post*) information to infer *ex ante* values.

[7]This is the term for the act of willfully offering misleading answers in the hopes of influencing the outcome of the survey and, ultimately, of policy.

values obtained by indirect methods (see below), generally finding close agreement. It should be recognized, however, that such comparisons are possible only for certain classes of non-marketed goods. For obtaining existence values, for instance, CV methods are the only available approach.

The indirect approaches (sometimes called revealed preference approaches) seek to uncover values for the non-marketed environmental goods by examining market or other types of behavior related to the environment as substitutes or complements. For example, treating money (in the form of a wage premium) as a substitute for on-the-job safety, the relationship between wage rates and accidental death rates in different occupations has been statistically examined, with the finding that such premiums do exist. These premiums represent a value for reducing risks of premature death that can be used to value occupational health and safety risks posed by alternative fuel cycles and, with appropriate caveats (see below), to value risks to life posed by environmental pollution. As another example, environmental quality and recreation are complementary in the sense that more visits will be made to recreation sites with better environmental quality. Observing behavior in the choice of recreation sites and the frequency of visits to sites of different levels of water quality and relating this behavior to miles and time for travel to the site has revealed willingness to pay for improvements in water quality at recreation sites.

As a third example, when costs are incurred to avoid impacts, these goods may be viewed as substitutes for environmental quality. By tracking spending on goods used to avoid pollution or its effects, one can gain some idea of WTP. For instance, if people buy bottled water solely to protect themselves from toxins in their tap water, we know that their willingness to pay for avoiding health risks from these toxics is at least equal to the cost differential between bottled and tap water. As pain, suffering, and other non-pecuniary costs are omitted from consideration, this approach provides underestimates of willingness to pay, assuming the other problems with this approach have been avoided. Unfortunately, if the substitute good provides other benefits, the estimates could be too large.

Aside from the problems and successes in applying valuation techniques to nonmarket commodities, there are special issues associated with valuing health and environmental damages in the context of the fuel cycle study: transferability of benefits/damage estimates and functions from one location or context to another; aggregation of damages across endpoints, locations, stages of the fuel cycle, and individuals; treatment of nonlinearities in damage functions; matching physical endpoints with economic start points; and treatment of the temporal perspective, including discounting/levelization. These issues are addressed in some detail in the Background Document (ORNL/RFF 1992).

Because of both conceptual and empirical difficulties raised by these special issues, the reader should be cautioned about the interpretation of the estimates of damages and benefits contained in this report. While reasonable attempts were made to estimate damages and benefits specific to the reference environments, some "short-cuts" were taken and strong assumptions made to address these special issues, particularly transferability, aggregation, and nonlinearities.

Transferability particularly becomes a difficult issue for assessing recreation damage, because the quality and availability of recreation assets varies greatly across locations. Had recreation impacts been estimated for the natural gas cycle as part of this study, these difficulties would have received much attention. As it was, we could not estimate any noticeable impacts. Therefore, the "benefits transfer" issues remain largely unexplored. Where benefits transfers could be made, for health pathways in particular, we assumed direct transferability of health dose-response functions and unit values (or valuation functions) from the setting and location in which they were derived to the reference environment. This assumption is reasonable where income and socioeconomic characteristics are not much different across locations. Even if such characteristics were different, this situation would be unimportant for the transfer unless these characteristics affected marginal responses or valuations. In general, dose-response and valuation functions are not specified to admit any marginal influences of these characteristics.

The aggregation issue was not dealt with in a sophisticated way, either, primarily because of lack of empirical studies to guide a more satisfying treatment. We intentionally do not sum the estimated residual damages and benefits. One of many reasons is that not all impact-pathways were valued. However, another reason is that in reality, individuals in the reference environment would be confronted with (offered) a package of impacts (both positive and negative) associated with the new plant. Their WTP to avoid or obtain this package may not necessarily equal to the sum of their WTP for each impact, depending on complementarity or substitutability of impacts (as well as physical interdependencies not picked up in the modeling of emissions to concentrations or concentrations to physical response).

The nonlinearity issue arises because many damage functions are non-linear, in that the estimate of damage depends on baseline emissions, concentrations, or physical impacts. This issue is handled reasonably well for the assessment of the ozone-morbidity damage pathway. There, the non-linearity in concentration-response functions is addressed by estimating impacts using a frequency distribution of daily peak ozone concentrations, rather than using the annual average of the daily peak readings. This issue does not even arise with some important pathways. Most notably, the concentration-response functions for the particulate-mortality pathway fit the linear model very well. Thus, the strategy of using temporally disaggregate air quality data to estimate this damage function is not necessary. For other functions, however, practical considerations have dictated that we use linear versions of non-linear functions. Note here that we do use a nonlinear valuation function for estimating WTP to avoid increased risks of premature death, where the nonlinearity is related to the size of the risk change.

The issue of *non-use* values, while not an issue special to this project, is nonetheless particularly controversial. One side in the debate over whether such values can be credibly estimated asserts that lack of familiarity with the "goods" at issue (such as an ecosystem, an endangered species, or a wilderness area) and the embedding effect (i.e., where WTP is sensitive to whether a good is valued by itself or as part of many other goods) make it inherently impossible to reliably estimate the WTP for such goods through hypothetical questioning. It is asserted (Kahneman and Knetch 1992) that observed WTP values are for the purchase of "moral satisfaction" not a WTP for marginal changes in the good. The other side suggests that the studies relied upon for these conclusions are faulty and that normal economic behavior can explain most of the observed allegedly inconsistent patterns of WTP responses (Smith 1992). Similar conclusions have also been reached about an Exxon-funded effort that concluded CV was an unreliable tool for eliciting non-use values. For example, one of the studies purporting to show that individual bids for saving ducks were insensitive to the number of ducks being saved (i.e., from 2,000 to 200,000 ducks annually (Desvousges et al. 1992)) has been criticized for defining scenarios that involve, in fact, a very nearly identical percentage of ducks being saved (from 1 to 2% of ducks on the flyway). In such a case, it may be unremarkable that WTP estimates for a group of individuals responding to one scenario are very similar to those from a group responding to a different scenario. One reason for our sparse treatment of non-use values is that the literature primarily addresses major changes in special ecosystems or species elimination whereas the changes to environmental assets associated with a single power plant are likely to be very small and the assets themselves may not be unique enough to generate substantial non-use values.

1.6 REPORT OUTLINE

This report demonstrates the collection, assessment, and application of existing literature to estimate selected damages and benefits from the natural gas fuel cycle. In Section 2, a brief review of other recent attempts to accomplish this goal is provided for contextual background. Section 3 provides a discussion of the organization and interpretation of the results. This discussion is critical to interpreting the intent of the analysis which follows in Sections 4 through 10--the intent being a detailed demonstration of methodology. Section 4 provides a technical characterization of the natural gas-to-electricity fuel cycle. Section 5 summarizes the major emissions and other residuals of the natural gas-to-electricity fuel cycle. Section 6 presents the priority pathways selected for more in-depth analysis, discussed in greater detail in Sections 7 to 10. Section 7 presents analysis of some of the major impacts and damages associated with drilling, extraction, and treatment of the natural gas. Section 8 discusses impacts from natural gas processing activities. Section 9 presents impacts and damages from the transportation stage of the fuel cycle. Section 10 presents impacts and damages from natural gas combustion. Section 11 presents a summary of the results and key conclusions.

Appendices A through D provide additional discussion. Appendix A provides supplementary information on natural gas and oil industry regulations. Appendices B and C present details of the atmospheric transport modeling and its results. Appendix D reports on the ecological impacts related to the natural gas fuel cycle.

2. PRIOR STUDIES OF DAMAGES AND BENEFITS FROM THE NATURAL GAS FUEL CYCLE

Several studies share similar characteristics with this study. These studies include *Environmental Costs of Electricity* by the Pace University Center from Environmental Legal Studies (1990), *Valuation of Environmental Externalities for Energy Planning and Operations* by the Tellus Institute (1990), *Social Costs of Energy Consumption* by Olav Hohmeyer (1988), papers from an ongoing study in the Australian state of Victoria and *America's Energy Choices* published by the Union of Concerned Scientists (1992). The following sub-sections briefly summarize the studies.

2.1 PACE REPORT

The intent of this study is "to review the literature on the methodologies used to assign monetary costs to environmental externalities and to present the results of studies which have applied these methodologies" (Pace 1990). Estimates in the Pace (1990) report are drawn from previous studies. Lack of economic valuation information for certain impacts causes these impacts to be excluded from the computations of economic damages. Notwithstanding its limitations, the Pace (1990) report stands as a comprehensive, path-setting, often-cited reference on the environmental costs of electricity.

The Pace study follows a five-step procedure in valuing environmental damages. The first step ascertains "the pollution sources, the quantity of...emissions and the constituents of the emissions that can cause environmental damages" (Pace 1990). The second step determines the dispersal of the emissions. Step three determines the populations (including people, flora and fauna) and the materials exposed to the pollutants. The fourth step determines the impacts on those populations and materials exposed to the pollutants. The fifth step estimates the economic value of that exposure. The economic value of risk involved with an environmental good or service was measured in terms of willingness to pay, the amount society would be willing to pay to avoid the environmental risk, and in terms of willingness to be compensated, the amount society would have to be compensated in order to incur the damage.

The report treats the effects of electricity generation on humans, flora and fauna, materials, and social assets (e.g., climate, recreation, and visibility). The damage estimates for SO_2 and NO_X are based primarily on health effects calculated from ECO Northwest's *Generic Coal Study* (1987). Dose-response relationships used for SO_2 were linear. Pace (1990) points out that this would not be a valid assumption for geographic areas with ambient air pollution concentrations different from the Northwest, for which these dose-response relationships were estimated. Estimates of the value of life are based on hedonic wage studies. The health effects costs for NO_X and SO_2 are heavily dependent on population density.

Particulate damages result primarily from visibility degradation (ECO Northwest 1984) with a large portion attributable to health effects (ECO Northwest 1987). Visibility effects of particulates are based on estimates of visibility impairment (person-kilometers of visibility lost) and their economic values; ECO Northwest (1984) chose the value of visibility from a range of values in studies they reviewed that used either contingent valuation or hedonic pricing, or both. The cost of CO_2 emissions reduction is based on the cost of sequestering carbon in trees in order to reduce climate change. Table 2.1-1 shows the tabulation of damage estimates in the Pace (1990) report.

Data are provided for two different natural gas-fired technologies--boilers and combined cycles. The combined cycle technology illustrates a scenario with no add-on controls and a scenario with the best available control technology (BACT) for NO_X and particulate control. No data are provided on water emissions, dust, sludge, or iron oxides. Emission rates and valuations are given in Table 2.1-2.

Table 2.1-1. Tabulation of damage estimates in Pace report (dollars/pound).

	Impact endpoint								
Pollutant	Mortality	Morbidity	Crop losses	Livestock	Timber	Materials	Ecosystems	Visibility	**Total**
SO_2	1.72	0.05	0.00	*a*	*a*	0.12	NA	0.14	**2.03**
NO_X	0.34	0.29	0.01	*a*	NA	0.01	NA	0.17	**0.82**
part.	0.33	0.03	0.00	0.00	0.00	0.00	0.00	0.83	**1.19**
CO_2	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	**0.0068**
Total	**2.39**	**0.37**	**0.01**	**0.00**	**0.00**	**0.13**	**0.00**	**1.14**	

Source: Pace University 1990. Pace University Center for Environmental Legal Studies, Environmental Costs of Electricity, prepared for New York State Energy Research and Development Authority and the U.S. Department of Energy, Oceana Publications, Inc. New York, pp. 209, 228, 276, 351.

[a]No information is given.

NA indicates not available.

Table 2.1-2. Emission rates and valuations in Pace (1991).

	Existing Steam Plant		Combined Cycle		BACT (SCR, SWI)	
	emission tn/GWh	valuation mills/kWh	emission tn/GWh	valuation mills/kWh	emission tn/GWh	valuation mills/kWh
SO_2	0	0	0	0	0	0
NO_X	1.290	2.116	1.89	3.0996	0.189	0.3099
Part.	0.016	0.037	0.0135	0.0321	0.0009	0.0021
CO_2	572	7.779	495	6.732	495	6.732
Total		**9.932**		**9.864**		**7.0441**

Source: Pace University 1990. Pace University Center for Environmental Legal Studies, *Environmental Costs of Electricity*, prepared for New York State Energy Research and Development Authority and the U.S. Department of Energy, Oceana Publications, Inc. New York, p. 357.

2.2 TELLUS REPORT

The Tellus report (1990) develops damage estimates for air emissions using an abatement cost approach. This method is different from the approach followed in this report and in ECO Northwest (1984, 1987) and Pace (1990). Abatement costs are viewed as an indicator of revealed political preference.

The report analyzes existing and proposed regulations in order to "estimate the value that society implicitly places on specific environmental impacts" (Tellus 1990). This method identifies the cost of implementing the technology required to meet the standards set by the regulations. This value is then taken as the value that the regulators, and thereby society, have placed on air emissions. The standards are regarded as the "revealed preference" of the regulators.

Abatement or control costs, however, do not necessarily reflect the costs of environmental risks faced by society. In order for a regulation-based cost to represent the cost of that risk, it must be assumed that legislators choose optimal control technologies--those equating costs and marginal benefits, rather than those based on a political, health, or distributional basis. Another limitation of the abatement cost approach is temporal. Past or current regulations may bear little resemblance to current damage costs.

The revealed preference approach is used to estimate the damages of eight air pollutants: (1) oxides of nitrogen (NO_X); (2) oxides of sulfur (SO_X); (3) particulates, both total suspended particulates (TSP) and particulates under 10 microns (PM_{10}); (4) volatile organic gases, volatile organic compounds (VOCs) and reactive organic gases (ROGs); (5) carbon monoxide (CO); (6) carbon dioxide (CO_2); (7) methane (CH_4); and (8) nitrous oxide (N_2O). The first five are under federal regulation standards. The basis for the revealed preferences are federal standards and the South Coast Air Quality Management District (SCAQMD) regulations.

Table 2.2-1. Tellus valuation of emissions based on abatement costs.

	Abatement Costs (constant 1989 dollars per pound)		
Emissions	Area-specific	Southern California	Global
Nitrogen oxides (NO_X)	3.25 (Northeast U.S.)	131.00	*a*
Sulfur oxides (SO_X)	0.75 (Entire U.S.)	37.50	*a*
Volatile organic compounds (VOCs)	2.65 (Non-attainment areas)	14.50	*a*
Particulates	2.00 (Entire U.S.)	22.00	*a*
Carbon monoxide (CO)	(not figured)	0.41	*a*
	Greenhouse gases		
CO_2	*a*	*a*	0.011
CO	*a*	*a*	0.024
Methane (CH_4)	*a*	*a*	0.11
Nitrous oxide (N_2O)	*a*	*a*	1.98

Source: Tellus Institute 1990. Valuation of Environmental Externalities for Energy Planning and Operations.
[a]No figures given in report.

Different fuel cycles are used to estimate the abatement costs. For example, cost estimates for controlling NO_X emissions are based on control technologies for new natural gas turbines in the northeast United States, but on afterburner controls in southern California. SO_X estimates for the Northeast are based on control technologies for coal-fired electricity generating plants, while southern California estimates are based on oil refinery cracking. Thus, damages from pollutants are estimated on a dollars per pound basis, regardless of the fuel cycle.

The pollutants CO_2, CH_4, N_2O, CO, and NO_X are referred to as the greenhouse gases because increased atmospheric concentrations of these pollutants can contribute to global warming and associated local and regional climate change. Since no regulations exist for these greenhouse gases, estimates are made for regulations which may result in the future. Externality costs for CO_2 are based on the mitigation cost of tree planting [as in Pace (1990)]. The costs of CH_4 and N_2O, and the greenhouse effects of CO and NO_X are based on the value of a global warming potential (GWP) index that weights each greenhouse gas relative to CO_2 with respect to its global warming impact. These weights are applied to the CO_2 costs to derive the costs of the other greenhouse gases. This methodology is based on the premise that because CO_2 and the other greenhouse gases all contribute to the greenhouse effect, it is reasonable to assume that the effects of the other gases could be offset by CO_2 controls.

2.3 HOHMEYER REPORT

One of the first attempts to develop fuel cycle-based social costs for fossil fuels and renewables was by Hohmeyer (1988). The purpose of the Hohmeyer (1988) study is "to give a first systematic evaluation of the external effects of energy systems" (Hohmeyer 1988, p. 1). The study's premise is that the market diffusion of energy systems using new and renewable sources of energy (such as solar and wind) is occurring much slower than the external costs and benefits would deem necessary. Fossil energy is grouped together and includes hard coal, lignite, petroleum, natural gas, and other solid fuels such as peat. Hohmeyer (1988) proceeds differently from the research in the present volume. The current study applies the damage function approach to estimate the marginal damage from an additional generation plant of a given technology operating in a specific reference environment. Hohmeyer (1988), on the other hand, estimates the total damage in the country (Germany).

Hohmeyer's approach is to estimate the fraction of "toxicity-weighted" emissions caused by electricity generation from fossil fuels (28%) and then to multiply this fraction by estimates of total damages from all pollution to various endpoints (health, forests, animals, etc.) in Germany that have been estimated by other researchers, primarily Wicke [referenced in (Hohmeyer 1988)]. For instance, to estimate health effects from fossil fuels, total health costs are estimated first from existing studies and then an assumption is made about the portion of these costs attributed to air pollution (for Wicke, 20 to 50%). Multiplying by 0.28 yields the estimate of health costs. In contrast to our approach, Hohmeyer's approach is not marginal or incremental, is not location specific, and does not draw any distinction between damage and externalities. Without further analysis of the

Wicke study and other studies cited, a judgement about the credibility of these damage estimates cannot be made. Table 2.3-1 shows the chain of calculations.

Damages to flora, fauna, and other endpoints are determined in the same manner. Hohmeyer takes the total damages for each population discussed--flora, fauna, mankind, materials, and climate--and attributes 28% of the damage to electricity production to arrive at his damage estimates. Table 2.3-2 lists these estimates.

Table 2.3-1. CO_2-equivalent damage potentials of different pollutants estimated by Hohmeyer.

Air pollutant	Emissions from power plants and from combined heat and power plants (million tons per year)	Toxicity factor	CO_2-equivalent weighted damage potential
Carbon monoxide (CO)	0.033	1.0	0.03
Particulate matter	0.152	100.0	15.20
Nitrogen oxide (NO_X)	0.859	125.0	107.38
Sulfur dioxide (SO_2)	1.863	100.0	186.3
Volatile organic compound (VOC)	0.01	100.0	1.0

Source: Hohmeyer, O. 1988. *Social Costs of Energy Consumption: External Effects of Electricity Generation in the Federal Republic of Germany*, Springer Verlag, New York.

Hohmeyer treated many of the subsidies to fossil fuels as externalities. The issue remains, however, of whether these subsidies actually affect prices and production costs. Many types of subsidies, such as oil depletion allowances and other tax advantages, are transfers from the American public to the oil industry that have important distributional but minor efficiency consequences.

Table 2.3-2. Damages estimated by Hohmeyer.

Damage category	Damage estimates (millions of 1982 $/year)
Damage to plant life (flora)	710 to 1,067
Damage to animal life (fauna)	11
Damage directly affecting mankind (mortality, morbidity)	189 to 4,748
Damage to materials	261 to 458
Effects on the climate	8 to 17
Total (by simple addition)	1,181 to 6,302

Source: Hohmeyer, O. 1988. *Social Costs of Energy Consumption: External Effects of Electricity Generation in the Federal Republic of Germany*, Springer Verlag, New York.
Currency conversion completed using a 1982 rate of 2.38 DM per U.S. $ (U.S. Dept. of Commerce, 1984).

2.4 VICTORIAN PROJECT

At the time of this writing, the state of Victoria, Australia, was working on a similar study. Their study seems to have broader coverage but less depth. The scope of the project included five main tasks:

(1) identification of the environmental and socioeconomic impacts associated with the range of energy supply and demand side options plausible for development in Victoria;

(2) identification of appropriate methodologies for quantifying the environmental and socioeconomic costs and benefits of these impacts in the short and long term;

(3) measurement or estimation of the costs and benefits of the environmental and socioeconomic impacts associated with particular energy resource options;

(4) identification of methods of incorporating environmental and socioeconomic externalities in the energy sector (e.g., taxes, pricing, weightings, etc.); and

(5) recommendation to Government of the most appropriate method(s) for incorporating environmental and socioeconomic externalities in energy planning and the decision making process.

2.5 UNION OF CONCERNED SCIENTISTS

America's Energy Choices is a report on a study undertaken by the American Council for an Energy-Efficient Economy, the Alliance to Save Energy, the Natural Resources Defense Council, and the Union of Concerned Scientists (UCS) with the objective of examining the role that energy efficiency and renewable energy technologies can play in meeting America's energy and environmental needs and problems over a forty-year period from 1990 to 2030. For each of four alternative energy scenarios the researchers evaluate the impact on energy use of such factors as energy prices, technological change, and structural shifts in the economy to determine both the roles that various energy sources would play in the nation's energy mix and the magnitudes of those sources' air pollutant emissions.

The study deals with four possible energy futures for the U.S.: the "reference" scenario, the "market" scenario, the "environmental" scenario, and the "climate Stabilization" scenario. The reference scenario, developed by drawing upon many of the assumptions and projections of the Department of Energy's *1990 Annual Energy Outlook* study, is, as *America's Energy Choices* puts it, that of a "business-as-usual" energy future in which current policies and trends prevail. It takes into account expected GNP growth, changes in population and energy prices, and the impact of the Clean Air Act. The market scenario is that of a situation in which such policies as the allocation of research and development funds to least-cost energy technologies are implemented to spur a more rapid introduction of cost-effective technologies and efficiency measures to the energy market. The environmental scenario is one in which the environmental costs of air pollutants are incorporated into energy prices by political regulations such as pollution taxation. The climate stabilization scenario, finally, ascribes a monetary value to carbon dioxide emissions to account for the possible consequences of global warming.

For each of the scenarios the researchers attempt to determine the make-up of the underlying energy mixes that would prevail in the residential and commercial, industrial, and transportation sectors. With that aim in mind, the costs of investments in an array of technologies and efficiency measures are compared to the cost of energy saved (i.e. to the cost avoided by not having to generate the saved energy) by each of those investments to determine their respective cost-effectiveness. In the case of the environmental and climate stabilization scenarios, furthermore, the emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), methane (CH_4), carbon monoxide (CO), total suspended particulates (TSP) and volatile organic compounds (VOC) for various energy sources are estimated and the corresponding monetary costs added to the market energy prices. *America's Energy Choices'* reported emission values for natural gas technologies, for example, are listed in tables 2.5-1 and 2.5-2 below. Table 2.5-1, based upon data from the EPA's National Emissions Data System and taking into account regional differences in such factors as environmental constraints and control technologies, lists the current, average emissions of conventional gas steam turbine plants and combustion turbines fueled by natural gas (CTNG) in lb/MMBtu for the north central, northeastern, southern, and western regions of the U.S.

Table 2.5-2 lists the emissions values for natural gas power supply options that the UCS study assumes are introduced later on in their scenarios. These options include combustion turbines having steam injection for 70 percent removal of NO_X, combined cycle units (NGCC) having steam/water injection for 80 percent removal of NO_X and oxidation catalysts for 80 percent and 30 percent reductions in CO and VOCs, respectively, as well as advanced fuel cell technology. The study does not assume any regional differences for these technologies.

In a table reproduced below (Table 2.5-3), *America's Energy Choices* lists monetary values for air emissions externalities developed by the Tellus Institute, the California Energy Commission, the New York State Public Service Commission, the South Coast Air Quality Management District, PACE University Center for Environmental Legal Studies, and the Swedish Environmental Protection Agency. The report does not discuss the CEC, NYSPSC, SCAQMD, PACE, BPA, or SEPA values other than to offer them as a comparison to the Tellus values, which the UCS study uses as a basis for its air pollutant costs. The report states that "since we have employed a real discount rate of 3 percent (and a real levelized fixed charge factor of 5 percent for thirty year investments), we have modified the capital cost component of the marginal control costs used as air pollutant values by a factor of one-half (Technical Appendixes p. F-9)." The modified Tellus values are listed in table 2.5-4. The Tellus Institute developed the original values by using the "revealed preferences" approach. That is, it studied existing and proposed environmental regulations to estimate values that society places on environmental impacts. It should be noted, however, that the UCS study does not use the CO_2 values listed in the tables below. Rather, a cost of $25 per ton, developed from estimates of the costs of pursuing a significant tree planting program, is used to mitigate atmospheric CO_2 levels for the climate stabilization scenario.

Table 2.5-1. Current Average Natural Gas Utility Emissions Factors (lb/MMBtu)

Steam Turbine	NO_X	SO_2	CO_2	CH_4	CO	TSP	VOC
North Central	0.50	0.0006	119	0.013	0.039	0.0034	0.0023
Northeast	0.27	0.0007	119	0.013	0.023	0.040	0.0012
South	0.25	0.0031	119	0.013	0.027	0.0047	0.0041
West	0.14	0.0048	119	0.013	0.055	0.0043	0.0023
CTNG							
North Central	2.78	0.0024	119	0.013	0.37	0.0089	0.19
Northeast	0.15	0.0058	119	0.013	0.056	0.0060	0.010
South	5.01	0.023	119	0.013	0.68	0.028	0.52
West	0.18	0.003	119	0.013	0.10	0.013	0.013

Source: The Union of Concerned Scientists 1992. *America's Energy Choices*, Cambridge, MA.

Table 2.5-2. New power plant emissions factors (lb/MMBtu).

	NO_X	SO_2	CO_2	CH_4	CO	TSP	VOC
NGCC	0.079	0.0006	119	0.002	0.022	0.013	0.0084
CTNG	0.118	0.0006	119	0.012	0.110	0.0133	0.0084
NG Fuel Cell	0.01	---	117	---	---	---	---

Source: The Union of Concerned Scientists 1992. *America's Energy Choices*, Cambridge, MA.

Table 2.5-3 Monetary Values for Air Emissions Externalities (1990 $/lb).

	Tellus	CEC	NYS	SCOQMD	Pace	BPA	Sweden
SO_2	0.78	9.07	0.43	39.2	2.12	0.20-1.80	1.19
NO_X	3.40	4.65	0.96	137.0	0.86	0.03-0.40	3.18
CO_2	0.012	0.004	0.0006	---	0.007	0.003	0.02
CH_4	0.12	0.04	---	---	---	---	---
CO	0.45	---	---	0.43	---	---	---
TSP	2.09	6.11	0.17	23.0	1.24	0.08-0.8	---
VOC	2.77	2.61	---	15.2	---	---	---

Source: The Union of Concerned Scientists 1992. *America's Energy Choices*, Cambridge, MA.

Table 2.5-4 Air Pollutant Values with Modified Capital Cost (1990)

Pollutant	Cost
SO_2	0.40
NO_X	2.92
CO_2	0.006
CH_4	0.06
CO	0.41
TSP	1.05
VOC	1.38

Source: The Union of Concerned Scientists 1992. *America's Energy Choices*, Cambridge, MA.

America's Energy Choices also provides levelized costs (cents/kWh) based upon the Tellus emissions externalities values and, for the conventional gas steam plant, regional differences. They are reproduced in Table 2.5-5.

Table 2.5-5. Air Emissions levelized costs (cents/kWh, 1990 $s).

	Air Emissions Costs
New Power Plants	
NGCC	0.21
NG Fuel Cell	0.02
CTNG	0.39
Gas steam turbine	1.44-2.22

Source: The Union of Concerned Scientists 1992. *America's Energy Choices*, Cambridge, MA.

2.6 DELUCHI'S REPORT

M.A. DeLuchi's *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity* is a report on the results of a study that aims to help evaluate the effects of various energy options on greenhouse gas-induced global climate change. The study uses projections for the year 2000 and data from various sources in conjunction with an energy use and emissions model to develop estimates of emissions of such greenhouse gases as methane (CH_4), nitrous oxide (N_2O), nonmethane organic compounds (NMOCs), carbon monoxide (CO), nitrogen oxides (NO_x), and carbon dioxide (CO_2) for a variety of transportation and electricity generation fuel cycles. These estimates are developed for each of several scenarios that differ in such assumptions as those about power plant efficiencies. The study also enables the comparison of each of the considered fuel cycles' global warming contributions by converting the estimates for non-CO_2 emissions into values for the CO_2 emissions that have the same temperature effect (CO_2-equivalent emissions).

With the aim of being comprehensive in scope, the DeLuchi study takes into account emissions resulting from the feedstock recovery and fuel production stages, from the transportation of feedstocks from the site of extraction to fuel production facilities, from the distribution of fuel from facilities to end users, and from the production and assembling of materials for vehicles, facilities, pipelines, well-drilling equipment and the like for each of the fuel cycles. The study also sees to it that a host of other factors are not overlooked in the analysis. Among these are any interconnections among the fuel cycles. That is, for each fuel cycle the study accounts for the emissions from the recovery, production, and transportation of any fuels providing the energy used to drive that cycle. Other factors considered include emissions from the use of energy to maintain and administer such modes of fuel distribution as pipeline transmission and ship transportation, the venting, flaring, and leaking of gases from oil wells and in the course of natural gas operations, as well as the production of nitrous oxide from the corona discharge of high-voltage transmission lines. Requirements of the Clean Air Act Amendments are also taken into consideration.

DeLuchi's emissions for the natural gas-to-power fuel cycle in terms of grams of CO_2-equivalent emissions per kWh of generated electrical energy have been tabulated for the study's base scenario in Table 2.6-1 below. Each of the non-CO_2 gas estimates was derived by converting the mass amount of the non-CO_2 gas emission into the mass amount of CO_2 emissions having the same warming effect in terms of degree-years over a period of 100 years (one degree-year is an increased surface temperature of one Celsius degree for one year). The original, non-CO_2-equivalent estimates are based upon data obtained from the EPA's *Compilation of Air Pollution Emission Factors* (AP-42) and other source, as well as from analyses of the carbon and energy contents of natural gas. To convert these estimates into their CO_2-equivalents, DeLuchi utilizes "equivalency factors" based upon those from an Intergovernmental Panel on Climate Change (IPCC) document. The table lists the emissions values for the boiler and turbine fuel cycles' upstream processes (feedstock recovery, fuel production, etc.) and power-generation stages. The power plant values are based upon the assumption that the efficiency of electricity distribution and transmission is 92% and that the power plants in the table have efficiencies, or heat rates, of 32%. With regard to NO_x, finally, DeLuchi assumes that in the year 2000 such power plant emissions will be reduced to 50% of uncontrolled levels.

Table 2.6-2 lists the total CO_2-equivalent emissions for the natural gas fuel cycle for the 100-year time period, as well as for 20 and 50-year periods. These totals can be obtained by summing both the emissions of CO_2 and the CO_2-equivalent emissions of the other gases for all stages of the fuel cycle, including that of power plant operations. It should be noted that in an addendum to the *Emissions of Greenhouse Gases* report, however, DeLuchi draws attention to some recent uncertainty about the validity of the equivalency factors used to derive the CO_2-equivalent emissions values. He states that they should not be thought of as embodying warming effects over 20, 100 and 500-year time periods as originally intended. The emissions values for the 20, 100 and 500-year "time periods" in

Table 2.6-2, therefore, should be regarded merely as estimates reflecting alternative scenarios for, or assumptions about, the warming potentials of the greenhouse gases.

Table 2.6-3 lists emissions factors in grams of CO_2-equivalent emissions per million Btu of fuel energy input for advanced natural gas power technologies. Included in the list are natural gas combined cycle, Intercooled-steam-injected gas turbine (ISTIG), chemically-recuperated ISTIG (CRISTIG), and natural-gas molten-carbonate fuel cell (NG/MCFC) technologies. Their efficiencies, or higher heating values, are also listed. The DeLuchi study also provides, incidentally, emissions factors for sulfur dioxide (SO_x).

Table 2.6-1 CO_2-equivalent Emissions of Greenhouse Gases from Power Plants and Upstream Processes in g/kWh Delivered to End User

Upstream Processes		
	Natural Gas Boiler	**Natural Gas Turbine**
CH_4	16.3	16.3
N_2O	0.7	0.7
NMOCs	1.1	1.1
CO	0.4	0.4
NO_x	21.9	21.9
CO_2	72.0	72.0
Upstream Total	112.4	112.4
Power Plants		
CH_4	0.0	3.6
N_2O	9.8	9.8
NMOCs	0.1	0.3
CO	0.6	1.7
NO_x	54.7	41.1
CO_2	606.3	605.2
Power Plant Total	671.5	661.6

Table 2.6-2. Total CO_2-equivalent Emissions for the Natural Gas Fuel Cycle in g/kWh Delivered to End User

	Natural Gas Boiler	Natural Gas Turbine
20-year case	1032	995
100-year case	784	774
500-year case	721	717

Table 2.6-3. Efficiency and Emissions of Advanced Natural Gas Power-Generation Technologies

	Natural Gas Combined Cycle	ISTIS	CRISTIG	NG/MCFC
Emissions (g/MMBtu)				
CH_4	15.7	15.7	15.7	0.5
N_2O	2.0	2.0	2.0	1.0
NMOCs	2.8	2.8	2.8	1.0
CO	51	51	51	1.0
NO_x	91	45	45	10
SO_x	0.3	0.3	0.3	--
Efficiency (%)	45	47	52	57

3. ORGANIZATION AND INTERPRETATION OF RESULTS

This chapter describes the organization of the results that follow, particularly in Chapters 7 through 11. Section 3.1 discusses the *types* of results that the reader should look for in studying this report. Section 3.2 discusses their *interpretation* and the most important caveats. These caveats should always be borne in mind in order that the report *add* to our base of knowledge, rather than provide "disinformation." Section 3.3 describes how our uncertainty about our estimates are explicitly portrayed in reporting the results of the study. Section 3.4 summarizes a notational system which will be used to provide information on that uncertainty and on the quality of some of the existing base of knowledge that was used for the calculations.[1]

3.1 TYPES OF RESULTS

This section identifies the most important types of results that are presented in this report, and describes the format for their presentation. There are three general types of results. Each type corresponds to one of the objectives of the study.

3.1.1 A Demonstration and An Account of the Methods

The first type of result is a demonstration of the damage function approach to the natural gas fuel cycle. Whereas ORNL/RFF (1992) provided a general discussion of the approach and of the issues in estimating the externalities of fuel cycles, our report presents an actual application for a specific fuel cycle. The description of this application provides an account of the types of data sources and methods that can be used in other studies of natural gas fuel cycle externalities.

Chapter 4 gives information on the reference sites, natural gas production and processing operations, and conversion technology. Chapter 5 identifies the major emissions and other residuals from natural gas fuel cycles. Chapter 6

[1]This system will be implemented and reported in a future draft of this report.

summarizes the major impact pathways and identifies those addressed in greater detail in this study.

Chapters 7 through 11 provide an account of the methods that were used to calculate the damages and benefits for each of the impact-pathways that was selected for detailed analysis. Chapter 7 pertains to the drilling, extraction and treatment stage of the fuel cycle. Chapter 8 takes account of natural gas processing activities. Chapter 9 concerns the transportation and storage stages of the fuel cycle. Chapter 10 pertains to the electricity generation stage. Chapter 11 presents a summary tabulation of the numerical results.

3.1.2 Numerical Estimates of Damages and Benefits

The second type of result, numerical results, are estimates of the marginal damages or marginal benefits associated with specific fuel-cycle activities or processes. These estimates are specific to the particular technology(s) that were analyzed, as well as to the specific sites. The nature and the magnitude of residual impacts depend on the power plant project and on the characteristics of the specific site.

Presentation of these results is in Chapters 7 through 10. Each chapter presents material on a separate stage of the fuel cycle. Each section describes a distinct impact-pathway. Parts within each section give estimates of emissions and changed concentrations, the ecological or health impacts, and the economic damages (or benefits) for each of the impact-pathways.[2]

The study considers gas turbine power plants as the benchmark for the current year (i.e. 1990) for natural gas-fired electric power generation. The future technology (in the year 2010) is the same except for significantly improved pollution control. None of the technologies are considered as being generic or representative of all natural gas technologies.

Illustrative calculations are done for two different reference sites, one in the Southeast U.S. and the other in the Southwest. The sources of the natural gas, the transportation routes, and the processing plants associated with each of these two reference power plant sites differ as well.

[2]The terms "economic damages" and "economic valuation" are generally used throughout this report, even though for economists, the "economic" descriptor is redundant.

A full suite of analyses for all potential impacts, for both sites, for all upstream and generation activities, and for both types of technologies was *not* done. It is prohibitively expensive to do a comprehensive analysis of all possible combinations. Thus, the analyses presented in Chapters 7 through 10 apply to some site(s) and technology(s), but not necessarily to all combinations. Table 3.1-1 presents a "road map" to indicate which parts of Chapters 7 through 10 apply to each of the technologies and years.

Estimates of impacts are in the physical units appropriate for the particular impact-pathway. Estimates of damages and benefits are expressed in terms of mills/kWh, and as the annual dollar damages or benefits for each impact-pathway (in 1989 dollars, adjusted for inflation). Where possible, the numerical values are presented as low, mid, or high estimates. These ranges do not necessarily represent a specific (say 90%) confidence interval. The reason is that these ranges are based on estimates from other studies and these other studies are not consistent in their definition of "low" and "high."

In most instances, the numbers used in, or stemming from calculations, are reported "as is," with many digits. The number of digits in these numbers does *not* reflect the actual precision of the calculations.

3.1.3 Identifying Information Quality and Gaps

The third type of result is the identification of where important quantitative information does not exist, or is highly imprecise. These information gaps are generally in the data on reference sites, which are required as inputs for some of the modeling; in the relationships between specific pollutants and their ecological and health impacts; and in the economic value of these impacts. Identifying these information gaps provides a research agenda for the future.

Chapter 11 includes tables that summarize the quality of the information that was available on the emissions, impacts and economic damages (and benefits) of the natural gas-to-electricity fuel cycle. Visual inspection of these tables provides a quick assessment of information needs. Chapters 7 through 10 discuss the data and analytical methods used in this study -- providing additional insight about data quality and the lack of information.

Table 3.1-1. Section numbers in the report that pertain to each of the two reference sites and technologies.

Activity/Residual/Endpoint	Sect. No.	SE 1990	SE 2010	SW 1990	SW 2010
Offshore drilling/ wastewater/ aquatic organisms, fisheries	7.1	■	■	■	■
Onshore drilling/ wastewater/ biodiversity	7.2	■	■	■	■
Drilling support activities/ dredging, navigation/ aquatic organisms, land use	7.3	■	■	■	■
Natural gas production/ accidents/ injuries	7.4	■	nd	nd	nd
Processing/ residuals/ health and ecology	8.1	■	■	■	■
Transportation/ pipeline emissions wildlife and crops	9.1	neg	neg	neg	neg
Transportation/accidents/ deaths, injuries	9.2	■	■	■	■
Generation/ ozone/crops	10.15	■	■	neg	neg
Generation/ ozone/health	10.14	■	■	neg	neg
Generation/ SO_2/health	10.3	■	■	■	■
Generation/NO_x/health	10.6	■	■	■	■
Generation/ particulates/health	10.7 and 10.8	■	■	■	■

■: applies to site and technology
nd: not done
na: not applicable
neg: negligible

3.2 INTERPRETATION OF NUMERICAL RESULTS

While demonstration of methodology is the most important objective of this study, many readers of this report will be drawn more to the numerical results. It is important to have the correct perspective in viewing these results.

3.2.1 Caveats in the Interpretation of the Results

The numerical results should *not* be interpreted as being *the* externalities of the natural gas fuel cycle. There are several reasons for this caution and all are important:

(1) The estimates do not include every emission, or impact. A limited number of impact-pathways were considered in detail. While the selected impact-pathways were regarded as being among the more important, others may be important as well. The lack of information is one of the main reasons why these other impact-pathways were not fully addressed.

(2) Only one natural gas conversion technology was analyzed in detail. The natural gas was assumed to be from both on- and offshore fields.

(3) Ecological and health impacts, and thus economic damages and benefits, are generally site-specific. The estimates pertain only to the two reference sites selected for the study. Analysis of other reference sites, including those in the same geographical region, could result in very different estimates. A corollary to this statement is that comparisons among alternative fuel cycles could vary, depending on the particular site.

(4) In many cases there is considerable uncertainty about the dose-response functions, the ecological and health impacts, and the relationships between impacts and their economic value.

(5) Adding the externalities of individual impact-pathways to estimate a total externality for the fuel cycle would likely overestimate it (assuming that every impact-pathway is quantified). Estimates of externalities for individual impacts are usually obtained in isolation, without taking into account a collection of impacts simultaneously and without any explicit constraints on individual or household income.

(6) It is not always clear when damages are in fact externalities. Some damages are reflected in higher prices paid for electricity, and are thus internalized. This issue is discussed in ORNL/RFF (1992). Unless

otherwise identified as externalities, the economic values derived in this study should be interpreted as the marginal damages and marginal benefits (and not necessarily externalities) associated with the addition of the natural gas plant and of the operations needed to support the natural gas plant.

Notwithstanding, the results are still informative. Comparisons can be made among different impact-pathways within a single fuel cycle. Comparisons can also be made between similar impact-pathways in different fuel cycles, keeping in mind that they pertain to only the specific sites studied. In any comparisons, the above-stated caveats should always be kept in mind.

3.2.2 Valuation Approach

Damages and benefits may be aggregated both within and across major impacts (keeping in mind the caveats above). For example, within the morbidity endpoints, both ozone and particulates affect symptoms and restricted activity days (RADs). Within an ozone analysis, adding symptoms to RADs double counts some of the symptoms (since one must have a symptom to have a RAD). However, considering both ozone and particulates, there is not necessarily any double counting when two different pollutants are linked to the same health endpoint, as long as the dose-response functions contain variables for both pollutants.

Discount rates are used to aggregate over time. The timing of damages and benefits is tracked for appropriate use of discounting techniques. Attention is paid to whether a damage is annualized, one-time only, or periodic. All damages and benefits are discounted to the present. They are expressed in "levelized" terms. The levelized cost (or benefit) is the constant annual payment (in real dollars, adjusted for inflation) that if paid over the life of the natural gas plant would sum up to the total present value of the damage or benefit.

Damage to the region surrounding natural gas fields, for instance, occurs annually. Thus, no further levelization is needed other than to divide by annual kWh. Mortality risks from, say, exposure to radon from coal mining operations occur over a worker's lifetime, and deaths generally occur only after a long latency period. However, the willingness to pay for risk reductions may be estimated by using a study that asks how much a person would be willing to pay today to reduce the risk of future mortality risks. In this case, the economic value of the expected reduction in risk would be credited to the current period, even though the actual risk would be experienced in the future. (Hedonic wage studies provide a value for the wages given up to reduce the risk of annual accident risk. In this context, annual wage differentials reflect willingness to pay for a current year's risk reduction and not for risk reductions beginning in 20 or 30 years.) Medical costs of morbidity experienced in the future would be credited to the future, however, and discounted to the present.

3.3 CONSIDERATION OF UNCERTAINTY

Uncertainties are taken into account in several ways. For this study, a standard approach to propagate uncertainties was applied by defining information as being low, mid, or high estimates. These estimates were used to construct an overall low, mid, and high estimate. The low estimate was computed by using the low estimates at each step in the pathway. The mid and high estimates were similarly computed. It can be shown that this approach results in confidence intervals on the endpoint of the analysis exceeding the confidence intervals used at each step in the pathway.

In addition to uncertainties about functions and parameter values at each link in the impact-pathway, there is uncertainty with regard to the baseline level of environmental quality. For instance, where dose-response functions are strongly nonlinear, the assumptions one makes about future baseline pollution levels is obviously important for determining where calculations should begin on the dose-response functions.

4. CHARACTERIZATION OF THE NATURAL GAS FUEL CYCLE

4.1 INTRODUCTION

The natural gas cycle examined in this project includes all activities from exploration to electricity generation from natural gas-fired power plants. Three main sources of external costs of the natural gas fuel cycle are investigated in this chapter. The first is wastes, both liquid and solid, and air pollution produced by the drilling stage of natural gas exploration. The second is methane leakage and internal combustion compressor emissions to the atmosphere due to the transport of natural gas through pipelines, and the third is emissions from combustion of natural gas during the electricity generation stage.

The total consumption of natural gas in 1990 for the U.S. was approximately 18.53 trillion cubic feet (tcf). The U.S. production of natural gas was 17.40 tcf with net natural gas imports of 1.36 tcf (7.2% of the annual total) (DOE/EIA 1991). Approximately 25% of natural gas produced in the U.S. comes from predominately oil producing wells (predominately oil producing wells have less than 1000 cubic feet (cf) of gas produced per barrel of oil produced; those wells having greater than 1000 cf of gas produced, per barrel of oil, are classified as gas wells).

The gas-liquid mixture making up the well stream contains methane, hydrocarbon liquids, free water, water vapor, solids, and other contaminates. Field treatment of the well stream is required to separate the liquid hydrocarbons from the gas. This is accomplished by one of the specific types of separators which is suited for processing a particular type of well stream mixture containing a variety of impurities.

After the primary contents of the well stream go through the separator process to remove the predominately liquid portion from gas, the gas flow itself must undergo processing by gas plant operations. This treatment of natural gas involves removing compounds from the gas that have value for resale and may possibly contain contaminates that would make the gas flow unsuitable for commercial resale. Some of the hydrocarbon compounds other than methane that have value for resale are ethane, propane, pentanes and hexane (both used for gasoline production). The non-hydrocarbon components that must be removed by gas plant operations are hydrogen sulfide, carbon dioxide, and water. Nitrogen, being an inert gas contained in the gas stream with no heating value, is ordinarily not removed.

In 1990, total natural gas consumption in the U.S. was 18.83 tcf. The natural gas consumed by electric utilities for electricity generation amounted to 2.78 tcf, or 14.7% of the total U.S. consumption. The Department of Energy projects the share of natural gas consumption by electric utilities to grow to 25.5% by 2010. Natural gas imports are projected to grow from 8% of total supplied to the U.S. in 1990 to 14% in 2010 (EIA - Annual Outlook for Oil and Gas 1991).

The format of this chapter is similar to the report on the oil cycle (ORNL/RFF 1996). The stages of the natural gas fuel cycle are identified, and the activities performed in each stage and the types of pollution and other environmental impacts resulting from each activity are discussed. This chapter supports the following chapter which discusses emissions.

The natural gas fuel cycle consists of eight major sources of environmental pollution. Each of the pollution sources are analyzed and are as follows: 1) water pollution from gas/oil well drilling, extraction, and field treatment, 2) hazardous wastes from gas/oil well drilling, extraction, and field treatment, 3) air emissions from natural gas extraction and field treatment, 4) water pollution from gas processing, 5) hazardous wastes from gas processing, 6) methane and other transport emissions from natural gas pipelines, 7) air emissions from gas-fired power plants, and 8) water pollution from gas-fired power plants.

It is important to bear in mind that it is the *incremental* quantity of natural gas, that is required to fuel a unit of production at the power plant, that is pertinent to any calculation of fuel cycle externalities — *not the total* emissions and discharges from all natural gas activity in the U.S. Table 4.1-1 lists the emissions associated with natural gas fuel cycles, the sources of these emissions, and the ecological and health resource categories that may be impacted.

Chapter 5 of this report will present estimates of the physical amounts of pollutants, wastes, and emissions from each of the eight sources. In addition, all assumptions concerning the sites for extraction and field treatment, processing facilities, pipelines, and power plants will be described in Chapter 5.

Table 4.1-1 Natural gas fuel cycle emissions, sources, and resource categories that may be impacted

Emissions	Sources	Resource Categories
	Air Emissions	
Carbon dioxide (CO_2) Carbon monoxide (CO)	Releases from drilling equipment, processing plant, and power plant stack	All impact categories
Nitrogen oxides Sulfur dioxide	Releases from drilling equipment, processing plant, and power plant stack	Health effect; biodiversity; crop production; tree growth
Acid aerosols	Formation in atmosphere from NO_x and SO_2; long range transport, acid deposition	Health effects; recreational fishing; crop production; tree growth; biodiversity
Ozone	Formation in the atmosphere from NO_x and HC	Health effects; change in crop production
Hydrocarbons	Fugitive emissions at drilling site, in pipeline, at processing plant; drilling equipment; power plant stack	Biodiversity; recreational and commercial fishing
Particulates, Acid aerosols	Power plant emissions	Health effects; recreational use of parks
Peroxyacetyl nitrate (PAN)	Formation in the atmosphere from NO_x and HC	Biodiversity
	Water Emissions	
Offshore: Produced water Drilling fluids Drill cuttings	Emissions from offshore drilling platforms	Commercial fisheries; recreational fishing; biodiversity
Onshore: Produced water Drilling fluids Drill cuttings	Discharge to coastal areas, underground injection, pond or pit storage, landfill	Biodiversity; Drinking water
Wastes and wastewater	Processing plant, power plant	Biodiversity
	Land Emissions	
Drilling fluids and muds	Land or pond disposal at drilling sites	Biodiversity; occupational health effects
Ash	Land disposal	Biodiversity; groundwater and soil contamination impacts
Land use	Production fields, processing plant, power plant	Biodiversity
Drilling platforms	Construction	Commercial fishing, recreational fishing
Dredging	Offshore and onshore construction of pipelines; access to onshore coastal areas	Commercial fishing, biodiversity
Navigation, pipelines	Shoreline activities associated with production	Recreational use of shoreline, biodiversity

4.2 NATURAL GAS EXPLORATION

Exploratory activities to locate natural gas reservoirs are similar to those undertaken for oil.[1] In addition to exploratory drilling to determine if gas is present in a promising formation, extensive regional examination of potential natural gas locations is performed. This exploration process consists of mapping the area of the potential gas deposit, and conducting seismic, gravimetric, and magnetic surveys to determine if the geologic structure is suitable for a potential natural gas reservoir.

In 1991, the total number of exploratory and development wells for both oil and gas totaled 28,220. Of the total, 11,920 (42.2% of the total) of the wells were successful in locating oil. Natural gas was found in 8,650 wells (30.6% of the total). Dry wells were found in 7,650 cases (27.1% of the total) [EIA 1991]. From 1985 through 1991, approximately 8% of the natural gas wells drilled were classified as exploratory wells (API 1992 a,b).

The waste products generated by the exploratory process are almost entirely due to drilling. Most of the wastes are water pollutants. A drilling fluid is circulated down the drill pipe and back up to the surface. A fluid system at the drilling site consists of tanks to formulate, treat, and store the fluids. Pumps are used to force the fluid through the drill pipe and back to the surface. A system of valves is used to control the flow of drilling fluids when the pressure exceeds the weight of the fluid column. Occasionally a "blowout" occurs when the reservoir pressure exceeds the valve safety parameters leading to the drilling fluids being ejected from the well.

Drilling wastes are usually in the form of drill cuttings and mud; when in production, produced water is the primary waste of the well. Produced waters from offshore platforms can cause environmental damage. These waste waters can contain oils, toxic metals, salts, and organic compounds.

4.3 DRILLING FOR NATURAL GAS

Most wells drilled by the oil and gas industry are to access reservoirs of oil or gas, although a significant number are drilled to obtain information about promising geologic formations. The drilling process for natural gas wells is similar

[1] In this fuel cycle study we assume existing natural gas formations, both on- and offshore, have previously been located so that exploratory activities to search for natural gas is unnecessary. We include the discussion in section 4.2 to illustrate the process if it were needed.

to that of oil. Exploratory drilling for natural gas uses the same rotary equipment and methods in development and production drilling. As of 1986, an estimated 7,486 offshore exploratory wells had been drilled, of these 5,206 had been drilled in federal waters. Of these exploratory wells drilled, oil was found in 5.0% of the cases and gas in 8.6% of the cases. The remaining 86.4% of the wells drilled (6,451) were dry holes. Historically, a majority (70%) of the exploratory wells are drilled in federal waters, the remaining 30% are drilled in state offshore waters (EIA 1991).

Exploration and development of natural gas occurs both onshore and offshore, similar to oil. The types and levels of pollution for the two locations of natural gas reservoirs differ markedly.

4.3.1 Onshore Drilling (2010 Scenario)

The production of natural gas for the Southeastern site in 2010 is assumed to be in Louisiana, onshore. Approximately 6.4% of the proven reserves in the U. S. are located in Louisiana. Both the 1990 and 2010 scenarios for the Southwest site receive natural gas from the San Juan basin in northwest New Mexico. Approximately 14% of proven natural gas reserves in the U. S. are located in New Mexico.

Cable-tool drilling can be utilized for shallow, low-pressure gas reservoirs, although rotary drilling is used almost universally for exploration and development. The rotary drilling method allows for the simultaneous drilling of the well and removal of the drill cuttings. This in turn allows wells to be drilled in excess of 30,000 feet. Well casings are periodically cemented into the well hole, which directs and stabilizes the drill stem. The casing also seals off freshwater aquifers, high-pressure zones, and other formations.

A drilling "mud" (water or oil-based fluid) is pumped down the hollow drill pipe and onto the bit for lubrication. The "mud", cuttings, and other additives are pumped back up through the drill hole and deposited in a reserve pit. If the well becomes obstructed, acid is introduced into the well hole and usually dissolves the barrier. Other fluids are often pumped into the drill hole (corrosion inhibitors, friction reducers, complexing agents, and cleanup additives) and some of them are returned to the surface when the well is completed or slowly released over time. Eventually these fluids require disposal.

An estimated 47.36 acres of land per trillion Btu of energy produced is used by a gas well during the initial production period of the well (U.S. Department of Energy 1983). After the well is in production the average estimated area of land required by the well is 38.93 acres per trillion Btu of energy produced. The amount of land required for a typical gas field of approximately 120 wells in the U.S. ranges from 420 to 640 acres depending on the size of the natural gas reservoir (on average 3.5 to 5.33 acres per gas well). This is a substantially smaller area than is required for oil wells, which require approximately 40 acres per well.

The Environmental Protection Agency has developed a methodology for estimating waste volumes from onshore drilling. EPA assumes that reserve pits are sized to accept the wastes predicted from the drilling operation. Therefore, the wastes generated from a drilling activity are equated with the volume of the reserve pit constructed to service the well.

The primary waste products from gas wells are in general, oils, heavy metals, toxicants, and dissolved solids contained in the drilling mud or produced water. Specifically, the waste products are oil and grease, suspended solids, phenol, arsenic, chromium, cadmium, lead, and barium. The drilling wastes from gas wells do not change significantly with different localities and therefore are not particular to any specific region in the U.S.

Potentially significant amounts of air pollution are created during drilling operations. Large diesel engines typically power the drilling equipment and emit significant quantities of particulates (possibly containing heavy metals and polycyclic organic matter), sulfur oxides, and oxides of nitrogen, all of which are subject to regulation under the Clean Air Act. These emissions can be serious during drilling of deep wells requiring large power outputs or in large fields where multiple drilling operations occur simultaneously. Newer drilling rigs utilize oil-fired turbines which emit similar pollutants in different proportions. The major air pollutants from these sources include NO_X, SO_X, HC, PM, CO, and CO_2.[2]

Other sources of air pollution include light organic compounds that may volatilize from reserve and other holding pits used as waste repositories during drilling. The light organics are volatilized from solvents, recovered hydrocarbons, and other chemicals used in the well drilling process. The volume of volatile organic compounds, however, is insignificant compared to diesel engine emissions.

Oil and gas wells abandoned at the end of their productive life can potentially cause extensive environmental damage to both the surrounding land

[2]Emissions due to use of electricity (used in drilling operations) generated in power plants are considered secondary emissions. These emissions are not examined because their impacts are considered minimal.

surface of the well as well as underground fresh water aquifers. There are an estimated 1.2 million abandoned oil and gas wells nationwide. An estimated 200,000 of the wells are not sealed properly with concrete plugs. Officials in Texas estimate that 40,000 to 50,000 of the abandoned wells could cause serious pollution problems (Texas Railroad Commission 1991). Typically, wells drilled into sandy formations were not plugged properly, and contain brine that can include heavy metals, radioactivity, and other toxins. This brine is often four times as salty as sea water and can flow up the well shaft with improperly constructed concrete plugs. Current state oil/gas industry regulations require the proper capping of wells that are decommissioned.

4.3.2 Offshore Drilling (1990 Scenario)

The 1990 scenario assumes natural gas production will be offshore of the Louisiana Gulf Coast for the Southeast Reference site. DOE has projected the percent of natural gas production from offshore sites in the U.S. will be 13.9% in 2010 (the comparable offshore production value for 1990 is 28.9%) [EIA 1991]. Offshore Louisiana natural gas reserves approximately equal the onshore reserves of almost 130 x 10^{12} cubic feet. Offshore Louisiana reserves are approximately 13% of total U.S. gas production.

For offshore drilling operations, drilling rigs may either be stationary or mobile. Stationary drilling rigs are used for development drilling into a proven natural gas reservoir and are assumed to be used for the offshore scenario. Mobile rigs are used for both exploratory and development drilling. For drilling in shallow waters and marsh areas, mobile drilling rigs are mounted on barges and rest on the bottom for drilling. For water up to 300 feet deep, drilling is accomplished by mounting the drilling rig on barges jacked up above the water on legs (pile-supported).

Deep water drilling operations (greater than 300 feet deep) have the drilling rig located on a floating vessel, or a semi-submersible vessel which is a floating platform with special submerged hulls which supports the drill rig above the water level. To transport drill rigs to marsh areas, canals are dredged to the drill sites so that the rigs can be floated in.

The produced waters from offshore platforms are of great concern environmentally. The produced waters include production wastes from extracted oil, deck drainage from the platform, sanitary and domestic wastes. The produced waters can contain oils, toxic metals, and organic chemicals. Significant pollutants in produced waters include oil and grease, arsenic, cadmium, copper, cyanide, lead, mercury, nickel, silver, zinc, organic carbon, and chlorides.

The oil and grease adhere to fish and destroy algae and plankton, thereby altering the aquatic food chain. Additionally, damage is likely to occur to the plumage and coats of water animals and fowl. Lead, zinc, and nickel have been known to be toxic to fish in low concentrations often killing fish eggs as well as contaminating many adult fish species. On the other hand, offshore drilling rigs attract fish and reduce costs for anglers, an environmental impact with economic benefits to anglers.

4.4 NATURAL GAS EXTRACTION

Developmental drilling for oil and natural gas utilize, in most cases, rotary drilling methods. Drilling machinery is used, not only to turn the bit, but also to add sections on the drill pipe as the drilling hole deepens, and finally to remove the drill pipe and the bit from the hole. Rotary drilling methods must also have a system for circulating a fluid down through the drill pipe and back up to the surface. The purpose of the drilling fluid is to remove the particles cut by the bit, and to cool and lubricate the bit as it cuts. In addition, as the well deepens, the fluid will stabilize both the well hole pressures and the walls of the well bore.

The drilling fluid system includes tanks to store and treat the fluids, and pumps to provide pressure for the fluid to move down the drill pipe and back to the surface. Additional machinery is used to remove cuttings, fines, and gas from the fluid returned to the surface. A controlling valve is used to prevent blowouts where drilling fluids are ejected from the well by uncontrolled underground pressures.

Onshore, discharges from drilling and fluid system machinery are passed to earthen (slush) pits next to the rigs. The pits are usually backfilled at the end of the drilling operation. On offshore drilling platforms, drilling muds can be reused when drilling is completed by a reconditioning process.

Conventional extraction and enhanced recovery are the two types of methods used to extract gas and oil/gas mixtures from reservoirs. Each of the methods create different types and intensities of environmental pollution.

4.4.1 Conventional Extraction Methods

Utilizing conventional extraction methods, natural gas from gas and oil/gas reservoirs is extracted by either the existing pressure of the underground gas reservoir or by using surface or subsurface pumps. Gas wells produce not only dry gas but also can produce varying quantities of light hydrocarbon liquids or condensates and salt water. As the fluids flow through valves and flow control devices at the well head an orifice choke valve maintains the required back pressure on the well by throttling the fluid flow rate.

At the surface, a separation process begins by which the various constituents in the fluids produced by the gas and oil/gas wells are divided. The fluids are usually introduced into a series of vessels for a two-stage separation process. Section 4.5 discusses the oil field separation process in detail.

Produced water (also known as "formation water" or "brine water") includes all waters and particulate matter associated with oil and gas producing formations. In some cases, water is produced at the beginning, end, or is not produced at all. Produced water treatment differs according to the size of the facility. Ponds are sufficient for small onshore production sites, whereas mechanical flotation systems are required where larger amounts of produced water are handled.

Produced water may have high levels of dissolved solids, oxygen demanding wastes, heavy metals, and toxins, in addition to oil and grease contamination. The type of technology used to treat the produced water depends on state or local regulations as well as cost effectiveness. The location of the production facility also affects the type of treatment used: 1) site condition such as dry land, marsh area, or open water, 2) proximity to shore, 3) local water and statues, and 4) type of receiving water body.

4.4.2 Enhanced Gas Recovery (EGR) Extraction Methods

Natural gas produced by enhanced gas recovery extraction (EGR) methods is expected to play an increasingly important role in supplementing U. S. gas supplies well into the next century. Approximately 20% of current U. S. natural gas production utilizes EGR technologies, and this percentage is expected to increase.

The primary technologies used for enhanced natural gas recovery are fracturing and directional drilling. Fracturing involves the use of either chemical explosives or water under pressure. Chemical explosives cause fracture networks in certain types of gas-bearing formations. The fracturing affects the permeability of formations which is a key variable in controlling the gas flow out of the formation. Hydraulic fracturing involves the use of water under high pressure to alter the surrounding geologic structure thereby allowing a higher flow rate of natural gas.

The environmental concerns surrounding the use of EGR technologies are different for each of the methods utilized. The adverse environmental impacts from the use of advanced hydraulic fracturing include air emissions and noise from the pressurized injection process. Preparing the well casing can cause leaks to groundwater or the surface. Water forced into gas bearing shales can cause contamination or interruption of nearby wells, and contamination of coal seams.

The use of chemical explosive fracturing has environmental impacts which are similar to advanced hydraulic fracturing. When the wells are constructed, noise, air emissions (hydrocarbons and H_2S), erosion, soil loss, and a deterioration in aesthetics may occur. Increasing the flow rate of natural gas by the use of explosives will result in CO, N_2O_2, NO, and CO_2 from the explosive blast itself. Finally, there is the danger of gas leaks or explosions from pipelines or storage tanks.

Direction drilling techniques for recovery of natural gas will result in air emissions (hydrocarbons and H_2S), erosion, and soil loss during the preparation of the drilling site. Drilling and production activities will result in noise and hazard of explosions. There are hazards of gas leaks or explosions from pipelines or storage tanks.

EGR processes have a considerably greater potential for causing air quality degradation than do conventional recovery technologies. In both conventional and EGR processes air quality impacts result from emissions associated with production and injection pumps and fugitive emissions from wellheads and handling and storage facilities. Additionally, EGR technologies produce emissions from the combustion engines of compressors, and emissions from steam boilers in steam flood operations.

4.5 PROCESSING OF NATURAL GAS

Approximately 20% of natural gas produced in the U.S. is jointly produced with oil. The petroleum and gas produced from oil/gas wells contain hundreds of hydrocarbon compounds with different densities and vapor pressures and are mixed with water, both liquid and vapor, solids and other contaminates. The physical states of gas, liquid, and vapor mixture change with a continuous pressure and temperature decline of the well stream.

4.5.1 Field Treatment of Natural Gas

The purpose of the field processing of the well stream is to remove the unwanted ingredients of the well stream and separate the desirable components into salable gas and petroleum liquids in a cost-efficient manner. The processing of natural gas in the field consists of four basic processes (Beggs 1984):

1) Separation of natural gas from free liquids and solid contaminates. The free liquids consist of crude oil, hydrocarbon condensate, and water.
2) Processing the gas to extract recoverable hydrocarbon vapors.
3) Gas processing to condensable water vapor which could possibly cause hydrate formation.
4) The removal of hydrogen sulfide, carbon dioxide, and other unwanted well stream components.

Gas-liquid Separators.

The critical step of field processing of natural gas involves the use of a separator to divide the well stream into free gases and hydrocarbon liquids. In addition to separating the hydrocarbon liquids from the well stream, liquid mist must also be removed. A further refinement of the separation process includes removing entrained gas from the liquids and ensuring that no mixing of the separated gas and liquids occur before discharge of the components from the separator.

There are three basic types of separators used for gas-liquid separation, the use of which is determined by cost efficiency. The three types are vertical, horizontal, and horizontal double-barrel. The vertical separator is used on well streams having a low to intermediate gas-oil ratio and is usually more expensive than alternative methods. This separator is the most expensive of the three types but may be desirable on off-shore platforms where space is at a premium.

Horizontal separators are less expensive than vertical separators and are more suitable for well streams with high gas-oil ratios or those with excessive foaming. The horizontal separators have low installation, maintenance, and transportation costs compared to the vertical type and can be stacked for various stage separations. This type of arrangement allows for improved space utilization.

The double-barrel horizontal separator is similar in operation to the conventional horizontal separator but with the advantage of handling a much higher liquid capacity. With the double-barrel horizontal separator the incoming free liquid is drained away from the upper to lower section with the gas flow passing by baffles at high velocities. Filter separators can be joined with the three conventional separators and are designed to remove very small liquid and/or solid particles from the gas stream.

Wastes produced by the gas-liquid separators include oil and grease, BOD, COD, chlorides, and sulfates. In addition, small quantities of dissolved solids, chromium, and zinc are also found in the waste stream. Fugitive emissions such as volatile organic compounds are released from all gas processing facilities depending on the process, age of plant, and number of components such as valves and connections. Additionally, compressor exhaust, and venting and flaring of methane occurs during gas processing.

Stage Separation.

In order to produce a more stable stock-tank liquid, stage separation is used. Up to three separators are used to gradually reduce the pressure on the reservoir liquids. The reason for this is to reduce the pressure on petroleum liquids containing large quantities of liquefied propanes, butanes, and pentanes. These liquid hydrocarbons will vaporize or flash when the petroleum liquids flow in the storage tank at a large pressure drop causing a substantial reduction in liquid recovery from the storage tank (most of the liquid in the storage tank would vaporize under these conditions).

Low Temperature Separation.

A low temperature separation is conducted to efficiently separate water and hydrocarbon liquids from the inlet well stream. This process usually recovers more hydrocarbon liquids from the gas than can be recovered with normal temperature separators. Water vapor condenses easily with this method which also facilitates dehydration of the gas stream. The cooling needed to perform the separation is provided by the expansion of the gas - a pressure differential of as low as 1000 psi can achieve the amount of dehydration desired.

Condensate Stabilization.

A drawback in using low temperature separation units is high vapor loss of the stock tank. When the pressure on the liquid is reduced from the low temperature separator to storage pressure, significant quantities of liquid propane and butane are vaporized with dissolved methane and ethane. These hydrocarbons are either burned or lost in the atmosphere. The process of condensate stabilization provides a means of removing methane and ethane from the liquid present in the bottom of the low temperature separator with a minimum loss of propane and butane. This allows a larger volume of stock-tank liquids available for sale.

The vertical stabilization vessel contains the hydrocarbon liquid in the lower section of the tower and is heated by either an indirect heater or steam coils. Ethane and methane are vaporized from the top of the stabilization vessel and are passed to the vent line or collected as fuel. The stabilized liquid at the bottom of the vessel, after being cooled, flows to storage. The additional amount of the condensed liquid recovered is dependent on the pressure and temperature at which the low temperature separator is operated as well as the chemical composition of the gas being processed.

4.5.2 Gas Plant Operations

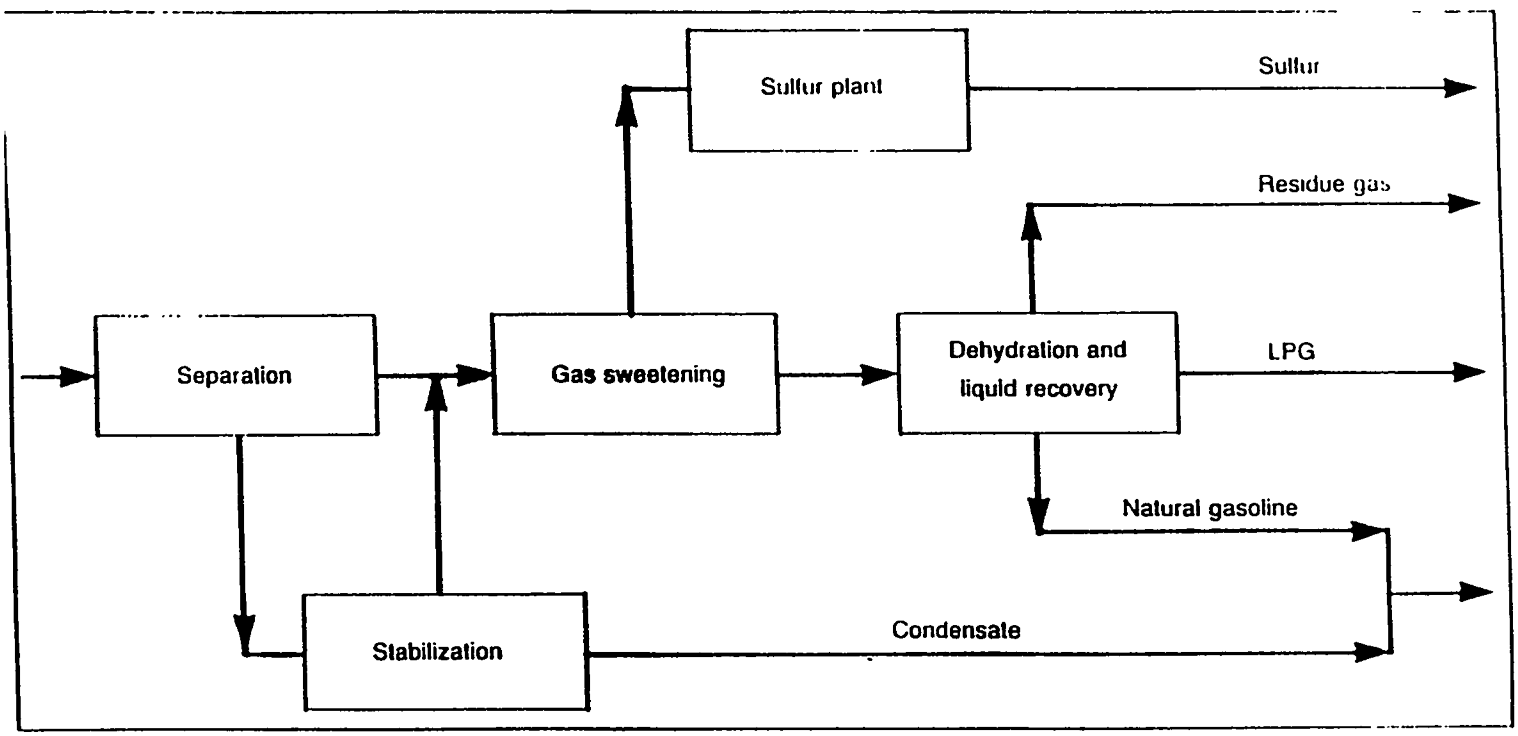
The treatment of natural gas involves the removal of contaminants or hydrocarbon compounds. The contaminants which may make the gas unsuitable for sale include hydrogen sulfide (H_2S), carbon dioxide, and/or water. Some H_2S at low levels is permissible in meeting gas sales specifications - above a certain level, the gas is labeled "sour gas." Water above a fixed level is removed by a dehydration plant. A gas sweetening plant is required to remove CO_2, or acid gas from the gas stream. Table 4.5-1 gives the normal components contained within a typical gas stream.

The gas sold to gas transmission companies must meet constituent requirements with respect to water content, hydrocarbon dewpoint, heating value, and hydrogen sulfide content. To satisfy the requirements of the sales contract most gas streams must be treated by a gas processing plant. Typical processes performed in a gas processing plant include 1) hydrocarbon removal, 2) dehydration, and 3) gas sweetening. A flow diagram representing the processes included in a natural gas processing plant is shown in Figure 4.5-1.

Table 4.5-1. Natural gas stream components

Component or hydrocarbons	Chemical formula	How utilized
Methane	CH_4	Primary NG fuel
Ethane	C_2H_6	Chemical feed stock
Propane	C_3H_8	Chemical feed stock
Pentanes	C_5H_{12}	Part of natural gasoline
Hexanes	C_6H_{14}	Part of natural gasoline
	Non-Hydrocarbons	
Hydrogen Sulfide (acid gas)	H_2S	Poisonous gas - converted to sulfur
Nitrogen	N_2	Inert gas
Water	H_2O	Removed to meet sales gas specs.

Fig 4.5-1 Typical Processes combined to form a gas plant



Hydrocarbon Removal

The removal of liquid hydrocarbons in the gas stream can be accomplished by passing the mixture through a large vessel allowing for deceleration and separation of the gas and liquids. Additionally, increasing the pressure and reducing the temperature in the vessel will add to the amount of liquid hydrocarbons condensed. In oil production, the use of a casinghead plant can recover ethane and heavier hydrocarbons and extract products from the gas stream including ethane, propane, isobutane and normal butane, and natural gasoline.

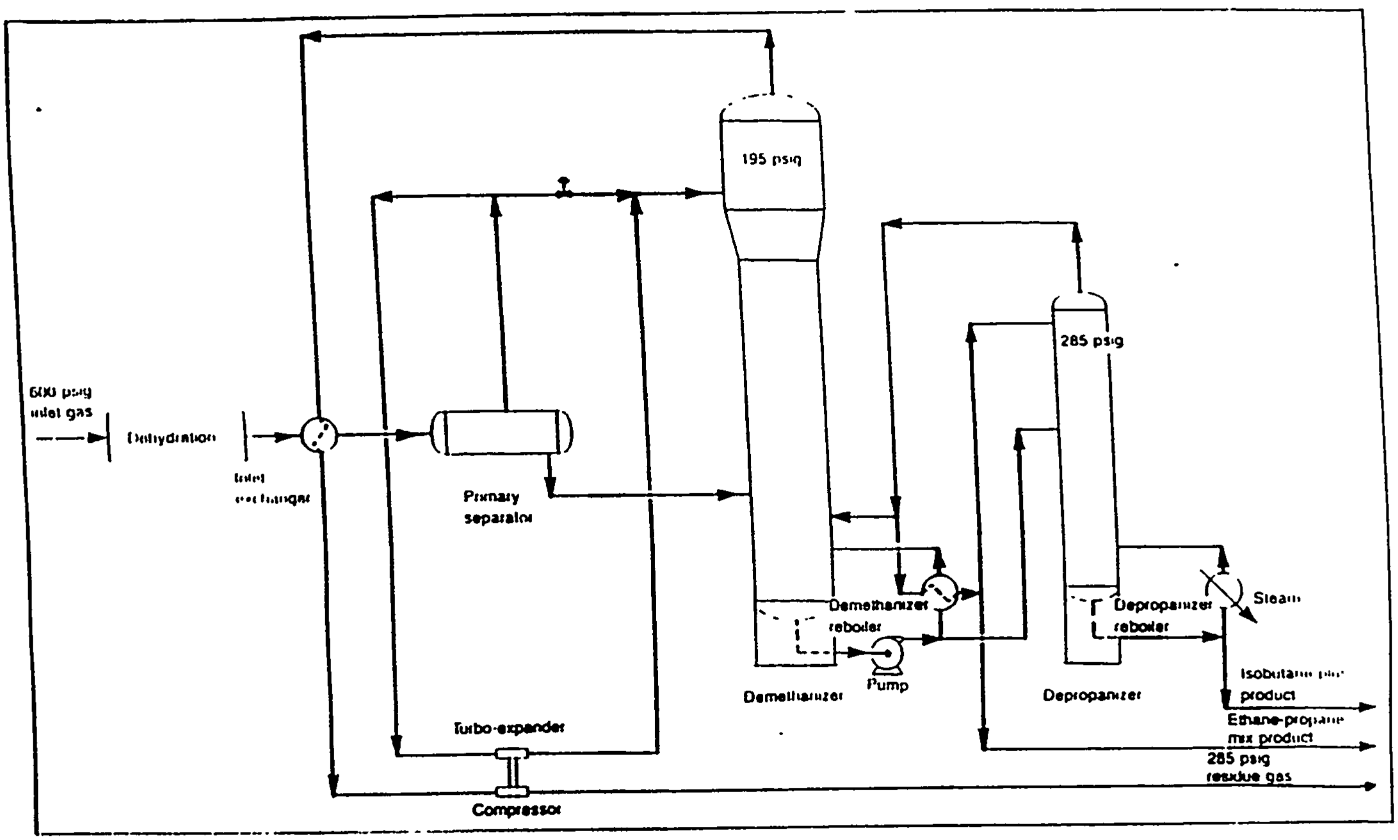
Compression Processing. The low pressure gas entering the plant inlet scrubber has a significant amount of liquids removed. The gas is then pressurized and cooled allowing for additional condensation of liquids.

Absorption Processing. The absorption process increases the recovery of more of the heavier hydrocarbons either for resale or to meet gas sales specifications. The absorption process consists of placing the raw compressed gas stream in contact with absorption or lean oil. During this process, predominantly heavy hydrocarbon components in the gas stream dissolve easily in the lean oil along with smaller amounts of lighter hydrocarbons. The lean oil is saturated with methane and ethane from a chiller before entering the absorber. This keeps the temperature of the lean oil from rising significantly and allows more absorption of propane to take place.

Some of the unwanted components of the rich oil, such as methane, coming out of the gas stream are flashed off at lower pressure. The rich oil is then passed through a de-ethanizer which supplies ethane for the plant with any excess going to the recycle compressor. The liquid hydrocarbons produced from the absorption plant can either be sold as a mixed stream or the components can be separated further in another processing plant.

Cryogenic Processing. The recovery of even larger amounts of ethane can be accomplished by utilizing low temperatures in an absorption plant which is considered to be in the cryogenic category. This process has become economical with the introduction of the turbine type expander-compressor. This process is schematically represented in Figure 4.5-2. The process is feasible where the gas stream is available under high pressure and after processing, the gas is needed to be under low pressure and close to the gas plant for final processing.

Fig. 4.5-2. Cryogenic gas plant



Adsorption Processing. This process recovers particular gases and hydrocarbon liquids (including water vapor) by utilizing solids having minute pores with large surface areas that have the ability to adsorb those gases and liquids. The solid materials having the ability to adsorb gases and liquids include activated carbon, bauxite, activated alumina, silica gel, and synthetic zeolites called molecular sieves.

The process utilizes a solid bed of adsorption materials in a cyclic batch type operation with two or more adsorption towers as shown schematically in Figure 4.5-3. One of the towers is on a drying cycle and the other regenerates the adsorption materials by heating the desiccant with hot gas which vaporizes the adsorbed hydrocarbons and water. This hot regeneration gas is then condensed, which removes most of the water and hydrocarbons from the system. The regeneration gas is then returned to the main gas stream to start the processing over.

Gas Dehydration

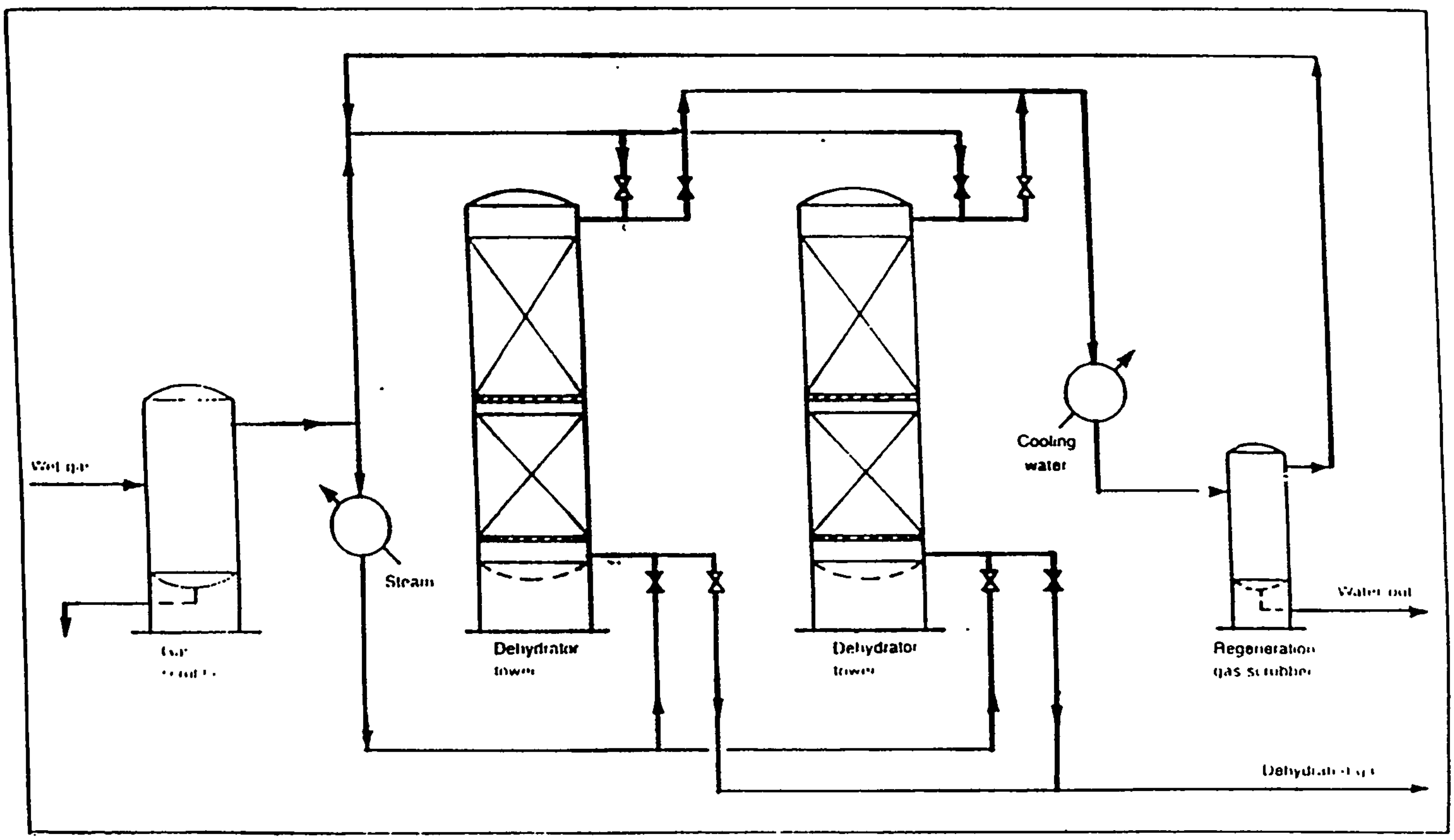
The gas dehydration process consists of three potential methods to remove water vapor from the natural gas stream. The methods utilize either a solid desiccant, a liquid desiccant, or refrigeration.

Solid Desiccant Dehydration. This process which is similar to adsorption hydrocarbon recovery, adsorbs water on bauxite, activated alumina, silica gel, or molecular sieves. There is some hydrocarbon liquid accumulated along with the condensed water recovered. This process can produce almost completely dry gas which is used as feed gas for the cryogenic type gas processing plant.

Liquid Desiccant Dehydration. This process brings the input gas stream into contact with a highly concentrated solution of triethylene glycol which serves as the desiccant. This process does not produce gas as dry as that treated with the solid desiccant dehydration process. However, the output gas is suitable for almost all uses except for input to cryogenic plants.

The absorber is a tower containing horizontal trays which has the input gas stream going toward the top with the glycol flowing downward. Application of heat to the water-rich glycol is required to strip out the water which leaves as steam. This type of processing is used widely with low temperature absorption type gas processing plants and for field locations which require little attention.

Fig. 4.5-3. Typical solid desiccant dehydration unit



Gas Sweetening

Certain natural gas streams are termed "sour" because they contain the extremely poisonous hydrogen sulfide (H_2S). Typical gas contracts limit the amount of hydrogen sulfide to 2.5 grains per thousand cubic feet (four parts per million). The chemicals used to remove hydrogen sulfide also remove carbon dioxide from the gas stream. The primary compound used to remove acid gases from the gas stream is a water solution of monoethanolamine (MEA). Other chemicals used to remove acid gases are diethanolamine (DEA) and Sulfinol. The first two chemicals remove acid gases by chemical reaction, whereas Sulfinol uses its chemical reaction ability with physical absorption. The physical process used is similar to liquid desiccant dehydration in that the sour gas enters the bottom of a contactor and flows counter-current with the MEA solution which travels downward. The MEA solution containing the H_2S is then processed by a regenerator where the solution is heated which strips the acid gases from the solution.

If small quantities of H_2S are contained within the gas stream but the quantities still exceed the limits set by gas sales contracts a material called an iron sponge or molecular sieves are used to remove the H_2S. The iron sponge consists of wood chips with an iron oxide coating. The iron oxide is converted to iron sulfide after contact with the sour gas. The iron sulfide chips cannot be used for many passes and have to be discarded frequently. If molecular sieves are used, regeneration can be accomplished by a heating process similar to other adsorption processes.

4.6 NATURAL GAS TRANSPORTATION AND STORAGE

The main environmental impact from the transportation and storage of natural gas is the venting to the atmosphere of methane, its primary constituent. During the transmission of natural gas through pipelines, methane can be emitted either through leaks or it can be vented on purpose due to normal operations, and maintenance and construction.

4.6.1 Pipeline Emissions

Natural gas or methane emissions from pipelines can be either voluntary or accidental. Venting of methane is commonly performed by gas pipeline personnel for a variety of reasons described below.

4.6.1.1 Normal operations

During normal operations of pipeline systems several voluntary measures are taken to vent methane. Three of the most common measures are as follows:

1) Natural gas can be used to operate various types of instruments including valves, controllers and pressure regulators. A portion of this gas is emitted to the atmosphere during the operation of these instruments.
2) Produced liquids that are collected in the gathering and transmission systems must be removed from the pipelines at specified locations. Natural gas is emitted to the atmosphere when the valves at these locations are opened to drain the liquids.
3) Relief valves are used to prevent gas pipelines and equipment from exceeding their maximum operating pressure. In the event of an overpressure, the relief valve opens releasing gas to the atmosphere.

4.6.1.2 Maintenance and Construction

Natural gas may be vented to the atmosphere on purpose during maintenance or new construction of gas process equipment and natural gas pipelines. The gas is routinely evacuated to the atmosphere from facilities to provide a non-flammable atmosphere and a safe operating condition before maintenance or construction can begin.

Pipelines and equipment are also purged of natural gas before construction and maintenance.

4.6.1.3 Natural Gas Equipment Leaks

Natural gas is unintentionally emitted to the atmosphere when pipelines, valves, or associated equipment leak. Although leakage does occur causing a loss of resource and income, inspection and surveys are conducted by natural gas companies to identify the root cause of leakage.

4.6.1.4 Methane Releases from Transmission Pipelines

A significant portion of the loss of methane to the atmosphere in this fuel cycle is due to leakage from transmission pipelines. Estimates as high as 0.5%, and perhaps even 1%, of methane throughput is thought to have been lost by leakage of long-distance pipelines in the U.S. Structural failure of portions of a transmission line, already under high pressure, is the usual reason for this leakage (AGA 1988). A survey of research on methane leakages of transmission pipelines and estimates for leakage at the Southeast Reference site is given in Chapter 9. Although methane leakage is not a priority concern in the U.S., it is of much greater significance in some countries, such as Russia, where leakage is reportedly of the order of 10%. Such leakages would significantly add to greenhouse gases in the atmosphere.

4.6.2 Emissions Due to Natural Gas Pipeline Transport Compressors

The natural gas industry uses engines to power compressors for pipeline transportation of gas (engines are also used for field gathering of gas from wells, underground storage, and gas processing plant applications). Pipeline engines are concentrated mainly along the Gulf Coast and the major pipelines. Gas turbines and reciprocating engines can be used to power compressors, although usage of large gas turbines has increased markedly over the past few years. Internal combustion (IC) reciprocating engines are more fuel efficient than gas turbines, although gas turbines emit significantly fewer pollutants than reciprocating engines.

4.6.2.1 Engine emissions and control measures

The major pollutant of natural gas-fired compressor engines is NO_x. NO_x is immediately formed in combustion due to the high temperature, pressure, and abundant air environment in the IC engines. CO and hydrocarbons are emitted, although these pollutants are produced in far smaller amounts than NO_x. External combustion boilers emit smaller amounts of the three pollutants than IC engines. Sulfur oxides can also form, but are usually low due to the negligible amount of sulfur contained in pipeline gas (EPA 1985).

The primary factors affecting NO_x emissions from compressor engines are the following:

1) air fuel ratio,
2) engine load (ratio of operating horsepower/rated horsepower),
3) intake air temperature, and
4) absolute humidity.

NO_x levels will <u>increase</u> with increasing engine load and intake air temperature. NO_x levels will <u>decrease</u> with increasing absolute humidity and air fuel ratio. A primary technique of reducing NO_x levels in gas turbine engines is the injection of water into the turbine combustion chamber. Reductions of NO_x levels of 80% can be achieved with water injection with minimal decreases in efficiency. Other NO_x reduction methods such as steam injection and exhaust gas recirculation are often impractical due to the unavailability of steam and the cost of exhaust cooling methods.

Reduction of NO_x in reciprocating gas-fired engines is accomplished by altering the air-fuel ratio. This is achieved by adjusting engine torque, speed, and intake air temperature. Water and steam injection are not cost effective for reciprocating engines, nor is exhaust gas recirculation. Emission factors for natural gas-fired compressors are presented in Chapter 5.

4.7 NATURAL GAS-FIRED ELECTRICITY GENERATION

Until the mid-1960s, gas-fired steam boiler technology was widely used in the U. S. as the process of choice for electricity generation. Improved reliability and efficiencies have led to widespread acceptance of gas turbine technology among electric utilities. In this subsection, we discuss the gas turbine technologies that are the benchmarks for the 1990 and 2010 timeframes. In addition, the environmental pollution produced from these technologies is discussed. These benchmarks are used for the purpose of illustrating the methodology and analytical approach for our study. They are not generic or representative technologies for the natural gas fuel cycle in general.

4.7.1 Generating Technology

The gas-fired electric generating technology selected for 1990 and 2010 analysis is the combined-cycle gas turbine. It is plausible that the gas-fired combined-cycle system assumed to be in use by utilities in 2010 would be associated with an adjacent coal gasifier unit (integrated gasification combined cycle (IGCC). The primary advantage of the IGCC system is that the utility would have the ability to replace potentially higher-priced natural gas with a lower-priced coal-derived fuel. This feature has made gas-fired combined-cycle capacity acceptable to several utilities (Power Engineering 1988). The nucleus of both systems (conventional combined-cycle and the IGCC) is the gas-fired combustion turbine in which natural gas is injected into compressed air in a combustion chamber. The fuel ignites, generating heat and combustion gases, and the gas mixture expands to drive a turbine, which is usually located on the same axle as the compressor. Various heat recovery, staged compression, and combustion designs are used to increase overall efficiency.

4.7.1.1 Combined Cycle Gas Turbine

A combined cycle gas turbine system consists of a combustion turbine/generator which generates electricity, a heat recovery steam generator which produces steam from the combustion turbine exhaust heat, and a steam turbine with condenser which generates additional electricity. This technology is assumed to be utilized for the 1990 power plant and is used primarily for base-load generation. Combined-cycle technology can significantly raise the overall thermal conversion efficiency of power plants. For example, the conversion efficiency of a new combined-cycle unit can be in the range of 40 to 47% (EPRI Journal 1988). We assume an efficiency of 41% for our analysis of 1990 combined-cycle technology.

The recovery of waste heat from the combustion turbine exhaust is usually accomplished by heat recovery steam generators (HRSGs). HRSG system designs include un-fired, supplementary-fired, and fully-fired heat recovery boilers. Un-fired HRSGs are convective heat exchangers that respond to the exhaust conditions of the gas turbine. They cannot be easily controlled to respond to process steam demands.

If the gas turbine exhaust has a sufficient oxygen content, fuel can be burned ahead of the HRSG to increase steam production rates relative to an un-fired HRSG. The supplementary firing capacity provides the ability to control HRSG steam production, independent of gas turbine operation.

A fully-fired HRSG is a unit having the same amount of oxygen in its stack gases as an ambient air-fired boiler. The HRSG is essentially a boiler with the gas turbine exhaust as its air supply. Steam production from fully-fired HRSGs can be six to seven times greater than the un-fired HRSG production rate.

Continuing advances in gas turbine technology may allow combined-cycle efficiencies to approach 60% by 2000 (GE 1996). This will be accomplished by increasing inlet temperatures to 2600° and implementing further improvements in combustion technology.

4.7.1.2 Combined Cycle Gas Turbine Control Technologies

The majority of natural gas-fired gas turbines used by electric utilities use one or a combination of the following two basic control technologies:

a) water or steam injection - This is the most common control technology for large combined-cycle gas turbines. NO_X emissions can be reduced by up to two-thirds using water or steam injection methods (compared to gas turbines with no controls). Higher levels of CO and HC may ensue due to lower temperatures within the combustor resulting in incomplete combustion.

b) Selective Catalytic Reduction (SCR) - All existing applications of SCR controls have been used with water or steam injection controls, although SCR can be used alone. This is a post-combustion control which reduces NO_X by reaction with ammonia and NO. Some SCR systems also utilize a CO catalyst to reduce CO simultaneously with NO_X.

Future gas turbine combined-cycle systems in 2010 will likely utilize dry-low NO_X technologies. The dry-low NO_X technology utilizing staged combustion, will provide NO_X emission levels of between one-half and one-fifth that of current SCR control technology. Similar reductions in CO are also expected.

4.8 REGIONAL REFERENCE ENVIRONMENT AND SCENARIO DESCRIPTION

4.8.1 Introduction

This section delineates the locations of the gas-fired plants and the related sites for natural gas production and processing, and describes the sites in terms of their baseline socioeconomic and environmental characteristics. Two sites were chosen as regional reference environments for the gas plants to illustrate the differences in the analyses that result from different socioeconomic and environmental conditions. This study uses a 50-mile radius from the plant site to define the boundaries of the local reference environment. One site is on the Southeastern United States and the other in the Southwest. The sites are selected solely for the purpose of illustrating the methodology for our fuel cycle analysis. The sites are not intended to be representative or "typical." No two sites, anywhere, are representative of all possible sites in the country.

Constrained by project resources, our site selections were areas that were already well characterized in terms of their socioeconomic and environmental parameters. Choosing sites in this manner considerably reduced our data collection efforts. Thus, we chose sites for which an environmental impact statement (EIS) had been prepared. Although some information in the EIS was updated (e.g., population, income), the availability of basic area descriptors significantly reduced our data collection efforts.

In selecting the variables to describe the reference environment, we have followed the standardized format for environmental impact statements as delineated by the National Environmental Policy Act (NEPA). Socioeconomic descriptors include population, economic base (employment and income), housing, government services, transportation, land use, water sources, and historic, cultural and archaeological features. Environmental parameters include the hydrology of both surface water and groundwater, water quality, meteorology, air quality, noise, geology and seismology, aquatic ecology and terrestrial ecology. At the onset of this study, we identified sources for these variables. In this section, we will present these sources. However, not all of these variables were used in the impacts and damages analyses in this report. Therefore, data are not presented for all the variables, and only the data used in the analyses are to be given a NUSAP rating (refer to Section 3.4 on NUSAP).

4.8.2 Reference Plant, Gas Production, and Processing Sites

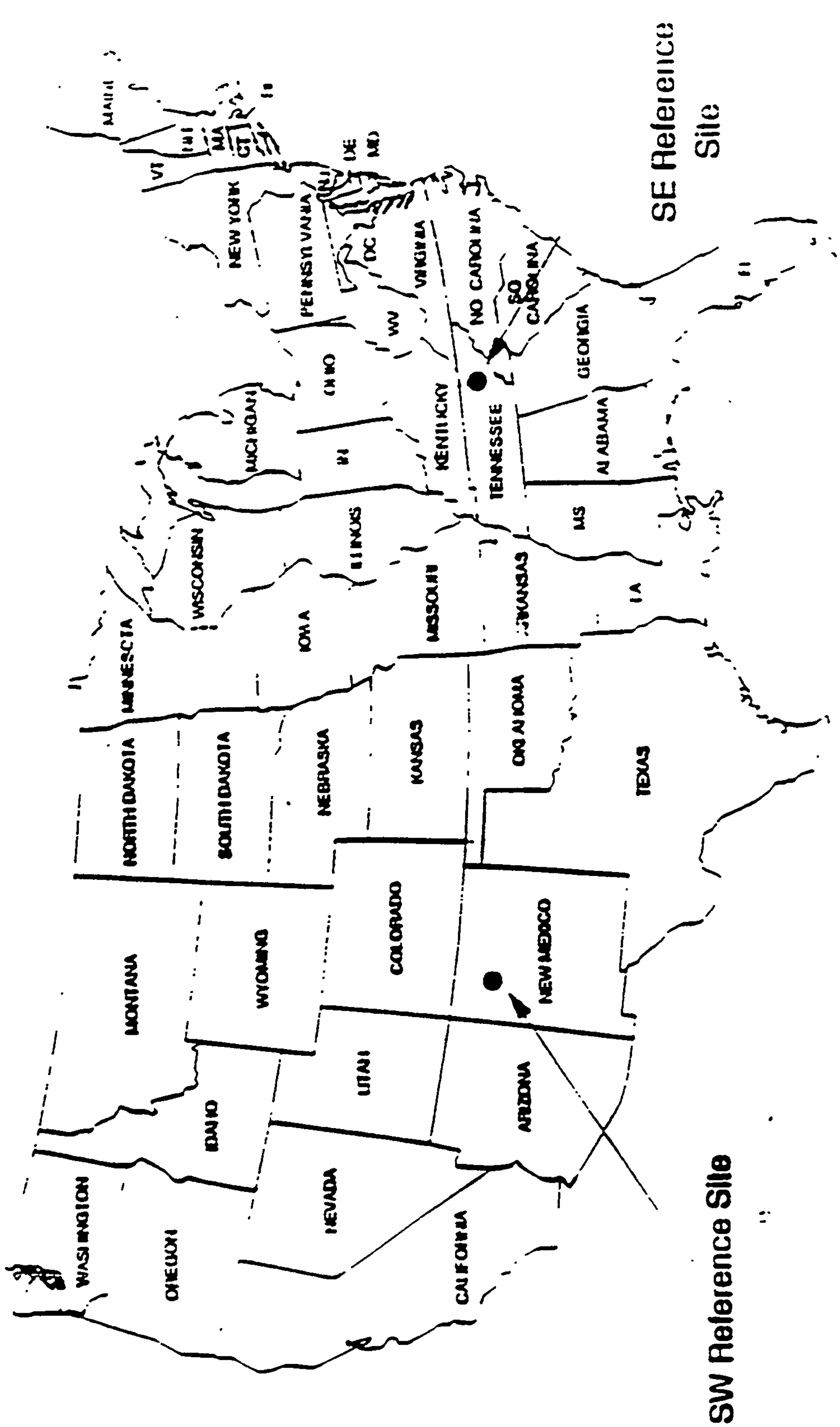
The site of the gas-fired power plant in the southeast region of the United States is what was to have been the location of the Clinch River Breeder Reactor (CRBR) in Roane County, Tennessee. This location is on the north side of the Clinch River and is approximately 25 miles west of Knoxville and 9 miles south of Oak Ridge (hereafter referred to as the Southeast Reference site). The site of the gas plant in the southwest region is that of the proposed, but never built, coal-fired New Mexico Generating Station (NMGS) in San Juan County, New Mexico—35 miles south of Farmington (hereafter referred to as the Southwest Reference site). Figure 4.8-1 is a map showing the locations of these two reference sites in the United States.

The natural gas for the Southeast Reference site in 1990 was assumed to be produced offshore of southern Louisiana. For the 2010 scenario, gas was assumed to come from an onshore site in southern Louisiana. For both scenarios, the processing plant is assumed to be in Yscloskey, Louisiana, which is close to New Orleans.

The natural gas is assumed to be transported by pipeline from the processing plant to the power plant site. The proposed route would be a main trunk pipeline from Yscloskey, Louisiana to Nashville, Tennessee. Secondary natural gas lines, owned by East Tennessee Natural gas Company, would transport the gas from Nashville to the power plant site in Roane County, Tennessee.

The natural gas for the Southwest Reference site was assumed to be produced and processed about 35 miles northeast of the power plant site near Bloomfield, New Mexico. Bloomfield sits atop the San Juan Basin, the largest producing natural gas field in North America. The processed gas would be transported by a trunk line from the processing plant to the power plant.

Fig. 4.8-1 Locations of the Southeast and Southwest Reference sites



4.8.3 Socioeconomic Parameters

As mentioned previously, socioeconomic descriptors of a region include population, economic base (employment and income), housing, government services, transportation, land use, water sources, and historic, cultural, and archaeological features. Sources for all of these variables will be discussed. However, we will present data mainly for those variables that were used in the analyses of impacts and damages.

Population

U.S. Bureau of the Census population data were used to derive population densities for both site-specific areas. Population data for a location near the Southeast Reference site were used as a proxy for the Southeast Reference site. These are 1989 data that were projected from 1980 U.S. Bureau of the Census data.[3] The data are estimates of population in specified distance intervals in 16 directions. The total number of people within 50 miles of the plant was 943,037. Tables 4.8-1 and 4.8-2 contain incremental and cumulative populations, respectively, for given distances.

For the Southwest Reference site, we were unable to obtain population numbers in distance increments from the plant. Therefore, the total population within a 50-mile radius was estimated with U.S. Bureau of the Census county-level data (1988). The population of the city of Farmington was added to an estimated rural population for the 50-mile radius to provide an estimated total population of 114,494 within 50 miles of the Southwest Reference site.

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[3] At the time that population data were being collected, the 1990 Census data were unavailable. However, we now have 1990 data for specified distance intervals for the 16 compass directions, using the hypothesized plant as the center of origin. These data will be included when this report is revised.

Table 4.8-1 Incremental counts of people by radial distance and sector direction, Southeast Reference site.

	Miles									
Sector	0-1	1-2	2-3	3-4	4-5	5-10	10-20	20-30	30-40	40-50
N	652	358	1,314	1,105	330	667	2,092	4,808	4,935	12,749
NNE	0	973	1,759	2,039	3,047	2,196	9,703	21,050	8,411	6,988
NE	0	682	874	550	778	5,925	11,429	8,274	6,292	14,392
ENE	0	0	0	0	0	4,333	30,995	21,892	11,581	21,618
E	0	0	0	205	909	5,270	123,499	58,872	17,884	18,495
ESE	0	0	122	883	325	5,482	59,542	24,080	17,733	14,330
SE	0	0	0	93	270	9,088	9,966	50,783	2,185	555
SSE	0	0	0	282	153	3,524	5,320	9,475	1,032	1,116
S	0	0	0	120	24	1,687	11,884	6,299	8,252	4,618
SSW	0	0	0	0	0	891	8,602	11,745	14,458	27,471
SW	0	0	0	0	0	112	5,910	4,646	8,171	9,873
WSW	0	0	0	391	0	431	18,410	12,238	6,944	5,519
W	0	211	323	418	155	1,971	5,377	2,465	6,325	19,948
WNW	441	371	1,300	674	286	1,936	5,244	3,616	2,689	5,599
NW	464	755	2,837	333	1,172	965	1,401	1,795	4,760	7,918
NNW	351	477	928	1,365	505	481	312	3,008	11,095	7,806
Total	1,908	3,827	9,457	8,458	7,954	44,959	309,686	245,046	132,747	178,995

Table 4.8.2 Incremental counts of people by radial distance and sector direction, Southeast Reference site

	Miles									
Sector	0-1	0-2	0-3	0-4	0-5	0-10	0-20	0-30	0-40	0-50
N	652	1,010	2,324	3,429	3,759	4,426	6,518	11,326	16,261	29,010
NNE	0	973	2,732	4,771	7,818	10,014	19,717	40,767	49,178	56,166
NE	0	682	1,556	2,106	2,884	8,809	20,238	28,512	34,804	49,196
ENE	0	0	0	0	0	4,333	35,328	57,220	68,801	90,419
E	0	0	0	2 05	1,114	6,384	129,883	188,755	206,639	225,134
ESE	0	0	122	1,005	1,330	6,812	66,354	90,434	108,167	122,497
SE	0	0	0	93	363	9,451	19,417	70,200	72,385	72,940
SSE	0	0	0	282	435	3,959	9,279	18,754	19,786	20,902
S	0	0	0	120	144	1,831	13,715	20,014	28,266	32,884
SSW	0	0	0	0	0	891	9,432	21,238	35,696	63,167
SW	0	0	0	0	0	112	6,022	10,668	18,839	28,712
WSW	0	0	0	391	391	822	19,232	31,470	38,414	43,933
W	0	211	534	952	1,107	3,078	8,455	10,920	17,245	37,193
WNW	441	812	2,112	2,786	3,072	5,008	10,252	13,868	16,557	22,156
NW	464	1,219	4,056	4,389	5,561	6,526	7,927	9,722	14,482	22,400
NNW	351	828	1,756	3,121	3,626	4,107	4,419	7,427	18,522	26,328
Total	1,908	5,735	15,192	23,650	31,604	76,563	386,249	631,295	764,042	943,037

There are several additional sources of population data, at differing levels of detail and aggregation. The U. S. Bureau of the Census publication *Census of Population and Housing, Census Tract Reports* (1980) contains population characteristics at the census tract level. These characteristics include age cohorts, sex, marital status, and race. Census tracts are defined for Standard Metropolitan Statistical Areas (SMSAs). Although the Southeast Reference site in Roane County does not lie within the Knoxville SMSA, much of the surrounding area does. The Southwest Reference site is not within, or near, an SMSA. Thus, census tract data are not available for that area. The *Characteristics of the Population, General Population Characteristics, United States Summary* has 1980 population for individual Indian reservations which could be useful for the Southwest Reference environment. Contained in these volumes are county-level data on total population, population density, population by age cohort, race and sex, as well as the number of households, number of persons per household, marital status and a number of other characteristics.

Economic Base, Housing, and Services

The *Characteristics of the Population, Number of Inhabitants, United States Summary* contains information on such characteristics as population densities, employment (by occupation and industry) and income. State sources of various social and economic variables, at the county-level, are the state statistical abstracts (i.e., the *New Mexico Statistical Abstract* and the *Tennessee Statistical Abstracts*). These publications contain data on population, income, employment, housing, and services.

The *New Mexico Statistical Abstract* contains state-level employment data by industry (mining is broken down by categories) and earnings and hours data at the state-level by industry. The *Tennessee Statistical Abstract* contains county-level employment by occupation and average wages. Additionally, the Bureau of Labor Statistics publishes employment, hours, and earnings data by state and selected areas within states.

Transportation

For transportation, the EIS's of both sites provide a listing of major roads, railroads, and airports.

Land Use

Land use descriptors in this study provide information on crop production, forests, and recreational fishing. Crop production data for the Southeast Reference environment were from the Tennessee Department of Agriculture. Specifically, there are four crops of interest: soybeans, wheat, corn, and tobacco. The estimated annual production of these crops (for methodology, see Section 10.1 in this report) for the Southeast Reference site are shown in Table 4.8-3. Crop data were not collected for the southwest as ozone modeling was not done for the southwest due to a lack of baseline emissions (see Air Quality in this section). An additional source of annual crop information at the county-level is the U.S Department of Agriculture's publication, *Census of Agriculture*.

Table 4.8-3. Crop production for the Southeast Reference environment

Crop	Production (1000s Bushels)
Soybeans	82.28
Wheat	274.54
Corn	673.00
Tobacco	3,253.30

The EIS for the Southwest Reference site states that forest covers nearly all of the 1364 acres of the site. Furthermore, it states that 37% of the acres are covered with hardwood, 47% by conifers, 11% by mixed forest types, and 5% of the land is nonforested. According to the EIS for the Southwest Reference site, within a 10-mile radius of the plant site, most of the vegetation is semiarid grass and shrubland vegetation.

Fishing

Recreational fishing is addressed in what is known as the "Creel Survey." Most states maintain a "Creel Survey." The survey contains several variables: fishing pressure (measured in trips/acre, hours/lake, or fish/acre), catch per unit of effort (both lake wide and for intended species), total estimated harvest size and average fish size. The data are too voluminous to present in this document, but a "Creel Survey" may be obtained from the Tennessee Wildlife Resources, the New Mexico Department of Game and Fish, and the Kentucky Department of Fish and Wildlife Resources.

Water Use

Water use information is in EISs and is available from the sources listed below for water quality.

Other Sites and Structures

The EIS for the Southeast Reference site lists historic and archeological sites, as well as natural landmarks. Additionally, historical sites may be obtained from the Tennessee Historical Commission and from the Tennessee Department of Environment and Conservation. The New Mexico Preservation Division maintains an inventory of historical and archaeological sites.

A final variable of interest is the stock of buildings for an area, in terms of the materials of which the buildings are made, for the purposes of evaluating the degradation caused by pollutants. We have been unable to identify any local, state, or federal sources of this information.

4.8.4 Environmental Parameters

Hydrology

Hydrology data for the Southeast Reference site are available from the Tennessee Valley Authority (TVA). An additional source is the Division of Public Water Supply in the Tennessee Department of Health and Environment. For the Southwest Reference site, there are two data sources: the United States Geological Survey (USGS) and the hydrology technical report prepared for the Southwest Reference site draft EIS (1982).

The Environmental Protection Agency (EPA) maintains and updates a water quality data base, for surface and ground water, called STORET. STORET contains information on a multitude of variables, among which are geographic data about the site of collection of water quality, the water's physical and chemical characteristics, municipal waste sources and disposal systems, pollution-caused fish kills and daily stream flow. Table 4.8-4 is a printout of water quality data for a point on the Clinch River near the Southeast Reference site (specifically, Clinch River mile marker 15.4). There is also a water quality technical report that was prepared for the Southwest Reference EIS. If desired, hydrological data obtained from a source other than STORET can be matched with STORET data by dates and times. Additionally, the Tennessee State Division of Public Water Supply performs regular chemical analyses on all public water supplies.

Table 4.8-4 Example of STORET (EPA water quality database) output

STORET RETRIEVAL DATE 91/07/30 PGM=INVENT PAGE:

476031 3342
35 53 44.0 084 23 18.0 2
BELOW CRBRP DISCHARGE
47145 TENNESSEE ROANE
/TYPA/AMBNT/STREAM TENNESSEE RIVER BASIN 040101
CLINCH RIVER 15.4
131TVAC 06010207003 0003.360 ON
0000 FEET DEPTH

PARAMETER	MEDIUM	RMK	NUMBER	MEAN	VARIANCE	STAN DEV	MAXIMUM	MINIMUM	BEG DATE	END DATE
00002 HSAMPLOC % FROM RT BANK	WATER		186	49.27400	470.1500	21.68300	95.0	5.0	75/03/11	77/10/12
00010 WATER TEMP CENT	WATER		186	16.42000	15.22700	3.902100	21.0	5.8	75/03/11	77/10/12
00011 WATER TEMP FAHN	WATER	$	186	61.55400	49.48000	7.034200	69.8	42.4	75/03/11	77/10/12
00061 STREAM FLOW, INST-CFS	WATER		7	5238.600	4530500	2128.500	7130	900	77/01/11	77/09/07
00070 TURB JKSN JTU	WATER		74	7.767600	92.09700	9.596700	50.0	1.6	75/03/11	77/10/12
00080 COLOR PT-CO UNITS	WATER		74	6.378400	12.43000	3.525700	17	1	75/03/11	77/10/12
00081 AP COLOR PT-CO UNITS	WATER		74	19.10800	167.1100	12.92700	75	6	75/03/11	77/10/12
00095 CNDUCTVY AT 25C MICROMHO	WATER		176	220.4600	2153.000	46.40000	270	100	75/03/11	77/10/12
00300 DO MG/L	WATER		186	8.376900	3.253600	1.803800	12.1	5.0	75/03/11	77/10/12
00301 DO SATUR PERCENT	WATER	$	186	83.67600	170.1600	13.04500	110.0	55.6	75/03/11	77/10/12
00310 BOD 5 DAY MG/L	WATER		10	1.190000	.0048889	.0699170	1.3	1.1	75/07/15	76/08/05
		K	27	1.000000	.0000000	.0000000	1.0	1.0	75/03/11	76/09/14
		TOT	37	1.037800	.0051969	.0720900	1.3	1.0	75/03/11	76/09/14
00335 COD LOWLEVEL MG/L	WATER		72	4.097200	2.793300	1.671300	8.0	1.0	75/03/11	77/10/12
		K	1	1.000000			1.0	1.0	75/05/22	75/05/22
		TOT	73	4.054800	2.885900	1.696800	8.0	1.0	75/03/11	77/10/12
00400 PH SU	WATER		177	7.626500	.1122800	.3350900	8.20	6.80	75/03/11	77/10/12
00410 T ALK CACO3 MG/L	WATER		101	86.90100	281.5000	16.77800	110	5	75/03/11	77/10/12
00415 PHEN-PH- LFIN ALK MG/L	WATER		101	.0000000	.0000000	.0000000	0	0	75/03/11	77/10/12
00530 RESIDUE TOT NFLT MG/L	WATER		73	8.671200	73.30700	8.562000	46	2	75/03/11	77/10/12
		K	1	1.000000			1	1	76/09/14	76/09/14
		TOT	74	8.567600	73.09800	8.549800	46	1	75/03/11	77/10/12
00605 ORG N N MG/L	WATER		74	.1059500	.0025368	.0503670	.320	.040	75/03/11	77/10/12
00610 NH3+NH4- N TOTAL MG/L	WATER		73	.0252050	.0003364	.0183420	.120	.010	75/03/11	77/10/12
		K	1	.0100000			.010	.010	77/05/10	77/05/10
		TOT	74	.0250000	.0003349	.0183010	.120	.010	75/03/11	77/10/12
00612 UN-IONZD NH3-N MG/L	WATER	$	74	.0004482	.0000001	.0003446	.001	.00002	75/03/11	77/10/12
00619 UN-IONZD NH3-NH3 MG/L	WATER	$	74	.0005449	.0000001	.0004191	.002	.00002	75/03/11	77/10/12
00630 NO2&NO3 N-TOTAL MG/L	WATER		74	.4209000	.0147160	.1213100	.64	.16	75/03/11	77/10/12
00665 PHOS-TOT MG/L P	WATER		70	.0164290	.0000725	.0085188	.050	.010	75/03/11	77/10/12
		K	3	.0100000	.0000000	.0000000	.010	.010	75/05/22	75/08/07
		TOT	73	.0161640	.0000711	.0084378	.050	.010	75/03/11	77/10/12
00666 PHOS DIS MG/L P	WATER		29	.0117240	.0000362	.0060172	.040	.010	75/04/16	77/10/12
		K	34	.0100000	.0000000	.0000000	.010	.010	75/03/11	77/07/13
		R	4	.7575000	.2352300	.4850000	1.000	.030	76/09/14	77/04/12
		TOT	67	.0553730	.0424830	.2061100	1.000	.010	75/03/11	77/10/12
00680 T ORG C C MG/L	WATER		65	2.027700	2.163900	1.471000	12.0	.9	75/03/11	77/07/13
		K	3	.2000000	.0000000	.0000000	.2	.2	77/10/12	77/10/12
		R	3	1.333300	.0633360	.2516700	1.6	1.1	76/08/05	76/08/05

Table 4.8-4 Example of STORET (EPA water quality database) output (continued)

TORET RETRIEVAL DATE 91/07/30 PGM=INVENT

476031 3342
35 53 44.0 084 23 18.0 2
BELOW CRBRP DISCHARGE
47145 TENNESSEE ROANE
TENNESSEE RIVER BASIN 040101
CLINCH RIVER 15.4
/TYPA/AMBNT/STREAM
131TVAC 060102070003 0003.360 ON
0000 FEET DEPTH

PARAMETER				MEDIUM	RMK	NUMBER	MEAN	VARIANCE	STAN DEV	MAXIMUM	MINIMUM	BEG DATE	END DATE
00680	T ORG C	C	MG/L	WATER	TOT	71	1.921100	2.132500	1.460300	12.0	.2	75/03/11	77/10/12
00681	D ORG C	C	MG/L	WATER		25	1.464000	3.097400	1.760000	9.5	.3	75/03/11	76/03/09
00916	CALCIUM	CA-TOT	MG/L	WATER		28	27.03600	14.11000	3.756400	33.0	20.0	75/03/11	76/07/15
00927	MGNSIUM	MG,TOT	MG/L	WATER		28	7.610700	.7358300	.8578100	8.8	6.5	75/03/11	76/07/15
00929	SODIUM	NA,TOT	MG/L	WATER		28	3.460700	2.955000	1.719000	6.90	1.90	75/03/11	76/07/15
00937	PTSSIUM	K,TOT	MG/L	WATER		28	1.192900	.0214340	.1464000	1.50	.90	75/03/11	76/07/15
00940	CHLORIDE	TOTAL	MG/L	WATER		30	2.800000	.2344900	.4842400	4	2	75/03/11	76/08/05
00945	SULFATE	SO4-TOT	MG/L	WATER		31	14.93600	8.796000	2.965800	21	9	75/03/11	76/08/05
00955	SILICA	DISOLVED	MG/L	WATER		31	4.525800	1.134000	1.064900	6.0	2.3	75/03/11	76/08/05
01027	CADMIUM	CD,TOT	UG/L	WATER		3	1.333300	.3333400	.5773500	2	1	75/03/11	75/10/15
					K	25	1.000000	.0000000	.0000000	1	1	75/03/11	76/07/15
					TOT	28	1.035700	.0357150	.1889900	2	1	75/03/11	76/07/15
01034	CHROMIUM	CR,TOT	UG/L	WATER		1	5.000000			5	5	75/09/16	75/09/16
					K	27	5.000000	.0000000	.0000000	5	5	75/03/11	76/07/15
					TOT	28	5.000000	.0000000	.0000000	5	5	75/03/11	76/07/15
01042	COPPER	CU,TOT	UG/L	WATER		19	50.52600	1094.200	33.07800	110	10	75/05/22	76/07/15
					K	9	10.00000	.0000000	.0000000	10	10	75/03/11	75/09/16
					TOT	28	37.50000	1100.900	33.18000	110	10	75/03/11	76/07/15
01045	IRON	FE,TOT	UG/L	WATER		27	282.2200	16641.00	129.0000	560	80	75/03/11	76/07/15
					K	1	10.00000			10	10	76/07/15	76/07/15
					TOT	28	272.5000	18671.00	136.6400	560	10	75/03/11	76/07/15
01046	IRON	FE,DISS	UG/L	WATER		2	75.00000	450.0000	21.21300	90	60	75/05/22	75/10/15
					K	22	50.00000	.0000000	.0000000	50	50	75/03/11	75/10/15
					R	1	160.0000			160	160	76/07/15	76/07/15
					TOT	25	56.40000	532.3400	23.07200	160	50	75/03/11	76/07/15
01047	FERROUS	IRON	UG/L	WATER		21	53.33300	353.3400	18.79700	100	30	75/03/11	75/10/15
					K	3	20.00000	.0000000	.0000000	20	20	75/05/22	75/09/16
					TOT	24	49.16700	434.0600	20.83400	100	20	75/03/11	75/10/15
01051	LEAD	PB,TOT	UG/L	WATER		5	18.20000	43.70000	6.610600	24	11	75/03/11	75/10/15
					K	23	10.00000	.0000000	.0000000	10	10	75/04/16	76/07/15
					TOT	28	11.46400	16.70300	4.086900	24	10	75/03/11	76/07/15
01055	MANGNESE	MN	UG/L	WATER		23	36.52200	60.08000	7.751100	50.0	10.0	75/04/16	76/07/15
					K	2	10.00000	.0000000	.0000000	10.0	10.0	76/07/15	76/07/15
					TOT	25	34.40000	109.0000	10.44000	50.0	10.0	75/04/16	76/07/15
01056	MANGNESE	MN,DISS	UG/L	WATER		3	13.33300	33.33400	5.773500	20.0	10.0	75/04/16	75/04/16
					K	18	10.00000	.0000000	.0000000	10.0	10.0	75/05/22	75/10/15
					R	1	40.00000			40.0	40.0	76/07/15	76/07/15
					TOT	22	11.81800	44.15600	6.645000	40.0	10.0	75/04/16	76/07/15
						1	50.00000			50	50	76/07/15	76/07/15

Table 4.8-4 Example of STORET (EPA water quality database) output (continued)

```
STORET RETRIEVAL DATE 91/07/30                FGM=INVENT
                                                      476031          3342
                                                      35 53 44.0 084 23 18.0 2
                                                      BELOW CRBRP DISCHARGE
                                                      47145   TENNESSEE          ROANE
                                                      TENNESSEE RIVER BASIN      040101
 /TYPA/AMBNT/STREAM                                   CLINCH RIVER 15.4
                                                      131TVAC                        06010207003 0003.360 ON
                                                      0000 FEET DEPTH
```

PARAMETER	MEDIUM	RMK	NUMBER	MEAN	VARIANCE	STAN DEV	MAXIMUM	MINIMUM	BEG DATE	END DATE
01067 NICKEL NI,TOTAL UG/L	WATER	K	27	50.00000	.0000000	.0000000	50	50	75/03/11	76/07/15
01067 NICKEL NI,TOTAL UG/L	WATER	TOT	28	50.00000	.0000000	.0000000	50	50	75/03/11	76/07/15
01092 ZINC ZN,TOT UG/L	WATER		16	45.00000	1173.300	34.25400	130	10	75/03/11	75/10/15
		K	12	10.00000	.0000000	.0000000	10	10	75/03/11	76/07/15
		TOT	28	30.00000	962.9600	31.03200	130	10	75/03/11	76/07/15
31501 TOT COLI MFIMENDO /100ML	WATER		11	294.5500	365890.0	604.8900	2000	10	75/04/16	75/09/16
		K	10	10.00000	.0000000	.0000000	10	10	75/03/11	75/08/07
		TOT	21	159.0500	204150.0	451.8300	2000	10	75/03/11	75/09/16
31616 FEC COLI MFM-FCBR /100ML	WATER		4	10.00000	.0000000	.0000000	10	10	75/04/16	75/08/07
		K	17	25.88200	1250.700	35.36600	100	10	75/03/11	75/09/16
		TOT	21	22.85700	1041.400	32.27100	100	10	75/03/11	75/09/16
46570 CAL HARD CA MG MG/L	WATER		28	99.14300	156.5800	12.51300	120	77	75/03/11	76/07/15
70300 RESIDUE DISS-180 C MG/L	WATER		74	124.1900	358.9300	18.94600	240	80	75/03/11	77/10/12
71900 MERCURY HG,TOTAL UG/L	WATER		3	.8000000	.6100000	.7810300	1.7	.3	75/04/16	75/10/15
		K	22	.2000000	.0000000	.0000000	.2	.2	75/03/11	75/10/15
		TOT	25	.2720000	.0904330	.3007200	1.7	.2	75/03/11	75/10/15
74041 WQF SAMPLE UPDATED	WATER		4	870760.0	.0000000	.0000000	870803	870723	75/10/15	77/01/11
84002 CODE GENERAL REMARKS	WATER	TXT	4	TEXT	TEXT	TEXT	TEXT	TEXT	75/10/15	77/01/11

Meteorology

Meteorological data (e.g., temperature, wind direction and speed, precipitation, incidences of hurricanes and tornadoes) are available from the National Oceanic and Atmospheric Administration (NOAA). There is a publication titled *Climates of the States* (1985) that contains NOAA data for each state for selected weather stations. According to the Southeast Reference site EIS, for the nearby ORNL weather station, mean average annual temperature is 58.5°F, annual relative humidity is 70%, and average annual precipitation is 51.52 inches. Wind speed and direction distributions (wind roses) for the southeast plant site are shown in Figure 4.8-2. According to the Southwest Reference site EIS, the mean average annual temperature for a weather station 12 miles southwest of the Southwest Reference site is 50.5°F, and average annual rainfall is less than 8 inches. The wind speeds are described by the Southwest Reference site EIS as moderate.

Other meteorological variables of interest include mixing height, the ambient ratio of VOC to NO_x and visibility. A source for mixing height data has been identified as a book by G.C. Holzworth (1972). An EPA (1989) document contains information on using ambient monitoring data to derive the VOC/NO_x ratio. Currently, researchers at the University of Tennessee-Knoxville and the Tennessee Air Pollution Control Division of the Department of Health and Environment are working on the issue of the sensitivity of ozone to changes in VOC and NO_x. Finally, the Office of Technology Assessment (1984) published a report that contains a map of the U.S. with visibility ranges. The visibility for the Southeast Reference site area is approximately 20 miles. The Southwest Reference site EIS lists the visibility for that area as an average of 128 miles.

Air Quality

Air quality data are from the National Air Data Branch of EPA. The specific data base is EPA's Aerometric Information Retrieval System (AIRS). This data base contains observations for the six criteria pollutants, by monitoring station, as well as observations for a variety of toxics. EPA also has a Toxic Release Information System (TRIS) data base. This data base includes emissions to air and water from certain manufacturers.

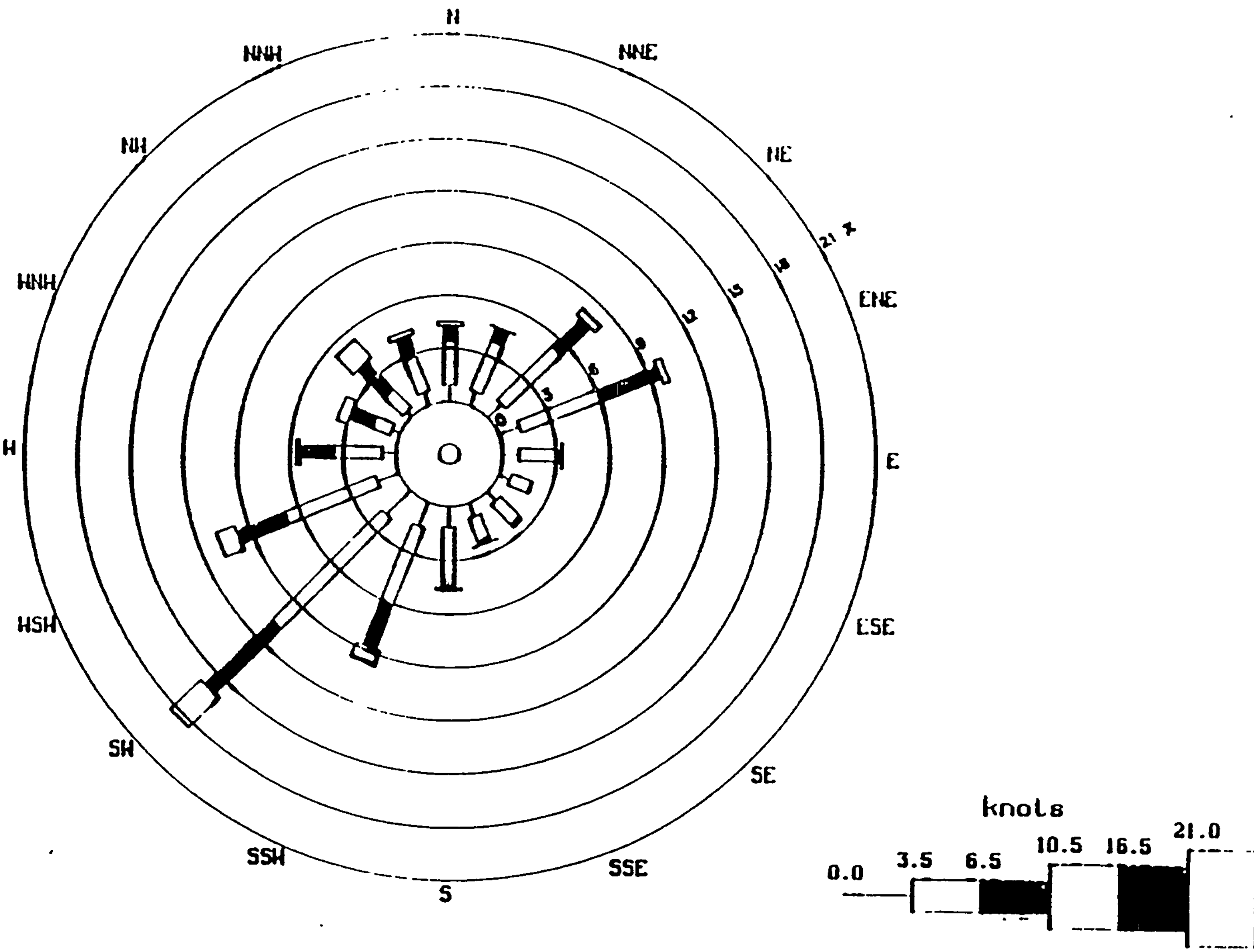

Fig. 4.8-2 Wind rose at 60 m height, June-Sept., 11 a.m.-7p.m., 1985-90. Data was taken from the K-25, DOE facility which is located 4.5 km north of the Reference site.

An emissions inventory of ozone precursors for counties in Middle and West Tennessee was obtained from the University of Tennessee, Department of Environmental Engineering, 1990. These emissions were used in the ozone modeling. A detailed description of the ozone modeling is contained in Appendix C of the Coal Document (ORNL/RFF 1992). An emissions inventory for the southwest was not obtained.

Noise

Baseline noise levels (measured in decibels) for the Southwest Reference site were specified in the EIS to be 32 to 35 dBA. Baseline noise levels for the Southeast Reference site were not provided in the EIS, and would need to be investigated further if any analysis required baseline noise levels.

Geology

The geology and seismology of the two areas are found in the EIS's for the two sites. There is also a Geologic Setting Technical Report that was prepared for the Southwest Reference site draft EIS.

Biodiversity

For the biodiversity of the area, including both aquatic and terrestrial ecology, we are concentrating on threatened and endangered species at this point. The Southeast Reference site EIS contains a list of threatened or endangered species. The Ecological Division of the Tennessee Department of Conservation has data on species that are threatened, endangered, of special concern, or that have been deemed in need of management. The Southwest Reference site EIS contains a list of threatened and endangered species. There is also a Threatened and Endangered Species Technical Report. A list of threatened or endangered plants in New Mexico is maintained by the Department of Forestry and Resources. The New Mexico Department of Game and Fish has an Endangered Species Program.

5. NATURAL GAS TO ELECTRICITY: WASTES AND EMISSIONS

5.1 INTRODUCTION

This chapter provides estimates of emissions and other residuals for various stages of the natural gas fuel cycle - from extraction to electricity generation from gas-fired equipment. The stages selected for this analysis are the primary polluting activities. Other activities that, according to the literature, do not have significant environmental impacts are discussed, but no quantitative estimates of pollutants are estimated.

We have considered the following activities to be potentially significant contributors to the external costs of natural gas fuel cycles:

- solid and liquid wastes from oil/gas well drilling, natural gas extraction, and gas treatment in the field,
- construction and navigation support activities in coastal wetlands
- volatile organic compound (VOC) air emissions from natural gas extraction and gas treatment in gas fields,
- hazardous wastes from natural gas processing,
- air emissions from natural gas processing,
- air emissions from gas-fired power plants, and
- VOC air emissions from natural gas pipelines and storage.

Emissions were estimated for two hypothetical power plant sites: Roane County, Tennessee (the Southeast Reference site) and Farmington, New Mexico (the Southwest Reference site). Additionally, the sites for fuel extraction, processing, and transportation for each of the two power plant sites have also been specified. The site-specific nature of the study is necessary in order to estimate the external costs of environmental pollution. The pollution activities listed above are region or site-specific; consequently, it is required that plausible representative sites of natural gas extraction, gas processing, and electricity generation be identified. Wherever possible, site-specific data to estimate emissions and wastes were used. Generic data were used for those activities where no site-specific information was available.

5.2 ASSUMPTIONS: SITES, PLANT SCALE, TRANSPORTATION MODE, AND TECHNOLOGY

5.2.1 The Selection of Sites

Two specific sites were chosen for each stage in the natural gas fuel cycle. The regional impacts of environmental pollution vary considerably due to differences in population size and density surrounding a site, climatic characteristics, existing pollution levels, and other factors. Two sites, widely varying in climate, fuel source, and demographic characteristics were chosen to provide a range of environmental impacts and externalities costs that may be indicative of those at other similar sites.

5.2.1.1 Sites of Natural Gas Production

Table 5.2-1 presents the amount of natural gas production in the nine U.S. census regions and Alaska for 1989.

Table 5.2-1. U.S. natural gas production for 1989 (in trillion cubic feet[a])

Region	Natural Gas Production
New England	0
Middle Atlantic	0.212
South Atlantic	0.224
East North Central	0.318
East South Central	0.305
West North Central	0.644
West South Central	13.700
Mountain	1.910
Pacific contiguous	0.365
Pacific noncontiguous (Alaska)	0.394
Imported natural gas	1.381
Total U.S.	19.400

[a] Source: EIA (1990). See Figure 5.2-1 for the state makeup of census districts.

As shown in Table 5.2-1, the U.S. relies on the West South Central (WSC) region as its major natural gas supply source (the WSC region consists of Texas, Louisiana, Oklahoma, and Arkansas. This census division represents 44% of the U.S. deliveries to industrial consumers and 53% of the deliveries to electric utilities). The WSC region is one of the two source regions in this study.

We do not consider imported natural gas as a source for either of the two sites. These same sites were used in the coal, oil, nuclear, and biomass (for the Southeast reference site) fuel cycle studies. The sites were selected so as to have some consistency across the different studies in terms of the site-specific characteristics of the environment and population. The sites are regarded as being plausible from a physical, though not necessarily an economic standpoint.

Natural gas used to power the electric generating plant in East Tennessee is assumed to be produced and processed in Southern Louisiana and transported by pipeline to Tennessee. For the Northwest New Mexico gas-fired plant, we assume that natural gas will be produced and processed approximately 35 miles away. The processing plant site is located above the San Juan Basin, the largest producing natural gas field in North America.

In this study, two target years have been established: 1990 and 2010. We assume that in 2010 the natural gas for the East Tennessee plant at the Clinch river site would have been extracted and processed onshore in Southern Louisiana. Louisiana is the most likely source of natural gas consumed in Tennessee. In 1989, 3.34 trillion cubic feet (tcf) of natural gas was transported from Louisiana to Mississippi. Of that amount, 70%, or 2.34 tcf was transported from Mississippi to Tennessee (EIA 1990). New Mexico consumes only 23% of the natural gas produced in the state. It produced 0.855 tcf of natural gas in 1989.

Natural gas production from offshore areas accounted for 29% (5.0 tcf) of total domestic gas production in 1990. Drilling offshore costs approximately four times per drilled foot as much as onshore drilling does ($409 vs. $93 per foot in 1989 dollars). In addition, offshore wells are usually deeper than onshore wells. In 1986, offshore wells had average depths of 11,112 feet with costs of more than $4,500,000 each to drill. This is contrasted with onshore wells that averaged 5,622 feet in depth at an average cost of $523,000 (AGA 1989).

DOE forecasts a declining contribution of offshore production to total U.S. production in the future. The offshore percentage of total production is estimated to be 14% in 2010 (EIA 1990). The total offshore natural gas production for 2010 is projected to be 2.7 tcf. Due to the declining share of offshore natural gas production we assume that in 2010 the natural gas processed in Louisiana that would be sent to the Southeast Reference site would continue to be extracted onshore in southern Louisiana. We assume that in 2010 the natural gas supplied to the Farmington power plant via the gas processing plant would continue to be produced in New Mexico's San Juan Basin gas field.

5.2.1.2 Natural Gas Processing Sites

The Louisiana Gulf Coast area is a net exporter of natural gas, and is the origin of several pipelines traveling northeast through middle Tennessee up to their final destination, the east north central portion of the U.S. We assume that the natural gas supplied to the East Tennessee power plant would come from the Louisiana Gulf Coast region.

Natural gas produced in the Louisiana Gulf Coast is assumed to undergo oil and gas separation at a gas separation plant in Terrebonne Parrish, Louisiana, then it is transported by pipeline to a gas processing plant in St. Bernard Parrish, Louisiana. This plant uses the refrigerated absorption process method to prepare the gas to end users. The close proximity of the plant to New Orleans will allow us to estimate environmental impacts in an urban setting.

A gas processing plant in San Juan county, New Mexico was selected to supply natural gas to the power plant located 35 miles south of Farmington, N.M. This plant has a capacity of 500 MMcfd and produces on average 488 MMcfd of natural gas. This plant also uses the refrigerated absorption gas processing method.

5.2.1.3 Natural Gas-fired Power Plants

As mentioned previously, two power plant sites were selected for the fuel cycle externalities project: the East Tennessee site and the Northwest New Mexico site. The East Tennessee site is located in Roane County, Tennessee at the Clinch River Breeder Reactor site. It is located twenty-five miles west of Knoxville and nine miles south of Oak Ridge. The Northwest New Mexico site is located in San Juan County, New Mexico, thirty-five miles south of Farmington. Throughout the report the sites are referred to as the Southeast Reference and Southwest Reference sites, respectively. Environmental and socio-economic information are available for both sites in order to analyze the health and ecological impacts resulting from the environmental pollution caused by the plants.

5.2.2 Transportation of Natural Gas

Natural gas is transported by pipelines with compressor stations supplying power to move the gas over the distances required. Compressor stations are spaced at approximately 75 mile intervals to provide power to transport the natural gas along the pipeline. To supply the Southeast Reference site, a main gas pipeline, 36 inches in diameter, delivers approximately 950 million cf/day. The compressor stations along the pipeline each produce approximately 10,000 horsepower. This main trunk pipeline travels from St. Bernard Parrish, Louisiana to Middle Tennessee. A secondary natural gas line transports the gas from the main gas pipeline in Middle Tennessee to the electric generating plant at the Southeast Reference site.

A similar sized main gas trunk line transports natural gas from the gas processing plant in San Juan County, New Mexico in a southwesterly direction. This gas pipeline carries the processed gas within six miles of the Southwest Reference site's electric generating plant where the gas is transported by a secondary gas pipeline.

5.2.3 Scale of Power Plants

In this study, we assume that the natural gas-fired power plants at the Southeast and Southwest Reference sites operate as base-load plants. Base-load plants were also considered for the other conventional-fuel plants in our fuel cycle externalities study. The average power capacity of 189 utility-owned gas-fired electric generating plants in the U.S. was calculated to be 520 MW from a Department of Energy report describing the inventory of electric generating plants in the U.S. (EIA 1990). The probable size of a base-load gas-fired multi-unit power plant built today, as well as in 2010, would be about 500 MW (Hagler-Bailly, personal communication, 1992). Smaller natural-gas-fired plants can also serve as intermediate or peaking plants. In this study, we thus assumed a base-load multi-unit 500 MW capacity for both plants.

5.2.4 Gas-Fired Power Plant Technology

The efficiency of gas-turbine power plants has steadily increased over the past thirty years, and is likely to increase further into the next century. In the 1960's, utility turbines of 10 to 25 MW were typically built with efficiencies of approximately 30%. In the two decades (in the 1970's and most of the 1980's), the representative capacity of combustion turbines was 50 to 100 MW with an average efficiency of 32%. The increasingly higher energy efficiencies have been obtained by raising the design fuel-firing temperature at the combustor outlet. Currently, the capacity of gas turbine units for utility applications in existence today are in the 135 to 150 MW range and have an efficiency of 35% (EPRI 1988).

Gas Turbine Technology

The combined-cycle gas turbine system is the most up-to-date technology utilized by natural gas-fired power plants in 1990. The combined-cycle system is a gas turbine with exhaust gases input to a heat-recovery steam generator that supplies a steam-turbine cycle. This is the most efficient system for generating steam and/or electric power in the 1990 time period. This configuration allows efficiencies to approach 45 - 47%.

Recent gains in efficiency by gas turbine units is due to new high-strength alloys coated with special materials for corrosion and oxidation resistance. The new materials allow for higher firing temperatures and therefore higher exhaust temperatures contributing to the higher efficiency. Unfortunately, the higher turbine temperatures which contribute to higher power outputs, also result in higher NO_x and CO emissions from the gas turbine. Water or steam injection is a popular way to lower NO_x formation, often yielding NO_x reductions approaching 70%.

The New Source Performance Standards (NSPS) set by the EPA limits NO_x emissions from new gas turbines to 75 ppm. Stricter emission levels have been set in states like California and Texas where NO_x is limited to 25 ppm. This trend is likely to expand to other states.

In order to comply with the more restrictive emission standards, additional technological developments such as a multiple combustor arrangement employing staged combustion is used. This system allows premixing of air and fuel upstream of the combustor and controls the fuel and air mixture as the system transfers from one burner stage to another. Other technical advances such as ceramic lined combustion chambers and multiple fuel nozzles can extend the period between overhauls and will achieve NO_x emission levels below 10 ppm (GE 1996). The NO_x as well as the emission levels of other pollutants produced by turbines at the gas-fired electric generating plant reference sites for the 1990 and 2010 scenarios are presented in section 5.3.6.

An advanced high-efficiency combined-cycle gas turbine has been produced by GE which obtains higher performance concurrent with substantially lower NO_x emissions and will be produced through the 2010 time frame. This gas turbine uses a combustion concept called "premix lean" which was developed by GE in order to achieve low NO_x emissions. High efficiency and low NO_x emissions conflict since higher performance requires higher firing temperatures, but lower NO_x emissions require lower combustion temperatures. Both performance and emission targets are met by changing the gas turbine cooling system. The purpose for this change is to regulate the temperatures effecting the gas turbine components controlling performance and emissions.

The premix lean technology has been introduced in current commercial gas turbine systems. With the technology, a large fraction of the compressor discharge air is mixed with the fuel prior to combustion, creating a lean mixture that produces low gaseous emissions when combusted in a stabilized combustion chamber. The solution to low NOx emissions with increased performance is a closed-loop cooling of the stage 1 nozzle of the turbine. This cooling concept has a dual-purpose by allowing higher firing temperatures to be achieved without combustion temperatures increases also permitting more compressor discharge air to flow to the head-end of the combustor for fuel premixing.

5.2.5 Natural Gas Consumption for the Two Power Plants

A capacity of 500 MW is proposed for each of the two natural gas-fired power plants placed in service in 1990. Assuming a 74.5% capacity factor for each of the two plants, the plants would generate 8.9 million kWh per day, or 3.263 billion kWh per year. If we assume a conversion efficiency of 41% for gas-fired combined cycle power plants, approximately 72.9 million cf of natural gas would be needed daily for each power plant (assuming 1,021 Btu/cf and 3,413 Btu/kWh). This converts to approximately 26.6 billion cf of natural gas per year for each of the two plants.

5.2.6 Natural Gas Consumption for Pipeline Transmission

This section provides the estimates of consumption of natural gas required by compressor stations to move natural gas from Louisiana to the Southeast reference site. The discussion shown in Section 5.2.2 gives the assumptions of pipeline characteristics transporting natural gas to the Southeast Reference site. A study by the American Gas Association (AGA 1991) provides estimates of the consumption of natural gas by compressor stations that transport natural gas through a hypothetical 2000 mile pipeline from Texas to New England. In addition, AGA also estimates emissions produced by the compressor stations. We assume that similar compressor stations exist on the Louisiana - Southeastern site transmission line.

The 2000 mile pipeline from Texas to New England is assumed to include 25 gas turbine compressor stations, each producing 10,600 horsepower and consuming a total of 788 million cf/year of natural gas for the pipeline. This pipeline delivers about 940 million cf/day of natural gas. The following assumptions are made in order to approximate the amount of natural gas consumed by compressors transporting the level of natural gas used annually by the power plant at the Southeast Reference site:

a) the natural gas pipeline from the gas processing plant in Louisiana to the Southeastern reference site is 880 miles in length.
b) we use the same compressor station spacing as the 2000 mile pipeline; therefore the 880 mile pipeline contains 11 compressor stations.
c) the daily natural gas consumption of the Southeastern site power plant is 7.8% of the natural gas flow of the pipeline (72.89 million cf/day / 940 million cf/day = 0.078).
d) The natural gas consumption of the 11 compressor stations due to the SE reference site is 1.66 million cf/day ([11 * 778 * 0.078] / 365 = 1.81 million cf/day).

The pipeline compressor stations consume approximately 2.5% of total natural gas power plant consumption at the Southeastern site (1.81 million cf/day / 72.8 million cf/day = 0.0248; 0.0248 * 100 = 2.48%).

5.2.7 Natural Gas Production per Gas Well

The total natural gas production from gas-only wells in Louisiana in 1986 was 4.560 trillion cf. This production total includes both on- and offshore gas wells. Natural gas production from onshore wells was 1.405 trillion cf. gas production from offshore wells was 3.151 trillion cf. The total number of producing gas wells in Louisiana in 1986 was 16,300 (two-thirds of the wells are considered marginal and produce less than 60,000 cf/day). We did not have information for the number of onshore versus offshore gas wells in Louisiana. Consequently, we estimate the average amount of natural gas produced per well per day by dividing the total onshore and offshore gas production by the total number of gas wells. The average daily gas well production is calculated to be 765 thousand cf. Dividing the sum of both the daily gas consumption for the gas-fired power plant at the Southeast Reference site and compressor stations associated with the pipeline (72.89 + 1.81 = 74.7 million cf/day) by the average amount of natural gas produced per well per day gives approximately 90 gas wells required to sustain the power plant.

The total natural gas production from gas-only wells in New Mexico in 1989 was 685 trillion cf (1,877 million cf/day). Approximately one-half of the 17,087 gas wells are marginal (producing less than 60,000 cf/day). If we assume one-half of the wells that are marginal produce 30,000 cf of gas per day for a total of 256 million cf/day, then the remaining wells produce the remaining 1,620 million cf/day. We assume only the productive wells supply the power plant. To calculate the number of wells supplying gas to the power plant we divide the total productive well output of 1,620 million cf/day by the estimated number of productive wells (one-half of the total gas wells - 8,540 wells). This results in 190 thousand cf/day per productive well. A withdrawal rate of 190 thousand cf/day will result in approximately 384 wells estimated to supply the Southwest Reference site power plant.[1]

5.3 THE AMOUNT OF EMISSIONS FROM THE SELECTED ACTIVITIES

5.3.1 Wastewaters and Solid Wastes from Gas Well Drilling, Gas Extraction, and Gas Treatment in Gas Fields[2]

5.3.1.1 Waste Sources

Gas well drilling, gas extraction, and gas treatment in gas fields produce wastewaters. The sources of wastewater include produced water, drilling muds (we use "drilling muds" for spent drilling fluids), drill cuttings, spent completion and workover fluids, wastewater from well treatment, deck drainage (mainly for offshore drilling), and sanitary wastes.

Various constituents are contained in these wastewaters. Depending on the method of disposing of wastewaters (e.g., underground injection or storage pit evaporation), these constituents may eventually remain in different media--water or land. For example, the constituents can be carried to water bodies (surface water or groundwater) as water pollutants, or they can be carried to land (i.e., the residuals of wastewater evaporation) as solid wastes. We estimate the total amount of wastes generated from the above sources, regardless of where the residues will eventually remain.

The significant or potentially significant constituents of wastewaters produced during well drilling, gas extraction, and gas treatment are oil and grease,

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[1]The consumption of natural gas due to compressor stations for the Southwest site will be negligible compared to the comparable consumption for the Southeast site. This is due to the short length of the pipeline requiring only one compressor station.

[2]We assume new wells are drilled to satisfy increased demand. In reality, gas field operators are continually drilling new wells in anticipation of near term demand and expanding production from existing wells to meet increasing current demand. Thus, the number of new wells required to meet requirements of the gas-fired power plants would be some unknown fraction of the amount of wells supplying each of the two reference sites.

COD (chemical oxygen demand), BOD (biological oxygen demand), heavy metals, TSS (total dissolved solids), and toxic materials (EPA 1976). The concentrations of waste constituents in wastewaters may vary widely among different regions, depending on rock formation in the drilling region, the composition of drilling fluids, and other factors. Three major waste sources are produced water, drilling muds, and drill cuttings.

Produced Water. Produced water includes all waters produced with the extracted oil/gas/water mixture. Most oil and gas producing geological formations contain a mixture of oil, gas, and water. The amount of produced water depends on the type of oil and gas producing formation and the stage of oil and gas production in an oil/gas field. Generally, the amount of produced water increases as an oil or gas reserve is depleted. Therefore, the ratio of produced water to extracted oil or gas varies among different regions, different wells in the same production field, and different production periods of the same producing wells. The constituents of produced water include oil and grease, heavy metals, sands, and a variety of salts. The concentrations of the constituents vary from one geographical area to another.

Drilling Muds. Drilling fluids are used to maintain hydrostatic pressure control in a well, lubricate the drilling bit, remove drilling cuttings from a well, and stabilize the walls of a well during drilling or workover. Two basic types of drilling fluids are used in well drilling: water-based and oil-based. Water-based fluids account for the majority of drilling fluids used in oil and gas production. Used drilling fluids are usually recovered and reused. The spent drilling fluids, or drilling muds, become wastewater and must be disposed.

Various additives may be added to drilling fluids to meet specific drilling activity needs. Four basic components account for approximately 90% (by weight) of all materials contained in drilling fluids: barite, clays, lignosulfonates, and lignites (EPA 1991a). Other components include lime, caustic soda, soda ash, and other additives.

Drilling fluid discharges from offshore oil and gas operations originate from the mud tanks, are generally in bulk form, and occur intermittently during well drilling. Table 5.3-1 shows an estimate of the drilling fluid discharge from a Gulf of Mexico well-drilling program.

Drill Cuttings. The circulation of drilling fluids from ground surface to well ends and the drilling fluids in return carry drill cuttings to the ground surface. Upon reaching the surface, fluids and cuttings pass into the shale shaker, a vibrating screen that removes large particles from the fluid. A de-silter, a hydrocyclone using centrifugal forces, can then be used to remove silt-sized particles.

The discharges from the solid removal system consist of drill cuttings, washing solution, and drilling mud that still adhere to the cuttings. Adhered drilling mud can account for as much as 40-60% (by weight) of drill cuttings (EPA 1991a).

Table 5.3-1. Drilling fluid discharge rates from offshore well drilling (EPA 1991a)

Depth Interval (feet)	Drilling Time (days)	Drilling Fluid Discharged (bbl)	Drill Cuttings Discharged (bbl)
0-500	1	2,500	722
500-1,000	2	5,000	578
1,000-3,000	6	1,200	1,590
3,000-8,000	27	1,350	1,760
8,000-16,000	61	3,050	1,730
16,000-20,000	30	1,900	361
Total	**135**	**15,000**	**6,740**

Solid wastes are also generated from other sources during well drilling and oil production. Such sources include produced sand and storage tank bottoms. Sands and other salts are separated from the oil/gas/water mixture during the on-site treatment of the mixture. Sand is produced at the rate of approximately one barrel of sand per 2,000,000 cubic feet of gas produced (EPA 1976). These solid wastes are eventually disposed of in landfills, by landspread, by roadspread, or by pit burial.

In estimating the wastes generated during gas production, we include only produced water and drilling muds. Due to the lack of data, we do not include other sources. We estimate the amount of wastewater pollutants from produced water and drilling muds as follows: First, we obtain information of the amount of wastewater from well drilling and gas production. Second, we obtain information on the concentration of water pollutants in different wastewater streams. Finally, we multiply the amount of wastewater by the concentration to estimate the total amount of water pollutants generated.

5.3.1.2 The Amount of Wastewaters

5.3.1.2.1 Offshore Drilling

In 1990, approximately 71% of all offshore natural gas production in the Gulf of Mexico took place off the Louisiana coast (EIA 1991b). Currently, more wells are drilled in shallow water than in deep water, and substantially more are drilled beyond four miles from shorelines than within four miles from shorelines (EPA 1991a). In the future, more wells will be drilled in deep water, farther away from shorelines.

The Amount of Drilling Muds and Drill Cuttings. In 1986, there were 989 wells drilled offshore, and the majority of them were in the Gulf of Mexico (EPA 1991a). EPA has presented data on discharges of drilling muds and drill cuttings from offshore drilling (EPA 1991a). In the Gulf of Mexico, the average depth per well is about 10,523 feet. Each of these average-depth wells produce 6,926 barrels of drilling muds and 1,471 barrels of drill cuttings.

The Amount of Produced Water. Produced water can constitute from 2% to 98% of the gross fluid produced at a given platform (EPA 1991a). In general, the volume of produced water is small during the initial production phase and increases as the formation approaches crude depletion. Produced water volumes are much greater for oil and for oil/gas structures than for gas-only platforms. Historically, over the life of a producing formation, approximately equal volumes of water and hydrocarbons have been produced (EPA 1991a).

The volume of produced water at a given platform can be highly site-specific. We do not have site-specific information on the amount of produced water. Data collected by EPA show that the amount of produced water from offshore gas platforms averages 14.5% of the produced waters generated from either oil-only platforms or joint oil/gas platforms. The average amount of produced waters per oil and oil/gas well in the Gulf is 468 Bbls/day. In the Gulf of Mexico, oil-only wells constitute 7.2% of total wells, gas-only wells - 49.4%, and oil/gas wells make up 43.3% of the total well inventory. We do not have data to allocate the amount of gas produced from gas-only wells versus oil/gas wells offshore in the Gulf, consequently we assume gas production is equally distributed on a per well basis for gas-only and oil/gas wells. Following these assumptions, we estimate that the amount of produced waters for wells producing gas offshore is 268 Bbls/day/well.

The number of wells per platform can range from one to forty. In the Gulf of Mexico, the average number of wells per platform is about six (EPA 1991a).

We use these estimated amounts of wastewaters for 2010. Although the amount in 2010 may be larger, as deeper wells are to be drilled and abundant gas formations are to be depleted, we do not have any information on the amount of wastewaters from offshore production for 2010.

In the U.S., about 20% of all gas produced is in the form of so-called associated gas, that is, gas produced along with oil in the same well (EIA 1991b). The waste production results noted above, are attributable to the production of both oil and associated gas. Thus, produced waste amounts need to be allocated between gas and associated gas, and oil. We use the shares of gas production from both gas-only wells and associated gas wells and oil production to divide the wastes between the two products. In 1990, about 17.51 trillion cubic feet of natural gas was produced in the U.S. Assuming that 20% of the volume was produced from oil-producing wells as associated gas, the oil-well production of natural gas was about 3.50 trillion cubic feet. Using a 1,020 Btu/ft^3 energy content for natural gas (EIA 1991d), this represents 3.61 quadrillion Btu of natural gas.

In 1990, 2.67 billion barrels of crude were produced in the U.S. Assuming an energy content of 5.8 million Btu/bbl for domestically produced crude (EIA 1991d), this amount translates into 15.5 quadrillion Btu of crude. We assume that one-third of all oil production comes from associated oil/gas wells. Using these assumptions we calculate gas production to account for 86.7% of all energy produced from gas wells and associated oil/gas wells. Consequently, we allocate 86.7% of the total waste produced to gas production. The calculated wastes due to natural gas production are given in Table 5.3-2.

Table 5.3-2. Wastes generated during offshore gas production

	Total Wastes	Wastes Due to Gas Production[a]
Drilling muds (bbl/well)	6,930	6,000
Drill cuttings (bbl/well)	1,470	1,280
Produced water (bbl/oil/gas well)	468	268 (gas well)

[a] We allocate 86.7% of the total wastes to the wastes due to natural gas production. See section 5.3.1.2.1 for discussion.

5.3.1.2.2 Onshore Gas Production

The Amount of Drilling Muds and Drill Cuttings. EPA and API have estimated the volume of drilling wastes in each of the oil-producing states of the U.S. (EPA 1987a). Table 5.3-3 presents drilling waste volumes for two states: New Mexico and Louisiana.

Table 5.3-3. Estimated drilling waste volumes produced during 1985 (EPA 1987a)

State	Drilling Waste Volume (bbl/well)	
	EPA Method[a]	API Method[b]
New Mexico	18,700	7,810
Louisiana	44,300	9,520

[a] EPA estimated drilling waste volumes based on the total available volume of reserve pits on production sites. EPA assumed that the total available pit volume for a well was the total volume of drilling wastes.
[b] API conducted a survey to obtain total drilling wastes. The estimated volume here includes drilling muds, drill cuttings, completion fluids, circulated cement, formation testing fluids, and other water and solids. However, the majority of the waste volume is from drilling muds and drill cuttings.

As shown in Table 5.3-3, EPA's estimated waste volume can be almost five times as high as API's estimated volume. The EPA estimates consider the storage volume of wastes areas to be equal to total drilling wastes, therefore we believe that EPA's method overestimates waste volumes. Thus, we use API's estimated waste volumes.

The Amount of Produced Water. An EPA study has assumed 17.2 barrels of produced water per million cf of natural gas produced for both the Gulf and Texas/Oklahoma regions. The only data available for New Mexico was produced water per barrel of oil produced in the Southern Mountain region (EPA 1987a). For our 1990 case, we assume 17.2 barrels of produced water per million cf of gas produced for both the Gulf Coast and New Mexico regions. For the 2010 case, the amount of produced water per million cf of gas produced will certainly increase, mainly due to the depletion of gas reservoirs in these regions. We have no information for 2010, therefore we assume the amount of produced water per million cf of gas for 2010 to be the same as that for 1990. We allocate 86.7% of the total waste production to natural gas production (for detailed discussion of this percentage allocation, see Section 5.3.1.2.1).

Table 5.3-4. Onshore wastes of natural gas production

Type of Waste	State	Total Waste	Waste Due to Natural Gas Production[a]
Drilling Waste (bbl/well)	New Mexico	7,810	6,770
	Louisiana	9,520	8,250
Produced Water (bbl produced water/million cubic feet of gas)	New Mexico	17.2	14.9
	Louisiana	17.2	14.9

[a] We allocate 86.7% of the total wastes to crude production. See section 5.3.1.2.1 for discussion.

5.3.1.3 Concentration of Constituents in Wastewaters

5.3.1.3.1 Produced Water

EPA has estimated the effluent concentrations of offshore produced water based on an analysis of produced waters from thirty platforms in the Gulf of Mexico (EPA 1991a). EPA lists the effluents (shown in Table 5.3-5) and their BPT concentrations for each type of platform depending on the predominant fuel produced - gas, oil, or gas/oil combined. We estimate the effluent concentrations attributable to the offshore production of gas by the following equation:

$$0.75*Effl_{GAS} + 0.25*Effl_{OIL/GAS}*0.867$$

The proportion of gas-only offshore wells to those producing oil and gas is approximately 0.75 to 0.25. In addition, we assume that gas production accounts for 86.7% of all energy produced form gas wells and associated oil/gas wells (see the discussion in section 5.3.1.2.1). The estimated effluent concentrations are presented in Table 5.3-5.

Since BPT effluent limitations to offshore drilling are currently in effect, we use these concentrations for 1990. EPA has proposed BAT limitations for existing sources, and NSPS for new sources (EPA 1991a). We use BAT concentrations for 2010. EPA neither proposed to regulate BOD and COD concentration nor presented BOD and COD data since the regulation of BOD and COD would double-count the regulation of oil and grease (oil and grease mainly cause BOD and COD). For the same reason, we do not include BOD and COD in our estimate.

Table 5.3-5. Effluent concentrations of offshore produced waters (EPA 1991a)

Pollutant	**Concentration (mg/liter)**	
	BPT Limit[a]	**BAT Limit**[b]
Oil and Grease	41.3	2.06
Benzene	4.93	0.25
Bis(2-ethylhexyl)phthalate	0.10	0.005
Ethylbenzene	0.67	0.033
Naphthalene	0.34	0.02
Phenol	5.77	0.29
Toluene	4.06	0.20
Priority Metals		
Copper	0.042	0.025
Nickel	0.031	0.019
Silver	0.013	0.008
Zinc	0.673	0.007

[a] These are the concentrations with the use of BPT technologies (i.e., gas flotation or gravity separation technology) (EPA 1991a).
[b] BAT concentrations are calculated with filter technology (EPA 1991a). Organic removal equal to 95% based on membrane filtration performance data on dissolved oil and grease. Copper removal equal to 40% based on general filtration data. Zinc removal equal to 99% based on improved performance of membrane filters compared to performance of deep-bed filters. We assume 95% removal of oil and grease, and 40% removal of nickel and silver.

Onshore Produced Water Concentrations. EPA has estimated produced water concentrations of arsenic, benzene, boron, sodium, chloride, and mobile ions (including chloride, sodium, potassium, calcium, magnesium, and sulfate) (EPA 1987a). Table 5.3-6 presents EPA's estimates.

Table 5.3-6. Constituent concentration of onshore produced water (EPA 1987a)

Constituent	Concentration (mg/liter)	
	BPT Limit[a]	BAT Limit[b]
Arsenic	0.02	0.012
Benzene	0.47	0.0235
Boron	9.9	5.94
Sodium	9,400	470
Chloride	7,300	365
Mobile ions	23,000	115

[a] EPA has estimated the 50th percentile value and the 90th percentile value. EPA used the 50th percentile value to represent a "best-estimate" waste characterization. It used the 90th percentile value to represent a "conservative" waste characterization. We use the 50th percentile value here.
[b] BAT concentrations are calculated with filter technology (EPA 1991a). We assume benzene, sodium, chloride, and mobile ions are removed by 95%, and arsenic and boron are removed by 40%.

We use BPT concentrations for 1990 and BAT concentrations for 2010. EPA did not estimate the concentration for some of the constituents presented in Table 5.3-5. For those constituents not presented in Table 5.3-6, we use the offshore concentrations in our estimation.

5.3.1.3.2 Drilling Muds

EPA has tested the concentrations of the major constituents of some generic drilling fluids. Table 5.3-7 presents concentration results based on EPA's tests.

Table 5.3-7. Constituent concentrations of drilling fluid[a] (EPA 1991a)

Constituent	Concentration (mg/liter)
pH	9.0
BOD_5	643
TOC	4,290
COD	11,400
Oil and Grease	1,520
Metals[b]	
Zinc	9.01
Beryllium	0.293
Aluminum	197
Barium	53.7
Iron	550
Cadmium	0.530
Chromium	101
Copper	5.70
Nickel	1.76
Lead	5.18
Mercury	0.090
Silver	0.004
Arsenic	1.56
Selenium	0.878
Antimony	0.274
Thallium	0.029

[a] EPA's test results are presented in mg/kg. We convert the concentration from mg/kg to mg/liter by using the average density of 1.6 kg/liter for drilling fluid, which we calculated based on EPA's result.
[b] EPA's test results for metals are presented in mg per kg of dry weight. We convert the dry weight concentration into wet weight concentration by using water content of 53.2% for drilling fluid, which we calculated based on EPA's data.

5.3.1.4 Total Amount of Constituents in Wastewaters

5.3.1.4.1 Offshore Gas Production

Produced Water. We use the waste production information in Table 5.3-2 and the concentration information in Table 5.3-5 to calculate the amount of constituents per barrel of produced waters. The calculated results are presented in Table 5.3-8.

Table 5.3-8. The amount of pollutants from offshore produced waters (g/bbl)

Pollutant	1990[a]	2010[b]
Oil and Grease	5.69	0.28
Benzene	0.679	0.034
Bis(2-ethylhexyl)phthalate	0.014	Neg.
Ethylbenzene	0.092	0.005
Naphthalene	0.046	0.002
Phenol	0.795	0.040
Toluene	0.599	0.028
Copper	0.006	0.003
Nickel	0.004	0.003
Silver	0.002	0.001
Zinc	0.093	0.001

[a] We use the constituent concentrations of BPT technology in Table 5.3-5 to calculate 1990 constituent amounts.

[b] We use the constituent concentrations of BAT technology in Table 5.3-6 to calculate 2010 constituent amounts.

Drilling Muds. We use the information on drilling muds produced during offshore well drilling in Table 5.3-2 and the constituent concentrations of drilling muds in Table 5.3-7 to calculate the constituent amounts per well drilled. We assume the amounts in 1990 and 2010 to be the same. The calculated results are presented in Table 5.3-9.

Table 5.3-9. Constituent amounts of drilling muds

Constituent	Amount (kg/well)
pH	9
BOD_5	614
TOC	4,100
COD	10,900
Oil and Grease	1,450
Zinc	8.6
Beryllium	0.28
Aluminum	188
Barium	51.3
Iron	525
Cadmium	0.51
Chromium	96.1
Copper	5.45
Nickel	1.67
Lead	4.94
Mercury	0.09
Silver	0.004
Arsenic	1.49
Selenium	0.84
Antimony	0.26
Thallium	0.03

5.3.1.4.2 Onshore Gas Production

Produced Water. We use the information on the amount of produced waters in Table 5.3-4 and the information on the constituent concentrations of produced water in Table 5.3-6 to calculate the constituent amounts per MMcf of gas produced. The calculated results are presented in Table 5.3-10.

Table 5.3-10. Constituent amount of produced water for Louisiana and New Mexico (g/million cubic feet of gas produced)

Constituent	1990[a]	2010[b]
Arsenic	0.047	0.028
Benzene	1.11	0.056
Boron	23.4	14.1
Sodium	22,200	1,110
Chloride	17,300	864
Mobile ions	54,400	2,720

[a] We use the constituent concentrations of BPT technology in Table 9 to calculate 1990 constituent amounts.
[b] We use the constituent concentrations of BAT technology in Table 9 to calculate 2010 constituent amounts.

Drilling Muds. We use the information on drilling wastes produced during well drilling from Table 5.3-4 and the information of the constituent concentration information from Table 5.3-7 to calculate the constituent amounts in drilling muds. The calculated results are presented in Table 5.3-11.

5.3.1.5 Waste Management Methods

Wastes generated during natural gas production are regulated by state and federal agencies (see Appendix A for the regulations of wastes generated during gas production). To meet waste regulations, a wide range of on-site control and treatment technologies have been developed to treat wastewaters produced from gas production. On-site control and treatment techniques involve the reduction or elimination of a waste stream through the re-use or recycling of waste products and the recovery and reuse of drilling fluids.

Table 5.3-11. The amount of pollutants generated from drilling fluid

Constituent	Amount (kg/well)	
	New Mexico	Louisiana
pH	9	9
BOD_5	693	605
TOC	4,620	404
COD	12,300	10,700
Oil and Grease	1,640	1,430
Zinc	9.7	8.48
Beryllium	0.316	0.276
Aluminum	212	185
Barium	57.8	50.3
Iron	592	517
Cadmium	0.593	0.499
Chromium	108	94.7
Copper	6.15	5.37
Nickel	1.89	1.65
Lead	5.58	4.87
Mercury	0.097	0.085
Silver	0.004	0.004
Arsenic	1.68	1.47
Selenium	0.946	0.827
Antimony	0.295	0.257
Thallium	0.031	0.028

Different types of end-of-pipe control technologies are used to separate oil and grease from wastewater. A gas flotation system creates gas bubbles that are released into the wastewater to be treated. As the bubbles rise through the wastewater, they attach themselves to an oil droplet in their path, and the gas and oil rise to the surface where they can be skimmed off.

A parallel plate coalescer is a gravity separator which contains a pack of parallel, tilted plates. Oil droplets pass through the pack and rise a short distance before striking the underside of the plates. Guided by the tilted plate, the droplets rise, coalescing with other droplets until they reach the tip of the pack where oil is carried away.

Filter systems use some types of media, such as granular and membrane, as filters. Waste streams pass through these filters, leaving oil droplets in the filter media. Eventually, the filter media is overloaded with oil droplets and must be replaced or cleaned. The granular media filtration system demonstrates a 40-60% removal of oil and grease from the concentration levels of the gas flotation system's effluent (EPA 1991a).

Gravity separation of oil from wastewater is accomplished by retaining wastewater in tanks or pits for a sufficient time to allow the oil and water to separate. These systems are characterized by large volumes of storage to permit long retention times. In the mid-1970s, about 75% of the oil-water separation systems in the Gulf Coast region were gravity separation systems (EPA 1976). Various types of chemicals can be applied to wastewater treatment systems to increase the separation efficiency of the systems.

There are three ways to dispose of treated wastewater: evaporation, underground injection disposal, and discharge to surface water. In some arid and semiarid areas, surface pits, ponds, or reservoirs can be used to evaporate water. Injection and disposal of produced water to underground reservoirs are extensively practiced by the petroleum industry. Surface water discharge is practiced by offshore and coastal oil producers. While surface disposal contaminates surface water, underground disposal may contaminate underground water.

Drilling fluids are usually reclaimed and reused during drilling activities. With onshore drilling, the discharge from shale shakers, de-silters, de-sanders, and spent drilling muds is placed in a large earthen pit. When drilling operations terminate, the pit is backfilled and graded over.

5.3.2. Air Emissions from Gas Extraction and Gas Treatment in Gas Fields

Emissions associated with gas well production can be divided into three categories: 1) emissions from power generation, 2) fugitive emissions, and 3) emissions from venting and flaring. Power is supplied for production operations by diesel-fired and natural gas-fired engines, and is used to drive pumps, gas compression, water injection and other operations. Emissions from the gas wellheads are primarily the result of fugitive losses from various components such as valves, connections, and open-ended lines at the wellhead. In wells where natural gas is not present in quantities sufficient for recovery, the gas may be vented or flared. In this case, emissions are light VOC and NO_x. If the natural gas is "sour", containing relatively high levels of H_2S, it may also emit high levels of SO_2.

VOCs (volatile organic compounds) emitted during gas extraction and treatment are mainly caused by leakage of gas during production and treatment, evaporative emissions from wastewater pits and storage tanks, and combustion of diesel fuels used to provide power for gas production and treatment operation. Recently, EPA found that the amount of VOC emissions from oil/gas production is substantial. For example, it is estimated that VOC emissions could be 50-100 tons per well annually (Jones 1991). To enforce the toxic air emission title of the 1990 Clean Air Act, EPA is currently in the process of proposing regulations on VOC emissions from oil production, transportation, and storage.

Emissions of other pollutants such as NO_x, SO_x, CO, and CO_2 are primarily caused by the combustion of diesel fuels used for gas production operations. PM emissions are mainly caused from dust. These emissions are minimal on a per-million cubic foot-of-gas-produced basis.

5.3.2.1 Gas Well Drilling and Development

The main sources of emissions during the gas exploratory phase are large internal combustion engines that supply power for drilling. In most cases, these engines are diesel-electric generators. Additional emissions can also come from earth-moving and other heavy-duty transportation equipment, which normally burn diesel fuel.

Emissions from venting and flaring may occur when unexpected high pressures of gas are encountered when drilling. The venting may then be necessary to prevent a blowout of the well. Once drilling commences, power is provided by either diesel engines or turbines. The turbines can either be natural gas-fired or diesel-fired.

Emission factors for large diesel and natural gas engines used in gas exploratory and development activities are obtained from EPA's AP-42 publication (EPA 1985). The emission data shown in Table 5.3-12 pertains to portable well-drilling equipment. Table 5.3-13 gives emission factors for large diesel engines powering drilling equipment, mud pumping and hoisting equipment, pumps, and auxiliary power generators. These engines are usually grouped in three to five units. Also contained in Table 5.3-13 are emission factors for dual-fuel engines used for power generation that burn primarily natural gas with a small amount of diesel fuel.

Table 5.3-12. Emission factors for portable well-drilling equipment (lb/thousand gal)

Pollutant	Fuel - Diesel
CO_2	102
Exhaust hydrocarbons	37.5
Evaporative hydrocarbons	negligible
Crankcase hydrocarbons	negligible
NO_x	469
Aldehydes	7.04
Sulfur oxides	31.2
Particulates	33.5

Emissions from natural gas-fired engines were compiled from the Resource Management Agency/APCD of Ventura County, California (Ventura Co. 1990). These emissions are given in Table 5.3-14.

Table 5.3-13. Emission factors for stationary large bore diesel and dual fuel engines

Pollutant	Diesel (lb/thousand gal)	Dual fuel[a] (lb/thousand gal)
Particulate	50	NA
NO_2	500	18
CO	130	5.9
VOC - Methane[b]	1	4.7
VOC - Nonmethane	13	1.5
SO_2	60	0.7

[a]Dual fuel engines operate on natural gas and use a minimum of 5 or 6% of diesel fuel to ignite the gas. They are used almost exclusively for prime electric power generation.
[b]Nonmethane VOC is 90% of total VOC from diesel engines but only 25% to total VOC emissions from dual fuel engines.

Table 5.3-14. Emissions for natural gas-fired engines (lbs/MMcf)

Pollutant	lb/million cubic feet gas
TOC	1,000
Reactive organic carbon	884
PM	10
SO_2	0.6
NO_x	2,500
CO	320

5.3.2.2 Natural Gas Compression

Natural gas is often compressed near the wellhead and reinjected into the oil or gas well. This high-pressure gas forces oil to the surface at oil wells and can be used for pressure maintenance at gas wells. The compressors used for such operations are likely to be similar to natural gas-fired pipeline compressors. The emission factors for natural gas-fired engines were obtained from AP-42 (EPA 1985) and are shown in Table 5.3-15.

Table 5.3-15. Emission factors for heavy duty natural gas-fired pipeline compressor engines (lb/thousand hp-hr)

Engine type	NO_2	Hydrocarbons
IC reciprocating engines	24.0	9.7
Gas turbines	2.9	0.2

The California Air Resources Board has developed emission factors for valves and fittings for various gas leases. The CARB has incorporated API emission factors into detailed component counts. Table 5.3-16 gives the emission factors of total organic gas and reactive organic gas for valves and fittings for wells in which the gas to oil ratio is greater than 500. The emissions include gas, liquid, mixture, and condensate.

5.3.2.3 Venting and Flaring Emission Factors

Flaring could be an important emissions source which could contribute to visibility degradation. The Texas Railroad Commission (TRC) is the only institution that has information on the amount of natural gas that is vented and/or flared. Venting and flaring permits from the TRC showed that 99.95% of gas releases were being flared and 0.05% of gas was vented. The California Air Resources Board (CARB) has indicated that flaring results in a 98% destruction efficiency for particulate matter and a 99.9% destruction efficiency for total organic gases.

Table 5.3-16. Gas well component emission factors (lbs/day-well x 10^{-4})

Component	Service	TOG emission Factors	ROG emission Factors
Valves	Gas	59,600	24,000
	Liquid	1.54	0.622
	Mixture	749	302
	Condensate	0	0
Fittings	Gas	53,600	21,600
	Liquid	24	9.98
	Mixture	2,460	991
	Condensate	0.207	0.083

The CARB uses the following emission factors for oil/gas field flares regardless of size:

NO_x	-	72 lb/MMcf
ROC	-	114 lb/MMcf
PM	-	3 lb/MMcf
SO_x	-	0.6 lb/MMcf
CO	-	40 lb/MMcf
TOC	-	1,200 lb/MMcf

5.3.2.4 Field Separation Facilities

The oil and gas stream may require several treatment and separation steps prior to gas processing at a gas plant, depending upon the quality of the hydrocarbon stream coming from the wellhead. The most common processes are oil and gas heating, gas or liquid separation, and gas dehydration (EPA 1992).

The heating of oil and gas close to the wellhead is sometimes necessary to prevent wax and hydrate formation. An indirect-type of heater assembly, often called a heater treater, has primary emissions consisting of fugitive leaks, stack emissions from combusted fuel, and from pneumatic instruments, which are likely to be powered by natural gas. Gas or liquid separators remove free gas from the oil and/or water stream. Two-phase separators remove most of the liquid from the gas. The three-phase separators separate water from liquid hydrocarbons. Emissions from the two and three-phase separators come from fugitive leaks, pneumatic instruments, and hydrocarbon evaporation from separated water.

The dehydration of natural gas typically is performed in a glycol-type dehydrator. Water containing trace hydrocarbons is boiled off in a regenerator with glycol reconcentrated. Emissions occur from the vapor vent from the regenerator, combustion gases from the regenerator, fugitive leaks, and pneumatic devices.

Water pollutants from onshore gas processing were reported by the U.S. Department of Energy (DOE 1983). These pollutants have been converted to units in pounds per 1,000 Btu of energy produced which corresponds to approximately pounds of pollutants per 1,000 cf of gas produced. Water pollutants produced from a gas processing plant are given in Table 5.3-17.

Table 5.3-17. Water pollutants from gas processing plants

Pollutant	lb/1000 cf gas
BOD	0.00342
COD	0.0224
Oil & Grease	0.0685
Chromium	0.00018
Zinc	0.00006
Tot. Disolv.Sol.	0.914
Chloride	0.171
Sulfate	0.137

5.3.3 Emissions from Gas Processing Plants

A total of 734 gas processing plants are operating in the U.S. In 1991 these plants were utilizing approximately 64.5% of their combined capacity. The total combined capacity is 68.2 billion cubic feet per day of natural gas. There are approximately 25 types of gas processing plants. A survey by Oil and Gas Journal classified the total population of plants by type. Table 5.3-18 gives the number of gas processing plants by type and the percentage of that type to the total number. Only gas processing methods having greater than 3% of the total are given.

Table 5.3-18 Distribution of gas plants by processing method

Processing Method	Number of Plants	Percentage of Total
Absorption	35	4.8
Refrigerated Absorption	132	18.0
Refrigeration	197	26.8
Cryogenic-Joule-Thomson	26	3.5
Cryogenic-Expander	249	33.9

Both the gas processing plant in the Gulf Coast of Louisiana supplying the East Tennessee generating plant and the New Mexico plant supplying gas to the generating plant near Farmington, New Mexico are the refrigerated absorption processing type. Gas processing plants are usually located close to the production sites. The main emission sources from the gas processing plants are fugitive losses, compressor exhaust, and venting and flaring.

The refrigerated absorption process method involves putting the compressed raw gas in contact with a liquid hydrocarbon called lean oil in an absorber where components in the gas dissolve in the lean oil. The heavier hydrocarbon components dissolve first, and the oil will hold more of them than the lighter components. The majority of the volume of the gas, called residue gas, leaves the top of the absorber while the absorbed components exit with the rich oil from the bottom of the absorber.

5.3.3.1 Sweetening

Amine treating of natural gas for the removal of hydrogen sulfide and carbon dioxide is probably the most widely utilized process for sweetening gas in the industry. However, the gas streams that are input to the both Louisiana and New Mexico gas processing plants are very low in H_2S therefore SO_2 emissions are extremely low.

5.3.3.2 Fugitive Emission Factors

The sources of fugitive emissions due to gas processing operations include valves, relief valves, open-ended lines, compressor seals, pump seals, and flanges and connections. EPA and the API conducted studies to determine the fugitive emission factors for up to 4 types of gas plants. The EPA study sampled four gas plants whereas the API examined only two plans. Additionally, the EPA used API data as well as their own. Consequently, we report the emission factors developed by EPA in Table 5.3-19.

Table 5.3-19. Fugitive emission factors by components for gas processing plant (lbs/day)

Component	Emission Factors[a]	
	VOC	THC
Valves	0.40	1.06
Relief valves	0.73	9.9
Open-ended lines	0.75	1.17
Compressor seals	2.2	10.78
Pump seals	2.64	3.3
Flanges and connections	0.024	0.057
Sampling connections		
Gas	0.035	0.70
Liquid	0.187	0.187

[a]VOC = Volatile Organic Compounds, THC = Total Hydrocarbons

5.3.3.3 Gas Plant Component Counts

Experimental data show that fugitive emissions from gas plants are proportional to the number of potential sources, and are not related to a plant's capacity, throughput, temperature, pressure, and age. Therefore, an accurate inventory of component types is essential to provide a reasonable prediction of emissions. The counts of gas plant component sources for refrigerated absorption plants was conducted by two studies from EPA and one by API. We have no information as to which of the studies is more accurate than the others, nor whether any of the three studies is more appropriate to the refrigerated absorption plants we have selected in Louisiana and New Mexico. Consequently, we average the component counts for the three studies and present the results in Table 5.3-20.

Table 5.3-20. Component counts for a sample of refrigerated absorption gas plants

Component	Component Count
Valves	2185
Relief Valves	34
Open-ended Lines	439
Compressor Seals	23
Pump Seals	41
Flanges and Connections	7362

In order to estimate the total yearly fugitive emissions for a refrigerated absorption gas plant, we multiply the daily emissions per component in Table 5.3-19 by 365, and the result times the component count in Table 5.3-20. This gives an estimate of yearly fugitive emissions by components for a refrigerated absorption gas plant and is shown in Table 5.3-21.

5.3.4 Pipeline Emissions

Methane is vented to the atmosphere during the transmission of natural gas by both voluntary actions by gas pipeline personnel conducting normal pipeline operations and involuntary events such as structural damage and accidents. The leaks due to normal operations are due to operation of pipeline equipment such as instruments, regulators, and valves. During maintenance and construction, pipelines and equipment are also purged of natural gas for safety reasons. Pipeline emissions of methane are thought to be in the range of 0.03 to 0.5% of total throughput. Chapter 9 gives a more detailed description of the factors contributing to pipeline emissions and presents an analysis of emissions at the Southwest Reference site.

Table 5.3-21. Fugitive emissions by components for refrigerated absorption gas processing plant (lbs/year)

Component	Emission Factors	
	VOC	THC
Valves	874	2,320
Relief valves	24.8	337
Open-ended lines	329	514
Compressor seals	50.6	248
Pump seals	108	135
Flanges and connections	177	420
Sampling connections[a]		
Gas	10.5	210
Liquid	56.1	56.1

[a]Although component counts for sampling connections were not given, we have estimated 300 of these components would be included in a refrigerated absorption gas plant.

5.3.5 Natural Gas Pipeline Compressor Emissions

Gas turbines and gas-fired reciprocating engines are both used to power compressors used to pump natural gas through pipelines. The use of large gas turbines as pipeline compressors has increased significantly over the past few years largely due to the increased reliability of turbines. Internal combustion (IC) reciprocating engines are more fuel efficient than gas turbines and are more costly, but turbines emit less air pollutants. The major pollutants emitted by pipeline compressors are NO_X, CO, HC, and SO_2. A discussion of the level of these major pollutants of pipeline compressors and their causes is found in Section 9.1.3.

5.3.6 Emissions from Gas-fired Electrical Generating Plants

5.3.6.1 The Amount of Air Emissions

The AP-42 emissions values from EPA (EPA 1993) are used to calculate emissions in pounds per million cubic feet of natural gas input. We assume the power plant at the 1990 reference site to utilize only steam injection to control NOx emissions but for comparison also present emission values for a plant using Selective Catalytic Reduction (SCR) with water injection. The 2010 emissions values assume the use of the Dry Low NOx technology (GE 1996) for control of NOx to 9 ppm and stage 1 closed-loop cooling for enhanced turbine performance.

Table 5.3-22 gives the calculated emission values for the five major pollutants discharged from electric utility gas turbines from the following technology scenarios.

1990 Emissions (AP-42 from EPA 1993)
a) Uncontrolled emissions
b) Controlled emissions - steam injection.
c) Controlled emissions - SCR with water injection.

2010 Emissions:
d) Dry Low NO_x with state 1 closed-loop cooling

Table 5.3-22. Emission factors for electric utility turbines (lbs/million cubic feet of natural gas)

	NO_x	HC	CO	PM	SO_2
1990 EMISSIONS					
Uncontrolled emissions: 1990 (AP-42)	449.2	24.5	112.3	19.7	neg.
Controlled emissions: 1993 (Revised AP-42)					
Water injection (0.8 water/fuel ratio)	143	[b]	[b]	[b]	
Steam injection (1.2 water/fuel ratio)	123	[b]	82	5.1	
Selective Catalytic Reduction with water injection[a]	30.6	14.3	27.0	[b]	
2010 EMISSIONS					
Dry Low NO_x	44.1	Neg.	82	5.1	Neg.

[a]The SCR with water injection controls for 1990 include the following emissions: TOC = 14.3, NH_3 = 6.6, Non-methane hydrocarbons = 3.3, and Formaldehyde = 2.8 (units in lbs/million cf of NG).

[b]Not tested

The emission factors for 1990 (revised AP-42 data) consist of current technology for gas turbine units purchased by electric utilities. The 2010 emission factors assume the use of Dry Low NO_x technology (GE 1996) for control of NO_x of 9 ppm and CO of 10 ppm.

6. IMPACT-PATHWAYS

This section provides an overview of the impact-pathways for the analysis of natural gas fuel cycles. From this overview the priority impact-pathways are identified. The priority impact pathways are the basis for impact estimation and economic valuation in subsequent chapters of this report.

6.1 OVERVIEW OF SOURCES OF EMISSIONS

The drilling, extraction and treatment of natural gas, the processing of the gas, the transport of natural gas to a gas-fired electric power plant, and the production of electricity are four major stages of the natural gas fuel cycle. Chapters 4 and 5 described the natural gas fuel cycle -- how natural gas is extracted and used to generate electric power, and the potentially more significant emissions and other residuals. Offshore, the primary factors that give rise to ecological and health impacts in the first stage of the fuel cycle are drilling fluids and waste and drill cuttings. The major air emissions that occur during this stage of the fuel cycle are from the use of diesel fuel. Onshore, the major land and water impacts are from deposits of solid and liquid wastes leading to contamination of surface and groundwater and loss of coastal wetlands from navigation and support activities.

During the second stage of the fuel cycle the processing of natural gas leads to air emissions of particulate matter, NO_x, SO_2, CO_2, hydrocarbons, and aldehydes.

The transportation of the gas through pipelines, which is the third stage of the natural gas fuel cycle, causes emissions of methane due to normal operations, maintenance and construction, and leaks. The major pollutant from natural gas transmission is the release of NO_x at compressor stations along the pipeline.

The final stage of the fuel cycle is electricity generation. This stage produces air emissions from the combustion of natural gas. Additionally, minimal emissions are introduced into the surrounding water from the power plant cooling system and from waste disposal. The impacts from the emissions from the natural gas fuel cycle are primarily ecological, having potential effects on crop yield and wildlife, and health effects from emissions to the air.

6.2 NATURAL GAS FUEL CYCLE IMPACT-PATHWAYS

Table 6.2-1 lists the emissions, environmental pathways, and impacts that were discussed in detail in Chapters 4 and 5 and Appendix D and gives the reasons why these were evaluated. Impacts which are assessed in detail are marked in italics. Table 6.2-2 lists the emissions, environmental pathways, and impacts that were not discussed in detail in Chapters 4 and 5 and Appendix D and gives the reasons why these were not evaluated.

6.3 PRIORITY IMPACT-PATHWAYS

This section lists the priority impact-pathways for our analysis of natural gas fuel cycles. All were selected based on an assessment of the emission and boundary assumptions in Chapters 4 and 5 of this report, and on a preliminary review of the literature. In general, the priority impact-pathways are among those thought to be more significant in terms of their potential for externalities.

Impacts from natural gas extraction and treatment:

- effects on organisms due to wastewaters from drilling
- effects on organisms due to wetland changes

Impacts from processing natural gas:

- ecological and health effects of emissions and other wastes from the processing plants

Impacts from natural gas transportation:

- effects on plants and wildlife due to leakage of methane from pipelines
- Deaths, injuries and property damage due to pipeline accidents

Priority impacts for the power plant stage of the cycle include:

- decreased crop yield from exposure to ozone formed from emissions of HC and NO_x
- morbidity and mortality from ozone formation from emissions of HC and NO_x
- morbidity and mortality from air emissions of combustion products.

Of the impacts listed above, the ones that have the greatest potential for more significant environmental and health impacts are those due to increases in atmospheric ozone and other air pollutants. Solid wastes leaching to ground water are also a concern, but were not analyzed due to lack of appropriate data.

Table 6.2-1 Primary emissions, pathways and ecological impacts linked to the natural gas fuel cycle

Emissions	Environmental Pathway	Impact	Impact Evaluation
		Air Emissions	
Carbon dioxide Carbon monoxide	Atmospheric dispersion	*Global warming*	Global/regional modeling needed
Nitrogen oxides Sulfur dioxide	Deposition on plant surfaces and soil.	Effects on plant growth, wildlife	Minimal impacts due to low concentrations
Acid aerosols from NO_x and SO_2	Long range transport, acid deposition	Effects on plants, wildlife	Qualitative evaluation
Ozone	Secondary formation in the atmosphere; long range transport.	*Effects on crop yield*; Effects on wildlife	Quantified; No impacts due to low concentrations
Hydrocarbons	Atmospheric dispersion	Effects on plants, wildlife	Modeling required to assess impacts
		Water Emissions	
Produced water			
offshore	Disposal at sea	*Effects on marine organisms*	Qualitative evaluation
onshore	Underground injection or disposal in pits or ponds	Migration to surface or groundwater	Qualitative evaluation
Drilling fluids			
offshore	Disposal at sea	*Effects on marine organisms*	Qualitative evaluation
onshore	Underground injection or disposal in pits or ponds	Migration to surface or groundwater	Qualitative evaluation
Drill cuttings			
offshore	Disposal at sea	*Effects on marine organisms*	Qualitative evaluation
onshore	Disposal in landfills	Migration to surface or groundwater	Qualitative evaluation
Suspended sediments	Dredging for pipelines or channels	Effects on estuarine organisms	Qualitative evaluation
		Other Factors	
Erosion	Coastal activities	Effects on marine organisms	Qualitative evaluation

Table 6.2-2 Emissions, pathways, and impacts of natural gas fuel cycle *not* examined in detail

Emissions	Environmental Pathways	Impacts	Impact Evaluation
	Air Emissions		
Particulates, Acid aerosols, Hydrocarbons Ozone	Primary emissions and secondary formation in atmosphere	Reduction in visibility	Modeling required to assess impacts
Peroxyacetyl nitrate (PAN)	Formation in the atmosphere from NO_x and hydrocarbons	Effects on plants	Insufficient data on ambient and increased concentrations
Methane	Release from pipelines: local effects and dispersion in atmosphere	Effects on plants and wildlife; global warming	Insufficient data on ambient and increased concentrations
Nitrogen oxides	Release at platform and pipeline compressor stations: local effects and dispersion in atmosphere	Effects on plants and wildlife	Minimal impacts due to small local contribution, dispersion
	Water Emissions		
Cooling water	Cooling system blowdown	Effects on aquatic organisms	Minimal impacts due to closed cycle and high dilution
Wastewater	Boiler water blowdown and other waste streams	Effects on aquatic organisms	Minimal impacts due to high dilution

Table 6.2-3 summarizes the emissions impacting health and safety from a natural gas fuel cycle.

Table 6.2-3. Primary emissions, burdens, pathways and human health impacts linked to the natural gas fuel cycle

Emissions/Burden	Environmental Pathway	Impact	Impact Evaluation
		Air Emissions:	
CO_2	Atmospheric dispersion	Global/regional impacts, including human health	Range in literature is summarized
CO	Atmospheric dispersion	Human health	Minimal impacts due to below-threshold concentrations
NO_X SO_x	Atmospheric dispersion	*Human health*	Quantified
Particulates	Atmospheric dispersion	*Human health*	Quantified
Ozone	Ozone Model + dispersion	*Human health*	Quantified
		Occupational Accidents:	
Production	Direct effect	*Days of work lost or restricted activity days/fatalities*	Quantified
Transportation	Direct effect	Days of work lost or restricted activity days/fatalities	Not quantified
Generation	Direct effect	Days of work lost or restricted activity days/fatalities	Not quantified

Table 6.2-4 lists health impact-pathways that were not discussed in detail, and gives reasons why these were **not** evaluated.

Table 6.2-4. Emissions, burdens, pathways and human health impacts of natural gas fuel cycle *not* examined in detail

Emission	Environmental Pathway	Impact	Impact Evaluation
		Air Emissions:	
Diesel exhaust during production	Atmospheric dispersion	Human health	Minimal impacts due to low expected concentrations
Hydrocarbons during generation	Atmospheric dispersion	Human health	Lack of knowledge on specific effluents
Inorganic particulates during generation	Atmospheric dispersion	Human health	Minimal impacts due to low expected concentrations
		Water Emission:	
Water discharge during generation	Runoff from cleaning wastes that contaminates drinking water	Human health	Lack of knowledge on specific effluents and concentrations

7. IMPACTS AND DAMAGES FROM GAS DRILLING AND PRODUCTION

7.1 EFFECTS OF WASTEWATERS ON MARINE FISHERIES AND BENTHIC FAUNA

7.1.1 Activities and Emissions

Drilling activities produce wastewaters as described in Sections 4.3 and 5.3. Effluent concentrations estimated by EPA (1991) are given in Table 5.3-5. Discharges of wastes and wastewaters which include produced water, drilling fluids, and drill cuttings from drilling platforms add hydrocarbons, metals, and solid materials to the sediments and hydrocarbons to the water column.

The 1990 scenario for the Southeast reference site assumes *offshore* drilling for natural gas in the Gulf of Mexico near the coast of Louisiana.[1] Dispersion models for drilling fluids and drill cuttings adequately describe short-term dispersion. In contrast, because of insufficient data on transport rates, current patterns, and the long-term behavior of discharge constituents, models have not been successful in adequately predicting the long-term dispersion of discharges from platforms (Payne et al. 1987). Dilution factors of 1,000 within one to three meters of the discharge and 10,000 within 100 meters downcurrent of the discharge have been measured in field studies (Neff 1987, U.S. Department of Interior 1991).

Drill cuttings are released directly to the sea floor (Menzie 1982), leading to potential sediment alteration and burial of benthic (bottom-dwelling) organisms (Petrazzuolo 1985). An estimated 1,275 barrels of drill cuttings per well are produced. Depending on quantities discharged and hydrographic conditions, drill cuttings may settle out rapidly near the platform forming piles several meters high

[1]We assume new wells are drilled to satisfy increased demand. In reality, gas field operators are continually drilling new wells in anticipation of near term demand and expanding production from existing wells to meet increasing current demand. Thus, the number of new wells required to meet requirements of the gas-fired power plants would be some unknown fraction of the amount of wells supplying each of the two reference sites.

and 100-200 meters in diameter or may be dispersed immediately or following resuspension (U.S. Department of the Interior 1991). In some cases, effects on water quality have been observed within 1,000-1,500 meters of platforms.

7.1.2 Impact on Commercial Fisheries and Benthic Fauna

The continued exploration for and development of oil and gas resources on the Outer Continental Shelf of the Gulf of Mexico has raised concerns regarding environmental impacts, specifically chronic effects. Federal studies including those of the Department of Interior (1991) have been implemented to address these concerns and ensure environmental protection. In spite of these efforts, chronic impacts on Gulf resources have been difficult to detect and quantify but remain of great concern. According to the U.S. Department of Interior (1991), no permanent degradation of water quality is expected in the offshore coastal environment. However, if produced water is discharged into isolated coastal areas such as shallow salt marsh environments with limited circulation, localized degradation of water quality may take place as long as the discharges continue.

Commercial fishing in the Gulf of Mexico is an important economic component of the United States. Commercial landings of all fisheries in the Gulf of Mexico during 1989 totaled nearly 1.8 billion pounds and were valued at about $649 million (U.S. DOC/NOAA/NMFS 1990). This was an 18 percent decrease in landings and a 7 percent decrease in value from 1988 landings. Moreover, landings data from the Louisiana area, the most heavily developed area, for several important commercial fisheries - shrimp, red snapper, and blue crab - indicated consistently lower catch-per-unit-effort than for the rest of the Gulf of Mexico. Although losses of fisheries resources are difficult to distinguish from natural variation, there has been a general decrease in landings in the Gulf of Mexico since the development of the petroleum industry. These decreases have been attributed primarily to overfishing.

Water quality criteria for saltwater organisms have been set for some of the priority pollutants of produced water and drilling fluid components (Table 7.1-1) (U.S. EPA 1992). At undiluted concentrations, ethylbenzene, copper, nickel, silver, and zinc would be acutely toxic to sensitive saltwater organisms. Benzene would be toxic under chronic exposure conditions. None of the pollutants would be toxic following a 10,000-fold dilution. Although these materials are diluted in the water, the possible additive effects of several components under chronic release conditions could potentially produce sublethal effects on sensitive stages of aquatic organisms within 1,000-1,500 meters of each site.

Table 7.1-1. Water quality criteria of produced water and drilling fluid constituents for saltwater organisms (mg/L)

Constituent	Acute	Chronic
Aluminum	-	-
Antimony	1.5[a]	0.5[a]
Arsenic (III)	0.069	0.036
Arsenic (V)	2.3[b]	-
Barium	-	-
Benzene	5.1[b]	0.7[b]
Beryllium	-	-
Cadmium	0.043	0.0093
Chromium (III)	10.3[b]	-
Chromium (VI)	1.1	0.05
Copper	0.0029	-
Ethylbenzene	0.4[b]	-
Iron	-	-
Lead	0.220	0.0085
Mercury	0.002	0.000025
Naphthalene	2.35[b]	-
Nickel	0.075	0.0083
Phenol	5.8[b]	-
Selenium	0.3	0.071
Silver	0.0023	0.00092[a]
Thallium	2.13[b]	-
Toluene	6.3[b]	5.0[b]
Zinc	0.095	0.086

[a] Proposed criterion.
[b] Insufficient data to develop criteria. Value presented is the lowest-observed-effect level.

Normally, the greatest impact from platform discharges is to benthic fauna. Local benthic fauna abundance and diversity were severely reduced within 100-200 meters of an oil separator platform off the coast of Texas (Armstrong et al. 1979). Although data are insufficient to quantify these incremental impacts on saltwater organisms, these localized, continuous emissions should be of concern in an area experiencing decreased fisheries landings and increased oil and gas development.

7.1.3 Economic Valuation of Loss of Commercial Fisheries and Benthic Fauna

While impacts based on past studies have been identified, there are no exposure-response functions to enable us to compute impacts for the specific reference-case scenarios. Thus, there is no economic valuation of impacts.

7.2 EFFECTS OF WASTEWATERS ON COASTAL WETLANDS

7.2.1 Activities and Emissions

The 2010 scenario for the Southeast Reference Site assumes *onshore* drilling for natural gas in southern Louisiana. Drilling activities produce wastewaters as described in Sections 4.3 and 5.3. Effluent concentrations estimated by U.S. EPA (1991, 1987b) are given in Tables 5.3-5 and 5.3-6.

In Southern Louisiana, gas production areas are located in or near coastal wetland areas on barge platforms or small coastal islands. Although 90% of all wastewaters are disposed of by underground injection, gas and oil producers operating near the Gulf Coast are allowed to discharge treated produced water as well as other drilling-associated wastes into tidally affected surface streams. Wastewaters are also disposed of in pits. "In this area, reserve pits are constructed out of the materials found on coastal islands, mainly from peat, which is highly permeable and susceptible to damage after exposure to reserve pit fluids. Reserve pits on barges are self-contained, but are allowed to be discharged in particular areas if levels of certain constituents in wastes are below specified limits. If certain constituents are found in concentrations above these limits in the waste, they must be injected or stored in pits" (unlined on coastal islands) (U.S. EPA 1987b).

Many operators in this area discharge produced water directly to adjacent water bodies; it is estimated that roughly 1.8 to 2.0 million barrels of produced water are discharged daily (U.S. EPA 1987b). The U.S. Department of the Interior (1991) estimates that approximately 434,000 bbl/day of produced water transported from offshore facilities are being discharged from 16 separation facilities located in coastal Louisiana salt marshes. (It is unclear whether this amount is part of or in addition to the U.S. EPA figure.) In some cases the receiving water bodies are predominantly freshwater (characterized by a salinity of <2 parts per thousand [ppt]). In 1985, the Louisiana Department of Environmental Quality adopted a permitting system which requires operators to apply for permits for these discharges. In 1991, the Louisiana Legislature required most produced water discharges to meet limitations similar to those of other industries in the state. If these limitations are not met, the operators have the option of reinjecting produced waters to underground formations (Louisiana Department of Environmental Quality 1992). Proposed U.S. EPA NPDES permit regulations would prohibit the discharge of produced water from production facilities into shallow coastal waters of the Gulf of Mexico.

Under existing state regulations, drill cuttings and drilling mud may also be discharged into estuaries. However, state policy does not permit discharge of drill cuttings within 1,300 feet of an active oyster harvesting area. The Louisiana Department of Environmental Quality does not allow discharge of whole drilling fluids (mud) into estuaries.

7.2.2 Impacts on Coastal Wetlands

Produced water discharges may impact wetland areas via toxic concentrations of chemical components (including salinity) and contamination of bottom sediments. Some impacts of produced water discharges from oil and gas operations in coastal wetlands of Louisiana were recently studied (API 1991, Boesch and Rabalais 1989). The API collected data on salinity stratification, hydrology, and hydrocarbon and natural radionuclide levels in water and sediment. Thirty-six discharges in a variety of habitats ranging from partially freshwater to saline marshes (characterized by a salinity of >16 ppt) were sampled. Physical settings ranged from canals to open water and water depth ranged from 1 to 5 meters. Discharge salinities ranged from 10 to 227 ppt (mean, 141 ppt). Salinity stratification occurred at less than half of the sites. Where present, the stratification associated with produced water discharges appeared to be localized to within 300 m of the production facility.

The total petroleum hydrocarbons (TPH) of the discharges ranged from 1.7 to 119 mg/L. No surface water samples contained detectable (0.5 mg/L) concentrations of TPH. Less than half of the bottom water samples contained detectable concentrations of TPH which were present only within 300 m of the discharge. The TPH concentrations of sediment samples collected from within 15 to 300 m of the discharge ranged from 100 to >500 μg/g (background concentrations in this area range from 10 to 50 μg/g).

Sediment radionuclide concentrations were low and did not appear to be concentrating in this area. Water column concentrations ranged from 0.0 to 3.5 pCi/L $^{226+228}$radium. These concentrations are elevated above background, but are below the EPA Drinking Water Standard of 5 pCi/L. Two sediment samples contained concentrations of ^{226}radium of 1.7 and 6.3 pCi/g.

The Boesch and Rabalais (1989) study concerned 16 oil and gas separation facilities in which produced water from offshore platforms is piped ashore for separation and disposal in Louisiana coastal waters. They documented substantial impacts around the discharge sites: (1) elevated salinity levels were present in a bottom plume extending out from the discharge site, (2) the produced water plume contained elevated levels of dissolved and dispersed hydrocarbons, organic acids, and trace metals, and (3) substantial hydrocarbon contamination of fine-grained sediments was observed extending out for several hundred meters to over one kilometer from the point of discharge.

The U.S. EPA (1987b) documented a case in which an illegal discharge of saline produced water (32 ppt) from an oil facility had severely damaged a cypress swamp. The area of damage was not specified. The canal into which the produced water was discharged was also used as a source of water for a crawfish farm. In the laboratory, a combination of salt stress and water logging were shown to have a negative effect on the growth of tupelo-gum (*Nyssa aquatica*) seedlings (Pezeshki et al. 1990). Tupelo-gum and bald cypress (*Taxodium distichum*) swamp forests border freshwater marshes in the northern portion of the Louisiana coastal drainage basins.

Water quality criteria for saltwater organisms were presented in Section 7.1-1. Water quality criteria for freshwater organisms are presented in Table 7.2-1 (U.S. EPA 1992). Lack of information on dilution factors and survey data on specific contaminants in the vicinity of discharges of produced waters preclude calculating potential impacts to aquatic organisms from acute and chronic exposures to these contaminants. However, discharges of chloride ranging up to 227 ppt (227,000 mg/L) would have acute effects on freshwater organisms in areas of limited circulation and dilution. The BPT Limit of 7,300 mg/L would likewise have acute effects if discharges took place in freshwater marshes of limited circulation.

7.2.3 Economic Valuation of Impacts on Coastal Wetlands

While impacts based on past studies have been identified, there are no site-specific data to enable us to compute impacts for the specific reference-case scenarios. Thus, there is no economic valuation of impacts.

Table 7.2-1. Water quality criteria of produced water constituents for freshwater organisms (mg/L)

Constituent	Acute	Chronic
Benzene	5.3[a]	-
Bis(2-ethylhexyl)phthalate (as phthalate ester)	0.94[a]	0.003[a]
Ethylbenzene	0.32[a]	-
Naphthalene	2.3[a]	0.62[a]
Phenol	10.2[a]	2.56[a]
Toluene	17.5[a]	-
2,4-Dimethylphenol	2.12[a]	-
Beryllium	0.13[a]	0.0053[a]
Cadmium	0.0039[b]	0.0011[b]
Chloride	860	230
Chromium (III)	1.7	0.21[b]
Chromium (VI)	0.016	0.011
Copper	0.018[b]	0.012[b]
Lead	0.083[b]	0.0032[b]
Nickel	1.4[b]	0.160[b]
Silver	0.00092[c]	0.00012
Zinc	0.120[b]	0.11[b]

[a]Insufficient data to develop criteria. Value presented is the lowest-observed-effect level.
[b]Hardness dependent; tested at 100 mg/L $CaCO_3$
[c]Proposed criterion.

7.3 EFFECTS OF SUPPORT AND TRANSPORTATION ACTIVITIES FOR OFFSHORE AND ONSHORE PRODUCTION ON COASTAL WETLANDS

7.3.1 Activities and Emissions

The 1990 scenario for the Southeast Reference site provides for drilling offshore of the coast of Louisiana whereas the 2010 scenario provides for onshore drilling in southern Louisiana. We assume, however, that pipeline and navigational channel infrastructure is already in place for the Southeast Reference site. We include the following discussion (sections 7.3.1 and 7.3.2) to describe the potential effects of these construction activities on the coastal environment if these facilities were to be built.

Within the coastal area, the impacts of construction of pipeline and navigational channels as well as construction of other support activities are similar for both offshore and onshore production. Moreover, since oil and gas are often produced from the same well, the impact from production of these two fuels could not be separated in the following discussion. Sixteen petroleum separation facilities are located in salt marsh environments along Louisiana's coastline.

Table 7.2-1. Water quality criteria of produced water constituents for freshwater organisms (mg/L)

Constituent	Acute	Chronic
Benzene	5.3[a]	-
Bis(2-ethylhexyl)phthalate (as phthalate ester)	0.94[a]	0.003[a]
Ethylbenzene	0.32[a]	-
Naphthalene	2.3[a]	0.62[a]
Phenol	10.2[a]	2.56[a]
Toluene	17.5[a]	-
2,4-Dimethylphenol	2.12[a]	-
Beryllium	0.13[a]	0.0053[a]
Cadmium	0.0039[b]	0.0011[b]
Chromium (III)	1.7	0.21[b]
Chromium (VI)	0.016	0.011
Copper	0.018[b]	0.012[b]
Lead	0.083[b]	0.0032[b]
Nickel	1.4[b]	0.160[b]
Silver	0.00092[c]	0.00012
Zinc	0.120[b]	0.11[b]

[a]Insufficient data to develop criteria. Value presented is the lowest-observed-effect level.
[b]Hardness dependent; tested at 100 mg/L $CaCO_3$
[c]Proposed criterion.

The coast of Louisiana consists of vast areas of estuarine wetlands interlaced with many streams and natural channels; the wetlands extend from the shore for 8 to 48 km inland. This coastal zone contains approximately 2,881,940 acres of tidal wetlands. There is very little beach area.

Because high land that can be served by roads and rail is not available along most of the Louisiana coast, vessels are used to support offshore oil and gas activities. These vessels extensively use dredged channels or deepened natural waterways. Although the channels may be natural, oil and gas related activities contribute to bank erosion by boat wakes, disposal of dredged material from channel maintenance, and alteration of natural hydrological processes (Boesch and Robilliard 1987). The coastal zone includes 192,258 acres of canals and spoil banks. Maintenance dredging of existing oil/gas well channels, canals, and slips is allowed in this area under the New Orleans District Corps of Engineers (NOD-22). In 1991, 141 acres of coastal wetland were impacted by NOD-22 permitted actions. Maintenance dredging is also authorized in previously impacted areas. In 1991, 78 additional acres were impacted by this type of permitted action (Louisiana Department of Environmental Quality 1992).

7.3.2 Impacts on Coastal Wetlands

Louisiana's coastal wetlands are recognized as a valuable natural resource which support a large recreational and commercial use. Loss of wetlands in Louisiana is due primarily to natural processes; however, human activities such as flood control and channeling of the Mississippi River have also impacted wetland acreage. The estimated loss from all causes in 1987 was 67 km^2, down from approximately 100 km^2/yr in the 1960s and 1970s (Louisiana Department of Environmental Quality 1992). During oil and gas production and support activities, saltwater, estuarine, and freshwater marshes may be degraded or lost by dredging of access channels, construction of pipelines and receiving terminals, and disposal of wastes from both offshore and onshore production. Dredging of navigation and pipeline canals and spoil disposal in marshes have interrupted water flow patterns and accelerated rates of saltwater intrusion. Discharge of highly saline produced water kills freshwater vegetation which holds the soil in place, resulting in the conversion of marsh to open water, which in turn increases the rate of saltwater intrusion and erosion (Boesch and Robilliard 1987; Louisiana Department of Environmental Quality 1992). Substantial inland saltwater intrusion has occurred in several areas, including areas as far inland as the city of Houma. At several points, wetlands and shallow coastal waters have been filled in to provide space for docks, warehouses, pipe storage, processing plants, or fabrication yards (Boesch and Robilliard 1987). The amount of land required for a typical land-based gas field with 120 wells in the U.S. ranges from 420-640 acres (U.S. Department of Energy 1983). Approximately 90 wells are required to provide natural gas for the proposed 500-MW power plant, entailing the use of 308-470 acres.

Approximately 200 oil and gas pipelines emanating from offshore waters under state or Federal jurisdiction have landfalls in Louisiana. In addition there are hundreds of pipelines from onshore production located in the coastal area. The size of the area affected by pipeline canal construction varies with the construction method and coastal area. Material dredged to form the canals is placed in canal-side spoil banks. A 30-m wide canal (70 to 150 m including spoil banks) traversing 20 km of coastal salt marsh could destroy 200 ha (494 acres) of marsh. Boesch and Robilliard (1987), using a conservative pipeline canal length of 10 km, estimated that the approximately 200 offshore pipelines crossing coastal wetlands could have resulted in loss of 20,000 ha of marsh. They note that, in addition, dredged canals tend to rapidly widen because of the highly erodible nature of wetland soils and spoil banks may impound standing water, disrupting natural hydrology. The U.S. Department of the Interior (1991) estimates that <200 hectares of coastal wetlands may be lost to erosion caused by navigation activities needed to support offshore oil and gas development activities over a 5-year period.

Foy (1991) used two different methods to estimate the contribution of oil and gas activity (primarily pipeline and navigation canals) in the Louisiana coastal zone and federal outer continental shelf region to Louisiana wetland loss over the period 1955-1980. The first method used wetland scientists' consensus estimates of total oil and gas induced wetland loss to determine the average oil and gas related wetland loss per thousand barrels of oil-gas equivalent and per well. Natural gas in thousands of cubic feet and oil in thousands of barrels were added together using a conversion factor of 1000 ft^3 equals 0.000176 bbl of oil. The second method used a time series model to determine the marginal oil and gas related wetland loss per 1000 bbl of oil-gas equivalent and per well. The model did not use consensus estimates. The two methods produced similar results. The time series estimates were 0.0060 acres/thousand bbl and 1.1797 acres/well. These results were similar to the lower bound averages for the consensus data, 0.0060 acres/thousand bbl and 1.3658 acres/well. The lower bound estimate was based on the data of Turner and Cahoon (1988) who determined that 30-59% of wetland loss during this period was due to oil and gas activity.

7.3.3 Economic Valuation of Loss of Coastal Wetlands

While impacts on coastal wetlands have been identified and estimates of wetland loss for some support activities have been made, there are no site-specific data to enable us to relate impacts to individual gas wells or related support activities. Thus, there is no economic valuation of impacts.

7.4 ACCIDENT RATES FOR OFFSHORE DRILLING

7.4.1 Non-Fatal Injuries

Offshore gas wells average about 11,100 ft in depth and require about 60 days to drill (Chapter 4). Assuming a crew of 20 persons per 12-hour shift and two shifts per day, a well requires about 480 person hours per day and 28,800 total hours to drill. Assuming a production rate of 765 thousand cf/day for each well (Chapter,000 5) it will require approximately 90 wells to supply 68.51 million cf/day to the generating facility. If 90 wells are required to supply the 68.51 million cf/day requirement of a single plant, and if these wells do not require replacement, then total labor amounts to 2.59 million hours.

Mueller et al. (1987) have reviewed the factors affecting individual injury experience among petroleum drilling workers on mobile platforms in the Gulf of Mexico. Their study investigated the injury history of 962 workers over a 44 month time period; no fatalities were observed during this period. They aggregated injury rates differently than the Bureau of Labor Statistics, and found that when they aggregated their "lost time" and "medical" cases, they more closely reflected the category of total reportable cases. The study at that time found very close agreement with the BLS accident rates for the time period under investigation (1979-1982). This similarity suggests that the mobile platforms working in the Gulf of Mexico generally experience similar accident rates to the more general class of "Oil and Gas field services" SIC code 138. This code has a rate of 184 work days lost per 200,000 hours reported for 1989 (NSC 1991). This rate amounts to 2,386 days lost for the drilling of 90 wells. Not included in this estimate are accidents on the production platforms. These accident rates should be much lower because the work is less risky and because there is only a small crew to service production platforms.

7.4.2 Fatal Injuries

The accidental death rate for mining and quarrying, which includes oil and gas extraction, is 43 per year per 100,000 workers. Based on the drilling requirements above, work related to drilling would be expected to result in 0.5 deaths.

8. IMPACTS AND DAMAGES FROM NATURAL GAS PROCESSING

8.1 EFFECTS OF WATER AND AIR EMISSIONS

8.1.1 Emissions

Chapters 4 and 5 provide data on wastes from processing. Residuals from this stage of the natural gas fuel cycle include both water and air emissions. Constituent concentrations of wastes vary, depending on the specific processing methods and waste management methods. Treated wastewaters are disposed of by underground injection, disposal, or discharge to surface water. In some arid and semiarid areas, surface pits, ponds or reservoirs are used to evaporate water. Water pollutants that are measured in waste streams include biological oxygen demand (BOD), chemical oxygen demand (COD), oil and grease, total dissolved solids, chromium, zinc, chloride, and sulfate. Discharges are regulated by the National Pollutants Discharge Elimination System (NPDES).

Air emissions from natural gas purification plants include particulate matter, NO_x, SO_2, CO_2, hydrocarbons, CO, and aldehydes (U.S. DOE 1983); fugitive emissions of volatile organic compounds and hydrocarbons; compressor exhaust; and venting and flaring. If present in significant amounts, sulfur and natural gas liquids such as propane and butane are recovered and sold as byproducts. A gas purification plant (process undefined) that handles 250 x 10^6 ft^3 of natural gas per day (heat content = 1000 Btu per ft^3) emits the following amounts of pollutants per year: particulates, 13.3 tons; NO_x, 3.35 x 10^3 tons; SO_2, 0.443 tons; hydrocarbons, 29.5 tons; CO, 0.295 tons; and aldehydes, 2.21 tons (U.S. DOE 1983). The amount of pollutants produced by the gas processing plant to supply 72.89 million cf/day required by the hypothetical gas-fired power plants in this study is shown in Table 8.1-1. Modeling was not conducted to determine atmospheric concentrations due to lack of data on the two processing plant sites. These differ from the sites of the power plants themselves. Thus estimates of incremental increases in atmospheric concentrations of primary pollutants for the two processing plants are not available.

Table 8.1-1. Gas processing plant pollutants produced by supplying one 500 MW gas-fired power plant (Tons/year)

Pollutant	Quantity
Particulates	3.92
NO_X	989
SO_2	0.132
Hydrocarbons	8.69
CO	0.087
Aldehydes	0.065

For both the 1990 and 2010 scenarios, natural gas for the Southeast Reference site will be processed in southern Louisiana; natural gas for the Southwestern Reference site will be processed in New Mexico.

8.1.2 Effects of Air and Water Emissions on Wildlife and Crops

Natural gas processing plants require land for tank farms to store gas condensates, recoverable oil, and for process facilities including settling ponds, water treatment plants, and disposal sites for wastes. Emission rates of airborne primary pollutants - CO, NO_x, SO_2, and particulates - and other toxic chemicals from the processing sites were only partially available, and time and data constraints did not permit modeling of air concentrations. Therefore, impacts on wildlife and crops from air emissions could not be quantified. Lack of data on concentrations of contaminants in wastewater and water quality of the receiving water bodies precluded descriptions of impacts on aquatic biota.

Data are also lacking for the baseline ambient air pollutant concentrations and for other parameters needed for atmospheric transport modeling at the refinery reference sites. In addition, data on water pollutants is limited to requirements of NPDES permits.

8.1.3. Economic Valuation

No economic valuation was done due to the lack of data on the impacts at the two processing sites.

9. IMPACTS AND DAMAGES FROM TRANSPORTATION OF NATURAL GAS

9.1 EFFECTS OF EMISSIONS FROM PIPELINES

As described in Section 5.3, methane is vented to the atmosphere during the transmission of natural gas through pipelines, normal operations, maintenance and construction, and leaks. The leaks due to normal operations are due to operation of instruments, regulators, and valves. During maintenance and construction, pipelines and equipment are also purged of natural gas to provide safe operating conditions.

9.1.1 Research on Pipeline Emissions

Three studies, one of which is ongoing, have been conducted to determine the extent of natural gas pipeline emissions in the U.S. A joint project by the Gas Research Institute and Pacific Gas & Electric in 1987 (GRI 1989) estimated that emissions attributable to distribution and transmission operations accounted for 0.14 percent. These researchers did not distinguish between distribution and transmission activities, but combined them to arrive at their result.

The American Gas Association conducted a survey of natural gas companies and estimated that transmission accounted for 0.06% of natural gas emissions and distribution accounted for 0.28% leakage. The leaks during transmission usually occur due to major structural failure. This is due to the fact that transmission pipelines are under high pressure so slow leaks are unlikely.

Currently, there is an ongoing study by Radian Corp. commissioned by the Gas Research Institute and the EPA that examines wells and pipelines for natural gas emissions. This project relies both on surveys of gas companies and on methane detection equipment to estimate total pipeline emissions. The new findings suggest that natural gas emissions from high-pressure transmission pipelines in the U.S. are likely to be in the range of zero to 0.5% of total gas production. In Section 9.1.2 the assumptions that Radian Corp. uses for their pipeline leakage analysis are provided. In addition, the results of their analysis for the pipeline supplying the Southwest Reference power plant are presented.

9.1.2 Pipeline Emissions at the Southwest Reference Site

There are various factors that contribute to the leakage of natural gas from transmission by pipelines. The most of important of these are:

1) age of the pipeline,
2) pipeline material,
3) number of meter regulation stations,
4) number of main line valve stations,
5) number of compressor pumping stations, and
6) pipeline pressure.

A preliminary analysis to estimate the emissions from the natural gas pipeline system supplying gas to the Southwest Reference Site south of Farmington, NW was conducted by Radian Corporation under joint contract with the Gas Research Institute and the U. S. Environmental Protection Agency (personal communication with Mike Cowgill and Matthew Harrison, Radian Corp. 1992). This jointly sponsored study has as one of its goals, a methodology to determine total natural gas leakage from extraction to electric generation.

For the analysis of the pipeline supplying the power plant at the Southwest Reference Site, Radian relied on a survey of a gas transmission company in California. This company had seven repaired leaks in 1991. The average duration of each of the leaks was assumed to be 24 hours. The leakage rate from this pipeline system was extrapolated to the pipeline supplying the Southwest Reference power plant by using characteristics of the pipeline.

The parameters required to determine pipeline leakage for the pipeline supplying natural gas from a natural gas processing plant located in Bloomfield, NM to the Southwest Reference Site are as follows:

1) 36" diameter main pipeline,
2) 38 miles in length,
3) 850 psi at beginning of pipeline,
4) One meter regulator station at the origin of the pipeline - gas processing plant at Bloomfield,
5) The pipeline is steel and 2 to 3 years old,
6) Two main line valve stations on the pipeline and one at the power plant,
7) pipeline carries approximately 900 million cubic feet of natural gas per day,

8) pressure drop at the end of the 38 mile line is 100 psi (850 down to 750 psi).

A secondary line branches off the main gas line (after 38 miles) and leads directly to the electric generating plant. The parameters of this secondary pipeline are as follows:

1) pipeline diameter is 12",
2) pipeline length is 9 miles,
3) pipeline pressure is 750 psi at beginning of secondary pipeline, 700 psi at end,
4) the secondary pipeline carries approximately 70 million cubic feet of natural gas per day.
5) the secondary line has one main line valve station located at the hypothetical power plant.

The estimated leakage of methane from the 36" main pipeline is 11.41 million cf/year. This results in a minimal leakage of approximately 0.003% of total throughput per year. Leakage of methane from the 12" secondary pipeline is estimated to be 0.881 million cf/year. This results in annual leakage of approximately 0.0034% of total throughput. These leakage rates are likely to be lower than the average leakage of existing natural gas pipelines in the U. S. due to age and material of the pipeline as well as the lower than normal number of meter regulator and main line valve stations. However, it is possible that the actual pipeline we examined may have leakage of methane lower than what Radian had estimated. In addition, no compressor stations are located on the pipelines from the gas processing plant to the electric generating plant.

9.1.3 Natural Gas Pipeline Compressor Emissions

Gas turbines and gas-fired reciprocating engines are both used to power compressors used for gas pipelines and the use of large gas turbines has increased significantly over the past few years. Internal combustion (IC) reciprocating engines are more fuel efficient, but gas turbines emit less air pollutants and are more costly.

Table 9.1-1 gives emission factors for compressor engines used in natural gas pipelines. The emission factors are in units of pounds of pollutants emitted per billion cubic feet of natural gas pipeline flow. These emission factors have been compiled from EPA's AP-42 document (EPA 1993).

Table 9.1-1. Emission factors for heavy duty natural gas-fired pipeline compressor engines (lb/billion cubic feet of natural gas)

Pollutant	Reciprocating engines	Gas turbines
Nitrogen oxides	3,400	300
Carbon monoxide	430	120
Hydrocarbons (C)	1,400	23
Sulfur dioxide	0.6	0.6

The size of pipeline transporting natural gas from the Louisiana Gulf coast to Middle Tennessee (before branching off to East Tennessee with a smaller pipeline) is 36 inches in diameter. Powering the natural gas through the pipeline requires one compressor station each 80 miles, with approximately 10,650 horsepower per station. The total fuel consumption at each station required to power the compressors is approximately 788 MMcf of natural gas per year.

9.1.4 Impacts of Methane Emissions on Wildlife and Crops

Slow leaks of methane from pipelines would have little impact on local wildlife and crops since methane would be dispersed in the atmosphere and it is not considered a toxic pollutant. Methane contributes to the greenhouse effect, but information on the impact of this effect has not been quantified. Modeling studies are required to understand local and long-range dispersion. No information on the site-specific impact of methane leakage from a pipeline break was located.

9.1.5 Economic Valuation of Pipeline Emissions

No economic valuation was done due to the lack of economic data on the impacts of methane leaks on wildlife and crops.

9.2 NATURAL GAS PIPELINE ACCIDENTS

9.2.1 Pipeline Leaks / Failures

Federal standards on pipeline safety are regulated by the Office of Pipeline Safety in the Department of Transportation. Information on pipeline incidents[1] or accidents is compiled this office annually. The Department of Transportation reports the number of fatalities, injuries, and leaks/failures for natural gas transmission pipelines annually (DOT 1991).

There are three major reasons for pipeline accidents. They are:

1) Damage by an outside force.

This is usually "third-party damage" and is the leading cause of pipeline damage and accidents. Approximately two-thirds of pipeline accidents in the past 15 years have been caused by the actions of outside parties (AGA 1988).

2) Material or Construction Defect.

Defects in the manufacture of pipe, valves, and fittings installed on gas pipelines or defects in assembling the materials is the second leading cause of reported incidents, at just over 13% in the last 15 years. Unlike third-party damages, gas pipeline companies and state regulators exercise some control over materials and construction techniques through design and control of construction practices.

3) Corrosion.

Corrosion, both external and internal, caused about 12% of reported pipeline incidents during the last 16 years, but fewer than 10% of the injuries/fatalities from pipeline failures were corrosion-related.

DOT's Office of Pipeline Safety compiles both transmission and distribution line accidents; however, for our study we consider only high-pressure transmission pipeline and gathering accidents. The gathering process involves the pipeline transportation of natural gas from gas processing facilities. The consequences of gas transmission pipeline accidents from 1982 through 1991 are reported in Table 9.2-1.

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[1]An incident means any of the following events: 1) a significant release of gas from a pipeline, 2) a death, or personal injury requiring hospitalization, 3) estimated property damage, including cost of lost gas, of $10,000 or more, or an event that is considered significant even if it does not meet the criteria of the above three descriptions.

Table 9.2-1. Natural gas transmission pipeline and gathering accidents.

Year	Fatalities	Injuries	Leak/failures[1]
1982	11	41	520
1983	2	25	453
1984	9	40	255
1985	6	12	127
1986	4	20	83
1987	0	13	68
1988	3	11	88
1989	22	19	98
1990	0	17	88
1991	0	12	71

[1]The large drop in leak/failures after 1984 is due in large part to the monetary damage reporting threshold increasing from $5,000 to $50,000.

9.2.2 Deaths, Injuries, and Damages due to Pipeline Accidents

Impacts

In 1991 there were 71 Transmission and Gathering Pipeline Incident Reports received by DOT. The causes of these incidents as well as the resulting property damage are reported in Table 9.2-2.

Table 9.2-2. Transmission and gathering pipeline incidents in 1991.

Cause of incident	No. of incidents	% of Total	Property Damages[1]	% of Total	Injuries
Internal Corrosion	10	14.1	$1,210	11.2	0
External Corrosion	6	8.5	498	4.6	0
Damage from outside forces	37	52.1	2,480	22.9	4
Construction or material defect	2	2.8	66.3	0.6	0
Other	16	22.5	6,570	60.7	8
Total	71	100.0	$10,800	100.0	12

[1]Property damages are in thousands of 1989 dollars.

Damages

To estimate the impact of pipeline accidents for each of the two reference sites in this study, we first scale the effects of reported accidents for the U. S. to the pipelines supplying the two reference sites (the southeast site has the same consumption of natural gas as the southwest site). We do this by calculating the ratio of annual gas movements to the SE power plant site to total U. S. gas movements by transmission pipelines. The U. S. value on gas movements was obtained for 1989 (DOE 1989).

The total annual gas movements to the Southeast reference site from the wellhead is 27.4 billion cf/year (the comparable value for the Southwest site is 26.6 billion cf/year due to lower pipeline compressor consumption). Total gas movements in the U. S. in 1989 was 46.18 trillion cf/year. The ratio of gas movements - SE site to total U. S. gas movements is 0.758 x 10^{3}. The average number of deaths due to transmission pipeline activities over the past ten years is 21.0. The equivalent number of injuries and pipeline leaks/failures is 5.7 and 89.0, respectively (the average number of leaks/failures was calculated over the past seven years due to the increase in threshold reporting limit commencing in 1985).

Multiplying the number of deaths and injuries for the U. S. given above, times 0.758 x 10^{-3}, scales these impacts to the pipelines supplying the reference sites. We use the same methodology as in the Coal fuel cycle report (ORNL/RFF 1994b) to estimate damages due to deaths and injuries caused by pipeline accidents. A value of $10,301, the average cost of nonfatal injuries for all industries developed in a study by the Urban Institute (Rossman 1991), is used to value each pipeline related injury. The damage estimates, given in mills/kWh are calculated by dividing the reference site damages in column 5 (converted to mills) by the annual power generation of the power plant, 3.263 billion kWh/year.

We estimate the damages associated with deaths due to pipeline accidents much like the damages for injuries. Section 6 of the coal fuel cycle report provides estimates of damages associated with fatal injuries to range from $1.6M to $8.5M, with a midpoint estimate of $3.5M. The estimated values are reported in Table 9.2-3.

In addition, the property damage values for leaks/failures listed in Table 9.2-2 are scaled by the same proportioning factor (0.758 x 10^{-3}) to estimate the monetary value of the property damages at the reference sites. These estimates of property damages are also given in Table 9.2-3.

Table 9.2-3. Estimated damages at reference sites due to pipeline accidents (1989 dollars)

Incidents	U.S. Avg	Ref. site	U.S. damages	Ref. site damages	Ref. site damages in mills/kWh
Deaths	5.7	0.0043	$20M	$14,000	0.00464
Injuries	21.0	0.0159	$0.216M	$150	0.000050
Leaks / Failures	89.0	0.0674	$13.6M	$9,400	0.00313

10. ESTIMATING THE EXTERNALITIES OF ELECTRIC POWER GENERATION

This chapter concerns the estimation of externalities associated with electric power generation using natural gas. A table of contents for Chapter 10 is given below as a reference. The effects of air and water emissions from natural gas-fired power generation on vegetation and wildlife generally cannot be quantified given the current state of knowledge; they are briefly discussed in Appendix D.

Contents of Chapter 10

This chapter gives an exposition of how to use the damage function approach by applying various analytical methods to the priority impact-pathways selected in Chapter 6. The estimates of externalities are for the Southeast and Southwest Reference sites. In a local or state planning context [discussed in Chapters 2 and 4 and in Section 5.4 of ORNL/RFF (1994b)], analysts can use the methods to compare actual (or likely) sites and technologies. In a national context, a representative set of sites would have to be used [again refer to Chapters 2 and 4, and Section 5.4 of ORNL/RFF (1994b)].

Each section within this chapter illustrates the use of a specific method for a different impact-pathway. Within a section, each subsection is relatively self-contained and generally consists of a discussion of the discharges (or other residual effect) of a fuel cycle activity, the resulting impacts, an economic valuation of the damages (or benefits) of these impacts, and an assessment of whether these damages (or benefits) are externalities. Since this report is essentially self-contained, it repeats significant portions of the material in Chapter 10 of the report on coal fuel cycles (ORNL/RFF 1994b).

10.1 ELECTRIC POWER GENERATION ACCIDENTS

10.1.1 Impacts of Electric Power Generation Accidents

As in any industry, occupational injuries occur during the normal course of operating a power plant. There are data on the total number of injuries for the electric services industry,[1] but not on the differences in the incidence of injuries across different technologies (oil, coal, nuclear, hydropower, etc.). Thus, our analytical method determines a national injury rate for the electric services industry, either per MW capacity or per gigawatt-hour of generation, and then multiplies this rate by the capacity or generation of the reference plants to determine the total number of injuries.

The average number of injuries per MW capacity and per million kWh in 1990 was 0.017 and 0.0016, respectively.

In 1990, the average employment in the electricity services industry was 456,000 and the number of lost workday injuries was approximately 12,800. In the same year, the U.S. installed capacity was 735,051 megawatts (MW) and the amount of electricity generated was 2,808,151 million kilowatt-hours (kWh). Thus, the average number of employees per MW capacity and per million kWh in 1990 was 0.620 and 0.162, respectively. The average

[1] This industry includes establishments engaged in the generation, transmission, and/or distribution of electric energy for sale.

number of injuries per MW capacity and per million kWh in 1990 was 0.017 and 0.0016, respectively. If these injury incidence rates are applied to the reference environments, both of which have an installed capacity of 500 MW and 3,219 million kWh per year production, then the estimates of the number of injuries per year are 8.5 and 5.15. As a "best" estimate, we use the average of the two estimates, 6.83 injuries per year. We assume that all of these injuries are non-fatal.

10.1.2 Damages of Generation Accidents

Two approaches are taken in the literature for estimating the willingness to pay (WTP) for reduction in non-fatal injuries [translated into the value of a statistical injury (VSI) where the purview of these studies is injuries on the job resulting in at least one lost work day]. One approach, exemplified by Pindus, Miller and Douglass (1991), may be termed a bottom-up approach as it seeks to identify the damage associated with an injury on a component-by-component basis, e.g., medical costs, work loss days, household productivity loss. Since no injury incidence information of sufficient specificity is available for the electricity generation industry, we apply an across-industry average cost of $10,301 per injury as provided by the Urban Institute in Pindus, Miller and Douglass (1991). This estimate includes medical costs, wage loss, and household productivity loss -but does not include any decrease in quality of life (e.g., pain and suffering).

The second approach is an hedonic wage approach, where variations in injury rates across types of jobs and industry classes and other variables are used to explain variations in wage rates and labor force participation. This is the approach used by most researchers to obtain values of a statistical life; indeed, many of these studies contain a variable for injury rate as well as a variable for accidental death rate. The two best examples of the hedonic wage approach provide estimates that, unfortunately, do not overlap: $17,000 to $34,000, with a best estimate of $26,000 (1989) for the Moore and Viscusi (1988) study and from $8,000 to $9,000 for the Martinello and Meng (1992) study.

We judgementally set a confidence interval for the value of a statistical injury (VSI) that spans the range of these two studies, from $8,000 to $34,000. For a best estimate, we choose the Urban Institute study's across-industry average value of the VSI of $10,300, which falls within this range.

...$8,000 to $34,000. For a best estimate, we choose the Urban Institute study's across-industry average value of the VSI of $10,300...

We use these estimates to calculate the occupational damages associated with electric power generation. The damages associated with non-fatal injuries in the generation, transmission, and distribution of the electricity produced by each of the reference plants is $54,600-$232,000 (mid-estimate of $70,300) per year, or 0.017 to 0.0721 mill/kWh (mid-estimate of 0.0218 mill/kWh).

10.1.3 Externalities of Generation Accidents

We presume that most of these accidents are to employees. To the extent that their medical insurance offsets what they would be willing to pay to avoid these accidents, the damages are internalized. The difference between the willingness to pay and the cost of the medical services are externalities.

10.2 GLOBAL WARMING POTENTIAL AND OTHER EFFECTS OF CO_2[2]

10.2.1 Emissions of CO_2

Many gases emitted by natural and economic activity are characterized by "greenhouse" properties. Their presence in the atmosphere retards the radiation of heat energy out into space. Other gases are involved in chemical reactions in the atmosphere that affect the concentrations of greenhouse gases. Gases which affect global climate include carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), and chlorofluorocarbons (CFCs). Table 10.2-1 reports pre-industrial, current and annual rates of changes of the concentrations of these gases.

Table 10.2-1. Atmospheric concentrations of greenhouse gases

	CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)	CFC-11 (ppt)	CFC-12 (ppt)
Pre-industrial	280	0.8	288	0	0
Current	350	1.7	310	280	484
Current Annual Rate of Change (%)	1.6	0.02	0.8	10	17

Source: Solow (1991)[3]

[2] For the sake of completeness, and because of the importance of this subject, we repeat much of the discussion that first appeared in ORNL/RFF (1994b, Section 10.2).

[3] This is one set of estimates of the growth of emissions. For instance, Steele et al. (1992) find that there has been a substantial slowing of atmospheric methane accumulation rates since 1983 and predict that if the deceleration continues steadily, methane concentrations will reach a maximum around the year 2006. Additionally, one would expect CFC emission and atmospheric accumulation

Many of these gases are associated with the emissions from fossil fuel electric plants. The Energy Information Administration[4] reports that electric utilities were responsible for 35% of U.S. carbon dioxide emissions in 1990. In contrast, electric utilities were directly responsible for less than 1/10 of 1% of methane emissions. Natural gas power plants emit less CO_2 (per kWh) than coal- or oil-fired plants. Nevertheless, CO_2 emissions from natural gas plants are far greater than those from renewable energy. The natural gas power plants at the Southeast and Southwest Reference sites emit an estimated 642 tons of CO_2 per gigawatt hour (GWh). Other natural gas-fired power plants could have different levels of emissions, but they would generally be of this order of maginitude.

The approach of this study, as described in some detail in Chapter 4 of ORNL/RFF (1994b), is to develop a marginal approach to estimate externalities that can be attributed to a single power plant. CO_2 and global warming issues, on the other hand, are addressed more appropriately at a national or preferably global scale. The cumulative effects of CO_2 emissions are dynamic and nonlinear. Thus, the discussion in this section on incremental CO_2 impacts diverges from the marginal perspective taken in most of the rest of this study. It discusses CO_2 impacts on an aggregate, average basis, rather than on a single plant, marginal basis.

10.2.2 Is Global Temperature Increasing[5]

It is difficult to develop a noncontroversial answer to the questions of whether global temperature is increasing and whether the increase is due to increases in carbon dioxide concentrations. One of the reasons underlying this difficulty is that historical data are of little help in answering the question. For example, it is possible to examine ice core samples which can measure pre-historical (going back over 160,000 years) temperature and carbon dioxide levels, and which suggest a correlation between carbon dioxide levels and temperature.[6] However, the changes in temperature generated by small changes in the earth's orbital characteristics are extremely large in comparison to the temperature changes associated with changes in the carbon dioxide levels (Solow 1991).

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rates to decline as a result of the Montreal Protocol. Cunnold et al. (1994) find that CFC accumulation rates began to decline prior to the Protocol.

[4] Energy Information Administration, 1993, *Emissions of Greenhouse Gases in the United States 1985-1990*, DOE/EIA-0573, Washington: U.S. Department of Energy.

[5] This discussion draws heavily from Kahn, James R., 1994. *An Economic Approach to Environmental and Resource Issues*, Harcourt Brace College Division, Dryden Press, Chapter 6.

[6] There exist alternative interpretations of the relationship between temperature and CO_2. For example, the analysis of Barnola et al. (1991) suggests that CO_2 changes lag, rather than precede, temperature changes.

Although there exist temperature data which have been recorded at numerous meteorological stations since the late 19th century, it is difficult to answer global climate change questions with these data. Weather stations tended to be located around cities (which grew larger and warmer in this period), the stations tended to be located in the Northern Hemisphere, and there were few oceanic records. It is important to have an appropriate distribution of temperature measurement sites since global warming can actually lead to a wide distribution of local effects. Despite the difficulty in interpreting past records, there seems to be a consensus that there has been an increase in mean global temperature of about 0.3 to 0.6°C over the last 100 years, although there is less consensus in attributing this to increased carbon dioxide emissions (Houghton et al. 1996, p.4).

People who are skeptical of the existence of global warming argue that the climatological models which are used to forecast the warming implications of greenhouse gas emissions predict a much stronger warming associated with cumulative carbon dioxide emissions than the 0.3 to 0.6°C which has been observed. Skeptics also argue that the bulk of emissions occurred after 1940 while the bulk of this warming occurred before 1940.

However, this "over-prediction" of global warming should not necessarily be used as evidence that the models are incorrect, as a variety of mechanisms have generated some cooling effects. In particular, there may be some carbon dioxide sinks (naturally occurring mechanisms which remove carbon dioxide from the atmosphere). Plants, which remove carbon dioxide from the atmosphere as they increase their biomass, are an important sink. Some of the emissions may have been removed from the atmosphere as a result of increased plant growth which was due to the presence of increased carbon dioxide in the atmosphere. Also, oceans are a carbon sink, which also may be mitigating global warming. However, it is not appropriate to assume that the effects of continued carbon dioxide emissions will continue to be mitigated by the functioning of carbon sinks, since scientists do not fully understand the role and extent of carbon sinks.

... National Research Council's Board of Atmospheric Science and Climate, ... predicts (based on a doubling of atmospheric carbon dioxide) a warming of 1.5 to 4.5 ° C. ... The Intergovernmental Panel on Climate Change, ... estimates a warming of about 0.2 ° C per decade, or 2 ° over the next one hundred years.

Regardless of the role of sinks, temperature rise has not tracked increasing greenhouse gas concentrations. One explanation for this is that other pollutants may be responsible for a cooling effect which has partially offset global warming.

Particulate emissions, particularly sulfate aerosols, block sunlight. This effect cools the lower atmosphere. Also, stratospheric ozone functions as a greenhouse gas, and its reduction is thought to be associated with a cooling effect.[7]

Although the extent of the discussion about the existence of global warming suggests an unresolved issue, there is a relatively widespread consensus among the scientists who study global warming. This consensus is based on computer models of the atmosphere, which predict warming based on emissions of greenhouse gases. One of the most widely cited studies of global warming is the ongoing work of the National Research Council's Board of Atmospheric Science and Climate, which predicts (based on a doubling of atmospheric carbon dioxide) a warming of 1.5 to 4.5° C (NAS 1991). The most recent report of the Intergovernmental Panel on Climate Change (IPCC), which is composed of scientists from many countries, projects a warming of about 0.2°C per decade, or 2°C over the next one hundred years (Houghton et al. 1996, p.6). This estimate is about one-third lower than the previous best estimate of the IPCC. The main reasons for the lower estimate are: lower emission scenarios, the inclusion in the projections of the cooling, effect of sulphate aerosols, and improvements in the treatment of the carbon cycle (Houghton et al.1996, p. 6).

Schneider (1991) summarizes the scientific literature concerning predictions of global climate change and estimates the confidence of the projections. This summary is presented in Table 10.2-2. Note that, in this table, the low end of the range of projected increase in average global temperature is the most recent IPCC best estimate. Note too that although the best estimate of temperature increase is at lower end of the range, the projected sea level rise of 0 to 8 cm, summarized in Table 10.2-2, is consistent with the most recent IPCC projection of 20-86 cm (Houghton et al. 1996, p. 385).

As can be seen in Table 10.2-2, Schneider believes the confidence of the level of global predictions to be high, but regional predictions to be less certain. This uncertainty of regional predictions is critically important for the estimation of damages, particularly with respect to changes in precipitation patterns. Since there will be some regions which gain as a result of global warming (for instance, some dry regions may experience more rainfall) and some regions which lose, identifying these regional effects is critical in actually computing the damages (and benefits) of global warming. If one focuses exclusively on the most damaging effects, a biased estimate is likely to result. Similarly a biased estimate will result from focusing on any benefitted areas.

[7] Reduction in stratospheric ozone is caused by chlorofluorocarbons (CFCs) which are greenhouse gases, which increase global warming. These two effects are thought to approximately offset each other. It is important to note that these offsetting effects are also likely to imply that the forthcoming ban on CFC production associated with the Montreal Protocol will not result in a significant reduction in future radiative forcing.

It should be noted that regional variation in the emission of greenhouse gases is not the source of variation in regional impacts. An important difference between emissions of greenhouse gases and other pollutants considered in our study is that there are no site-specific effects. It does not matter if a unit of carbon dioxide is emitted in East Tennessee or New Mexico or Kalamazoo, the long-term effect on global warming (in terms of both global averages and regional impacts) will be the same.

A 1992 study by Kelly and Wigley suggests smaller warming effects than either the IPCC (1990) or NAS (1991) studies, but generally consistent with the more recent IPCC study. Kelly and Wigley predict that the warming over 1990-2100 associated with a doubling of atmospheric carbon dioxide is between 1.7 and 3.8° C. This prediction is within the interval suggested by the National Research Council, but with a tighter spread and a lower upper bound.[8] Most of the decrease in the interval is associated with a reduction in the upper boundary of the warming effect.[9]

10.2.3 Potential Impacts of Global Warming

Before presenting a discussion of the quantitative estimates of the costs and benefits of global climate change, a qualitative discussion of the effects of global climate change is presented. The purpose of this discussion is not to prove or refute the existence of a particular impact, but to present a discussion of the type of effects that have been estimated. More detailed discussions are given in Watson et al. (1996). Difficulties in actually estimating these effects will be discussed later.

Vegetation Response to Altered Climate

Quantitative evaluation can be made of the effects of altered climate on vegetation response. The rate of every physiological process in a plant, including growth and reproduction, is strongly influenced by temperature. However, both the structural development, as well as the physiological response of a plant, may vary greatly depending not only upon the absolute value of temperature mean, maxima, and minima, but also on the temperature pattern of the plant's environment (Meyer, Anderson, and Bohning 1965). Because these response

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[8] Kelly and Wigley (1992) investigated the link between CO_2 accumulation and global temperature, controlling for the link between solar cycles and temperature. Their regression results suggest a narrower range and less warming (0.8 to 2.2° C) from a doubling of atmospheric CO_2, than the NAS (1991) estimates.

[9] Karl et al. (1991) argue that there exists evidence that suggests that the detectable warming (to date) has been mostly nocturnal, mostly in the winter and mostly at high latitudes. If this is the case, the consequences of a given average warming would be less significant than for some other distribution of the average temperature change.

Table 10.2-2. Schneider's summary of ranges and uncertainty of global climate change

Phenomena	Projection of probable global average change[a]	Regional average	Significant transients[b]	Confidence of projections: Global average	Confidence of projections: Regional	Estimated time for research that leads to consensus (years)
Temperature[c]	+2 to +5C	-3 to +10 C	Yes	High	Medium	0 to 10
Sea Level	0 to 80 cm[d]	(*d*)	Yes[e]	High	Medium	5 to 20
Precipitation	+7 to +15%	-20 to +20%	Yes	High	Low	10 to 40
Direct Solar Radiation	-10 to +10%	-30 to +30%	Possible	Low	Low	10 to 40
Evapotranspiration	+5 to 10%	-10 to +10%	Possible	High	Low	10 to 40
Soil Moisture	*f*	-50 to +50%	Yes	*f*	Medium	10 to 40
Runoff	Increase	-50 to +50%	Yes	Medium	Low	10 to 40
Severe Storms (*g*)	*f*	*f*	Yes	*f*	*f*	10 to 40

[a] For an "equivalent" doubling of atmospheric CO_2 from preindustrial level.

[b] Long-term processes after which the state of the environment may be very different from the current state.

[c] Based on three dimensional model results. If only trace gas increases were responsible for 20th century warming trend of about 0.5 degrees C, then this range would be reduced by perhaps 1° centigrade.

[d] Assumes only small changes in Greenland and W. Antarctic ice sheets in 21st century. For equilibrium, hundreds of years would be needed and up to several additional meters of sea level rise could be accompanied by centuries of ice sheet melting from an equilibrium warming ≥ 3° C.

[e] Increases in sea level at approximately the global rate except where local geological activity prevails or if changes occur to ocean currents.

[f] No basis for quantitative or qualitative forecasts.

[g] Some suggestions of longer season and increased intensity of tropical cyclones as a result of warmer surface temperatures.

Source: Schneider, "Climate Change Scenarios for Greenhouse Increases," in *Technologies for a Greenhouse Constrained Society*, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1991.

characteristics vary greatly by species, and are largely unknown for many species of natural vegetation, quantitative response functions for temperatures that are appropriate for use in valuation do not exist. Information on potential CO_2-temperature interactions in plant response are even more poorly understood.

Moisture is the second important climatic variable likely to be part of global climate change. If a shortage of water available to a plant occurs, both cell division and cell enlargement are adversely affected. In general, the more frequent and the longer the periods of water insufficiency during the growing season, the less the overall growth (Meyer, Anderson, and Bohning 1965). While elevated CO_2 can enhance water use efficiency in plants (Norby 1989), the current state of science is inadequate to permit estimation of water-CO_2 interaction relationships.

Increases in Crop and Forest Growth Associated With Enhanced Atmospheric CO_2 Concentrations

Vegetation is an important sink for atmospheric CO_2 through photosynthesis and is an important source of CO_2 through decomposition of dead organic matter. Forest ecosystems account for the dominant fraction (~67%) of global photosynthesis (Norby 1989, Kramer 1981). It has been well documented that CO_2-enriched atmospheres, by stimulating photosynthesis, increase the growth of plants (Norby 1989) and the accumulation of carbon in the biosphere (Idso unpublished). As a result, increased plant growth must ultimately be considered in any economic analysis of the impacts of global change because there is potential economic benefit that offsets some of the various negative effects of climate change. Unfortunately, at the present time, quantitative response functions capable of adequately capturing not only long-term tree growth responses to elevated CO_2 but also the interactions with fluctuating water and nutrient supplies, and competition, do not exist (Norby 1989).

Kimball (1983) reviewed approximately 70 published reports on effects of CO_2 enrichment on the economic yield of 24 agricultural crop species. The responses across crop types (flower, fruit, grain, leaf, roof and tuber, etc.) were expressed as mean relative yield increases ranging from 12% (flower crops) to 52% (roof and tuber crops). The average for all agricultural crops taken to a mature harvestable yield was 28%. These results are of little use, however, in the development of quantitative response functions since some of the studies involved only two CO_2 concentrations, all were either growth chamber or greenhouse studies with optimal nutrient and water regimes, and potentially sub-optimal light quantities. Combining studies with widely varying environmental conditions may present an unrealistic interpretation of the true response. The studies reviewed by Kimball do support the conclusion that under controlled conditions short-term yield increases of approximately 30% might be expected from a range of agricultural crop species. Whether such increases would be of equal magnitude under field conditions or whether they would be sustained under field conditions is impossible to determine from the data Kimball presents.

Scientists are concerned with the CO_2 fertilizer effect for two major reasons. First, if the fertilizer effect is prominent, it can serve to explain a major portion of the carbon that is unexplained in many of the global carbon cycle models. The existence of a large fertilizer effect, and the increased forest growth that results, may serve to mitigate the climate change impact of CO_2 emissions. Therefore, understanding the fertilizer effect would allow the formulation of better predictions of climate change. Second, the CO_2 fertilization may have a positive effect on agriculture through a variety of mechanisms. The increased growth may improve yields per acre (of both agriculture and forestry), and the fertilizer effect also is hypothesized to increase the efficiency of water usage by plants, which would reduce the cost of production in areas that rely on irrigation or that get dryer as climate changes.

Like many areas of climate change science, the "fertilizer effect" is an area where direct effects are much better understood than indirect effects. There is a significant body of work that shows that the direct effects of CO_2 fertilization are positive and large. For example, Polley et al. present data that suggest that

> ...this increase in CO_2 has enhanced biospheric carbon fixation and altered species abundances by increasing the water-use efficiency of biomass production of C3 plants, the bulk of the Earth's vegetation....Leaf water-use efficiency and above ground biomass/plant of C3 species increased linearly and nearly proportionately with increasing CO_2 concentrations.

However, while it is scientifically feasible to test these direct effects, it is more difficult to test for the existence of indirect effects and constraints. For example, would increased CO_2 concentration also increase the presence and aggressiveness of weeds, which would have a negative effect on agricultural yields? Similarly, will higher temperatures increase pest populations? Insect populations are very likely to increase in a warmer global climate. Also, to what extent will the fertilizer effect be constrained by other factors which limit plant growth, such as the availability of nitrogen and other nutrients? Finally, is there a level of atmospheric CO_2 concentrations above which further increases do not affect plant growth? Until these questions are satisfactorily answered there will be considerable controversy over the extent of the fertilizer effect.

Although there have been shown to be increases in nitrogen use efficiency with increased CO_2 that offset short-term N shortages, as more and more N is sequestered in woody tissues, there may be long-term implications for ecosystem N cycling that would offset some of those benefits (Norby, Personal Communication). Similarly, in forests where certain cation nutrients (e.g., Ca, K) are at or near limiting to growth, the benefits of enhanced CO_2 may be less than calculated. Bazazz and Fajer (1992) point out that interspecies competition, changing predator-prey interactions, changes in nutrient cycling and other factors can affect the growth response to enhanced CO_2. They postulate that it is not evident that increased CO_2 levels will lead to overall benefits to plants.

Eamus and Jarvis (1989) concur that as individual plant response is considered in the context of the complex network of processes operating at larger spatial scales (e.g. forest type, or region) there is insufficient information about the effects of CO_2 on the larger scale processes to permit reasonable predictions. Future changes in land use, cropping and management practices, new genotypes, and fertilization regimes are all likely to have significant impacts on crop and forest productivity. Future change in CO_2 will be evaluated against a background of these other changing factors. Emaus and Jarvis concluded that in that context, the effects of increasing CO_2 may be relatively small in comparison to those resulting from future changes in land use and management practices.

Graham et al. (1990) suggest that although ecosystem level phenomena are likely to change in response to elevated CO_2 and climate change, the direction of the changes will depend on highly (ecosystem) specific circumstances. They predict that the most significant long-term effect of elevated CO_2 and climate change on forest ecosystems is likely to be changes in disturbance regimes, and in successional patterns in the unmanaged, mixed species stands that dominate the globe's forests.

Further, Kauppi et al. (1992) recently presented data for European forests that suggest that accumulation of carbon in European forest biomass may account for 8-10% of the "missing" carbon flux in the global carbon budget. Their measurements occurred over a period of 20 years across Europe, and estimated an annual accumulation of 70-105 million tons of carbon in European forests in the period 1971-1990. Their information appears to contradict the public perception of forest decline in Europe, since they estimate that standing timber inventories and forest growth increased between 1971 and 1990 by 25 and 30%, respectively. The authors (Kauppi et al. 1992) suggest that fertilizer responses to nitrogen are playing a dominant role in a major portion of the European forest area at the present time.

Agricultural Response to Altered Climate

The impacts of climatic change on total agricultural productivity can be mitigated to a degree by the ability of farmers to adapt. This is, of course, more true in large countries like the United States that have a diversity of crops and climate zones (NAS 1991) and good mechanisms for disseminating information on adaptive agricultural techniques to farmers (OTA 1993). While total damages may be small (they may also be large), the local effects may be extensive. In the United States, agricultural communities and individual farmers have been hard hit throughout history by natural events (drought, flood, etc.) and economic events (high interest rates in the late 1970s, low prices, changing consumer preferences, etc.). The ability of these communities to adapt has been limited, and the hardships remain unmitigated. In addition, one could construct a climate change scenario in which the areas of the United States with fertile soils become much dryer. Even if the other areas of the United States receive more moisture, this would not compensate for the loss of moisture in the fertile soil areas. This scenario is merely speculative, because it is difficult to make regional predictions given current states of knowledge. It does, however, illustrate how particular sorts of regional change could be associated with greater damages than the average global change.

One study (Rosenberg and Crosson 1990) has looked quite carefully at adaptation to climate change from consideration of conditions in the 1930s, incorporating effects of earlier planting and change in tillage practices, for example, in a four state region in the midwest. They find that in the absence of adaptation, output in 2030 would be 20% lower than it would have been without climate change, but that adaptation can virtually eliminate these losses. Cline (1992) makes adjustments of their results taking into account that the warming being considered is much larger (2.5 degrees versus 1 degree in the 1930s), to find significant losses in agriculture (over 10% of output). Kane et al. (1992) estimate that the losses to agriculture from climate change may be as much as $13 billion per year ($1986), while Adams et al. (1988) indicate that it could be as high as $34 billion per year ($1982).

Kane et al. (1992) estimate that the losses to agriculture from climate change may be as much as $13 billion per year ($1986), while Adams et al. (1988) indicate that it could be as high as $34 billion per year ($1982).

Smit et al. (1988) reviewed literature suggesting potential shifts in cropping patterns under climate change. Under some scenarios, high yielding U.S. corn varieties could replace Canadian varieties, and higher yielding winter wheats could replace northern spring wheat varieties. Such changes could lead to alterations in the regional distribution and intensity of farming. The agricultural sector is accomplished at adapting continuously to the risks associated with normal climate variability, and is expected to make further adaptations to future climate change, with market forces rewarding and encouraging the rapid spread of successful adaptation (Office of Technology Assessment, 1993).

The agricultural sector is accomplished at adapting continuously to the risks associated with normal climate

Managed Forest and Grasslands

Since trees have relatively long lifetimes, the ability for adaptation is less than in crop agriculture (NAS 1991). Mature forests could be harvested and replanted with the species that are appropriate for the new climatic conditions. Young forests can be replaced with appropriate species without too large a cost. According to the National Academy of Science, the biggest impacts will be on "middle aged" trees, which are too valuable to abandon, but which will be costly to maintain under less than favorable climatic conditions.

Musselman and Fox (1991) concluded that temperate forests of the future would look different than they do now, or may exist in different geographic areas, necessitating that management decisions be made at the largest possible scale, keeping local considerations in view.

Suburban homeowners may find themselves with an inappropriate species of turf grass under new climatic conditions. As the existing grass weakens, it can be reseeded with the appropriate species of turf grass, which will eventually overtake the weakened, inappropriate species. Ornamental shrubbery and trees will be more expensive to replace, but other options may be open to the homeowners such as more frequent watering and shading of sensitive shrubbery.

Water Resources

Since global change will include regional changes in precipitation, it will certainly have impacts on the regional distribution of surface and groundwater resources. These impacts are difficult to quantify accurately with current information.

These impacts, however, can be mitigated with the construction of adaptive water projects such as dams and canals, although these take time, as do other sorts of adaptive responses (NAS 1991). Adaptive responses would include genetically engineered improvements in the water efficiency of crops, technological innovation in water intensive industries (less wasteful irrigation methods, for example) or the movement of activities to areas with sufficient water.

Again, there is less ability to react to specific regional changes. For example, some scientists [see Gore (1992) for a popular summary of this discussion] believe that one of the impacts of global warming will be a reduction of the snowpack in the mountains from which Southern California draws its drinking water. This will occur from both reduced precipitation and warmer winter temperatures that will allow less snow accumulation. The reduction of the snowpack will reduce the total volume of surface water and dramatically reduce summer flows. This will have important ecological and economic consequences. The water situation in Southern California is already perilous. Further disruptions could make the region incapable of supporting current levels of population and economic activity. While some adaptations are possible (drastically reducing the availability of subsidized water for crop irrigation), worse case scenarios might call for the movement of a significant portion of the population of Southern California to wetter regions. Similar scenarios can be constructed for other areas of the Southwest.

... there is less ability to react to specific regional changes.

Marine and Coastal Environments

The National Academy of Sciences lists marine and coastal environment impacts as among the types of impacts of global warming for which the least adaptive options exist. Nature is much slower in adapting than humans. Sea level rise may be sufficiently swift that existing wetlands are flooded more rapidly than new wetlands can form. In addition, one of the adaptations of man (building dikes and seawalls), may have profound impacts on the coastal environment, as rising sea levels flood existing wetlands and sea walls prevent the creation of new wetlands. This could generate large ecological and economic impacts, as wetlands are critically important to marine and coastal ecosystems. It should be noted, however, that the current consensus is that sea level rise will be quite slow.

... the current consensus is that sea level rise will be

Natural Landscapes and Ecosystems

Natural landscapes and ecosystems are areas in which adaptations are likely to be less of a factor. For a variety of reasons, the National Academy of Sciences believes adaptability of natural ecosystems is more problematic than managed ecosystems. Part of this assessment is due to the time scale of rapid global climate change in comparison with the time scale of slow adaptation of nature. Part of this is because of the isolation of natural ecosystems by agricultural and urban land, which inhibits the migration of plant and animal species. The possibility of significant effects on forests and forest ecosystems cannot be precluded and should probably be expected.

Human Health

Since human populations are found in the most extreme climates on earth, one can argue that the human species is remarkably adaptable to climatic differences. Changes in climate can change the distribution of vectors that carry human disease, and generate important health impacts in this indirect fashion. In developed countries such as the United States, however, improvements in health technology take place at a sufficiently rapid pace as to mitigate (but not eliminate) this concern. In the poorer countries, this might not be the case (NAS 1991).

Industry and Energy

The chief concern for industry is with the availability of sufficient water supplies (NAS 1991). Since the long-term planning horizon for industry is short in relation to the period over which global change is likely to occur, industry should be able to adapt and move to appropriate locations. This could generate big winners and losers in terms of regional economic activity and cause significant dislocation costs to workers.

Settlements and Urban Structures

A potentially large impact, and one of the few areas for which there is an existing body of research [see Yohe (1991) for example], is on the potential inundation of coastal structures. Much opportunity for adaptation exists, however. Existing areas of high value can be protected by sea walls and other barriers. Existing areas of low value can be allowed to depreciate, and new structures constructed on higher ground. Such adaptations are dependent on the existence of the availability of higher ground. In countries that are characterized by low income, low elevation and high population densities (such as Bangladesh, Egypt and Seychelles) opportunities for such adaptations do not exist.

In countries that are characterized by low income, low elevation and high population densities (such as Bangladesh, Egypt and Seychelles) opportunities for such adaptations do not exist.

The Importance of Adaptation

The magnitude of the costs of potential global change is directly proportional to the existence of opportunities to adapt. Although adaptation may mitigate some of the impacts of global warming, adaptation is costly itself. Table 10.2-3 summarizes some of the major impacts, and the opportunities for adaptation. It should be noted that regional impacts are likely to be much more severe than average national or global impacts. This concentration of impacts could make adaptation more difficult and will generate regional inequities.

The nature of global climate change, and the ability to adapt to it may be dramatically altered by the potential for indirect effects which may have important and dramatic consequences. The National Academy of Sciences lists three of these effects:

(1) CH_4 could be released as high latitude tundra melts, providing a sudden increase of CH_4, which would add to greenhouse warming.

(2) The combination of increased run-off of fresh water in high latitudes and a reduced temperature differential from equator to pole could result in radically changed major ocean currents leading to altered weather patterns.

(3) There could be a significant melting of the West Antarctic ice sheet, resulting in a sea level several meters higher than it is today. (NAS 1991).

While there is not enough evidence to conclude that these dramatic changes will take place, there is also not enough evidence to preclude them (NAS 1991). Other secondary effects that may be important include an increase in the frequency and severity of tropical storms due to ocean warming, changes in snowpack, and a change in the distribution of insect pests due to changes in frost occurrence.

Table 10.2-3. Sensitivity and adaptability of human activities

Activity	Low sensitivity	Sensitive but adaptation at some cost	Sensitive, adaptation problematic
Industry and energy	X		
Health	X		
Farming		X	
Managed forests and grasslands		X	
Water resources		X	
Tourism and recreation		X	
Settlements and coastal structures[a]		X	
Human migration[a]		X	
Political tranquility[a]		X	
Natural landscapes			X
Marine ecosystems			X

Source: NAS (National Academy of Sciences) 1991. *Policy Implications of Global Warming*, National Academy Press, Washington.

[a] Adaptation is much more problematic in those low income, less developed countries where a significant amount of densely inhabited land is subject to inundation (e.g. Egypt or Bangladesh). (This note not from source of table.)

10.2.4 Economic Valuation of the Impacts of Global Climate Change

The marginal damage function is much more complex for carbon dioxide than for most other pollutants associated with the combustion of natural gas. There are several reasons for this, including the existence of major scientific uncertainties, nonlinearities and time dependencies. For these reasons, one must be much more cautious in expressing estimates of the social costs of the global warming effect of natural gas fuel cycles.

> ***... one must be ... cautious in expressing estimates of the social costs of the global warming effect of natural gas fuel cycles ... major scientific uncertainties ...***

Examples of major scientific uncertainties are:

(1) The nature and magnitude of carbon dioxide sinks

(2) The effects of stratospheric ozone on warming

(3) The atmospheric chemistry of methane

(4) Regional climatic effects

Major nonlinearities include:

(1) The radiative forcing (heat trapping capacity) associated with a marginal unit of emissions of a particular gas will be a nonlinear function of the stock of that gas and the stock of other gases which are thermally forcing at the same wavelength.

(2) Global warming is nonlinear in thermal forcing.

(3) Physical consequences may be nonlinear in warming.

(4) Social welfare losses may be nonlinear in both physical consequences (i.e. sea level rise or changes in precipitation patterns) and warming.

(5) The regional distribution of changes in radiative forcing is a function of the atmospheric chemistry of the different greenhouse gases and their regional distribution.

Finally, many of the relationships may be time-dependent. Important time-dependencies include:

(1) Stocks accumulate from emissions in a dynamic fashion, and may not follow a simple flow model as decay may be a function of stock levels.

(2) Cumulative global warming depends dynamically on the time path of forcing. Different time paths which arrive at the same point will lead to different levels of warming.

(3) The damages or social welfare losses associated with global warming are time dependent. Since technology is changing over time, and adaptive strategies can be employed, a given level of warming will be likely to create greater damages the earlier that it occurs.

(4) Temporal separation of those who pay the costs of mitigation and those who benefit from it.

The relationship between carbon dioxide emissions and social damages may be better understood by looking at a mathematical expression for the damages associated with a unit of emissions at a particular moment in time. This can be done by characterizing the relationship between emissions (at a point in time) and the time path of social consequences with a series of general functional relationships. Let $E_1(t)$ be the emissions of carbon dioxide at time t, $S_1(t)$ the corresponding stock of carbon dioxide, and S_j the stock of each gas which might decay to carbon dioxide (e.g. methane). Then

$$S_1(t)=\int_0^t [\varphi(\ E_1(\tau)\ )+\Upsilon(\sum_1^m S_j(\tau))]d\tau\ +\ S_1(0) \tag{1}$$

Here, ϕ summarizes the sinks and atmospheric chemistry that lead to declining CO_2 concentrations over time. The Υ function illustrates how other gases decay to carbon dioxide. This equation indicates that the stock of CO_2 at any time is a function of the emission path of CO_2 [1st term of right hand side of equation (1)], the stocks of other gases which may decay to CO_2 [2nd term of equation (1)], and the initial stock of CO_2 [3rd term of equation (1)].

In Equation (2), $F_1(t)$ represents the instantaneous thermal forcing associated with $S_1(t)$. $F_1(t)$ may also be a function of other gases with a similar blocking wavelength, but this effect will be ignored to allow the damage function to be expressed more simply.

$$F_1(t)=\theta(\ S_1(t)\ ) \tag{2}$$

Let W(t) be the total warming at time t, where the summation takes place over k greenhouse gases, then

$$W(t)=\int_0^t \sum_{i=1}^{k} \psi(\ F_i(\tau)\ )d\tau \tag{3}$$

Here, ψ describes the nonlinear effect of total forcing on the rate of temperature change.

A contemporaneous damage function [equation (4)] can be defined as a function of the level of warming, the speed at which warming takes place, the time interval over which the warming takes place and the geographic distribution of warming [this effect is not formally modelled in equation (4)]. The causal relationship between the level of warming and damages requires little explanation, but the relationships between the speed of warming and damages and between the time interval and damages merit further discussion. Both the speed of warming and the time interval are important because they partially determine the ability of natural and economic systems to adjust to warming.

Also, many socioeconomic variables, such as the size of the economy, population and technology are time-dependent. The stocks of each gas are an argument of this damage function, as the stocks may have positive or negative effects independent of the warming effect. For example, carbon dioxide is hypothesized to be associated with a fertilization effect, which stimulates plant growth. This has a positive impact on social welfare, as it would appear as a negative factor in this contemporaneous damage function. Since CFCs deplete stratospheric ozone, they have a negative effect on social welfare and would appear as a positive factor in the contemporaneous damage function.

$$\delta(t) = \omega(\ W(t), \frac{\partial W}{\partial t}, S_1(t), S_2(t) \ldots S_j(t), t) \tag{4}$$

Equation (5) represents the present value of the time stream of damages (including both negative and positive effects). It should be noted that this function is the only relationship which has been presented which contains a discount factor (e^{-rt}).

$$D=\int_t^{\infty} \delta(\tau)e^{-rt}d\tau \tag{5}$$

The marginal present value of the time stream of damages associated with carbon dioxide can be computed as the derivative of equation (6) with respect to the emission of a unit of carbon dioxide at a particular point in time. A derivative of the form $\partial D/\partial E_1(t_1)$ can be found according to the chain given by equation (6).

$$\frac{\partial D}{\partial E_1(t_1)} = \frac{\partial D}{\partial \delta(t)} \frac{\partial \delta(t)}{\partial W(t)} \frac{\partial W(t)}{\partial F_1(t)} \frac{\partial F_1(t)}{\partial S_1(t)} \frac{\partial S_1(t)}{\partial E_1(t_1)} + \frac{\partial D}{\partial \delta} \frac{\partial \delta}{\partial S_1(t)} \frac{\partial S_1(t)}{\partial E_1(t_1)} \tag{6}$$

The most important point that can de deduced from an examination of equations (5) and (6) is that the damages from a unit of emissions at a particular point in time are critically dependent on the emissions that took place previously and on the emissions that will take place some time in the future. The uncertainty associated with the future emissions path is qualitatively different than the uncertainty associated with the scientific relationships, the uncertainty associated with future adaptation to climate change, or the future damages associated with a given level of warming. The reason for this is that the future time path of emissions partially depends on choices of policy makers and is partially determined by exogenous forces (such as the industrial policy of countries that are not part of a global warming agreement). The ability of policy makers to partially determine the time path of emissions implies that it is difficult to characterize the uncertainty associated with the time path of emissions and that any analysis that attempts to measure damages should conduct a sensitivity analysis to determine the range of damages associated with different emission scenarios.

The development of these mathematical formulations of a properly conceived damage function have been included to illustrate how difficult it is to trace the pathway between the emissions of carbon dioxide and the creation of damages at some time in the future. The empirical attempts at estimating damages that are discussed in the following pages do not attempt to specify the complete pathway, because there is not sufficient information to do this. Rather, they make assumptions about the nature of critical parts of the pathway. Therefore, when examining these empirical studies, one should realize that they represent reasonable attempts to characterize a difficult problem, but that other reasonable attempts might vary substantially.

The most recent, and a very comprehensive, study of the potential damage from global warming is a literature survey by Cline (1992). The study focused on damages to the U.S. alone with a doubling of CO_2 concentrations, and also for an extreme case, where CO_2 concentrations increase to the point to raise temperatures 10°C on average. The study estimates damages associated with agriculture, sea level rise, heating and air conditioning, water supply, human health, air pollution in general, ecological damage, and damage in several other minor categories. It is based on the assumption that a doubling of CO_2 concentrations over natural (pre-industrial) levels would lead to 2.5° C in warming and concludes that this will produce annual damages about four times those estimated by Nordhaus (1991). Nordhaus had omitted many damage categories [see Cline (1992) for more on the limitations of the Nordhaus study and Nordhaus (1991) for limitations of Cline (1992)]. Cline suggests that other temperate-zone developed countries would have similar net losses, with losses in developing countries being higher as a percentage of GDP and losses in high latitude countries being less.

The work of Nordhaus is based on a dynamic economic growth model and does not incorporate non-market impacts. A summary of his results is contained in Table 10.2-4.

Cline (1992) further considered that, without "aggressive policy" action, temperatures will rise an additional 7.5°C above the 2.5° rise associated with the CO_2 doubling benchmark (i.e., a 10 degree increase) in 300 years (an assumption based on extrapolating population, fuel use, and income growth, following several analysts). Cline's scenario entails integrating under a nonlinear damage function from 10 back to 2.5 degrees warming. The benefits of avoiding this temperature increase are calculated to be several times larger than the benefits under the 2.5 degree warming scenario.

Although the work by Nordhaus and Cline has been widely discussed as pointing to drastically different levels of damage, their work is actually remarkably consistent. As Reilly and Richards (1993) point out, if one looks at the GDP effects of an effective doubling of atmospheric CO_2 concentrations, both studies point to a loss of world GDP of approximately 1%. While Nordhaus only measures effects that actually influence GDP and produces estimates of approximately one quarter of a percent of GDP, he suggests that taking into account the effects that he did not measure would increase the measure to about 1 to 2% of GDP (Cline 1992). While Cline produces estimates for a more severe increase in CO_2 concentration (10 degree increase in mean global temperature over 300 years), when the doubling of atmospheric CO_2 is examined, and when non-market effects are added to the Nordhaus estimates, the two different reports are relatively consistent.

Reilly and Richards develop estimates of the value of controlling CO_2 emissions in the context of developing a global warming potential index which is based on the relative values of controlling the various greenhouse gases. They base their damage estimates on the agricultural impacts of global warming, which have been estimated by Cain et al. (1992) and then extend these estimates to other economic sectors. They also net out the CO_2 fertilization benefits of increased CO_2, which Reilly and Richards[10] report to equal $1.33 per metric ton of CO_2,

[10] Reilly and Richards (1993) report this CO_2 fertilization effect, which is based on an assumed 20% increase in yields. This increase in yield then becomes an input to the agro-economic model

when calculated with a 2% discount rate ($0.65 at r=5% and $0.43 at r=8%). Their results, which are calibrated to the emissions from the reference plants, are reported in Table 10.2-5.

Table 10.2-4. Nordhaus' (1991) impact estimates for different sectors, for doubling of CO_2

Sectors	Cost (billions of 1981 $)
severely impacted sectors	
farms	10.6 to - 9.7
forestry, fisheries, other	small
moderately impacted sectors	
construction	negative
water transportation	?
energy and utilities	
electricity demand	1.65
non-electric space heat	-1.16
water and sanitary	positive?
real estate	
damage from sea level rise	
loss of land	1.5
protection of sheltered areas	0.9
protection of open coasts	2.8
hotels, lodging, recreation	?
Total central estimate	
national income	6.2
% of national income	0.26

Source: Nordhaus (1991)

described in Cain et al. (1992). The $1.33 per metric ton estimate is an output of this model.

> ***Reilly and Richards develop estimates of the value of controlling CO_2 emissions ... base their damage estimates on the agricultural impacts ... and then extend these estimates to other economic sectors. ... also net out the CO_2 fertilization benefits ...***

The method for extrapolating a damage estimate for a doubling of CO_2 in one hundred years to a per ton of CO_2 emissions is to assume that total damages increase from zero to the estimated level according to some functional form, such as a linear function, quadratic function, logarithmic or exponential function. Then the damages at each point in time are estimated from this extrapolation function, converted to present value terms, and summed. The damages are then divided by total emissions to arrive at the per metric ton estimate. Estimates are then placed in a per kilowatt hour framework by multiplying by the tons of CO_2 per kilowatt-hour of generation for the Southeast and Southwest reference sites, and converting from metric tons.

It is extremely important to note that the Reilly and Richards study is an illustrative study to emphasize a method for defining global potential warming indices. Nonetheless, their results are reported in Table 10.2-5 because they illustrate the sensitivity of damages to the functional form of the damage function and to the choice of discount rate.

A more meaningful measure of the global warming damages associated with a kilowatt-hour of electric generation from gas fuel cycles can be generated by applying this estimate to the more rigorous Cline or Nordhaus estimates of total damages. Reilly and Richards do this, looking at the 1% of GDP damage estimates that can be drawn from both the Cline and Nordhaus studies. Reilly and Richards report that the Nordhaus and Cline studies imply a marginal value of CO_2 control of $3.55 dollars per metric ton if the damage function was quadratic and $5.27 per metric ton if the damage function was linear. This is done using a five percent discount rate (personal communication with Reilly). Calibrations of these values to the reference sites are contained in Table 10.2-6.

It must be strongly emphasized that these results are estimates of damages which do not include the full range of non-market benefits and are based on assumed emissions paths. Actual emission paths could vary substantially from the optimal path (derived from a dynamic optimization model which chooses a path to minimize control costs plus damages) which Reilly and Richards calculate. However, an optimal emissions path is dependent on international policy reducing emissions to the optimal level over time. Obviously, this is not likely to occur in the short-run, and such an international consensus is not likely to occur for some

Table 10.2-5. Illustration of the sensitivity of global warming damages from natural gas use (dollars per kWh) to the choice of functional form and discount rate

Marginal Value of CO_2 Control ($/metric ton)[a]	Both Reference Sites (642 tons of CO_2 emissions /GWh)
12.72[b,d]	0.0082
10.9[c,d]	0.0070
3.55[b,e]	0.0023
5.27[c,e]	0.0034
2.0[b,f]	0.0013
3.45[c,f]	0.0022

[a] marginal value of CO_2 control taken from Reilly and Richards (1993, p.55) and converted to 1989 dollars
[b] quadratic formulation
[c] linear formulation
[d] discount rate of 0.02
[e] discount rate of 0.05
[f] discount rate of 0.08

Reilly and Richards report that the Nordhaus and Cline studies imply a marginal value of CO_2 control of $5.1 dollars per metric ton if the damage function was quadratic and $6.1 per metric ton if the damage function was linear.

time. In particular, if large developing countries such as China and India fuel their industrial expansion by burning coal, the actual concentration of atmospheric CO_2 will increase much more quickly than the optimal path postulated by Reilly and Richards. In addition, the path chosen by Cline and Nordhaus (doubling of atmospheric CO_2 over the next one hundred years) does not really reflect a likely path, but a benchmark chosen by scientists to compare the effects of CO_2 emissions based on a standard set of assumptions about changes in atmospheric concentration of CO_2. Not only could the actual path be different from this doubling scenario, but the warming associated with a doubling could be more or less than that assumed by Nordhaus and Cline.[11]

Table 10.2-6. Marginal present value of CO_2 control in \$/kWh (assumes 5% discount rate)

	Both Reference Sites (642 tons of CO_2 emissions /GWh)
Quadratic damage function	\$0.0029
Linear damage function	\$0.0039

Source: Calculations by authors based on Reilly and Richards' (1993) use of Cline (1992) and Nordhaus' (1991) damage estimates of 1% of GDP from a doubling of CO_2 concentration in the atmosphere.

...these results are estimates of damages which do not include the full range of non-market benefits and are based on assumed emissions paths.

Since all estimates are based on a particular time path of emissions, and since so few studies have taken place, it is difficult to make a quantitative assessment of the sensitivity of damages to the time path of emissions. This is critically important to policy for several reasons. First, emissions might prove to be substantially different than the paths which are assumed in these economic studies. Second policy makers must know how much more valuable it is to control emissions today, versus waiting to control them at some period in the future. Finally, the value of reducing CO_2 emissions will also depend on the time paths of reducing emissions of other greenhouse gases, as well as the time path of emissions of CO_2.

In summary, it should be noted that the estimates of the value of controlling carbon dioxide emissions have been included in this report for illustrative purposes and to summarize the published estimates of damages. While there is considerable uncertainty surrounding these estimates, they have been reported to reflect the work that has been published to date. A better understanding of the benefits and damages

[11] For example, studies by Kelly and Wigley (1992) argue that the actual warming associated with a doubling of atmospheric CO_2 would be less than the 2.5°-3° C assumed by Nordhaus and Cline. However, this should not be construed to imply that global warming is unimportant. Both sets of authors believe that potential global climate change is a serious issue which must be addressed.

associated with global warming awaits the measurement of non-market impacts and the implementation of studies which show the sensitivity of damage estimates to different assumptions about the time paths of emissions. In addition, better knowledge of scientific relationships is required to have a better understanding of economic damages. Since decisions to emit CO_2 do not account for these damages they are externalities.

10.3 EFFECTS OF SULFUR DIOXIDE (SO_2) ON HEALTH

The estimated SO_2 emissions from our baseline natural gas power plants are negligible. Thus, impacts and damages are likewise estimated to be negligible.

10.4 FERTILIZATION BENEFITS OF NO_X EMISSIONS

10.4.1 Deposition of Nitrogen

Nitrogen oxides are emitted during the operation of an natural gas-fired power plant. These emissions are primarily nitrogen oxide (NO) with lesser quantities of nitrogen dioxide (NO_2). Emissions of NO_x from the Southeast Reference power plant are each estimated to be 0.499 tons/GWh (46.9 grams/second).

Once these pollutants are emitted into the atmosphere they may react chemically with oxidizing species such as O_3, OH and H_2O_2 to form a strong acid, HNO_3. This compound may be deposited on the soil both directly by dry deposition and by removal in rainfall. This deposition results in additions of nitrogen (N) to soils. The rate of wet deposition is highly variable from both a temporal and geographic standpoint. Some of the pollutants may be transported long distances and since some of the reactions occur slowly in the atmosphere deposition can occur over a very wide area. Regional scale modeling is therefore required to estimate more precisely the deposition pattern of a single power plant. This regional modeling is more complex than the local-scale modeling undertaken for this study and is beyond the scope of this study. No estimates of the increases in N were calculated.

10.4.2 Benefits of Crop Growth Increases from Nitrogen Deposition

The final Integrated Assessment of the NAPAP program (NAPAP 1991) calculated benefits associated with a very large (viz., 50%) increase or decrease in passive sources of N crop fertilization in the eastern half of the United States. A 50% increase in passive sources of N increased total welfare by $241 million annually for the 31 eastern state region. Furthermore, even assuming the full $241 million annual benefit, this value is, by comparison, ~10% of the estimated

$2.4 billion damage estimates associated with current ambient ozone levels on crops whose total value is ~$50 billion annually. The annual benefit would be less than 0.5% of the total value of the crops. Since this benefit is estimated as occurring with a 50% increase in passive sources of N and since a power plant would contribute far less than that, we take the benefits of N deposition to be very small.

10.4.3 Impacts: Increases in Forest Growth

Response functions do not exist upon which to base an evaluation of N fertilization of forests on a large scale. As a result, the discussion of increases in forest growth is primarily qualitative in nature.

...possibility that atmospheric N dispersion is at least partially benefitting large acreages of N-deficient forests throughout the United States...

Atmospheric deposition contains nitrogen which, as an essential plant nutrient, has the theoretical potential for beneficial as well as detrimental effects on forest nutrient status. Typical N deposition values (5-25 kg/ha/yr) are within the range of forest N growth increments (1-5 kg/ha/yr; Cole and Rapp 1981) leaving the possibility that atmospheric N deposition is at least partially benefitting large acreages of N-deficient forests throughout the United States (Shriner et al. 1990). Recent results suggest N deposition may be excessive in some forests, especially high-elevation forests in the eastern United States. In these systems, inputs in excess of N demand result in nitrate leaching of soils, soil acidification, and associated depletion of cation nutrients such as calcium and magnesium. The N deposition rates shown to cause high rates of NO_3 leaching tend to be on the order of 20 kg/ha/yr or more (Van Miegroet and Cole 1984, Ulrich et al. 1980). Because of the long life cycles of forest trees, short-term benefits of N deposition may be offset by longer-term leaching losses of cation nutrients from forest soils (Brandt 1987, Abrahamsen 1980). While benefits would be expected to be maximized in nutrient poor, low producing sites where N is limiting, not all plants in deficient soils seem to respond (Elkey and Ormrod 1981).

Mixed hardwood forests of east Tennessee District 6 are characterized as being typically N-limited (Johnson and Van Hook 1989), meaning that atmospheric inputs are an important component of their N economy. Research on Walker Branch Watershed, Tennessee, indicates that this mixed hardwood forest received approximately 40% of the N requirement for the annual woody growth increment (stem growth) from atmospheric deposition. This inorganic N input represents 5-10% of the total ecosystem requirement for N on an annual basis (Lindberg et al. 1986).

10.4.4 Benefits of Increase in Forest Growth from NO_x Emissions

No quantitative estimates are possible, but any increase in forest growth as a result of a power plant's NO_x emissions appears to be small, and limited to nitrogen deficient soils.

10.5 EFFECTS OF NO_x (AND PARTICULATE MATTER) ON VISIBILITY

One of the more common effects of air pollution is visibility reduction due to the absorption and scattering of light by airborne liquid and solid materials. Two classes of visibility impairment are atmospheric discoloration and visual range reduction (increased haze).

NO_x emissions are converted in the atmosphere to the reddish-brown gas, nitrogen dioxide. This gas may discolor the plume. Particulate emissions and secondary aerosols also discolor the atmosphere. Increased haze is caused principally by primary particulate emissions and secondary aerosols, such as sulfates (EPA 1988).

Two distinct kinds of atmospheric conditions are associated with the two classes of visibility impairment. Atmospheric discoloration is greatest during periods of stable, light winds that occur after periods of nighttime transport (EPA 1988). These conditions can contribute to maximum plume coloration. However, since the plume would tend to remain intact during such conditions, discoloration would generally be limited to a shallow vertical layer. The plume might be perceptible but the general atmospheric clarity would not be impaired.

Two distinct kinds of atmospheric conditions are associated with the two classes of visibility impairment ... Atmospheric discoloration ... decreased visual range ...

Conversely, increased general haze (decreased visual range) is greatest during light wind, limited mixing or stagnation conditions after daytime transport (EPA 1988). The conversion of gaseous precursor emissions to secondary aerosol is more rapid under these conditions and an increased haze and loss of clarity in landscape features would result.

Visually significant points of interest near the Southwest Reference site include the Bisti and De-na-zin Wilderness Study Areas, Chaco Culture National Historical Park, Shiprock, and Mesa Verde. An annual average visual range of 80 miles (130 kilometers) was reported for these areas for 1980 (DOI 1982).

Visually significant points of interest near the Southeast Reference site include the Great Smokey Mountains National Park, Cherokee National forest and Nantahala National forest. The National Park Service has conducted visibility monitoring at the Look Rock, Tennessee monitoring station. The annual average visual range at the Great Smoky Mountains National Park was reported to be 55 kilometers during the period 1980 to 1983 (Reisinger and Valente 1985).

Although regional haze is the most extensive and serious form of visibility impairment throughout the United States, it is caused by multiple sources located throughout a region. A single emission source may contribute to such a problem but is generally not the sole (or even major) contributor (EPA 1988). Regional haze analysis requires more complicated regional dispersion models than were available for this study.

Section 10.6 in ORNL/RFF (1994b) discusses studies by Chestnut and Rowe (1990), McClelland et al. (1990), Decision Focus (1990) and NERA (1993) that attempt to estimate the value of changes in visual range. The impacts of reduced visual range affect both residential and recreational values.

While the studies are interesting, they are too imprecise to include in our final tabulation of externalities. Since we do not model reduction in visual range, we do not use the unit values of NERA and others.

The impacts of reduced visual range affect both residential and recreational values...

10.6 EFFECTS OF NO_X ON HEALTH

10.6.1 Emissions and Changes in Concentration of NO_x

When natural gas is burned, nitrogen oxides (NO_x) are formed. These compounds are primarily nitric oxide (NO), with much smaller quantities of nitrogen dioxide (NO_2). Nitrogen oxide is formed from the oxidation of nitrogen in natural gas and the thermal fixation of nitrogen in the combustion air. NO_x emissions from the reference power plants were estimated to be 0.499 tons/GWh (1,630 tons/year or 46.9 grams/second).

The ground-level pollutant concentrations of NO_x that could be expected to occur as a result of the operation of the 500 MW reference natural gas-fired power plant were predicted with an atmospheric dispersion model. Using stack information (i.e., stack diameter, exit gas velocity, and exit gas temperature), the model predicts the release height of pollutants to the atmosphere. Wind direction, wind speed and other meteorological measurements made in the vicinity of the stack are used to predict the dimensions of the plume (i.e., its vertical and horizontal width) and its travel path downwind. The model calculates pollutant concentrations at receptor locations that are defined by a system of grid points. The Environmental Protection Agency Industrial Source Complex Long-Term (ISCLT) model (EPA 1986) was used to predict the annual average ground-level concentrations of NO_x expected to occur as the result of operating the reference power plant. A description of the computer modeling is presented in ORNL/RFF (1994a, Part I), and results specific to the natural gas fuel cycle analysis are presented in Appendix C.

10.6.2 Impacts of NO_x on Health

Epidemiological studies have generally not found significant effects of nitrogen dioxide at ambient levels on morbidity endpoints. The primary concern about NO_2 lies in its role as a precursor to ambient ozone (see Section 10.15). One recent study that does find a significant direct effect of NO_2 on health is Schwartz and Zeger's (1990) analysis of the daily effects of air pollution on students beginning nursing school in Los Angeles in the early 1970's. Most effects of NO_2 on health were insignificant, except for the effect of NO_2 on daily incidence of phlegm.[12]

Table 10.6-1 shows the dose-response function based on the Schwartz and Zeger (1990) study. For application to this study, the statistical relationship between the daily incidence of phlegm and 24-hour average NO_2 concentration reported in their study has been linearized, expressed in annual terms, and reworked to calculate population effects instead of individual probabilities of experiencing effects. The uncertainty of the coefficient is assumed to be characterized by a normal distribution with a mean and standard deviation based on those reported in the original studies.

A 95% confidence interval of between 5.2 and 405 phlegm-days, with a mean of 205 phlegm-days, is estimated within 50 miles of the Southeast plant. Extending the analysis out to 1,000 miles, this interval is 40 to 3,149 with a mean of 1,595. The corresponding impacts for the Southwest reference environment range from 0.2 to 15 phlegm-days (mean 7.6) within 50 miles, or from 2.1 to166 (mean 84) phlegm-days within 1,000 miles.

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[12] Even this result may be obscured by the confounding of the NO_2 effect by O_3 exposure. Notwithstanding, it was the best available study. A more recent report of the effects on lower respiratory tract disease in children is from the U.S. Environmental Protection Agency's (1991) external review draft of the Air Quality Criteria for Oxides of Nitrogen, pp. 14-35 to 14-43.

Table 10.6-1. Linearized dose-response function for effects of NO_2 on morbidity

Schwartz and Zeger (1990):

Δ phlegm-days per year = C_{phlegm} Pop ΔNO_2

where

ΔNO_2 = Change in population-weighted annual average NO_2 concentration

Pop = Total population over which population-weighted NO_2 concentration is determined

C_{phlegm} = Normal (mean=0.00xx, standard deviation=0.00xx)

10.6.3 Damages to Health from NO_x Exposure

No studies have ever asked for the willingness-to-pay to avoid a phlegm-day. Hence, there are no estimates of damages. However, this is *not* to say that they are zero.

10.7 EFFECTS OF PARTICULATES ON MORTALITY[13]

10.7.1 Emissions and Changes in Concentration of Particulates

Particulates is a term used to describe dispersed airborne solid and liquid particles. The composition and emission levels of particulate matter composition and emission levels from gas-fired turbines are a complex function of turbine

[13] Our air dispersion modeling does *not* account for the formation of acid aerosols from NO_x emissions. Acid aerosols are part of PM_{10}. Thus, our estimates of PM_{10} externalities underestimates them. A fraction of the NO_x emissions are transformed into nitrates. It is complicated to take these acid aerosols into account. Estimates must account for long-range atmospheric chemistry (these aerosols are dispersed great distances); ozone, as well as nitrate, formation from NO_x; gaseous versus aerosol phases of the nitrates; and wet and dry deposition. Furthermore, the dose-response functions for acid aerosols are unreliable. Studies are inconclusive about the role of acid aerosols in the overall PM_{10} dose-response relationship. Although this analysis was beyond the scope of this study, it is undoubtedly a major priority for future research. Several recent studies, including that of our European colleagues in this project, indicate that acid aerosol impacts (particularly sulphate aersols) may be the most important of those that can be quantified.

design (EPA 1988). Emission levels are also a function of the particulate control device employed. Steam injection is used to control particulate emissions for the power plant at each reference site. Total particulate emissions from the reference power plants were estimated to be 0.021 tons/GWh. The primary interest in particulate matter centers around the fraction known as PM_{10}, which is particulate matter with an aerodynamic diameter less than 10 micrometers.[14]

The ground-level pollutant concentrations of total suspended particulates (TSP) and PM_{10} that could be expected to occur as a result of the operation of the 500 MW reference gas-fired power plant were predicted using atmospheric dispersion modeling. Using stack information (i.e., stack diameter, exit gas velocity, and exit gas temperature), the model predicts the release height of pollutants to the atmosphere. Wind direction, wind speed and other meteorological measurements made in the vicinity of the stack are used to predict the dimensions of the plume (i.e., its vertical and horizontal width) and its travel path downwind. The model calculates pollutant concentrations at receptor locations which are defined by a system of grid points.

The Environmental Protection Agency Industrial Source Complex Long-Term (ISCLT) model (EPA 1986) was used to predict the annual average ground-level concentrations of particulates expected to occur as a result of the operation of the power plant. A description of the computer modeling is presented in ORNL/RFF (1994a).

10.7.2 Impacts of Particulates on Mortality

This section describes the estimates of impacts with, and without, a dose-response threshold. The reference case is with a threshold of 30 $\mu g/m^3$ [refer to the discussion in Paper 5 of ORNL/RFF (1994a)]. The existence of a threshold is uncertain, however, so that we also offer an analysis without a threshold.

These studies found effects and similar dose-response functions at very high concentrations and at ambient concentrations currently found in U.S. cities, even cities in attainment of the National Ambient Air Quality Standards (NAAQS) for particulates.

Over the last few decades, numerous epidemiologic studies have reported associations between daily concentrations of ambient particulate matter and mortality among the general population in various cities. These studies found effects and similar dose-response

[14] More recently, interest is focusing on the finer particulates, $PM_{2.5}$.

functions at very high concentrations and at ambient concentrations currently found in U.S. cities, even cities in attainment of the National Ambient Air Quality Standards (NAAQS) for particulates. Dose-response functions have been determined for various measures of particulates, but the specific causative agent and biological mechanism are unclear at this time.[15] However, it is important to note that using the daily time-series studies, PM_{10} or TSP is consistently associated with mortality across a wide range of climates, seasons, covariates and populations. Overall, the evidence is fairly compelling that increases in particles which contribute to PM_{10} mass are associated with increased risk of mortality. Another set of studies has found consistently significant associations between annual particulate measures and annual mortality rates over a cross section of cities for various years. The former set of studies is more convincing, however, because studying mortality in a given city over time has the effect of controlling for many of the possible intervening variables associated with comparing data from one city with data from another city.

Table 10.7-1 provides a summary of this research [see ORNL/RFF (1994a, Part III)] for nine mortality studies, converting the results of each to common units for comparability. These conversions include expressing the pollutant in terms of 24-hour average PM_{10} concentrations using well-known (if imperfect) conversion ratios and expressing the estimated coefficient for the linear dose-response function in terms of the percentage change in mortality related to a 10 $\mu g/m^3$ change in PM_{10}. None of these studies estimate by how much mortality is premature, although some studies rule out the possibility that the observed mortalities result in only few days of life shortening.

Incorporation of a Dose-Response Threshold of 30 $\mu g/m^3$

The following discussion details how we incorporate the consideration of a threshold into the assessment of health impacts from particulate air pollution. We assume a threshold of 30 $\mu g/m^3$ annual average PM_{10} for observing health responses to particulate matter, except for adult chronic bronchitis for which we assume that effects are observed only if the PM_{10} concentration exceeds 100 $\mu g/m^3$ for more than 10 days each year.

In the absence of a threshold, the input to the linear dose-response equations is simply the sum of the exposure level times the population for all geographical areas in the reference environments. However, when the threshold is considered, the required input is the product of the exposure level and the population summed over only those populations exposed to baseline levels above the threshold. This

[15] Refer to Section 4.7.3 of ORNL/RFF (1994b) for a concise, general discussion of the use of dose-response relationships to estimate health impacts; and to Part III (Paper 5) of the Analytical Methods and Issues Document (ORNL/RFF 1994a) for more discussion of the scientific evidence on the effects of particulate matter on human health, including a summary of the most contentious issues.

requires information about the variation in baseline levels throughout the reference areas.

To assess the baseline particulate levels for the population residing in Metropolitan Statistical Areas (MSAs) in the two reference environments, we use Table 5-6 in the EPA National Air Quality & Emission Trends Report, 1992 which lists the population for each of the MSAs in the country, their annual average PM_{10} concentration, and the second highest 24-hr average PM_{10} concentration over the year.

We then aggregate the MSA information by State to determine the fraction of the State's urban population that was above the threshold in 1992. There is considerable variation from State to State, including neighboring States. The fraction above the 30 $\mu g/m^3$ threshold varies from 0% to 100% across all 50 States. The fraction for New Mexico, where the Southwest Reference plant is located, is 84%. The MSAs in these States significantly exceed the national fraction, which is calculated to be 55%.

To assess baseline concentrations for rural (Non-MSA) populations, we turn to monitoring data from the Aerometric Information Retrieval System we find no compelling evidence that the concentrations at these stations are any higher or lower than those in surrounding MSAs. Roughly one-half of the stations recorded annual averages above the 30 $\mu g/m^3$ threshold. For convenience, we assume the baseline conditions of the MSAs and rural areas to be equivalent. Any error introduced by doing so is limited by the small fraction (22%) of the population that resides in areas not located in MSAs.

We divide the area within 1,000 miles of each plant into polar grid cells where each grid cell is defined by a directional sector and a range in the distance from the plant. For each grid cell, we determine the input to the dose-response functions, which are linear above the threshold, calculating the product of the population, the fraction of the population above the threshold, and the change in concentration (determined from the air dispersion modelling). We sum over all grid cells within 1,000 miles to calculate the impacts for each reference environment.

The fraction of the population above the threshold is assigned to each grid cell in the following manner. If the grid cell falls entirely within a State, the fraction for that State is used. If the grid cell covers more than one State, the average fraction is used, taking into account the amount of the grid cell's area falling into each State. Implicitly, this approach assumes that the population above the threshold is uniformly dispersed across all populations in each State.

For the local area within 50 miles of each plant, we do not use the fraction for the State in which the plants reside. Instead, to increase specificity, we use the fraction of the monitoring stations within a 50 mile radius of the plant that recorded levels above the threshold. For the Southwest site, the one monitor within the 50 mile radius recorded levels below the 30 $\mu g/m^3$ threshold. We therefore assume that no PM_{10} health damages occur in the Southwest site within 50 miles of the plant. Within 50 miles of the Southeast plant, 9 of 13 monitoring stations, or 69%, recorded levels exceeding the threshold. We assume that 69% of the population within the local area are exposed to levels exceeding the threshold. The results are in bold in Tables 10.7-2 and 10.7-3.

A more precise approach for handling this threshold issue might involve using counties and/or cities as the units of analysis. Information from monitoring stations in or near these areas could be used to determine whether the population

Table 10.7-1. Estimates of the mortality effects of a change in PM_{10}

City	Author	Original measure	Mean PM_{10} equivalent	Estimated percent change in mortality due to 10 $\mu g/m^3$ change in PM_{10}: Mean	Lower and upper bounds*	
London, England	Mazumdar et al. (1982); Ostro (1984, 1985); Schwartz and Marcus (1986, 1990)	BS	80	0.31	0.29	0.33
Ontario, Canada	Plagiannakos and Parker (1988)	Sulfate	48	0.98	0.49	1.47
Steubenville, Ohio	Schwartz and Dockery (1991)	TSP	61	0.64	0.44	0.84
Philadelphia, Pennsylvania	Schwartz and Dockery (1991)	TSP	42	1.20	0.96	1.44
Santa Clara, California	Fairley (1991)	COH	37	1.12	0.73	1.51
Los Angeles, California	Shumway et al. (1988)	KM	65	2.31	0.9	2.7
100 U.S. cities	Ozkaynak and Thurston (1987)	Sulfate	44	1.49	0.92	2.06
117 U.S. cities	Evans et al. (1984)	Sulfate	53	0.721	0.37	1.10
197 U.S. cities	Lipfert et al. (1988)	Sulfate	38	1.09	0.55	1.64

Note: BS = British Smoke; TSP = Total Suspended Particulates; COH = Coefficient of Haze.
*Based on plus and minus one standard deviation from the mean value.

in the area exceeds the threshold. We decide against this more rigorous approach, however, because the uncertainty about the thresholds overwhelms the benefits of greater precision about the size of the population.

Tables 10.7-2 (a) and (b) show the estimated total number of premature deaths for the Southeast Reference environment, when confining the analysis to within 50 and within 1,000 miles of the plant, respectively. The low and high estimates, referring to the 5th and 95th percentiles, solely reflect the uncertainty of the dose-response coefficients. Additional results are presented for the Schwartz and Dockery studies in the original emissions units (TSP). For the Southeast Reference environment within 50 miles of the plant the lowest 5th percentile estimate of the group of dose-response relationship was an expected increase of 0.00099 deaths while the highest 95th percentile estimate was 0.03 deaths. In the absence of a threshold, damages are about 50% greater. Damages out to 1,000 miles are approximately eight times larger than damages within 50 miles for both threshold assumptions. Tables 10.7-3 (a) and (b) provide the same information for the Southwest Reference environment. The Schwartz and Dockery (1991a) dose-response relationship is used in the final tabulated results.

Table 10.7-2a. Particulates—mortality: deaths per year for the Southeast site [for 0-50 miles][1]

Study	Low	Mid	High
Schwartz and Marcus (1990)	0.0091	0.0103	0.0115
	0.0063	**0.0071**	**0.0079**
Plagiannakos and Parker (1988)	0.0027	0.0149	0.0272
	0.0018	**0.0103**	**0.0187**
Schwartz and Dockery (1991a)-PM_{10}	0.0047	0.0097	0.0147
	0.0033	**0.0067**	**0.0102**
Schwartz and Dockery (1991a)-TSP	0.0026	0.0054	0.0081
	0.0018	**0.0037**	**0.0056**
Schwartz and Dockery (1991b)-PM_{10}	0.0123	0.0183	0.0242
	0.0085	**0.0126**	**0.0167**
Schwartz and Dockery (1991b)-TSP	0.0068	0.0101	0.0133
	0.0047	**0.0069**	**0.0092**
Fairley (1990) (1991)	0.0073	0.017	0.0268
	0.005	**0.0117**	**0.0185**
Schumway et al. (1988)	0.0249	0.0351	0.0454
	0.0171	**0.0242**	**0.0313**
Evans et al. (1984)	0.00143	0.011	0.0205
	0.00099	**0.0076**	**0.0141**

[1]Numbers in bold are with a threshold.

Table 10.7-2b. Particulates—mortality: deaths per year for the Southeast site [for 0-1,000 miles][1]

Study	Low	Mid	High
Schwartz and Marcus (1990)	0.071 **0.046**	0.080 **0.052**	0.089 **0.057**
Plagiannakos and Parker (1988)	0.021 **0.013**	0.115 **0.074**	0.210 **0.136**
Schwartz and Dockery (1991a)-PM_{10}	0.037 **0.024**	0.075 **0.049**	0.114 **0.074**
Schwartz and Dockery (1991a)-TSP	0.020 **0.013**	0.041 **0.027**	0.063 **0.040**
Schwartz and Dockery (1991b)-PM_{10}	0.095 **0.062**	0.142 **0.091**	0.188 **0.121**
Schwartz and Dockery (1991b)-TSP	0.053 **0.034**	0.078 **0.050**	0.103 **0.067**
Fairley (1990) (1991)	0.056 **0.036**	0.132 **0.085**	0.208 **0.134**
Schumway et al. (1988)	0.193 **0.124**	0.272 **0.175**	0.352 **0.227**
Evans et al. (1984)	0.011 **0.007**	0.085 **0.055**	0.159 **0.102**

[1]Numbers in bold are with a threshold.

Table 10.7-3a. Particulates—mortality: deaths per year for the Southwest site [for 0-50 miles][1]

Study	Low	Mid	High
Schwartz and Marcus (1990)	0.00065 **0**	0.00073 **0**	0.00082 **0**
Plagiannakos and Parker (1988)	0.00010 **0**	0.00055 **0**	0.00100 **0**
Schwartz and Dockery (1991a)-PM_{10}	0.00017 **0**	0.00036 **0**	0.00054 **0**
Schwartz and Dockery (1991a)-TSP	0.00010 **0**	0.00020 **0**	0.00030 **0**
Schwartz and Dockery (1991b)-PM_{10}	0.00046 **0**	0.00068 **0**	0.00090 **0**
Schwartz and Dockery (1991b)-TSP	0.00025 **0**	0.00037 **0**	0.00049 **0**
Fairley (1990) (1991)	0.00027 **0**	0.00063 **0**	0.00099 **0**
Schumway et al. (1988)	0.00092 **0**	0.00130 **0**	0.00168 **0**
Evans et al. (1984)	0.00005 **0**	0.00041 **0**	0.00076 **0**

[1]Numbers in bold are with a threshold.

Table 10.7-3b. Particulates—mortality: deaths per year for the Southwest site [for 0-1,000 miles][1]

Study	Low	Mid	High
Schwartz and Marcus (1990)	0.0072 **0.00473**	0.00813 **0.00533**	0.00906 **0.00594**
Plagiannakos and Parker (1988)	0.00108 **0.00071**	0.00611 **0.00401**	0.01113 **0.0073**
Schwartz and Dockery (1991a)-PM_{10}	0.00194 **0.00127**	0.00399 **0.00262**	0.00604 **0.00396**
Schwartz and Dockery (1991a)-TSP	0.00107 **0.00070**	0.00219 **0.00144**	0.00332 **0.00218**
Schwartz and Dockery (1991b)-PM_{10}	0.00505 **0.00331**	0.00749 **0.00492**	0.00993 **0.00652**
Schwartz and Dockery (1991b)-TSP	0.00278 **0.00182**	0.00412 **0.00270**	0.00546 **0.00358**
Fairley (1990)	0.00298 **0.00196**	0.00698 **0.00458**	0.01098 **0.0072**
Schumway et al. (1988)	0.01019 **0.00669**	0.01440 **0.00945**	0.0186 **0.01221**
Evans et al. (1984)	0.00059 **0.00039**	0.00449 **0.00295**	0.0084 **0.00551**

[1]Numbers in bold are with a threshold.

The Schwartz and Dockery (1991a) study is used for valuation purposes for two reasons: (1) this study was conducted in Steubenville Ohio, which is more similar to our southeastern reference environment than are cities where other studies were conducted; and (2) this study and its companion study for Philadelphia are the most recent and highest quality studies. The original results for TSP are used to avoid reliance on the PM_{10}/TSP conversion ratio.

The Schwartz and Dockery (1991a) study is used for two reasons: (1) this study was conducted in Steubenville, Ohio, which is more similar to our Southeast Reference environment... ...and (2) most recent and highest quality studies...

Using this study, and assuming the existence of the threshold at 30 μ/m^3, a 95% confidence interval of between 0.0018 and 0.0056 premature deaths, with a mean of 0.0037 deaths, is estimated within 50 miles of the Southeast plant. Extending the analysis out to 1,000 miles, this interval is 0.013 to 0.040 with a mean of 0.027. The corresponding impacts for the Southwest reference environment are zero within 50 miles, or from 0.00070 to 0.00218 (mean 0.00144) premature deaths within 1,000 miles.

10.7.3 Mortality Damages from Particulates

While there is much uncertainty over exactly how particulates raise risks of death, it is clear that risk factors include being old and having respiratory or cardiovascular disease. Using the most convincing evidence on the effects of particulates on premature mortality (Schwartz and Dockery 1991), the effects on older people are clearly dominant, with relative risks of 1.09 for people 65 years and older and 1.02 for people younger than 65.[16] At the same time, people with chronic obstructive pulmonary disease (COPD) are by far the most at risk, with a relative risk of 1.19 versus relative risks of 1.11 for those with pneumonia and 1.09 for those with cardiovascular disease. Deaths from these diseases are overwhelmingly concentrated in elderly people. For instance, 86% of deaths from pneumonia occur in people 65 or older, and virtually all deaths from emphysema would occur in this age group.

The risk factors for premature death from exposure to particulates imply that the WTP for reduced risks of death of older people with chronic illness is an appropriate measure of damage. As a fairly large percentage of younger people will eventually have chronic respiratory or heart disease (5% or more with COPD, over 7% with heart disease) and also find themselves at risk of premature death from particulate exposure, it would also be appropriate to use a measure of WTP for future reduced risks of death taken from younger people and add this to the WTP of older people with chronic illness. There are no studies providing such measures.

Another issue concerns the degree to which lifetime is reduced by particulate exposure. If those who are dying prematurely would have died in, say, another week in any event, the benefits of reducing particulates would be low or even trivial. Schwartz and Dockery (1991a,b) rule out such trivial benefits, but the literature offers no guidance on the years "saved" by reducing particulate concentrations.

This leaves us with two approaches to measure damages associated with additional premature mortality in the population from exposure to concentrations of particulates: (i) multiplying estimates of the average value of a statistical life (from Fisher, Chestnut, and Violette 1989) by the change in the number of premature deaths; and (ii) multiplying the value of a statistical life associated with

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[16] Relative risks of 1.0 would imply no excess risk. Relative risks of 1.09 imply that risks are 9% higher than for people not exposed to particulates who are 65 years old or older.

a disease with a latency period by the change in the number of premature deaths using Mitchell and Carson (1986). We settle on using Approach (i) for the reasons discussed below.

Approach (i) is based on scenarios involving accidental death and is taken from prime-age adults. As discussed in ORNL/RFF (1994a, Part IV), it will likely overestimate WTP for the case considered in this section. In this sense, approach (ii) is attractive because, although it also uses a study that polls prime age adults, the study incorporates a latency period, with the implication that a relatively small number of life-years will be saved (since for disease with a long latency, people are usually old when they die). However, this study examines WTP from death by cancer, not from a respiratory or heart disease. Values may differ by cause of death.

For approach (i), we use values of a statistical life (VSL) estimates ranging from $1.6-$8.5 million (with a mid-value estimate of $3.5 million). For the purposes of the Monte Carlo simulation, a lognormal distribution with a median of $3.7 million and geometric standard deviation (GSD) of 1.53 is assumed for the uncertain VSL estimate.

Though approach (ii) is conceptually appealing, we do not use it for the calculation of particulate damages because the mortality risks associated with particulates are well outside of the range of risks investigated by Mitchell and Carson. In their contingent valuation (CV) study, they examined the relationship between VSL estimates and risk reductions of a cancer-causing substance -- trihalomethane -- in drinking water. The risk reductions considered in their study were considerably higher (0.04/100,000 to 9/100,000) than the risks from particulates in this study (maximum of 0.005/100,000). Applying the highly non-linear exponential equation presented in their study to the Southwest Reference environment results in VSL estimates of $35 million. Compare this to the VSL estimate of $180,000 that Mitchell and Carson find for a 8/100,000 risk reduction from baseline cancer risk levels in the general population.[17] In addition to the inability to credibly extrapolate from the results of their study, we are further prohibited from using their study because they examined willingness to pay to reduce risk rather than the willingness to pay for increased levels of risk, which would be more appropriate for our study.

Based on the Schwartz and Dockery (1991a) study, Tables 10.7-4 (a) and (b) provide low, mean, and high estimates of the welfare loss associated with excess deaths resulting from the change in TSP in the Southeast Reference environment. If there is no dose-response threshold, then a 95% confidence interval on damages ranges from 0.0021 to 0.014 mill/kWh within 50 miles, or from 0.017 to 0.11 mill/kWh within 1,000 miles of the plant. Tables 10.7-5 (a) and (b) present the same information for the Southwest Reference environment, for

[17] VSL falls with greater reductions in risks, although the WTP for a given risk reduction rises with the size of the risk reduction, but at a diminishing rate, according to models posited by Mitchell and Carson.

which the damages range from 0.000079 to 0.00048 mill/kWh within 50 miles, and from 0.00091 to 0.0055 mill/kWh within 1,000 miles of the plant. Figures 10.7-1 (a) and (b) are plots of the cumulative density function (CDF) for total damages for the Southeast Reference environment.

With a dose-response threshold of 30 $\mu g/m^3$, then a 95% confidence interval on damages ranges from 0.0015 to 0.0093 mills/kWh within 50 miles, or from 0.011 to 0.069 mill/kWh within 1,000 miles of the plant. Tables 10.7-5 (a) and (b) present the same information for the Southwest Reference environment, for which there are no damages within 50 miles, and from 0.0006 to 0.0036 mill/kWh within 1,000 miles of the plant.

Table 10.7-4a. Particulates-mortality: damages per year (in thousands of 1989 dollars) for the Southeast site [for 0-50 miles][1]

This table assumes impacts based on Schwartz and Dockery (1991a)-TSP	VSL method		
	Low	Mid	High
Total pathway damages	7.0 **4.8**	22 **15**	45 **31**
Total pathway damages (mills/kWh)	0.0021 **0.0015**	0.0066 **0.0046**	0.014 **0.0093**

[1] Numbers in bold are with threshold.

Table 10.7-4b. Particulates—mortality: damages per year (in thousands of 1989 dollars) for the Southeast site [for 0-1,000 miles][1]

This table assumes impacts based on Schwartz and Dockery (1991a)-TSP	VSL method		
	Low	Mid	High
Total pathway damages	55 **35**	170 **110**	350 **230**
Total pathway damages (mills/kWh)	0.017 **0.011**	0.052 **0.033**	0.11 **0.069**

[1] Numbers in bold are with threshold.

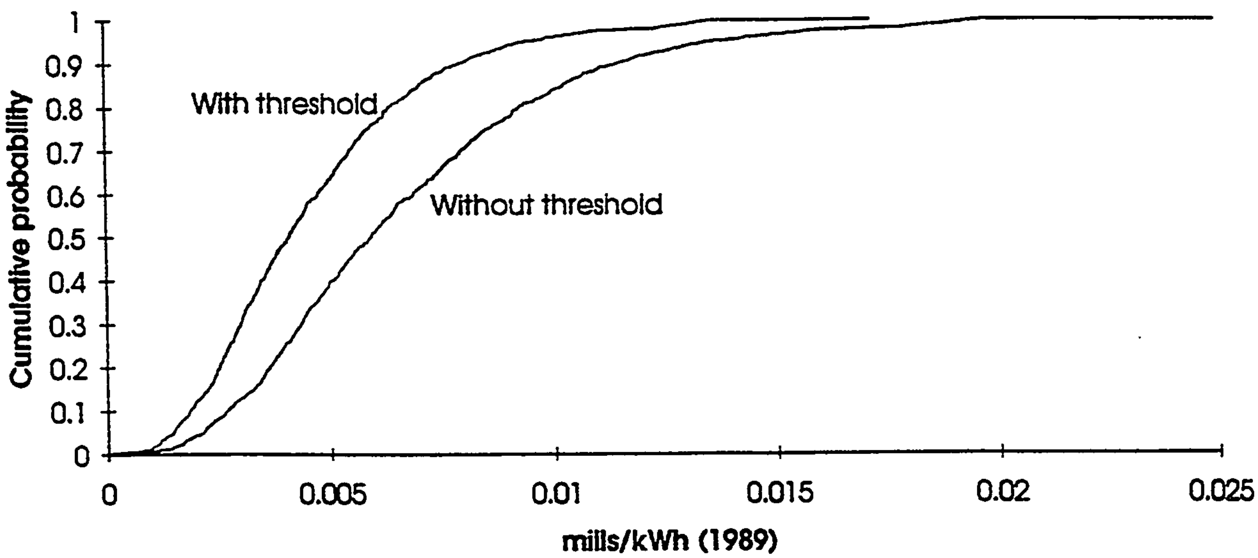

Figure 10.7-1 (a). Particulate -- mortality damages within 50 miles of Southeast plant with and without 30 microgram/cubic meter threshold

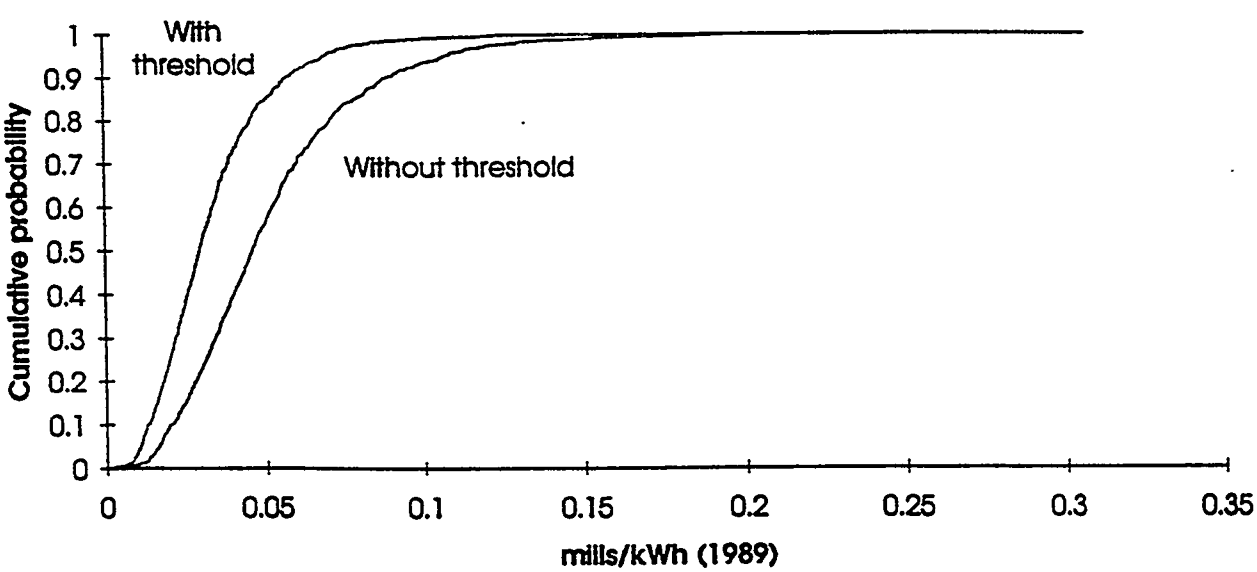

Figure 10.7-1 (b). Particulate -- mortality damages within 1000 miles of Southeast plant with and without 30 microgram/cubic meter threshold

Table 10.7-5a. Particulates—mortality: damages per year (in thousands of 1989 dollars) for the Southwest site [for 0-50 miles][1]

This table assumes impacts based on Schwartz and Dockery (1991a)-TSP	VSL Method		
	Low	Mid	High
Total pathway damages	0.26 **0**	0.78 **0**	1.6 **0**
Total pathway damages (mills/kWh)	0.000079 **0**	0.00024 **0**	0.00048 **0**

[1]Numbers in bold are with threshold.

Table 10.7-5b. Particulates—mortality: damages per year (in thousands of 1989 dollars) for the Southwest site [for 0-1,000 miles][1]

This table assumes impacts based on Schwartz and Dockery (1991a)-TSP	VSL Method		
	Low	Mid	High
Total pathway damages	3.0 **2.0**	8.8 **5.8**	18.0 **12.0**
Total pathway damages (mills/kWh)	0.00091 **0.0006**	0.0027 **0.0018**	0.0055 **0.0036**

[1]Numbers in bold are with threshold.

10.8 EFFECTS OF PARTICULATES ON MORBIDITY[18]

Dose-response functions for particulates have been identified for respiratory hospital admissions, emergency room visits, restricted activity days and symptoms in adults, lower respiratory illness in children, and asthma attacks. Below, we estimate impacts for each endpoint and present estimates of aggregate morbidity effects. Then, we estimate damages for each endpoint separately and aggregate taking care to avoid double-counting.

These pathways can be made clearer by referring to Fig. 10.8-1. Here, a "normal" adult with a symptom may have a restricted activity day (RAD). If he has a RAD it may be serious enough to visit the emergency room or be admitted to a hospital, and if the former, the emergency room patient may be admitted to the

[18] Refer to the footnote at the beginning of Section 10.7.

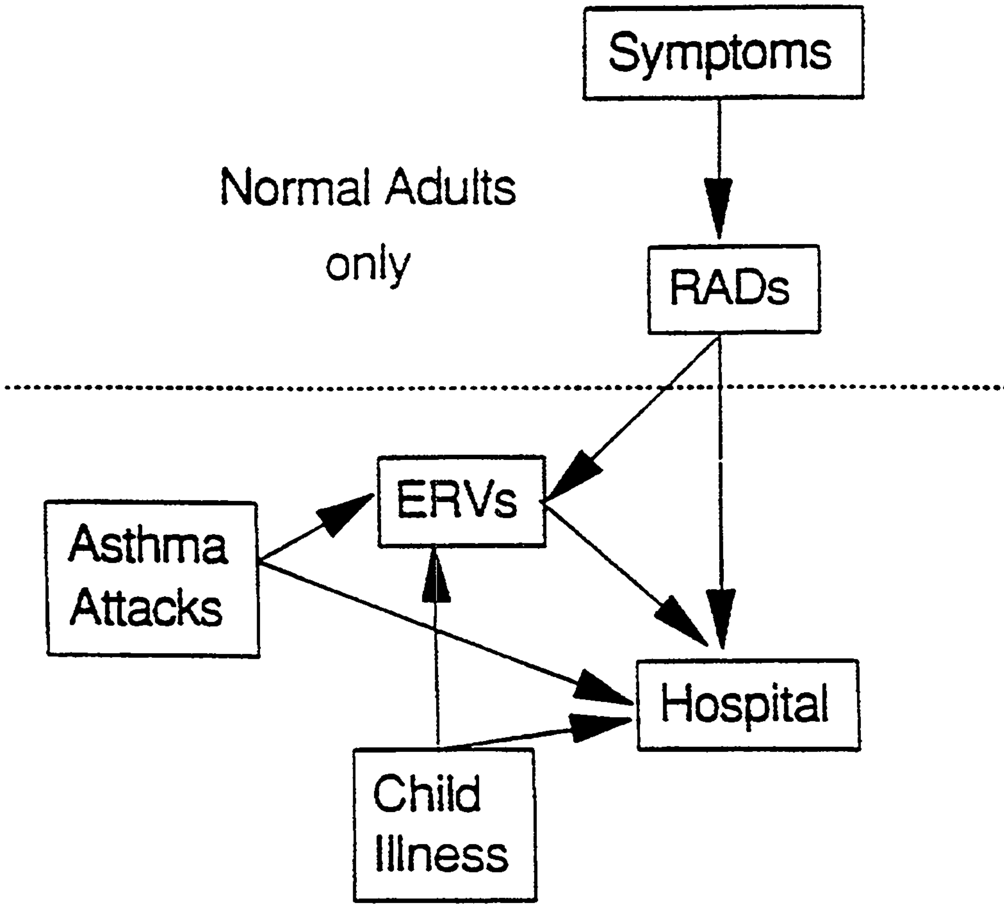

Figure 10.8-1. Flowchart of particulate-morbidity effects.

hospital. We assume that having a RAD is a necessary condition for an emergency room (ERV) or hospital visit (RHA). In addition, asthmatics, whether children or adults, may be admitted to the hospital or emergency room, as may non-asthmatic children.

10.8.1 Impacts of Particulates on Morbidity

The following shaded table (Table 10.8-1) shows the results of a wide-ranging literature search for the best studies providing dose-response functions for the particulate-morbidity pathway. Note that impacts are defined in terms of endpoints that are events which can be valued in economic terms. Chronic respiratory disease risks and impaired pulmonary function are reflected to some degree (though not completely) in these endpoints, but are not precise enough endpoints themselves to value in economic terms.

From the study by Plagiannakos and Parker (1988), annual respiratory hospital admissions per 100,000 population were related to annual average SO_4 concentrations, but TSP was not significant.

Pope found a similar relationship using PM_{10} as the pollution measurement. We use Plagiannakos and Parker's results converted to PM_{10} using a "standard" ratio of SO_4 to PM_{10} [ORNL/RFF (1994a, Part III)]. The PM_{10} effect implied by this study is bracketed by that implied by the effects found by Pope for two valleys in Utah.

To estimate effects associated with emergency room visits/100,000 people, we rely on the Samet et al. (1981) study, which could not separate effects of SO_2 and particulates; the estimates below are based on the results for TSP. We use the Krupnick, Harrington, and Ostro study (1990) to estimate the annual change in "any" symptom-days/person and Ostro (1990) to estimate the annual change in RADs/person associated with change in PM_{10}.

Dockery et al. (1989) found statistically significant associations for PM_{15} (converted to PM_{10}) and both the proportion of children with bronchitis over a year and the proportion with a chronic cough over the year. The dose-response function for the probability of an asthmatic experiencing an attack related to sulfates (SO_4) is taken from Ostro et al. (1991) and converted to PM_{10}.

Finally, a recent study (Abbey et al. 1993) is the first to find a dose-response function relating the incidence of chronic respiratory disease to particulate exposures. Abbey et al. finds significant effects only if there are at least ten days with TSP at least 100 $\mu g/m^3$. Our approach involves estimating the concentration that is exceeded exactly 10 days a year, or 2.7% (10/365) of the year. To do this, we make some assumptions about how the daily concentrations are distributed over the year, given only the annual mean and the second highest daily concentration for each MSA. By assuming the daily concentrations to be lognormally distributed (a common assumption), the annual mean and the second highest daily concentration are sufficient to estimate the complete lognormal distribution. We are then able to estimate the concentration that is exceeded 2.7% of the year. If this concentration exceeds 100 $\mu g/m^3 PM_{10}$, then the population is considered to be above the threshold, otherwise it is below. For the rural population, we again assume that the fraction of the population above the threshold is the same as that of the MSAs.

Table 10.8-1 Linearized dose-response functions for effects of PM_{10} on morbidity.

Respiratory hospital admissions *(Plagiannakos & Parker 1988)*:
Δ RHA per year = C_{RHA} · Pop · ΔPM_{10}

Emergency room visits *(Samet et al. 1981)*:
Δ ERV per year = C_{ERV} · Pop · ΔPM_{10}

Symptom-days *(Krupnick et al. 1990)*:
Δ symptom-days per year = $C_{symptom\text{-}day}$ · Pop · F_{adult} · ΔPM_{10}

Restricted activity days *(Ostro 1987)*:
Δ RAD per year = C_{RAD} · Pop · $(1-F_{asthmatic})$ · F_{adult} · ΔPM_{10}

Children bronchitis *(Dockery et al. 1989)*:
Δ children bronchitis cases per year = $C_{children\ bronchitis}$ · Pop · $F_{children}$ · ΔPM_{10}

Children chronic cough *(Dockery et al. 1989)*:
Δ children chronic cough cases per year = $C_{children\ cough}$ · Pop · $F_{children}$ · ΔPM_{10}

Asthma attacks *(Ostro et al. 1991)*:
Δ asthma attacks per year = $C_{asthma\ attacks}$ · Pop · $F_{asthmatic}$ · ΔPM_{10}

Chronic bronchitis in adults *(Abbey et al. 1993)*:
Δ chronic bronchitis in adults = $C_{adult\ bronch}$ · Pop · F_{adult} · ΔPM_{10} · T

where

ΔPM_{10} = Population-weighted annual average PM_{10} concentration
Pop = Total population over which population-weighted PM_{10} concentration is determined
$F_{children}$ = Fraction of Pop that are children
F_{adult} = Fraction of Pop that is adult
$F_{asthmatic}$ = Fraction of Pop that is asthmatic
T = 1, if number of days within year in which baseline 24 hr average TSP $\geq$ 100 $\mu g/m^3$ $\geq$ 10
= 0, otherwise
C_{RHA} = Normal (mean=0.000102, standard deviation=0.0000625)
C_{ERV} = Normal (mean=0.0002354, standard deviation=0.0001283)
$C_{symptom\text{-}day}$ = Normal (mean=2.05, standard deviation=0.47)
C_{RAD} = Normal (mean=0.0575, standard deviation=0.0275)
$C_{children\ bronchitis}$ = Normal (mean=0.00159, standard deviation=0.000805)
$C_{children\ cough}$ = Normal (mean=0.00184, standard deviation=0.000924)
$C_{asthma\ attacks}$ = Normal (mean=0.000912, standard deviation=0.00045)
$C_{adult\ bronch}$ = Normal (mean=6.15×10^{-5}, standard deviation=3.07×10^{-5})

Working this threshold into the analysis is similar to the incorporation of the 30 $\mu g/m^3$ annual average threshold, but slightly more complicated since the information required to determine if an MSA exceeds the threshold is not listed in the EPA National Air Quality & Emission Trends Report (1992). Instead, the report lists only the annual average and the second highest 24-hr average PM_{10} concentration over the year.

Tables 10.8-2 (a) and (b) show the estimated number of impacts by endpoint for the Southeast Reference environment, when confining the analysis to within 50 miles and within 1,000 miles of the plant, respectively. The low and high estimates, referring to the 5th and 95th percentiles, solely reflect the uncertainty of the dose-response coefficients. Referring only to mean estimates, assuming the 30 $\mu g/m^3$ threshold for the Southeast Reference environment within 50 miles of the plant, the ranking in terms of number of cases per year is: respiratory symptom-days (1,669), RADs (45), asthma attacks (18), children with chronic cough (0.51), children with chronic bronchitis (0.44), ERVs (0.257), RHAs (0.111), and, finally, adults with chronic bronchitis (0). Tables 10.8-3 (a) and (b) show the number of impacts for the Southwest Reference environment, which are zero within 50 miles, and within 1,000 miles, are about one-nineteenth of the corresponding number of impacts for the Southeast Reference environment. As noted previously, the difference is attributed to the order of magnitude difference in population, to the combination of population distribution and wind direction, and to the lower background concentrations of PM_{10} in the Southwest (which are below the health effects threshold).

Table 10.8-2a. Particulate—morbidity: number of impacts per year for the Southeast site [for 0-50 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	13.8	65	115
--Ostro (1987)	**9.5**	**45**	**79**
Emergency room visit	0.0386	0.373	0.708
--Samet et al. (1981)	**0.0266**	**0.257**	**0.487**
Asthma attack-day	5	26	48
--Ostro et al. (1991)	**3.4**	**18**	**33**
Child chronic bronchitis	0.108	0.64	1.17
--Dockery et al. (1989)	**0.074**	**0.44**	**0.81**
Child chronic cough	0.128	0.739	1.35
--Dockery et al. (1989)	**0.088**	**0.51**	**0.93**
Respiratory hospital admission	0	0.16	0.32
--Plagiannakos and Parker (1988)	**0**	**0.111**	**0.223**
Respiratory symptom-day	1510	2,424	3,338
--Krupnick et al. (1990)	**1,040**	**1,669**	**2,299**
Chronic bronchitis in adults	0.011	0.062	0.113
--Abbey et al. (1993)	**0**	**0**	**0**

[1] Numbers in bold are **with** a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP $> 100\ \mu g/m^3$.

Table 10.8-2b. Particulate—morbidity: number of impacts per year for the Southeast site [for 0-1,000 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	107	500	894
--Ostro (1987)	**69**	**323**	**576**
Emergency room visit	0.3	2.89	5.5
--Samet et al. (1981)	**0.193**	**1.86**	**3.53**
Asthma attack-day	38	204	370
--Ostro et al. (1991)	**24.8**	**132**	**239**
Child chronic bronchitis	0.84	5	9.1
--Dockery et al. (1989)	**0.54**	**3.2**	**5.86**
Child chronic cough	0.99	5.7	10.5
--Dockery et al. (1989)	**0.64**	**3.7**	**6.7**
Respiratory hospital admission	0	1.24	2.51
--Plagiannakos and Parker (1988)	**0**	**0.8**	**1.62**
Respiratory symptom-day	11,700	18,800	25,900
--Krupnick et al. (1990)	**7,539**	**12,100**	**16,700**
Chronic bronchitis in adults	0.086	0.48	0.88
--Abbey et al. (1993)	**0.063**	**0.35**	**0.64**

[1]Numbers in bold are with a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP $> 100\ \mu g/m^3$.

Table 10.8-3a. Particulate—morbidity: number of impacts per year for the Southwest site [for 0-50 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	0.5	2.4	4.2
--Ostro (1987)	**0**	**0**	**0**
Emergency room visit	0.0014	0.0138	0.026
--Samet et al. (1981)	**0**	**0**	**0**
Asthma attack-day	0.184	0.98	1.77
--Ostro et al. (1991)	**0**	**0**	**0**
Child chronic bronchitis	0.004	0.024	0.04
--Dockery et al. (1989)	**0**	**0**	**0**
Child chronic cough	0.005	0.027	0.05
--Dockery et al. (1989)	**0**	**0**	**0**
Respiratory hospital admission	0	0.006	0.012
--Plagiannakos and Parker (1988)	**0**	**0**	**0**
Respiratory symptom-day	56	90	123
--Krupnick et al. (1990)	**0**	**0**	**0**
Chronic bronchitis in adults	0.0004	0.0023	0.0042
--Abbey et al. (1993)	**0**	**0**	**0**

[1] Numbers in bold are **with** a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP > 100 $\mu g/m^3$.

Table 10.8-3b. Particulate—morbidity: number of impacts per year for the Southwest site [for 0-1,000 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	5.6	26.5	47.3
--Ostro (1987)	**3.7**	**17.4**	**31.0**
Emergency room visit	0.0158	0.153	0.29
--Samet et al. (1981)	**0.0104**	**0.1**	**0.19**
Asthma attack-day	2.04	10.8	19.6
--Ostro et al. (1991)	**1.34**	**7.1**	**12.8**
Child chronic bronchitis	0.044	0.262	0.48
--Dockery et al. (1989)	**0.029**	**0.172**	**0.315**
Child chronic cough	0.052	0.303	0.55
--Dockery et al. (1989)	**0.0343**	**0.199**	**0.363**
Respiratory hospital admission	0	0.066	0.133
--Plagiannakos and Parker (1988)	**0**	**0.043**	**0.087**
Respiratory symptom-day	619	993	1,368
--Krupnick et al. (1990)	**406**	**652**	**897**
Chronic bronchitis in adults	0.0046	0.0255	0.0464
--Abbey et al. (1993)	**0.0014**	**0.008**	**0.015**

[1]Numbers in bold are with a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP > 100 $\mu g/m^3$.

10.8.2 Morbidity Damages and Externalities from Particulates

To convert the above estimates of acute effects into damages, estimates of individual WTP to avoid such effects are needed. An approach is also needed for aggregating these partly non-separable damages to avoid double-counting. The ideal WTP measures would capture all the medical costs, pain and suffering, time loss, and fear of an acute illness experience. This experience might also include a restriction in activity, an emergency room visit, or a hospital stay. Thus, the WTP measure would address a hierarchy of effects ranging in severity from minor symptoms to hospital stays. Unfortunately, as there are no such measures of WTP available, we must make do with proxies.

Referring back to Fig. 10.8-1, we deal with the overlap between adult RADs and adult symptom-days by valuing all RADs and adding to this the value of residual symptom-days (see Section 10.14). The Health Interview Survey data base used to estimate RADs omits hospital and emergency room days. Thus, values associated with these measures can be added to values for RADs without double-counting. On a WTP basis, avoiding double-counting of emergency room and hospital visits is problematic since estimates of the WTP of people to avoid these experiences do not exist. Instead, we have medical costs for each type of visit, plus we assume that a work loss day (WLD) is encountered for each day of either an emergency room or hospital visit. Since emergency room visit charges are typically added to hospital charges, we feel justified in considering their sum as involving no double-counting of medical costs.

There is a clear potential for double-counting RADs and symptom-days since the latter are a necessary condition for the former. We address this issue by valuing all RADs plus valuing any excess of symptom-days over RADs.

A certain number of asthma attack days and child illness days will have emergency room visits and hospitalization associated with them. Estimates of the WTP to avoid an asthma attack day (taken from Krupnick 1987) already include these consequences (on average). We do not have estimates of the percentage of asthma attacks resulting in emergency room visits. Based on data on hospitalization of asthmatics from the Heart, Lung and Blood Institute (1982) and an estimate of 9.9 asthma attacks per year per asthmatic on average in Krupnick (1987), we estimate that 0.5% of asthma attack-days result in hospitalization. We assume that 1% of asthma attacks result in emergency room visits.

Unit values (Table 10.8-4) for "any" symptom-days (midpoint=$6) and asthma attack days (midpoint=$30) are taken from Krupnick et al. (1989). Values for a RAD are estimated as part of this project using a weighted average of values for the components of a RAD (bed-disability days (BDDs), work loss days (WLDs), and other RADs). BDDs and WLDs are conservatively valued at the average daily before-tax wage for full-time workers (to reflect social opportunity costs) in the reference environments ($69.70 in Tennessee in 1989 dollars, and $73 in New Mexico[19]), while other restricted activity days (which are less severe) are valued as minor restricted activity days (MRADs) ($21.48; Krupnick et al. (1989). Weights are taken from the 1979 Health Interview Survey, with MRADs 38% of RADs. This approach yields a value of a RAD of $51.38 in Tennessee. Respiratory related RADs (RRADs) are valued in the same way, using weights specific to respiratory conditions. In this case, minor respiratory related restricted activity days (MRRADs) are only 21% of total RRADs. Thus, the value of an RRAD is $59.58.[20]

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[19] Since the average wage is so similar in the two reference environments, we use the Tennessee wage throughout.

[20] Note that valuing an RRAD higher than a RAD is a departure from the literature. However, an RRAD is more likely to result in a BDD and a WLD than an average RAD.

Table 10.8-4. Unit values for particulate-morbidity endpoints (in 1989 dollars) for the Southeast Reference environment

Pathway endpoint	Low	Mid	High
Respiratory hospital admission (Krupnick and Cropper 1989)		$6,306	
Emergency room visit (RCG/Hagler, Bailly 1988)		178	
Restricted activity day (Krupnick et al. 1989)		51	
Any symptom-day (Krupnick et al. 1989)	3	6	12
Asthma attack-day (Krupnick et al. 1989)	11	30	49
Child chronic bronchitis (Krupnick et al. 1989)		132	
Adult chronic bronchitis (Viscusi et al. 1991 and Krupnick and Cropper 1992)	57,000	210,000	500,000

Emergency room visits were estimated by RCG/Hagler, Bailly (1988) as the value of a work loss day as equal to $90 in 1986 dollars. We use this approach updated to 1989 dollars ($178). Hospitalization costs ($6,306 per event in Tennessee) are estimated using Krupnick and Cropper (1989) to obtain a weighted average of hospital cost per hospitalization event for admittances for chronic bronchitis and for emphysema, which is $1,801 in 1977 dollars, plus the value of days lost, equal to a weighted average length of stay (LOS) times the average daily wage. LOS was 9.1 days for chronic bronchitis and 9.8 days for emphysema (Heart, Lung, and Blood Institute 1982).

We do not have estimates of WTP to avoid an increased annual risk of bronchitis and chronic cough as they apply to children (although we have estimates of medical costs and WTP to reduce risks of chronic bronchitis in adults). However, Krupnick and Cropper (1989) report an estimate of the average yearly medical costs associated with chronic bronchitis in children up to 10 years old. Inflating this 1977 estimate of $42 to 1989 dollars, medical costs are $132. As this estimate of costs is probably a very small percentage of total costs, which would include the value of parent time, pain and suffering, etc., we feel that double-counting is not an issue.

Viscusi et al. (1991) and Krupnick and Cropper (1992) examined the WTP to reduce the risks of chronic respiratory disease using conjoint analysis. This analysis involves asking respondents to choose between two cities to live in, where both are preferred to his present city and the cities differ in terms of the risk of developing chronic bronchitis (or respiratory disease in general) from living there and in one other characteristic, either the probability of dying in an automobile accident or the cost of living. An interactive computer program changes the magnitudes of these differences to drive the subject to a point of indifference between the two cities. At this point, the auto-death chronic bronchitis tradeoff is known and a statistical case of chronic bronchitis can be monetized by use of a value of a statistical life or, for the chronic bronchitis-cost of living tradeoff, the value of a case can be obtained directly. The two studies use the same protocol, except that Krupnick and Cropper chose a sample of subjects who had relatives with chronic respiratory disease and asked a second set of questions to obtain WTP to reduce risks of a chronic respiratory disease with symptoms *just like their relative's.*

Viscusi et al. estimated an average value of a statistical case of chronic bronchitis of $1.3 million for the first tradeoff and $0.93 million for the second. Krupnick and Cropper's estimates using the same protocols are $1.47 million and $2 million. Median values (which the authors believe are more reliable) are $0.58 and $0.46 million for Viscusi et al. and $0.66 and $1 million for Krupnick and Cropper. This comparison may be misleading, however, as the sample characteristics were quite different between the two studies, the former being more representative of the general population.

Whether any of these values can be used here is questionable, since in the Viscusi et al. study the case of chronic bronchitis was described to the subjects and this case was quite a severe one, more severe than the average case is likely to be. The first part of the Krupnick and Cropper study suffers from the same bias, while the second part, which permits valuation based on the severity of the relative's disease, may be more representative of average severity but is not strictly limited to chronic bronchitis, including asthma, emphysema, and chronic obstructive lung disease, the latter a catch-all category. As chronic bronchitis may be relatively less severe than asthma and emphysema, it is perhaps not surprising that the WTP estimates for the second set of questions are actually larger than for the first set, except for the responses to the chronic disease-cost of living tradeoff (the mean is slightly lower and the median is the same across the two sets of questions).

For valuation purposes, one possibility is to use the regression results in Krupnick and Cropper explaining WTP for the second set of questions to adjust severity of the disease to an average level. This might be appropriate for matching the health endpoints in the Abbey et al. study, as Abbey also found significant associations between air pollution and asthma and obstructive airway disease. If we stick to chronic bronchitis, however, the Krupnick and Cropper estimates will be too high.

Therefore, our preference is to use the Viscusi et al. estimates, with the median estimates chosen for their greater stability and insensitivity to outliers. As their use of a $2 million value of a statistical life is arbitrary, we use the results for the chronic bronchitis-cost of living trade-off, about $500,000 per case. To adjust for severity, we use the elasticity of severity on this tradeoff as estimated by Krupnick and Cropper. This elasticity evaluated at the means is about 1.16, meaning that a 1 percent change in the severity scale (which ranges from 0 to 13, where 13 is the most severe, corresponding to the Viscusi et al. description of a case of chronic bronchitis) results in a 1.16% change in the value of a case of chronic disease, which we assume applies to any of the respiratory diseases tested. As the mean severity score was 6.47, which is 50% of the Viscusi et al. implied severity, we multiply 1.16 by 50% to see that the value of a case falls by 58% when severity drops by half. So the value of a statistical average case of chronic bronchitis is $210,000. We use the unadjusted median estimate for the 95th percentile estimate. Assuming a log normal distribution, the 5th percentile estimate is $57,000. Damages from this endpoint are added to the aggregation of damages for the other endpoints.

In addition to the value of a case of chronic bronchitis in adults, for the purposes of the Monte Carlo simulation, a lognormal distribution has been fit to the ranges of unit values, excepting asthma attacks for which a normal distribution is assumed. Where a point estimate is given, perfect certainty is also assumed in the Monte Carlo simulation. The results of the Monte Carlo simulations are presented in Tables 10.8-5 (a) and (b) and Tables 10.8-6 (a) and (b) for the Southeast and Southwest reference environments. In addition to the mean estimate, the tables show the low and high estimates (5th and 95th percentiles) of annual marginal damages by symptom type and total damages per kWh accumulated within 50 and within 1,000 miles of the plants.[21] The range reflects only the uncertainty in the dose-response functions and unit damage values of the quantified pathways. If there is no dose-response threshold, then the mean estimates of aggregate morbidity damages from particulates for the four cases --within 50 miles of the Southeast plant, within 1,000 miles of the Southeast plant, within 50 miles of the Southwest plant, and within 1,000 miles of the Southwest plant -- are 0.0061, 0.055, 0.00023, and 0.0029 mill/kWh, respectively. If there is a threshold of 30 $\mu g/m^3$, then the corresponding damages are 0.0042 and 0.038 for the Southeast, and 0 and 0.002 for the Southwest. Damages associated with the categories of symptom-days, adult chronic bronchitis, and RADs, in that order, appear to comprise the vast majority of the damages for the Southeast Reference environment. Figures 10.8-2 (a) and (b) and Figs. 10.8-3 (a) and (b) show the CDFs for total damages for the Southeast and Southwest Reference environments. Since there are no factors that internalize these damages, they are externalities.

[21] Note that the Mid values for the "Total pathway damages are less than or equal to the sum of the individual pathway values because the latter may contain some double-counting due to overlapping symptoms. Also, note that according to probability theory, the sum of the 5th percentile (i.e., "Low") values is always less than the 5th percentile of the total. The opposite is true of the 95th percentile values.

Table 10.8-5a. Particulates—morbidity: damages per year (in thousands of 1989 dollars) for the southeast site [for 0-50 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	0.67 **0.46**	3.3 **2.3**	5.9 **4.1**
Emergency room visit	0.0039 **0.0027**	0.065 **0.045**	0.12 **0.084**
Asthma attack-day	0.088 **0.061**	0.79 **0.55**	1.7 **1.1**
Child chronic bronchitis	0.016 **0.011**	0.086 **0.059**	0.15 **0.10**
Child chronic cough	0.00058 **0.0004**	0.0041 **0.0028**	0.011 **0.0073**
Respiratory hospital admission	0.034 **0.024**	1.1 **0.73**	2.1 **1.5**
Any symptom-day	6.8 **4.7**	15 **10.0**	27 **19**
Adult chronic bronchitis	0 **0**	0 **0**	0 **0**
Total pathway damages	11 **7.9**	20 **14**	32 **22**
Total pathway damages (mills/kWh)	0.0035 **0.0024**	0.0061 **0.0042**	0.0097 **0.0067**

[1]Numbers in bold are **with** a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP > 100 $\mu g/m^3$.

Table 10.8-5b. Particulates—morbidity: damages per year (in thousands of 1989 dollars) for the Southeast site for [0-1,000 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	5.5 **3.5**	26 **17**	45 **29**
Emergency room visit	0.041 **0.026**	0.52 **0.34**	0.96 **0.62**
Asthma attack-day	0.96 **0.62**	6.1 **3.9**	13 **8.1**
Child chronic bronchitis	0.11 **0.069**	0.65 **0.42**	1.2 **0.79**
Child chronic cough	0.0044 **0.0028**	0.031 **0.02**	0.075 **0.048**
Respiratory hospital admission	0.19 **0.13**	8.1 **5.2**	16 **11**
Any symptom-day	53 **34**	120 **78**	220 **140**
Adult chronic bronchitis	4.1 **4.1**	22 **22**	40 **40**
Total pathway damages	110 **75**	180 **120**	280 **190**
Total pathway damages (mills/kWh)	0.033 **0.023**	0.055 **0.038**	0.087 **0.058**

[1]Numbers in bold are with a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP > 100 $\mu g/m^3$.

Table 10.8-6a. Particulates—morbidity: damages per year (in thousands of 1989 dollars) for the Southwest site [for 0-50 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	0.030 0	0.12 0	0.22 0
Emergency room visit	0.00032 **0**	0.0025 **0**	0.0046 **0**
Asthma attack-day	0.0048 **0**	0.029 **0**	0.06 **0**
Child chronic bronchitis	0.00073 **0**	0.0032 **0**	0.0058 **0**
Child chronic cough	0.000024 **0**	0.00015 **0**	0.00037 **0**
Respiratory hospital admission	0.00083 **0**	0.038 **0**	0.075 **0**
Any symptom-day	0.25 **0**	0.59 **0**	1.1 **0**
Adult chronic bronchitis	0 **0**	0 **0**	0 **0**
Total pathway damages	0.41 **0**	0.77 **0**	1.3 **0**
Total pathway damages (mills/kWh)	0.00013 **0**	0.00023 **0**	0.00039 **0**

[1]Numbers in bold are **with** a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP > 100 $\mu g/m^3$.

Table 10.8-6b. Particulates—morbidity: damages per year (in 1989 dollars) for the Southwest site for [0-1,000 miles][1]

Pathway endpoint	Low	Mid	High
Restricted activity day	0.39 **0.25**	1.4 **0.93**	2.5 **1.6**
Emergency room visit	0.001 **0.66**	0.027 **0.018**	0.051 **0.034**
Asthma attack-day	0.052 **0.034**	0.34 **0.22**	0.69 **0.46**
Child chronic bronchitis	0.0078 **0.0051**	0.035 **0.023**	0.063 **0.041**
Child chronic cough	0.00027 **0.00018**	0.0016 **0.001**	0.0038 **0.0025**
Respiratory hospital admission	0.032 **0.002**	0.42 **0.28**	0.83 **0.55**
Any symptom-day	2.8 **1.8**	6.3 **4.2**	11 **7.5**
Adult chronic bronchitis	0.20 **0.20**	1.1 **1.1**	1.9 **1.9**
Total pathway damages	5.6 **3.9**	9.4 **6.6**	14 **9.8**
Total pathway damages (mills/kWh)	0.0017 **0.0012**	0.0029 **0.002**	0.0044 **0.003**

[1] Numbers in bold are **with** a threshold of 30 $\mu g/m^3$ annual average PM_{10}. Estimates of chronic bronchitis are based on a threshold of at least 10 days/year with 24-hr average TSP > 100 $\mu g/m^3$.

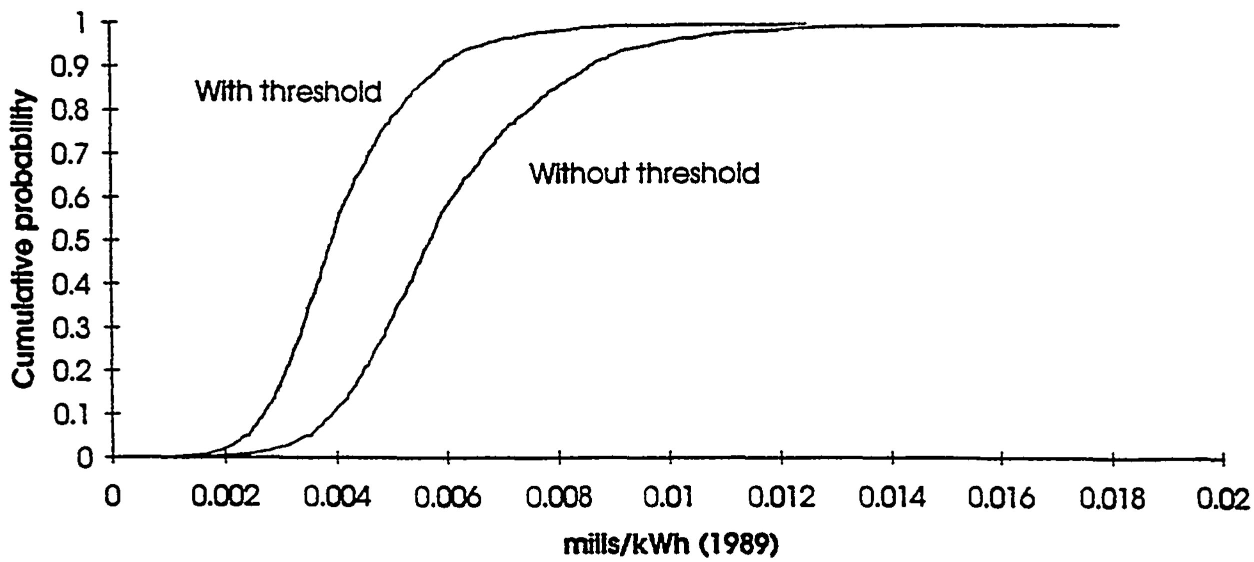

Figure 10.8-2 (a). Particulate--morbidity damages within 50 miles of Southeast plant with and without 30 microgram/cubic meter threshold

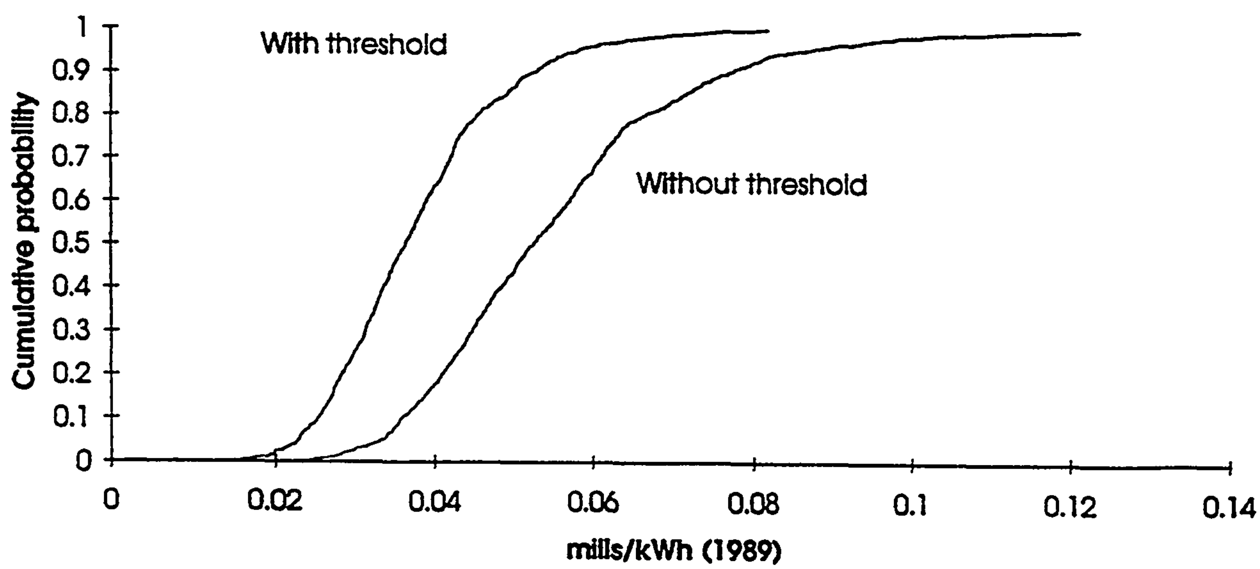

Figure 10.8-2 (b). Particulate--morbidity damages within 1000 miles of Southeast plant with and without 30 microgram/cubic meter threshold

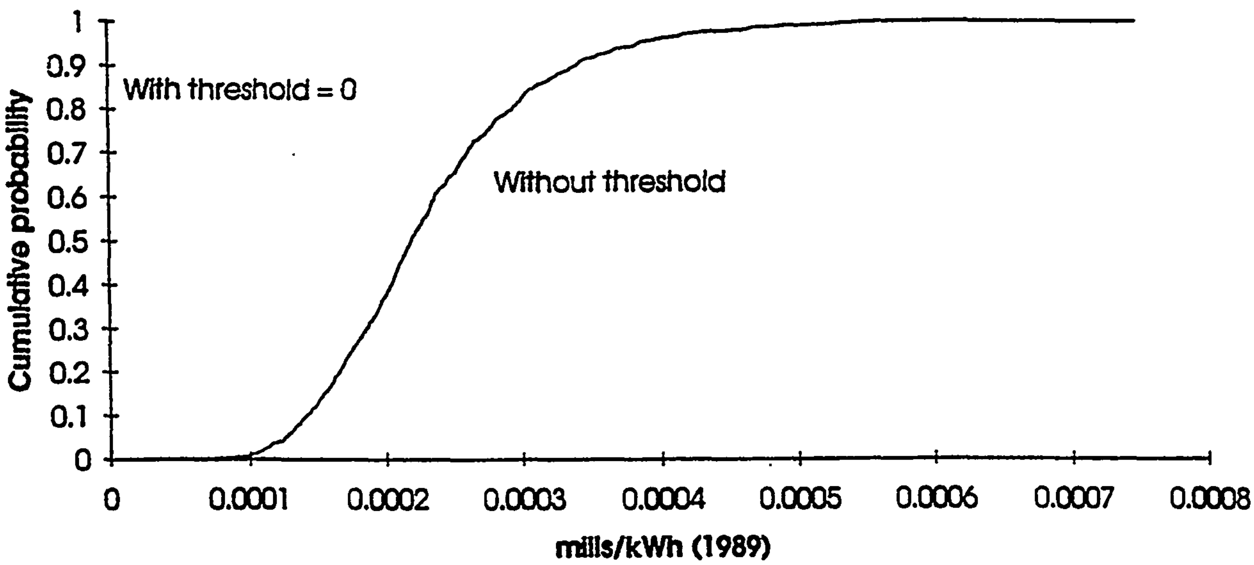

Figure 10.8-3 (a). Particulate--morbidity damages within 50 miles of Southwest plant with and without 30 microgram/cubic meter threshold

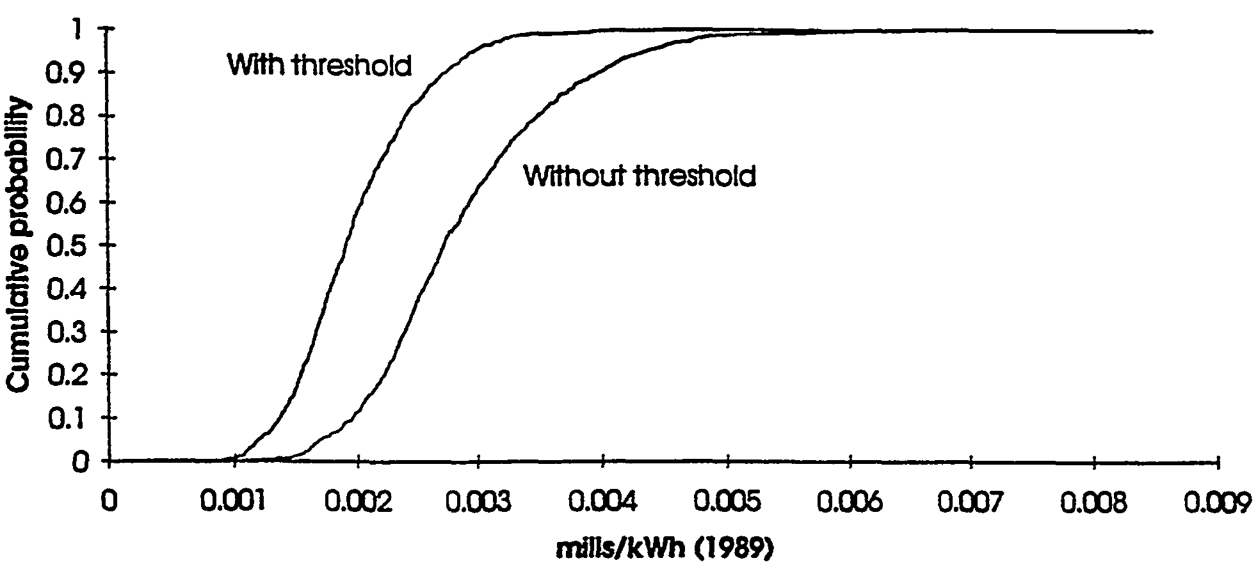

Figure 10.8-3 (b). Particulate--morbidity damages within 1000 miles of Southwest plant with and without 30 microgram/cubic meter threshold

10.9 EFFECTS OF PARTICULATES ON MATERIALS

10.9.1 Emissions of Particulates

Total particulate emissions from the Reference power plants were estimated to be 0.021 tons/GWh. PM_{10} emissions were estimated to be 100% of the total particulate emissions i.e., 68 tons/year or 1.95 grams/second. This estimate was based on the particle size distribution of emissions from an electrostatic precipitation used to control particulate emissions (EPA 1988).

Total particulate emissions from the Reference power plants were estimated to be 0.021 tons/GWh.

The ground-level pollutant concentrations of total suspended particulates (TSP) and PM_{10} that could be expected to occur as the result of the operation of the 500 MW reference gas-fired power plant were predicted using atmospheric dispersion modeling. A description of the computer modeling is presented in ORNL/RFF (1994a, Part I). The highest predicted ambient annual concentration of PM_{10} from the Southeast Reference plant site is 0.02 micrograms per cubic meter ($\mu g/m^3$). The highest predicted ambient annual concentration of PM_{10} from the Southwest Reference plant site is 0.023 $\mu g/m^3$.

10.9.2 Impacts of Particulates

Zinc, calcareous stone and paint are particularly at risk from impacts involving not only wet and dry deposition of SO_2 and NO_x, but also particulate solids (Short and Mills 1991). Particulates also have damaging effects on glass surfaces by staining which causes loss of natural light transmission. Particulates of all sizes also soil fabrics and other surfaces.

10.9.3 Damages to Materials from Particulates

The WTP to avoid or reduce material soiling or other impacts is not simply the replacement or cleaning costs of the materials. If the materials are monuments or other public, special objects, they may have a cultural value beyond replacement or cleaning costs.

There have been few attempts at estimating materials damages because of a paucity of dose-response functions, a lack of materials inventories (where the inventory required should contain data on the position and type of materials, as well as future trends in the use of materials), and few surveys that adequately capture the full range of behavioral responses to material effects. In the U.S., there are only a handful of contingent valuation studies that address WTP to preserve monuments and other cultural resources, with emphasis on acid rain damage (Charles River Associates 1983).

The literature is largest with respect to materials soiling. Cummings et al. (1981) statistically related TSP concentrations to expenditures on residential cleaning, but the approach ignored certain types of consumer responses and did not measure WTP. Manuel et al. (1982) is a more theoretically satisfying attempt because this study estimated a model of consumer behavior in response to soiling that captures the production and consumption of cleanliness. That study examines the relationship between consumer expenditures and air pollution levels. This approach has the advantage of avoiding the need for dose-response functions and materials inventories, but the aggregate nature of the analysis and the difficulty of attributing expenditure variation to particular pollutants or their effects makes such estimates highly uncertain. Nevertheless, because estimates are based on a dataset of consumer expenditures for 24 SMSA's (The Bureau of Labor Statistics' Consumer Expenditure Survey), the study results can be generalized to a variety of areas. Note, however, that the data are over 20 years old.

Both RER (1991) and NERA (1992) in their studies of damages in the South Coast Air Basin (SCAB) and NERA (1993), in a similar assessment for Nevada, rely on Manuel et al.'s (1982) study to estimate the materials damages from particulates. However, they handle the uncertainty in different ways, coming to vastly different conclusions about damages avoided from particulate reductions in the SCAB.

The original Manuel et al. study did not report soiling damage separately from some other effects of particulates and used a measure of TSP inconsistent with that used in our study -- the second highest 24-hour average over the year. NERA (1993) reports that it arranged for the consulting firm that performed the original study (MathTech) to redo the analysis, relating annual average PM_{10} and SO_2 concentrations to the soiling damage estimates. The analysis accounts for possible interaction effects between particulates and SO_2 and permits non-linearities in the damage function. NERA reports that at the baseline particulate levels associated with our reference environments, ie., an annual average around 40 $\mu g/m^3$ PM_{10}, the LOW, MID, and HIGH damages per household for a 1 $\mu g/m^3$ change in PM_{10} (\$1990) are \$0.58, \$2.88, and \$5.09, respectively. Only the HIGH estimate is the least bit sensitive to baseline SO_2 concentrations, but the interaction effects are small enough to be ignored. These estimates may underestimate damages because they ignore the value of time for do-it-yourselfers.

Whatever damages exist, they are externalities. They are not reflected in the prices of electricity. Because of the lack of baseline inventory data, however, we do not estimate materials damages and externalities.

10.10 EFFECTS OF ACIDIC DEPOSITION ON RECREATIONAL FISHERIES

10.10.1 Emissions and Acidic Deposition

Emissions of SO_2 and NO_x from the electricity sector have been a major contributor to acidic deposition. The chemistry of acid deposition involves the oxidation of both SO_2 and NO_x in the atmosphere by strongly oxidizing species such as O_3, OH and H_2O_2 to form strong acids H_2SO_4 and HNO_3. These are deposited both directly by dry deposition (particulate and gaseous acid precursors) and by removal in rainfall. The rate of wet deposition (rain, snow, fog) is of course highly variable both in space and time. Emissions of SO_2 from natural gas technologies are negligible. Thus, effects of acidic deposition from natural gas plants are much less than those from coal plants.

Some of these reactions occur only slowly in the atmosphere so that deposition occurs over a very wide area. Regional scale modeling is therefore required to determine the incremental effects of an individual power station.

Local-scale atmospheric emissions models (e.g., plume models) are reliable only to a distance of about 50 km from the source. Long-range transport modeling studies were performed for National Acid Precipitation Assessment Program (NAPAP 1991), but source-specific results that could be used for this report are not available at this time.

10.10.2 Impacts of Acidic Deposition on Recreational Fisheries

The principal source of quantitative information on effects of acidic deposition on recreational fishing is the NAPAP and its associated State of Science/Technology reports (e.g., L. Baker et al 1990; Turner et al. 1990; J. Baker et al. 1990; and Thornton et al. 1990). These reports summarize the surveys, models, data sets, and conclusions about relationships between acidic deposition and effects on aquatic biota from the 10-year NAPAP study.

Rivers draining the southwestern region are well buffered (i.e., neutralized) by geological processes and are not likely to be acidified by an additional power plant in the region. Landers et al. (1987) found in the Western Lake Survey [part of the National Surface Water Survey, (NSWS)] that there were numerous lakes in the high-elevation mountain regions of the West that have low acid neutralizing capacity (ANC) and are potentially highly sensitive to effects of acidic deposition, though currently no lakes are acidic. NAPAP did not model future effects in the West because no regional effects have been documented to date and because uncertainty in current and project wet and dry deposition to these lakes is very high.

Two steps were employed in NAPAP's regional modeling process: (1) modeling of watershed chemistry, to relate deposition scenarios to projected long-term chemical characteristics of the surface water, and (2) modeling of fish responses to changes in pH and other water quality parameters. Long-term regional water chemistry projections ultimately were based principally on the Model of Acidification of Groundwater in Catchments (MAGIC) water chemistry model (Church et al. 1989; NAPAP 1991; Turner et al. in press). The principal biotic response model employed was an empirical model derived from observed associations between fish population status and acid-base chemistry in field studies. The output of the combined models consists of region-specific estimates of the fraction of streams or lakes with long-term acid-base chemistry suitable for fish survival under different scenarios of sulfur deposition. In general, changes in fish densities were not modeled in the NAPAP work.

To quantify the incremental effects of a single power plant more accurately, additional research is needed to: (1) reduce uncertainty in projections of future regional atmospheric deposition (or to hypothesize specific scenarios for evaluation), (2) reduce uncertainty in estimation of wet and dry atmospheric deposition (of acidifying and neutralizing substances) to individual watersheds, (3) improve our ability to model all important watershed processes that affect water chemistry and fish response on both long-term (or chronic, 50-year) and short-term (or episodic, storm event) time scales (and to survey all the input data for the watersheds needed to drive the models), and (4) improve our models of fish response to short- and long-term changes in water chemistry. Further discussion is given in ORNL/RFF (1994b, Section 10.11). Due to these limiting factors, no numerical estimates can be calculated.

10.11 EFFECTS OF ACIDIC DEPOSITION ON CROPS

Research studies of the impacts of acid rain on crops have generally found no significant effects on crop yield. The results of these studies, as thoroughly reviewed by Shriner et al. (1990), are summarized in Table 3.7 in ORNL/RFF (1994a, Part II).

Since no reduction in crop yields are anticipated to result from increased acid rain, there are no damages or externalities. Thus, Chapter 11 lists the damages and the externalities as zero, in the tabulation of numerical results.

10.12 EFFECTS OF ACIDIC DEPOSITION AND OZONE ON FORESTS

10.12.1 Impacts of Acidic Deposition and Ozone on Forests

It is difficult to evaluate the damage costs of a natural gas fuel cycle that are associated with the effects of acidic deposition and ozone on forests. This difficulty is due to large sources of variability in the response of forest vegetation to these pollutants, both in space and time. The 10-year NAPAP research and assessment program made major advances in the science necessary to understand the response of individual seedlings, and in some cases, mature trees, to air pollution stress. In many cases, however, there is still not a quantitative linkage between seedling response, whole mature tree response, and forest stand or ecosystem response. NAPAP was unable to develop a linked model of dose-response leading to economic valuation of effects. In the absence of such capability, sensitivity analyses were performed using a range of growth reduction estimates due to pollution stress as input to the forest econometric model.

10.12.2 Damages to Forests from Acidic Deposition and Ozone

The effects of increasing pollution on forests can reduce social welfare by reducing the productivity of commercial forests and by changing the characteristics of forested lands used for recreation. In addition, changing the character of any forested lands may reduce the welfare of non-users. The first two effects are discussed in the following section. Nothing more will be said about the third because we have found no studies relating changes in forest characteristics to existence values (or other non-use values).

<u>Commercial Effects</u>

Turning to commercial effects first, the appropriate measure of changes in social welfare as a result of a change in the yield of commercial forests is the change in consumer and producer surplus. NAPAP SOS #27 reviews the U.S. valuation literature concerning this effect, concluding that the TAMM (Timber Assessment Market Model) (which has been recently updated to TAMM90) is one of the best known of the forest market models and devoting its entire commercial forest valuation discussion to this model and its applications. This econometrically estimated simulation model of market supply and demand is spatially explicit for North American forests, containing a forest inventory projection system differentiated by age-class. The yield reductions of particular stands of trees as a result of pollution is an input into the model. With lower tree growth, inventories fall, which lowers stumpage supplies and raises stumpage prices; this raises production costs and prices, lowering consumption. The model then produces estimates of changes in consumer and producer surplus. For reductions of 5% in hardwood growth and 10% in softwood growth in the south and 5% reductions in both types of trees in the north (relative to base case growth), the TAMM90 model found welfare losses of $0.5 billion in the year 2000 (in 1967 dollars), rising to $3 billion by 2040. Results for the southeast (our reference environment) could be extracted from this model. In 1989, these losses would more than triple.

Of course, those scenarios are far greater in magnitude than the effects from a reference power plant. While ozone, in particular, is an important stress on terrestrial ecosystems, NAPAP was unable to develop any dose-response relationships. Thus, we are unable to calculate damages.

... NAPAP was unable to develop any dose-response relationships.

<u>Recreation Effects</u>

Turning to recreation effects of a change in forest condition, according to NAPAP SOS #27, very few studies examine the welfare losses associated with a change in forest characteristics at one or more recreation sits. NAPAP found no studies linking acid deposition changes in forests to recreation losses. Very few studies examine welfare losses when characteristics of many recreation sites change simultaneously, none associated with acid deposition.

Crocker (1985) and Peterson et al. (1987) estimated WTP of recreationists (and, for the latter study, property owners) on forested lands near Los Angeles to avoid vegetation damage from ozone-induced injuries. Crocker used photographs showing various degrees of damage to the San Bernardino National Forest to elicit WTP with a CV survey. People were WTP $1.35 less per trip to a forest that looked moderately damaged relative to a forest that was slightly damaged. Peterson et al. used CV techniques to estimate WTP for a one-step decrement on a forest quality ladder showing various degrees of ozone damage in the San Bernardino and Angeles national forests. WTP average $38 annually for recreationists and $119 annually for adjoining property owners, with about 75% of values classified as non-use. The values from these studies, however, are inadequate for estimating damages and externalities in our study since the dose-response and valuation relationships are inadequately estimated.

10.13 EFFECTS OF ACIDIC DEPOSITION AND OZONE ON MATERIALS

The literature gives a number of dose-response relationships for damages to materials from acidic deposition and ozone. These damage functions do not account for the great variability expected under uncontrolled conditions, which are different from those considered in the studies. Also, as discussed in Section 10.9, the willingness to pay to avoid or reduce impacts on materials is not simply the replacement, repair, or cleaning costs. In any event, the lack of an inventory on buildings and materials precludes our making any estimate of the damages. Further discussion is given in Section 10.14 of ORNL/RFF (1994b).

10.14 HEALTH EFFECTS OF OZONE

10.14.1 Precursor Emissions and Change in Ozone Concentrations

Exhaust gases from power plants that burn fossil fuels contain concentrations of sulfur dioxide (SO_2), nitric oxide (NO), particulate matter, hydrocarbon compounds and trace metals. Estimated emissions from the operation of the hypothetical 500 MW natural gas-fired power plant are given in Table 5.3-22. Ozone is considered a secondary pollutant. It is not emitted directly into the atmosphere but is formed from other air pollutants, specifically, nitrogen oxides (NO_x) and non-methane organic compounds (NMOC) in the presence of sunlight. (NMOC are sometimes referred to as hydrocarbons, HC, or volatile organic compounds, VOC).

Ozone formation depends on the ratio of NMOC concentrations to NO_x concentrations. Figure 10.14-1 is a typical ozone isopleth generated with the Empirical Kinetic Modeling Approach (EKMA) option of the Environmental Protection Agency's (EPA) Ozone Isopleth Plotting Mechanism (OZIPM-4) model.

The shape of the isopleth curves in Figure 10.14-1 is a function of the region (i.e., background conditions) where ozone concentrations are simulated.

The location of an ozone concentration on the isopleth diagram is define by the ratio of the NMOC and NO_x coordinates of the point, known as the NMOC/NO_x ratio (NRC 1991). The diagonal line from the lower left to the upper right corresponds to an NMOC/NO_x ratio of approximately 8/1. This line defines two areas of the graph. Areas to the left of the line have low NMOC/NO_x ratios and are described as NMOC-limited. In these areas, such as highly polluted urban areas characterized by relatively high concentrations of NO_x, the addition of NO_x emissions results in little or no increase in ozone concentrations and may actually result in lower ozone concentrations due to the scavenging of ozone by NO_x emissions (see equation [1] below). Assumptions that there is uniform scavenging of ozone within 50 km of a power plant may be a reasonable first approximation in areas with low NMOC/NO_x ratios (but are clearly less desirable than the more precise modeling that we demonstrate in this study). The area to the right of the line in Fig. 10.14-1 has high NMOC/NO_x ratios and is described as NO_x-limited. Rural areas, such as the Southeast Reference site, and suburbs downwind of cities are often characterized by high NMOC/NO_x ratios. Since the only source of ozone in the troposphere is from the photolysis of NO_2 (equations [2] and [3] below), any increase in NO_x emissions in NO_x-limited areas results in higher ozone concentrations (NRC 1991).

While most large power plants are considered significant sources of NO_x emissions, NMOC emissions from power plants are not considered significant and do not typically require control. Since NMOC emissions from power plants are not present in sufficient quantities to provide an optimal hydrocarbon to NO_x ratio within the plume, ozone formation from the emissions of power plants is the result of a complex series of reactions involving NO_x emissions from the plant reacting with ambient concentrations of hydrocarbons, hydrocarbon derivatives, and ozone. Ambient hydrocarbons may be from either man-made or natural sources.

Initially, ozone that may be present in the ambient air reacts with the NO from the power plant to form nitrogen dioxide (NO_2) and oxygen (O_2), described by the reaction:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad [1]$$

This reaction causes the characteristic ozone depletion observed near the stack in power plant plumes. Ozone depletion is defined here as ozone concentrations within the power plant plume that are less than those outside the power plant plume. In the presence of sunlight, within the first few tens of kilometers of the plant, the photochemistry within power plant plumes (with low hydrocarbon concentrations) can be described by these three equations (White 1977), known as the NO_2 photolytic cycle:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad [1]$$

$$NO_2 + h\nu \rightarrow NO + O(^3P) \qquad [2]$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M \qquad [3]$$

where M is any energy-accepting third body, usually nitrogen (N_2) or O_2 and $O(^3P)$ is one of two electronic states of oxygen known as the triplet-P (Seinfeld 1975). NO_2 absorbs ultraviolet energy from the sun which breaks the molecule into NO and a ground state oxygen atom $O(^3P)$. Energy from solar radiation is represented by $h\nu$, which is the product of Planck's constant (h) and the frequency of the electromagnetic wave of solar radiation (ν). The net effect of these three reactions is conversion of the NO emissions to NO_2 with no increase in ozone concentrations.

The net generation of ozone in power plant plumes can only occur in the presence of reactions which compete with the ozone depletion reaction [1]. Further downwind, as the plume disperses, ambient air containing pollutants from other sources, most importantly reactive hydrocarbons, becomes entrained into the plume. Reactive hydrocarbons in the ambient air participate in a complex series of oxidation reactions which result in the formation of highly reactive radicals.

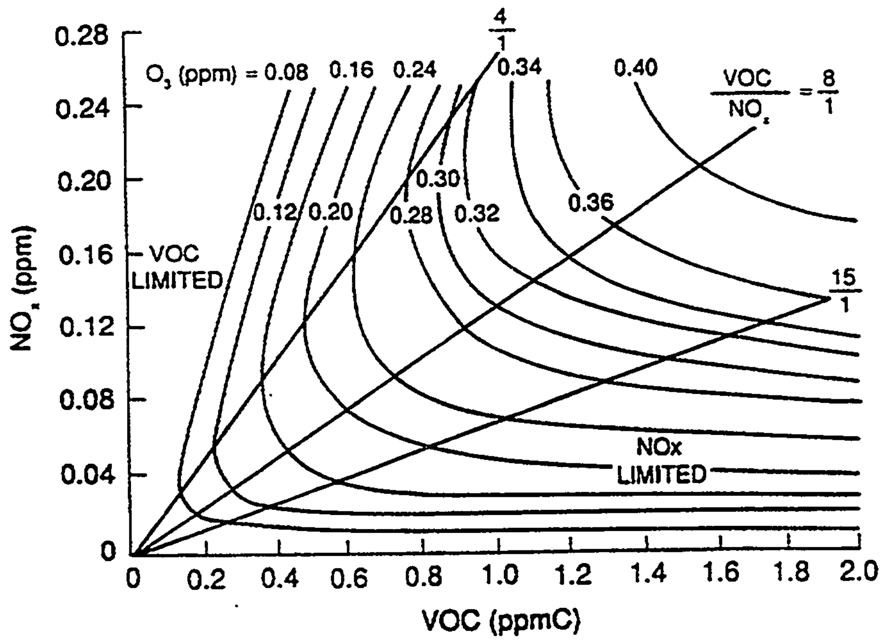

Figure 10.14-1. Typical ozone isopleths generated with the EKMA option of EPA's OZIPM-4 model. The NO_x-limited region is typical of rural and suburban areas and the VOC-limited region is typical of highly polluted urban areas.

Source: National Research Council (NRC), (1991): Rethinking the Ozone Problem in Urban and Regional Air Pollution, National Academy Press, Washington, D.C.

An extremely important intermediate compound in this series of reactions is a group of hydrocarbon derivatives known as aldehydes, most importantly formaldehyde. These compounds play a key role in photochemistry since they are the major source of radicals (Gery et al. 1989) which compete with the ozone depletion reaction [1]. Formaldehyde is also emitted directly from such sources as automobiles, forest fires, manufacturing, printing, and spray painting (Graedel 1978). Formaldehyde (and other aldehydes) react in the presence of sunlight to form the highly reactive hydroperoxy radical ($HO_2\bullet$) by the reactions (Carlier et al. 1986):

$$HCHO + h\nu \rightarrow H\bullet + HCO\bullet \qquad [4]$$

$$HCO\bullet + O_2 \rightarrow HO_2\bullet + CO \qquad [5]$$

Ozone depletion is slowed by the reaction of NO with the hydroperoxy radical ($HO_2\bullet$):

$$HO_2\bullet + NO \rightarrow OH\bullet + NO_2 \qquad [6]$$

as well as, the alkylperoxy radical ($RO_2\bullet$, where R is any organic fragment):

$$RO_2\bullet + NO \rightarrow RO\bullet + NO_2 \qquad [7]$$

as the ozone generating reactions [2] and [3] continue in the plume. Eventually, the ozone concentration within the plume may exceed ambient levels.

The formation of ozone is controlled by a combination of conditions, including ambient ozone concentrations which provide the mechanism necessary for the initial conversion of NO to NO_2, reactive hydrocarbon concentrations of the ambient air mass, and the rate of entrainment of ambient air within the plume. These conditions, as well as sufficient photochemical activity, determine whether ozone levels in the plume will eventually exceed ambient levels to form the widely documented ozone "bulge" (Keifer 1977; Meagher et al. 1981; Luria et al. 1983; Gillani and Wilson 1980; Davis 1974).

To summarize, the major factors in the formation of excess ozone in power plant plumes are:

1. NO_x emissions from the plant,
2. ambient ozone concentrations,
3. reactive hydrocarbons,
4. favorable ratio of ambient hydrocarbons to plume NO_x,
5. atmospheric mixing, and
6. sufficient photochemical activity (sunlight and temperature).

The potential impact of the power plant NO_x and NMOC emissions on ozone concentrations was modeled for the Southeast Reference site. Ozone modeling was not done for the Southwest Reference site because the background ozone concentrations are low, below the 80 ppb threshold used for health effects. Also, crops are few in the region. Thus, there are no ozone-related impacts for the Southwest Reference sites.

For the Southwest Reference site, modeling was done using the U.S. Environmental Protection Agency model, Ozone Isopleth Plotting Mechanism (OZIPM-4) and a new model developed for this study, the Mapping Area-Wide Predictions of Ozone model (MAP-O_3). The OZIPM-4 model is a trajectory model which predicts ozone concentrations as a function of travel time. The MAP-O_3 model provides spatial resolution by predicting the location of the plume during each hour of the day, for the ozone season. The MAP-O_3 model predicts area-wide ozone concentrations over the ozone season, by combining ozone concentrations predicted with the OZIPM-4 model with plume trajectories calculated from wind speed and direction measurements. A detailed description of the OZIPM-4 and MAP-O_3 modeling is presented in ORNL/RFF (1994a, Part I).

These, and other, atmospheric models are limited. In particular MAP-O_3 and OZIPM-4 are more suitable for estimating local and ozone concentrations than long-range (e.g., 1,000 km) transport. But they represent the best-available tools for estimating changes in concentrations in externalities-related studies.

Results from the MAP-O_3 model for the health effects portion of the fuel cycle analysis are in tabular form. The peak daily ozone increment due to the power plant, as well as the daily peak background ozone concentrations, are reported at each location in a polar grid (each downwind distance and sector) for each day of the ozone season (provided the combined total of the background and the increment due to the plant were greater than or equal to 80 ppb). This criterion was met (and results were reported) for twenty-eight days during the 1990 season. One of the twenty-eight high days was in the month of May, six were in June, nine were in July, seven were in August and five days were in September.

A peak daily ozone concentration of 5 ppb occurred over a wide area, from 130 kilometers in the northeast (NE) direction to 30 kilometers in the southwest (SW) direction

As stated above, results for the health effects study are in tabular form and correspond to twenty-eight days of the ozone season. (If the actual results used in the health effects portions were presented here graphically it would require 28 figures, one for each day). Figure 10.14-2 is provided here simply to illustrate the spatial distribution of daily peak ozone concentrations during the 1990 ozone season at the Southeast Reference site. (Results from the MAP-O_3 model were converted to Cartesian coordinates and written to files for import to the isopleth graphing routine

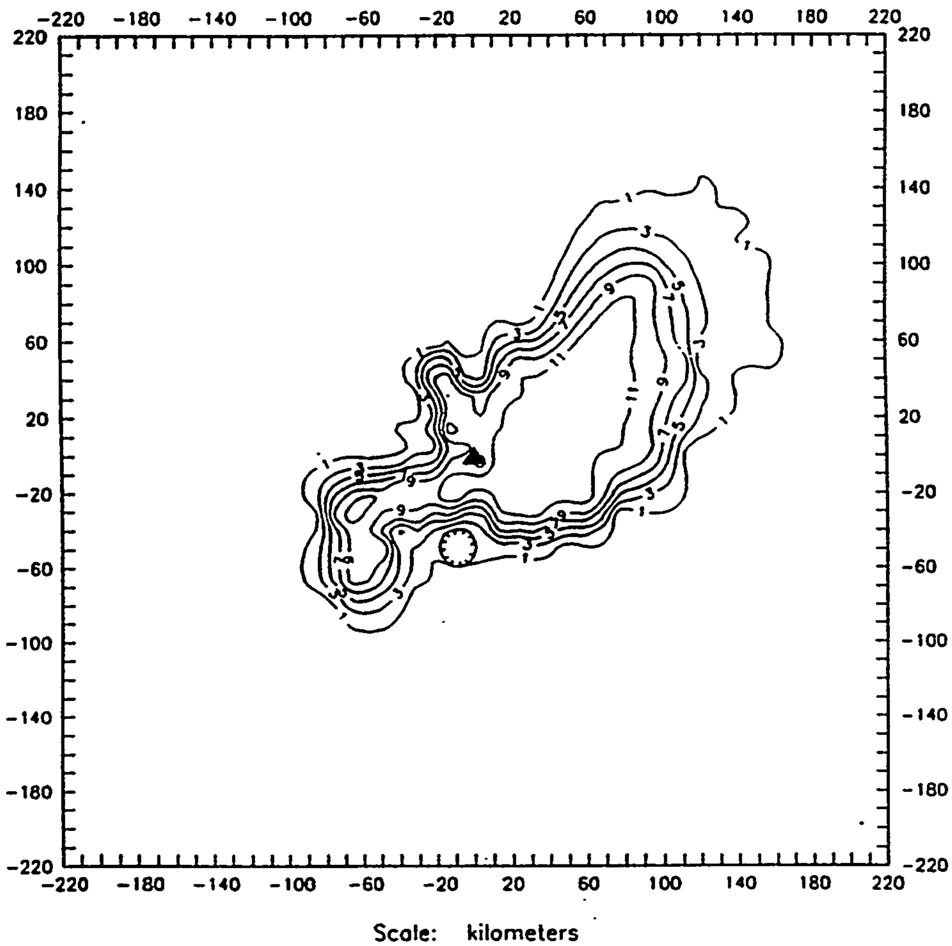

Figure 10.14-2. Maximum daily peak incremental ozone concentrations (ppb) (one hour average) for May to September 1990 due to emissions from the gas-fired power plant at the Southeast Reference site

SURFER). The power plant is shown in the center of each isopleth map with a triangle marker. The scale of the figure is in kilometers from the plant. Ozone concentrations are reported in parts per billion (ppb) by volume.

The ozone concentrations shown in Fig. 10.14-2 are the maximum daily peak ozone concentrations at each location in the receptor grid. As seen in Figure 10.14-2 the greatest increase in daily peak ozone concentration due to the power plant emissions during the ozone season, was 11 ppb, occurring within 115 kilometers in the northeast direction to 25 kilometers in the southwest direction. An increase in daily peak ozone concentration of 1 ppb was seen as far away as 190 kilometers in the northeast direction and 110 kilometers in the southwest direction.

10.14.2 Impacts of Ozone on Health

Ozone is a highly active oxidizing agent capable of causing injury to the lung (Mustafa and Tierney 1978). Lung injury may take the form of irritant effects on the respiratory tract which impair pulmonary function and result in subjective symptoms of respiratory discomfort. These symptoms include, but are not limited to, cough and shortness of breath, and they can limit exercise performance.

The vast database on the effects of ozone on humans and animals provides abundant evidence of its adverse acute effects. Laboratory-based human and animal studies have suggested effects on pulmonary host defenses and the immune system. In addition to acute effects, a wide range of subchronic and chronic effects have been identified in laboratory-based animal studies. Because chronic exposures are some cumulative function of a series of acute exposures a linkage exists between acute and chronic exposures, but the mechanisms, at present, are not fully defined.

10.14.2.1 Morbidity

The results of studies in animals and the range of chronic effects observed suggest that there is a significant potential for chronic effects in humans. In addition, the types of morphological changes caused by ozone in animals are also observed in the lungs of cigarette smokers. These changes are generally interpreted as representing early stages of chronic lung disease in smokers. Nonetheless, several epidemiological studies tend to support a concern about the potential for chronic effects in humans (Detels et al. 1987; Knudson et al. 1983; Kilburn et al. 1985). While there are acknowledged imperfections in their studies, they suggest an increased rate of lung function decline with ozone exposure that has also been observed in animal studies. Notwithstanding, at present, there is no definitive evidence from epidemiological studies that ambient ozone exposures cause chronic effects in humans.

ORNL/RFF (1994a, Part III) summarizes evidence from human clinical, epidemiological and field studies regarding the acute effects of ozone on human pulmonary function. Risk estimates for a number of urban areas have been performed using existing or projected levels of ozone (e.g., Hayes et al. 1987; Whitfield 1988; Fig. Krupnick and Kopp 1988; Hayes et al. 1989; and Hayes et al.

performed using existing or projected levels of ozone (e.g., Hayes et al. 1987; Whitfield 1988; Fig. Krupnick and Kopp 1988; Hayes et al. 1989; and Hayes et al. 1990). These estimates were developed for both pulmonary function and lower respiratory tract symptoms. Pulmonary function is not a useful measure for assessing damage. Pulmonary decrements have not been linked to specific symptoms of ill health by the medical community and without a symptom, there is no corresponding measure of the willingness to pay to avoid the pulmonary decrement.[22]

We thus focus on specific symptoms to measure health impacts. The particular symptoms chosen for our analysis, based on the earlier development of Krupnick and Kopp (1988), are as follows:

Epidemiologically-Based Endpoints

1. Total Respiratory Restricted Activity Days (TRRAD), used by Portney and Mullahy (1986). This measure is based on responses by adults over a two-week recall period. The effects model was based on an average for a two-week period of daily one-hour maximum concentrations of ozone, as recorded within a 20-mile radius of the study's respondents. The authors found no effects of ozone on bed-disability days (BDDs) or work-loss days (WLDs). Hence, they recommended that these effects be designated as M (minor) RRADs.

2. Any-symptom or condition day (Krupnick, Harrington, and Ostro 1987). This study resulted in a variety of response functions for a variable that took the value of one if any of 19 symptoms or conditions were present on a given day and zero otherwise. Except for eye irritation and headache, these symptoms and conditions were all respiratory related. The response function is based on adults and daily one-hour maximum ozone concentrations. In the accounting framework, the total number of Any-Symptom Days is reduced to remove double counting other endpoints.

3. Asthma-attack day (Holguin et al. 1985). Based on a 12-hour period of observations on identified asthmatics, and related to total oxidants, this study was modeled by Krupnick and Kopp (1988).

4. Eye-irritation day (Schwartz, Hasselblad, and Pitcher 1989).

5. Days of coughing (Schwartz, Hasselblad, and Pitcher 1989). This study investigated the relationship between total oxidants, coughing, eye irritation and chest tightness. Only the first two symptoms were

[22] Increased risk of subsequent mortality due to lower than expected pulmonary function is implicitly addressed in Section 10.14.2.2.

found to be significantly associated with oxidant exposure to members of the total population.

Clinical Based Study

6. Cough incidence (McDonnell et al. 1983).

7. Shortness of breath (McDonnell et al. 1983).

8. Pain upon deep inspiration (McDonnell et al. 1983).

McDonnell et al. (1983) found the difference in symptom scores taken before and after two-hour ozone exposures in a clinical setting. Morton and Krupnick (see Krupnick 1988) obtained the raw data from this study and performed a re-analysis, and then developed a procedure for adapting results from two-hour incidence to a symptom-day measure. Krupnick (1988) also found that the McDonnell et al. study provided the steepest dose-response function of any of the four "key" clinical studies relied upon by EPA's Clean Air Scientific Advisory Committee as evidence of the effect of low-level ozone on acute health.

Several steps were required to apply the Krupnick and Kopp (1988) results to estimate the effects of ozone on health at our two reference sites:

(1) The concentration-response functions from Krupnick and Kopp (1988) were coded into a simple Fortran program using the middle value coefficients plus the upper and lower 75% confidence limits.

(2) For the months of May, June, July, August and September, during which ozone production is significant at the southeastern site, daily one-hour maxima were transcribed from the EPA's Aerometric Information Retrieval System (AIRS) data base modified by a factor of 0.773 as described in ORNL/RFF (1994a, Part I). This calculation provides an estimate of the baseline (i.e., background) concentration near the power plant. The incremental changes in ozone concentrations were added to this background level. These increases in ozone concentrations were obtained from the modeling described in ORNL/RFF (1994a, Part I) using the median ozone conditions. The baseline and its increment were used as input to the health effects algorithms.

(3) On the basis of data presented in EPA (1986), and the recent studies by Larsen et al. (1991) and McDonnell et al. (1991), both finding consistent lung function decrement with exposures at the lowest exposure level utilized (80 ppb), we choose to adopt a threshold for respiratory effects at 80 ppb. In the execution of the computer code, the U.S. Environmental Protection Agency's Aerometric Information Retrieval System (AIRS) data (the baseline) plus the additional incremented attributed to the reference plant were checked for values below 0.08 ppm.

(4) The populations used for this evaluation comprise two cases. The first was the 50-mile population. The second was consistent with the population overlain by the ozone plume having an ozone concentration of 80 ppb or greater for one hour, regardless of the distance from the power plant.

The following equations (in the shaded boxes) give details on the dose-response functions used in this analysis.

Tables 10.14-1a and 10.14-1b show the estimated number on impacts by endpoint for the Southeast reference environment. The low and high estimates, referring to the 5th and 95th percentiles, solely reflect the uncertainty of the dose-response function coefficients. Table 10.14-1a gives estimated impacts within 50 miles (80 km) of the power plant. Table 10.14-1b gives the total impacts for the maximum extent of the ozone plume.

Table 10.14-1a. Annual health effects estimated to occur from ozone exposure (in thousands) within 50 miles (80 km)[1]

Southeast Reference site	Low	Mid	High
1. Total restricted activity day	0	3.3	5.8
2. Any-symptom day	4.7	7.2	12
3. Asthma-attack day	0.25	0.40	0.59
4. Eye-irritation day	8.3	10	12
5. Cough day	2.7	3.9	5.8
6. Cough incidence	16	24	34
7. Shortness of breath	8.6	14	19
8. Pain upon deep inspiration	5.1	13	22

[1] Note that these estimates reflect the size of the power plant.

Dose-response functions: ozone

Days of coughing: Based on Schwartz, Hasselblad, and Pitcher (1989),

$$\Delta c = \{[1/(1+\exp(-\gamma-\beta X_1))] - [1/(1+\exp(-\gamma-\beta X_0))]\} \text{ (pop)}$$

where

Δc = change in number of coughing incidents for the day

X_0 = daily 1-hour maximum for total oxidants, baseline in reference environment
Total oxidants are set equal to ozone/0.9

X_1 = daily 1-hour maximum for total oxidants including reference plant

γ = -1.98

β = 0.40, 0.61, 0.82

pop = entire population

Days of eye irritation: Based on Schwartz, Hasselblad and Pitcher (1989),

$$\Delta e = \{[1/(1+\exp(-\gamma-\beta X_1))] - [1/(1+\exp(-\gamma-\beta X_0))]\} \text{ (pop)}$$

where

Δe = change in days of eye irritation

X_0 = daily 1-hour maximum for total oxidants, baseline in reference environment

Total oxidants are set equal to ozone/0.9

X_1 = daily 1-hour maximum for total oxidants including reference plant

γ = -2.48

β = 1.72, 2.02, 2.32

pop = entire population

Dose-response functions: ozone (continued)

Incidences of coughing: Based on McDonnell et al. (1983),

$$\Delta C = \{[1/(1+\exp(-\gamma-\beta\omega X_1))] - [1/(1+\exp(-\gamma-\beta\omega X_0))]\}\ f\theta(\text{mpop})$$

where

ΔC	=	change in number of coughing incidences in two-hour period t
X_0	=	daily maximum hourly ozone concentration, baseline in reference environment
X_1	=	daily maximum hourly ozone concentration including reference plant
γ	=	-1.742
β	=	10.961, 14.1, 17.239
mpop	=	entire population
θ	=	percent of a two-hour period the population is exercising
f	=	the incidence-day factor
ω	=	the scaling factor for two-hour period t

Dose-response functions: ozone (continued)

Incidences of shortness of breath: Based on McDonnell et al. (1989)

$$\Delta C = \{[1/(1+\exp(-\gamma-\beta\omega X_1))] - [1/(1+\exp(-\gamma-\beta\omega X_0))]\}\ f\theta(\text{mpop})$$

where

ΔC = change in number of shortness of breath incidences for two-hour period t

X_0 = daily maximum hourly ozone concentration, baseline in reference environment

X_1 = daily maximum hourly ozone concentration including reference plant

γ = -0.076

β = 4.938, 7.265, 9.562

mpop = entire population

θ = percent of a two-hour period the population is exercising

f = the incidence-day factor

ω = the scaling factor for two-hour period t

Dose-response functions: ozone (continued)

Any symptom or condition (ARD): Based on Krupnick, Harrington, and Ostro (1987).

$$\Delta ARD = \beta^* (X_1 - X_0) (apop)$$

where

ΔARD	=	change in the number of days of "any" symptoms/conditions
β^*	=	marginal change in the stationary probability of experiencing any symptom/condition
	=	$p_0(1-p_1)\beta[p_1+(1-p_0)]/(1-p_1+p_0)^2$, where p_0 is the conditional probability of illness on day t given wellness on day t-1, p_1 is the conditional probability of illness on day t given illness on day t-1, and β is the ozone coefficient from the logit model regression.
	=	0.13, 0.20, 0.27
X_0	=	daily maximum ozone concentration, baseline in reference environment
X_1	=	daily maximum ozone concentration including reference plant
apop	=	adult population

Dose-response functions: ozone (continued)

Total respiratory-related restricted activity days (TRRADs): Based on Portney and Mullahy (1986),

$$\Delta TRRAD = TRRAD_0 \,[\exp\,[\beta(X_1 - X_0)] - 1]\,(apop)$$

where

ΔTRRAD	=	change in number of respiratory-related restricted activity days for the 2-week period
$TRRAD_0$	=	baseline per capita TRRADs for a 2-week period
X_0	=	average daily 1-hour maximums of ozone concentrations for each 2-week period, baseline in reference environment
X_1	=	average daily 1-hour maximums of ozone concentrations for each 2-week period including reference plant
apop	=	adult population
β	=	2.63, 7.99, 13.34

Dose-response functions: ozone (continued)

Asthma attacks: Based on Holguin et al. (1985)

$$\Delta a = [m/(1+m) - p]\ (apop)$$

where

$$m = [p/(1-p)]\ \exp\ (\beta\omega X_1 - \beta\omega X_0)$$

and

Δa	=	change in number of asthma attacks for the 7AM-7PM or 7PM-7AM period
p	=	baseline number of attacks per asthmatic for the day
X_0	=	maximum 1-hour ozone concentration for 7AM-7PM, baseline in reference environment
X_1	=	maximum 1-hour ozone concentration for 7AM-7PM including reference plant
apop	=	asthmatic population [estimated to be about 5% of the U.S. population (from Evans et al.)]
ω	=	scaling factors for half-day periods
β	=	3.58, 6.20, 8.82

Table 10.14-1b. Health effects estimated to occur from ozone exposure (in thousands) for the maximum extent of the ozone plume[1]

Southeast Reference site	Low	Mid	High
1. Total restricted activity day	0	3.5	6.8
2. Any-symptom day	3.1	8.3	13
3 Asthma-attack day	0.28	0.43	0.61
4. Eye-irritation day	9.3	11	13
5. Cough day	2.6	4.3	5.8
6. Cough	20	26	33
7. Shortness of breath	11	15	20
8. Pain upon deep inspiration	11	15	22

[1] Note that these estimates reflect the size of the power plant.

Portney and Mullahy's (1986) equation underestimates the total impact in that impacts on children are not included. Young children experience 5 to 10 times the incidence of acute respiratory episodes compared with adults. Additional research is needed to estimate dose-response functions for children.

10.14.2.2 Mortality from Exposure to Ozone

There is some limited epidemiological evidence that daily ozone concentrations are related to the risk of death. This evidence comes from two studies by Kinney and Ozkaynak (1991, 1992), one for New York, the other for Los Angeles. The authors used daily time series of death rates and pollution levels, following protocols quite similar to those followed by Schwartz and Zeger in their particulate-mortality studies. Unlike the body of particulate-mortality studies, however, cross-sectional studies have not identified an ozone-mortality link and the Schwartz and Zeger studies found no such link, either (although ozone levels were far lower in the cities they examined). We conclude, therefore, that it is premature to accord this link a central role in our damage estimates and follow NERA (1993) in assigning only a small probability that these effects exceed zero.

Using a linear ordinary least squares (OLS) model, Kinney and Ozkaynak (1991) find a small but statistically significant effect of ambient oxidants (ozone data were not available for this period) lagged one day on total and cardiovascular mortality rates, but not respiratory mortality rates. The authors settle on an oxidant effect of 0.3 deaths per one part per hundred million (pphm) average daily peak oxidants.[23] The daily peak standard is 12 pphm. The population of Los Angeles County during this period averaged about 7.2 million, with daily mortality averaging 152, 87, and 8 for total, cardiovascular, and respiratory mortality, respectively. Average daily peak oxidant levels were 7.5 pphm. The implied elasticity of the total mortality rate with respect to oxidants is:

[23] We assume that the ozone concentration is approximately equal to oxidants, since the impacts are difficult to distinguish.

$$\frac{\Delta\ Mortality}{\Delta\ Ozone} \cdot \frac{E\ [Ozone]}{E\ [Mortality]} = 0.3 \left(\frac{7.5}{152} \right) = 0.0148,$$

where E denotes the average value.

Statistically significant effects on mortality were also seen with temperature and with NO_2, a particulate measure, and CO, although collinearity among these three pollutants makes it impossible to disentangle their separate effects.

The New York study found somewhat larger effects of ozone on mortality rates: 0.55 deaths per pphm daily peak ozone, based on 163 deaths per day, implying an elasticity of 0.018. Because of a lack of documentation from this study at the time of our report, we rely on the Los Angeles results.

Because of the lack of corroborating studies using this new approach, for the Monte Carlo analysis, we assign 90% of the mass at zero, with 10% normally distributed around 0.00197. The standard error around the unadjusted coefficient (0.3) is 0.009. The mean number of annual ozone-induced premature deaths in the Southeast region are estimated to be 0.02, with a low estimate of 0 deaths and high estimate of 0.2 deaths. The mean value is based on the Monte Carlo simulation, which gives non-zero values even though we assign a 90% probability that the value is 0. Because these results are based tenuously on an ozone-relationship mortality that has been derived in only one published study (Kinney and Ozkaynak 1991), we report the mean value from this simulation as the *HIGH* case in the summary tables in Chapter 11.

Dose-response function for premature deaths from ozone exposure

Premature deaths: Based on Kinney and Ozkaynak (1991),

$$\Delta D = \beta \bullet D_B \bullet \Delta O \bullet 365 \bullet pop$$

where

ΔD = the change in annual deaths
β = the percentage change in the daily death rate per pphm change in average peak daily ozone concentrations
= (0.3 deaths per day/pphm)/(152 total deaths/day) = 0.00197
D_B = the baseline daily death rate (26 for the Southeast Reference environment; not considered for the southwest because of the low background concentrations)
ΔO = the change in average daily peak ozone concentration in pphm
pop = population

10.14.3 Damages and Externalities from Ozone

10.14.3.1 Morbidity Damages and Externalities from Ozone

To convert these predicted increases in acute effects (see Table 10.15-1) - symptoms, asthma attacks, and restricted activity days - into damages, estimates of individual WTP to avoid such changes are needed. An approach is also needed for aggregating these partly non-separable benefits to avoid double-counting. The full details on the WTP estimates and the aggregation approach are available in Krupnick (1987) and Krupnick and Kopp (1988). Here, the approach is summarized.

Three CV studies (Loehman et al. 1979; Tolley et al. 1986; and Dickie et al. 1987) have used bidding procedures to elicit estimated values for respiratory symptom days, with estimates ranging from $1 to $25 and more, on average, depending on the symptom, its severity, and whether a complex of symptoms are experienced.

All of these studies have significant drawbacks, mainly related to their age—the CV studies were performed before many of the most important advances in CV methodologies. At the same time, they offer quite consistent ranges of estimates for willingness-to-pay to avoid a particular type of symptom.

Krupnick's (1987) detailed analysis of these studies' strong and weak points led to a choice of values for the acute effects that attempted to make a fine distinction between studies. In a subsequent study by Krupnick and Kopp (1988), this approach was abandoned and "ballpark" estimates of values were used instead. Here, both sets of estimates (updated to 1989 dollars) are provided (Table 10.14-2) and used; the "ballpark" any symptom-day values are used to estimate morbidity damages when relying on epidemiological dose-response functions and the more specific and finely differentiated specific symptom-day values are used to estimate damages when relying on clinical dose-response functions.

For the purposes of the Monte Carlo simulation, all of the underlying distributions of the unit values in Table 10.14-2 are fit with lognormal distributions, with the exception of asthma attack values, which are fit with a normal distribution.

Table 10.14-2. Unit values of ozone-morbidity end-points (in 1989 dollars)

Endpoint	Low	Medium	High
Any symptom day (Krupnick and Kopp 1988)	2.98	5.97	11.93
MRRAD (Krupnick and Kopp (1988)	13.13	21.48	36.40
Asthma attack (9)	10.74	29.84	48.93
Specific Symptoms (Krupnick 1987)			
Cough	1.66	4.77	13.13
Short breath	0.72	9.55	21.48
Chest tightness	2.98	5.97	21.48
Throat irritation	2.90	3.58	10.31
Eye irritation	2.98	5.97	12.95
Upper respiratory	5.04	5.37	8.74
Lower respiratory	2.07	5.32	14.81

One problem in the use of these studies to estimate population benefits is that most studies simply multiply the total number of symptom-day reductions by the relevant unit values to obtain benefits. This may be incorrect if one assumes (with some empirical justification) that marginal valuations decline with additional days illness reduced. Hall et al. (1989) pooled the WTP estimates from asthmatics in the Rowe and Chestnut (1985) study with estimates for respiratory symptom reductions from the Loehman study to estimate WTP as a function of days sick. This function is $WTP = WTP_1 * N^{-0.5}$, where WTP_1 is the unit value and the number of symptoms per person per year, (N), was obtained by dividing total estimated symptom-days reduction (16 per year for a person living in Los Angeles) by population. Overall this procedure resulted in WTP estimates only 24% of what they would have been with N assumed equal to 1.0.

Four caveats are in order, however. First, the distribution of symptom-days for each person cannot be estimated from the data but must be determined by dividing total days reduction by population. Second, the studies finding declining marginal WTP are unclear about whether these days of reductions are to be experienced continuously or spaced over a year. WTP responses would likely be quite sensitive to this spacing. Third, outside of the Los Angeles area, and for small enough changes in ambient air quality, N may be less than 1.0, which would mean that the Hall et al. procedure would raise WTP above that obtained when N is assumed to equal 1.0. Is this reasonable, since no one actually experiences half a symptom-day? Fourth, the estimated decline in marginal WTP is very sensitive to assumed functional form, but there is too little information in the literature to estimate such functions confidently. In our calculations, we assume that N = 1.0.

As noted in the above section, two types of health effects estimates are generated—one from clinical studies and the other from epidemiological studies. The former cannot be used directly with the above estimates of value because the values are for a day's effect, while the clinical dose-response functions estimate 2-hour incidences of health effects. Thus, use of health effect estimates from the clinical studies requires converting incidences into days, for example, the number of two-hour incidences of coughing that would be valued equally to a "day" of coughing. There are no studies to rely on for these estimates. We therefore assume a range of 1.0 to 9.0 (incidences per day), with a best estimate of 3.0.

Aggregations

Once the damages from increased ozone levels from a scenario have been computed for the individual dose-response functions, these benefits must be aggregated to obtain the total benefits from that scenario. Because of the different approaches to estimating dose-response functions taken by the epidemiological and clinical studies, separate aggregations are used for each of these classes of studies. In addition, damages for the clinical aggregation are calculated for a "low clinical" and a "high clinical" case, where the "low" case assumes that eight two-hour incidences equal a symptom-day and the effects of ozone are restricted to heavy exercise periods and the "high" case assumes that one two-hour incident equals a symptom-day and the effects of ozone are felt at any exercise rate above rest.

For the aggregation of the results of individual epidemiological studies, one key issue is accounting for overlap between a symptom-day and a MRRAD. Note that, logically, any time a MRRAD is experienced, one or more respiratory symptoms or conditions must be experienced. At the same time, not all experiences of a symptom result in a MRRAD. One simple and reasonable procedure for accounting for the overlap is to count all of the MRRADs and only those symptom-days that exceed the number of MRRADs (A possible complication to this procedure would be if the reduction in the number of MRRADs exceeded the reduction in the number of symptom-days. Fortunately, this does not occur).

In line with the above discussion, the damages from an increase in MRRADs (computed only for adults, as no effect of ozone on RADs in children is apparent) are counted and added to the damages from "residual" additional "any" symptom-days (additional "any" symptom-days minus additional MRRADs) predicted using the "any symptom-day" function estimated by Krupnick, Harrington, and Ostro (1990). These are added to the damages from additional asthma attacks estimated by Holguin et al. and applied to the entire asthmatic population. The eye irritation-day and cough-day damages for children (taken from the Schwartz, Hasselblad, and Pitcher study) are then added.

For the clinical aggregation, the symptoms reductions predicted by the set of clinical studies are restricted to those from the dose-response functions estimated by Morton and Krupnick using the underlying data from all four of the key clinical studies and those taken from the McDonnell et al. study, as these provide the largest damages. The estimates of effects and damages from the individual symptoms are simply applied to the entire population and summed together.

Tables 10.14-3(a) and (b) show morbidity damages by endpoint for the Southeast Reference environment, when confining the analysis to within 50 and within 1,000 miles of the plant, respectively. The low and high estimates, referring to the 5th and 95th percentile, solely reflect the uncertainty of the dose-response function coefficients and the unit damage values. The tables are split to show aggregate damages based on epidemiological studies and clinical studies. Within 50 miles of the Southeast plant, the mean estimate of damages is 0.062 mill/kWh for Aggregation I and 0.065 mill/kWh for Aggregation II. The confidence intervals reported are also similar, 0.037-0.1 mill/kWh for Aggregation I and 0.025-0.13 mill/kWh for Aggregation II. Extending the analysis to 1,000 miles of the plant increases ozone damages by a relatively small proportion, as compared to the large increase in damages when the analysis is extended to a 1,000 mile radius for particulates. Figures 10.14-3(a) and (b) show the cumulative density function (CDF) for total damages per kWh based on the epidemiological studies within 50 and within 1,000 miles of the Southeast plant. All estimates of ozone-related damages are considered to be externalities. No factors have been identified that internalize any of these damages.

Table 10.14-3a. Ozone—morbidity: damages per year (in thousands of 1989 dollars) in the Southeast [for 0-50 miles]

Aggregation	Pathway endpoint	Low	Mid	High
I Epidemiological studies	Minor respiratory restricted activity day	1.1	79	170
	Any symptom-day	8.3	47	110
	Asthma attack-day	3.2	12	23
	Eye irritation-day	31	66	120
	Cough-day	5.9	22	51
	Total pathway damages I	120	200	310
	Total pathway damages I (mills/kWh)	0.037	0.062	0.095
II Clinical studies	Cough incidence	8.9	50	150
	Shortness of breath	9.8	78	230
	Pain upon deep inspiration	14	87	200
	Total pathway damages II	83	210	420
	Total pathway damages II (mills/kWh)	0.025	0.065	0.13

Table 10.14-3b. Ozone—morbidity: damages per year (in thousands of 1989 dollars) in the Southeast [for 0-1000 miles]

Aggregation	Pathway endpoint	Low	Mid	High
I Epidemiological studies	Minor respiratory restricted activity day	0	87	190
	Any symptom-day	5.1	52	120
	Asthma attack-day	3.9	13	25
	Eye irritation-day	34	73	130
	Cough-day	6.4	23	52
	Total pathway damages I	130	220	340
	Total pathway damages I (mills/kWh)	0.039	0.068	0.1
II Clinical studies	Cough incidence	9.5	53	140
	Shortness of breath	12	81	240
	Pain upon deep inspiration	33	96	200
	Total pathway damages II	100	230	430
	Total pathway damages II (mills/kWh)	0.031	0.07	0.13

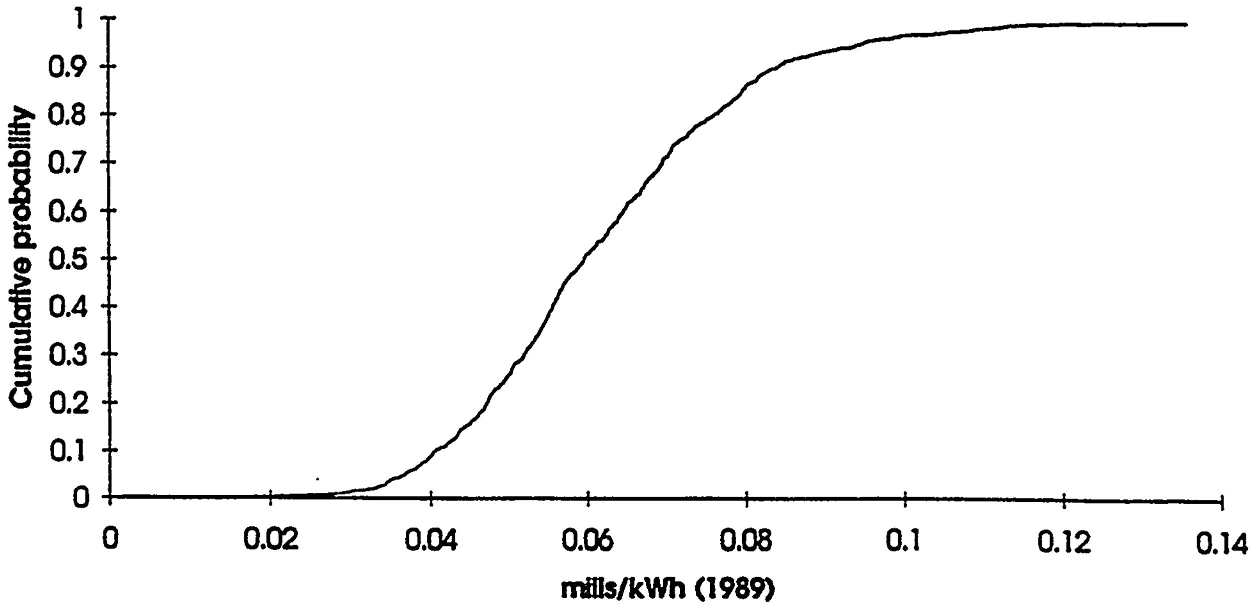

Figure 10.14-3 (a). Ozone -- morbidity damages within 50 miles of the Southeast plant based on epidemiological studies.

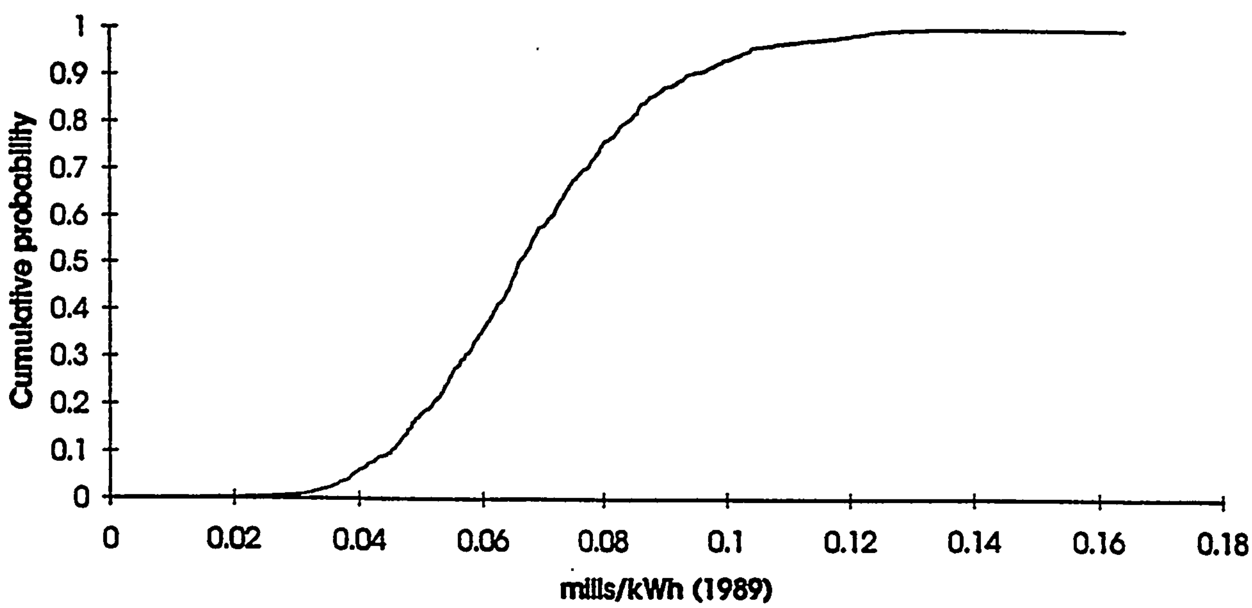

Figure 10.14-3 (b). Ozone -- morbidity damages within 1000 miles of the Southeast plant based on epidemiological studies.

10.14.3.2 Mortality Damages and Externalities from Ozone

Premature deaths from ozone are valued using Fisher, Chestnut, and Violette (1989), for the same reasons it was chosen for valuing premature deaths from exposure to particulates. For a full discussion of the issues, consult Section 10.8. Using a value of a statistical life (VSL) based on this study (lognormally distributed with median $3.7 million and geometric standard deviation of 1.53, we get mean ozone-mortality damages for the Southeast Reference environment to be 0.037 mills/kWh, while the low (5th percentile) estimate is 0 and the high estimate (95th percentile) is 0.32 mills/kWh. In the cumulative distribution function (CDF) for this pathway, because of the way in which the uncertainty of the dose-response function was characterized, there is a 90% chance that damages are zero. The characterization of the uncertainty accounts for the mean being much closer to the low estimate than the high estimate.

As stated previously, however, these results are based on a single paper reporting an exposure-response relationship. Thus, we judgementally set the mean estimate to be the HIGH estimate in the summary tabulation in Chapter 11.

10.15 EFFECTS OF OZONE ON CROPS[24]

10.15.1 Precursor Emissions and Change in Ozone Concentrations

Exhaust gases from power plants that burn fossil fuels contain concentrations of sulfur dioxide (SO_2), nitric oxide (NO), particulate matter, hydrocarbon compounds and trace metals. Estimated emissions from the operation of the hypothetical 500 MW natural gas-fired power plant are given in Chapter 5. Ozone is considered a secondary pollutant, since it is not emitted directly into the atmosphere but is formed from other air pollutants, specifically, nitrogen oxides (NO_x) and non-methane organic compounds (NMOC) in the presence of sunlight. Additionally, ozone formation is a function of the ratio of NMOC concentrations to NO_x concentrations.

While most large power plants are considered significant sources of NO_x emissions, NMOC emissions from power plants are not considered significant and do not typically require control. Since NMOC emissions from power plants are not present in sufficient quantities to provide an optimal hydrocarbon to NO_x ratio within the plume, ozone formation from the emissions of power plants is the result of a complex series of reactions involving NO_x emissions from the plant, reacting with ambient concentrations of hydrocarbons, hydrocarbon derivatives and ozone. Ambient hydrocarbons may be from either man-made or natural sources.

[24] Refer to Appendix D for discussion of SO_2 impacts on crops and forests.

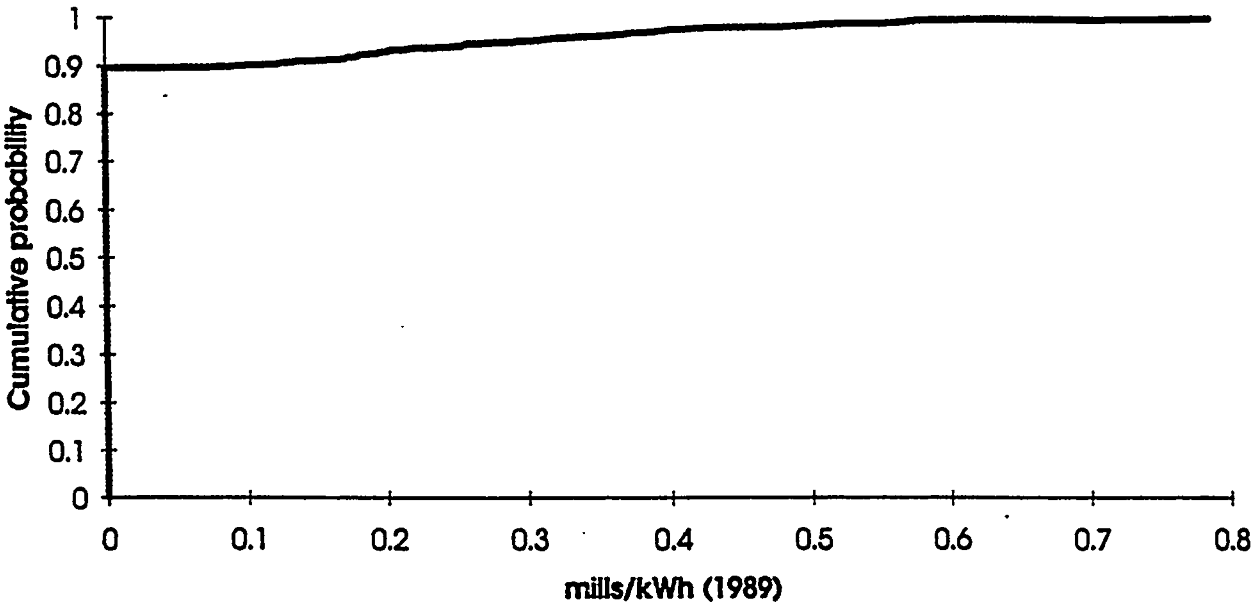

Figure 10.14-4 (a). Ozone--mortality damages within 50 miles of the Southeast plant

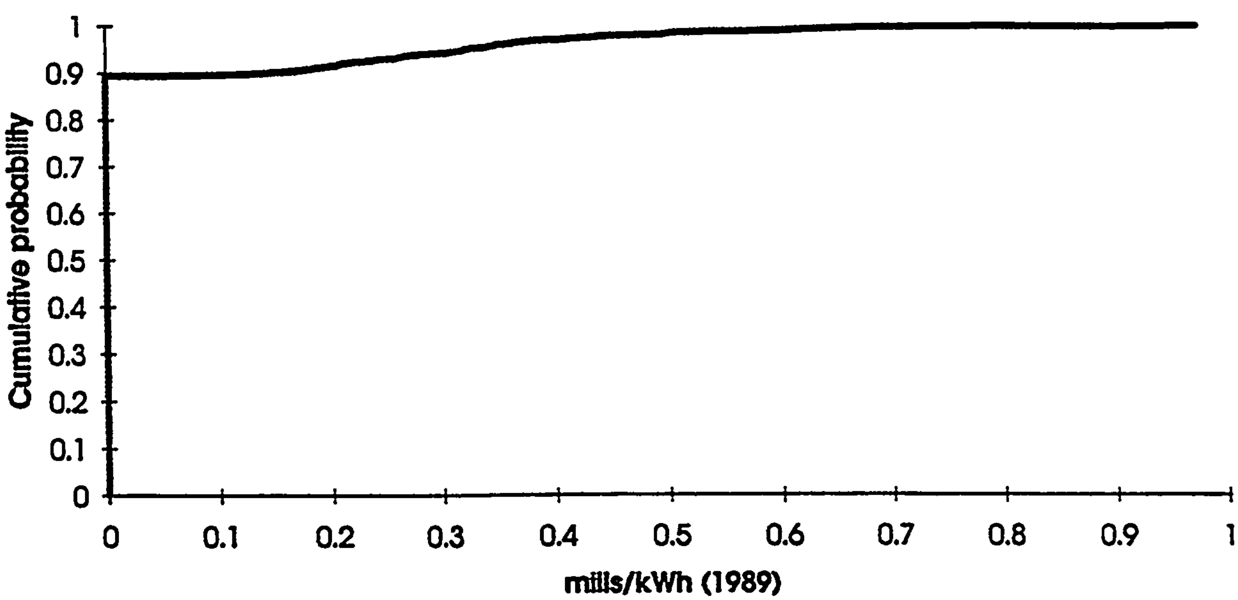

Figure 10.14-4 (b). Ozone--mortality damages within 1000 miles of the Southeast plant

The formation of ozone within a power plant plume, is controlled by a combination of conditions, including ambient ozone concentrations which provide the mechanism necessary for the initial conversion of NO to NO_2, reactive hydrocarbon concentrations of the ambient air mass, and the rate of entrainment of ambient air within the plume. These conditions, as well as sufficient photochemical activity, determine whether ozone levels in the plume will eventually exceed ambient levels to form the widely documented ozone 'bulge' (Keifer 1977; Meagher et al. 1981; Luria et al. 1983; Gillani and Wilson 1980; Davis 1974).

The natural gas fuel cycle analysis requires that an estimate be made of ozone concentrations that occur in the vicinity of a gas-fired power plant located at the Southeast Reference site, due to emissions of nitrogen oxides (NO_x) and non-methane organic compounds (NMOC) from the plant. Ozone modeling is not done for the Southwest region due to the low background levels of ozone and the lack of agricultural activity in the vicinity of the site for the power plant.

The crop effects analysis requires an estimate of the seasonal 9 a.m. to 9 p.m. average ozone concentrations due to the plant. This modeling requirement presents a unique challenge, since all the currently available computer models which simulate ozone formations are designed to predict hourly and instantaneous ozone concentrations, over a period of several days at most. These predictions are primarily for comparison to the National Ambient Air Quality Standard (NAAQS) of 120 ppb (one-hour average) not to be exceeded more than once per year.

The potential impact of the power plant NO_x and NMOC emissions on ozone concentrations was modeled for the Southeast Reference site using the U.S. Environmental Protection Agency model, Ozone Isopleth Plotting Mechanism (OZIPM-4) and a new model developed for this study, the Mapping Area-Wide Predictions of Ozone model (MAP-O_3).[25] The OZIPM-4 model is a trajectory model which predicts ozone concentrations as a function of travel time. The MAP-O_3 model provides spatial resolution by predicting the location of the plume during each hour of the day, for the ozone season. The MAP-O_3 model predicts area-wide ozone concentrations over the ozone season, by combining ozone concentrations predicted with the OZIPM-4 model with plume trajectories calculated from wind speed and direction measurements. A detailed description of the modeling approach is presented in ORNL/RFF (1994a, Paper 3).

Results from the MAP-O_3 model, for the crop effects portion of the natural gas fuel cycle analysis are shown on isopleth maps in Figures 10.15-1 and 10.15-2. (Results from the MAP-O_3 model were converted to Cartesian coordinates and written to files for import to the isopleth graphing routine SURFER.) The power plant is shown in the center of each isopleth map with a triangle marker. The scale of each figure is in kilometers from the plant. The changes in ozone concentrations

[25] OZIPM-4 is the type of model commonly used in analyses for electric utilities and State Public Utility Commissions. MAP-O_3 was developed and applied for the first time in this study (ORNL/RFF 1994a).

are reported in ppb. Results are presented separately for two cases; one with and one without ozone depletion. (Ozone concentrations above the background level will be referred to as ozone bulges and ozone concentrations below the background level will be referred to as ozone depletions.)

Figure 10.15-1 shows the predicted impact of the natural gas-fired power plant emissions on the seasonal (May-September) 12-hour (9 a.m. - 9 p.m.) average ozone concentrations due to ozone bulges only. These results represent an upper bound estimate of the impact of the power plant emissions on ozone concentrations, since ozone scavenging is not accounted for. As seen in Figure 10.15-1, the highest 12-hour seasonal average ozone concentration (based on ozone bulges only) is 0.8 ppb (the smallest isopleth line) and occurred approximately 30 kilometers from the plant in the east northeast (ENE) direction. The lowest isopleth plotted in Figure 10.15-1 is 0.01 ppb. This increase in seasonal average ozone concentration occurred as far away as 260 kilometers from the plant in the northeast direction (NE) and 170 kilometers in the southwest (SW) direction.

Figure 10.15-2 shows the predicted impact of the natural gas-fired power plant emissions on the seasonal 12-hour average ozone concentrations due to both ozone bulges and depletions. These results represent a mid-estimate of the impact of the power plant emissions on ozone concentrations. The highest 12-hour seasonal average ozone concentration is 0.6 ppb (the smallest isopleth line) and occurred approximately 20 kilometers from the plant in the east northeast (ENE) direction. The lowest positive isopleth plotted in Fig. 10.15-2 is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 240 kilometers from the plant in the northeast direction (NE) and 160 kilometers in the southwest (SW) direction. The results shown in Figure 10.15-1 and 10.15-2 are essentially the same since NO_x emissions from the natural gas-fired power plant do not cause significant ozone depletion on a seasonal average.

In addition to the results seen in Fig. 10.15-1 and 10.15-2, the seasonal 12-hour average measured background ozone concentration of 53 ppb was also used in the crop effects portion of the study.

10.15.2 Impacts of Ozone on Crops

Losses of crop production caused by ozone increases associated with the reference power plant were calculated for each county that had about one-quarter or more of its area inside the 0.1 ppb (i.e. total concentration of 53.1 ppb) isopleth yielded by the dispersion modeling discussed above. The estimates are based on existing ambient ozone levels within the region (53 ppb 12-hr average, 9 a.m. to 9 p.m., May through September) and on modeled increases in ozone concentrations resulting from the power plant (12-hr average, 9 a.m. to 9 p.m.).

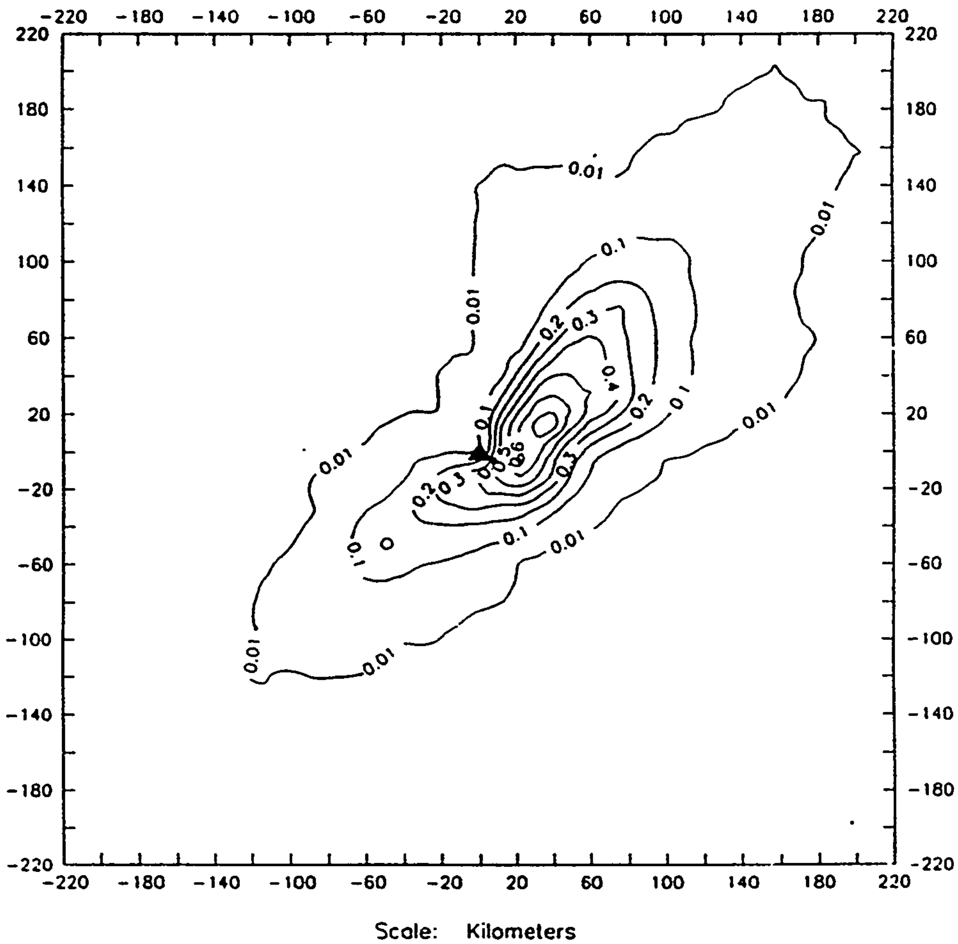

Figure 10.15-1. Positive incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the natural gas-fired power plant at the Southeast Reference site, (positive concentrations are above ambient)

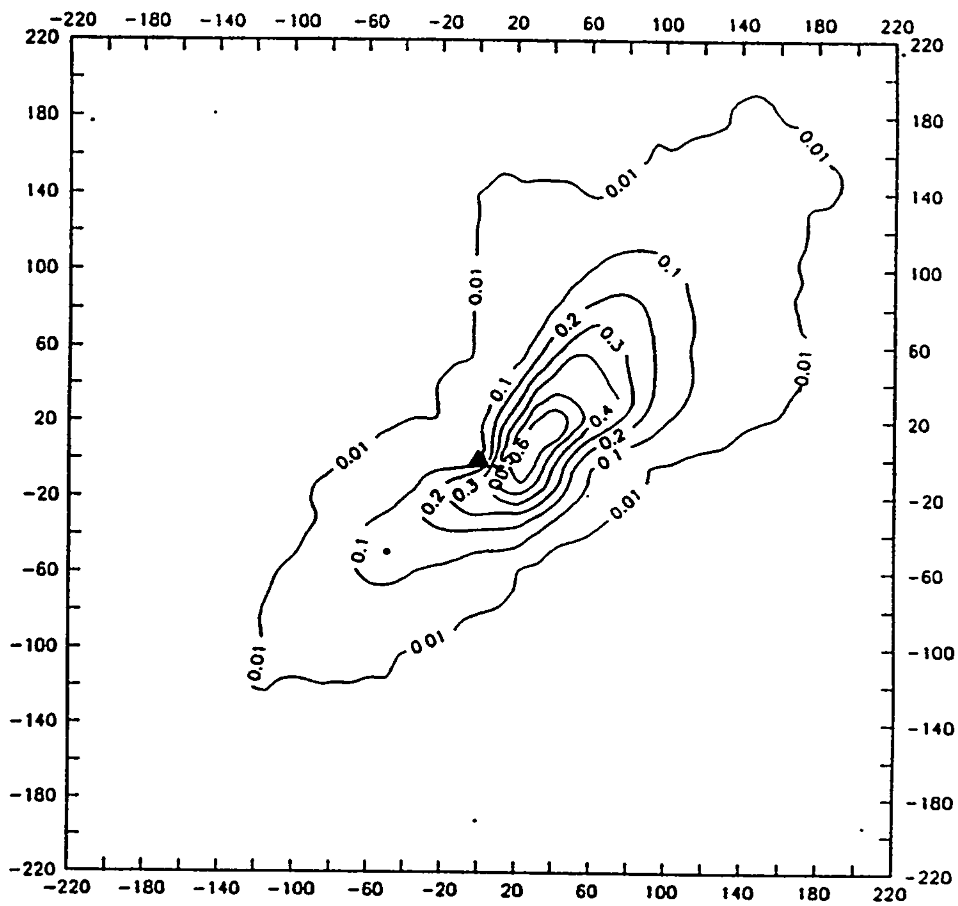

Figure 10.15-2. Total incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the natural gas-fired power plant at the Southeast Reference site, (total concentrations include both positive and negative incremental concentrations)

Ozone-induced crop loss in each county was approximated by a four-step calculation that yielded the following for each county: (Step 1) the new average ozone concentration representing the various levels of modeled ozone concentrations over the entire county during power plant operation; (Step 2) the percent crop losses in that county resulting from the modeled ozone concentration and from the existing ozone concentration (53 ppb); (Step 3) the production of each crop under the modeled and existing ozone concentrations; and (Step 4) the quantity of crop loss caused by the power plant.

In the first step, isopleths of ozone concentrations generated by air dispersion modeling were overlaid on a regional map showing county boundaries. The fractions of each county within the areas between successive isopleths (i.e., the fraction between 53.01 and 53.1 ppb isopleths, that between 53.1 and 53.3 isopleths, etc.) were calculated based on map area measurements obtained with a polar planimeter. The average ozone concentration in each area between two successive isopleths was calculated as the average of the two isopleth concentrations (e.g., an average of 53.2 ppb represents the area between the 53.1 and 53.3 ppb isopleths). This yielded two or more of these averages for each county, because areas between two or more pairs of successive isopleths were present in each county. Finally, these averages for the different modeled ozone concentrations in the county were averaged to obtain the overall average ozone concentration for the county during power plant operation.

In the second step, the percent loss of each crop in each county was estimate (interpolated) by applying the modeled ozone concentration to the crop dose-response data provided in Table 10.15-1 (refer to Appendix B for further discussion), assuming a linearized dose-response function. This linearization of Heagle et al.'s (1988) Weibull functions is justified by the small incremental increase in annual average ozone concentration due to the power plant. Percent crop loss was also determined for the *existing* ozone level without the power plant.

In the third step, the crop production during power plant operation was calculated from the percent loss applied to the county's potential production in the absence of ozone. This potential production was calculated from the known production under existing conditions and the percent crop loss (under existing conditions) estimated from the dose-response data (see Table 10.15-2 for the calculation). Finally, to determine the amount of crop loss caused by the power plant, the crop production during power plant operation was subtracted from the existing crop production.

Table 10.15-1. Crop yield losses in (percent) estimated to result from various ozone concentrations

Crop	Mean ozone concentration during growing season (ppb)				
	40	50	60	70	80
Soybeans					
(Average of 22 experiments with about 10 cultivars)	5.6%	10.1%	15.5%	21.5%	28.4%
Tobacco					
(Average of 2 experiments)	5.0%	9.0%	13.0%	18.0%	23.0%
Wheat					
(Average of 5 experiments with 3 cultivars)	9.0%	15.0%	20.8%	26.8%	33.2%
Corn					
(Average of 3 experiments with mixtures of 5 cultivars)	1.7%	3.7%	6.7%	10.3%	15.7%
Red clover hay	9.0%	19.0%	31.0%	44.0%	59.0%
Alfalfa hay (2 experiments, 1 cultivar)	5.0%	8.0%	11.5%	15.5%	19.0%

Source: Heagle et al. (1988).

Table 10.15-2. Outline of the procedure for calculating the crop loss associated with the hypothetical power plant in any given county

1. Obtain the existing ozone concentration
2. Determine the new ozone concentration occurring during power plant operation
3. Determine the percent crop loss for the existing ozone concentration and for the new ozone concentration, according to the dose-response data
4. Determine the potential production in the absence of ozone:
   $$PP = P / [(100 - Pc)(0.01)]$$
   where PP = potential production, P = production under ambient conditions, and Pc = the percent crop reduction under ambient conditions
5. Calculate the crop production during power plant operation by using the potential production and the percent crop loss under the new ozone concentration
6. Calculate the crop loss resulting from power plant operation by subtracting the new crop production from the existing crop production

Existing crop production and the estimated incremental crop losses associated with power plant operation are shown in Table 10.15-3. The table also shows the total crop loss in all affected counties in Tennessee and elsewhere (including only those counties about one-quarter or more within the 53.1 ppb isopleth). In counties mostly beyond the 0.1 ppb isopleth, the crop losses are assumed to be very small.

10.15.3 Damages and Externalities to Crops from Ozone

In valuing the crop losses due to increased ambient ozone in the Southeast Reference environment, one must estimate the change in social welfare due to these losses. This change can be broken down into two parts: (1) the change in consumer surplus and (2) the change in producer surplus.[26]

One parameter that could potentially change both consumer and producer surplus is a price increase due to a reduction in crop output. In the crop market, however, the ozone-induced changes are so small relative to national output (on the order of 0.001%) that the price impacts would be negligible. Because of this, we can assume that market prices are not affected by the ozone-induced crop reductions.

We value the welfare losses in the market for a crop as the loss in yield times the market price, i.e. the market value of the lost crop. The loss in yield can be derived using the dose-response functions for ozone on crop yield and crop data from the reference environment. The estimated damages are tabulated in Table 10.16-3.

The crops listed in Table 10.15-3 are not all the crops in the counties affected. We assume that they comprise half of the total value in crops and that they are affected by ozone in a way similar to the listed crops. The resulting damages are $124,000 per year or 0.06 mills/kWh -- all of which is considered an externality.

10.16 EFFECTS OF PLANT CONSTRUCTION AND OPERATION ON EMPLOYMENT

10.16.1 Employment Impacts

In this section we present a methodology and report an estimate of the net employment benefits (negative damages) that may result from construction and operation of an natural gas-fired power plant in Tennessee or New Mexico (the Southeast and Southwest reference environments considered in this study). The methodology and data for this calculation are described in more detail in ORNL/RFF (1994a, Part V). It is important to note that similar employment benefits will accrue in varying degrees to each fuel cycle. For example, the majority of employment benefits that we identify result from the construction of the facility, and other types of facilities will share similar benefits. Consequently, evaluation of these employment estimates must occur through a comparison between fuel cycles, rather than a direct comparison between these estimates and other damage estimates.

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[26] For an explanation of these terms, see ORNL (1994a, Part IV).

Table 10.15-3. Damages to crops by ozone

Crop	Units	Baseline production	Loss in Production	Damage	Unit-Price
Soybean	1000 bushels	337	0.081	479	$5.95/bu.
Wheat	1000 bushels	538	0.116	297	$3.03/bu.
Corn	1000 bushels	2,035	0.302	528	$2.57/bu.
Tobacco	1000 lb	34,960	9.247	28,000	$1.747/lb.
Alfalfa Hay	1000 tons	77	0.015	1,410	$93/ton
Other Hay	1000 tons	795	0.0669	31,400	$47/ton
TOTAL				$62,200	

The second context for assessing employment effects is in a project or investment specific context, which is the relevant context for this study. In this setting macroeconomic tradeoffs, for example between employment and inflation, are usually ignored because an individual project is assumed to have little effect on prevailing wages and prices. A main source of controversy in estimates of employment benefits is that many analyses fail to distinguish between impacts analysis at the project specific level and net economic impacts.[27] For example, in the early days of benefit-cost analysis as it was applied to water development projects, advocates for those projects often counted *all* of the employment opportunities involved with such a project as economic benefits. In addition, secondary and indirect employment that was created by spending of earnings from primary employment would also be counted. This same approach might typically be applied today by business interests who want to advocate public investments in a specific locale.

The role of economists has frequently been to point out the inadequacy of simple impacts analysis. In many cases economists oppose estimation of employment benefits because under many (possibly, almost all) circumstances economists believe that labor markets work well enough that payments to labor can be considered an adequate reflection of the marginal social cost of the economic resource utilized in production. Included in this perspective is a recognition that

[27] Sanghi (1991).

some "frictional" unemployment is considered to be an efficient way for the labor market to allocate resources, often referred to as the "natural rate of unemployment." When this position is correct, reducing local unemployment through investment projects generates a simple transfer of income from another part of the country or from another group of people, rather than a net increase in social wealth. Most economists believe this is an approximately adequate picture of most labor markets, *unless* a compelling case can be made that unemployment is widespread and expected to be chronic and persistent. In the latter case, the social opportunity cost of employing the unemployed is considered to be below the market wage, so that new employment opportunities produce a net increase in social wealth rather than a transfer of income.[28]

The problem with impacts analysis is that it ignores the opportunity cost of workers who would be employed in the new project. If a worker was previously employed, and if we assume that labor markets work efficiently so that market wages reflect the marginal value of labor services provided, then the net economic benefit of employing a worker in a new job would be the wage at the new job less the wage at his or her previous employment. Since, in most instances these wages would be close together, one could conclude that in this hypothetical example there would be few or no economic benefits associated with the new job creation. Low rates of unemployment are generally considered *a priori* evidence that employment benefits do not exist. Conversely, rates of unemployment above what is considered the natural rate are generally considered *a priori* evidence that employment benefits might exist.

It is noteworthy that a region may have persistently higher rates of unemployment than the national average in many sectors of the economy.[29] Consequently, employment benefits are possible even when the nation is viewed as "fully employed." This possibility raises another set of economic considerations. Some economists would oppose policies to correct for regional unemployment because such policies, such as public works projects, serve to delay the sometimes painful but necessary adjustments that must occur in a competitive economy. On the other hand, some economists would note that policies to stimulate employment may help ease the path of adjustment, lowering its cost. More importantly, such policies may be instrumental in the development of skills and work experience, often termed "human capital," that can make a regional economy more vital. We emphasize that in the context of this study both these perspectives have limited relevance because we are not evaluating corrective policies but attempting to account for the effects of a project specific investment.

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[28] Hamilton et al. (1991).

[29] Some economists would argue, however, that regional differences in unemployment rates may simply reflect long-term frictional forces or even different utility functions among individuals living in different regions.

In summary, new employment opportunities create real (net) benefits only when there exists a situation in which labor resources would otherwise be involuntarily idle or under-utilized in a chronic, persistent way. When properly specified, these benefits are equivalent to the difference between the private cost of labor (the market wage) and society's opportunity cost (or the shadow price) of labor.[30] In a perfectly competitive economy the wage rate and the shadow price will coincide. Hence, the market wage will be a good measure of society's opportunity cost of labor because it will be just sufficient to draw labor away from its next most productive activity. However, when the ideal circumstances that characterize a competitive economy are not satisfied then the opportunity cost of labor will differ from the market wage. For example, persistent unemployment in a specific occupation and region of the country may cause the opportunity cost of labor to be less than the market wage, which may be rigid due to a number of institutional factors. When inputs to the production of energy services stand idle or under-utilized at their current market price or wage their market prices will not represent social costs.[31]

Any under-utilized factor of production is subject to a similar analysis, whether it be capital, natural resources, labor or commodities. In this study we ignore factors other than labor inputs. It is widely felt that capital markets have become increasingly efficient and capital increasingly mobile over the last few decades. New financial institutions and instruments, and the consolidation of economic enterprises have contributed to this trend. With regard to natural resources, an argument can be made in some cases that resource depletion exceeds the optimal rate, but it is widely felt that in general resource markets work efficiently. Furthermore, we lack a simple test of the performance of resource markets. Consequently, we focus exclusively on labor markets and the possibility that workers are previously unemployed or under-employed. In this case, society's opportunity cost of employing workers in new activities is less than their wage.

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[30] Labor input into the production of new energy services draws labor away from other activities. Economists refer to the value of goods and services that society must forego in order to direct labor into new activity as society's opportunity cost of the labor input, or the shadow price of labor. Implicit in this formulation is the idea that social welfare is an aggregation of individual welfare. The concept of opportunity cost includes the value of service flows provided from idle time and nonmarket activities, so in general the opportunity cost of an unemployed person's time is not zero. A seminal discourse of the use of shadow prices for investment decisions is found in Lind (1982).

[31] The possibility that resources would remain idle or under-utilized at current market prices or wages begs the question as to why prices or wages do not adjust. If a resource is under-utilized because its price is too high, a simple view of markets would suggest that price would fall until it equals the marginal value that the resource would have in some productive use. An empirical analysis must recognize that prices and wages do not always adjust in such a smooth fashion. Prices and wages may be *rigid* due to long-term labor contracts, the existence of market power, or other phenomena.

Equivalently, it is sometimes stated that there are hidden benefits that result from new employment in this activity.

Empirical analysis hinges on the assessment of labor markets that are affected by specific investments associated with the natural gas fuel cycle. We emphasize that although estimation of employment benefits, and evaluation of policies that address employment benefits, remain controversial in economics, the theoretical underpinning that we outline above is widely accepted, if difficult to measure and empirically verify. If potential employment benefits are ignored or set equal to zero, this is *equivalent to the assumption* that labor markets work effectively and that there is approximately zero unemployment above the natural rate of unemployment including frictional unemployment. The approach we outline here and in ORNL/RFF (1994a, Part V) contains an empirical analysis of this question. To account precisely for the extent to which the employment of labor services makes use of previously under-utilized resources it would be necessary to trace each unit of labor employed to its source and to inquire into its alternative use. This discussion follows the general literature in proceeding under the assumption that there is insufficient information to allow such a precise accounting.[32] Instead we assert that it is sufficient to observe persistent unemployment (above the natural rate of unemployment) in relevant labor markets in order to conclude that employment benefits exist.[33]

Factors to consider in the evaluation of relevant labor markets include the employment profile of the fuel cycle. This includes a temporal dimension. Employment associated with new generating capacity is typically described in two phases: construction (which is temporary in nature) and operation (which is long-term). Second, the profile must be sector-specific, according to employment categories for which unemployment data can be obtained. Examples are: laborers, petroleum engineers, economists, etc. Third, the profile must be region-specific. In principle, the relevant region will vary with each sector depending on characteristics of the labor market. For example, refinery workers may be drawn from a several county area while petroleum engineers may be drawn from a national employment market.

Unemployment must be estimated for each relevant employment sector and region. In principle, one would prefer to use statistical techniques to forecast unemployment into the relevant time horizon. A reasonable first-order

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[32] This analysis utilizes a partial equilibrium approach, in which the labor market is modeled in isolation from other segments of the economy. (See Ward and Deren, 1991). A more rigorous technique is to construct a general equilibrium model that allows individuals to optimize in response to price changes and adjust their own behavior accordingly. (See Squire and van der Tak, 1975.) However, general equilibrium models of regional economies are unlikely to exist and those that do are unlikely to capture features of particular concern to our study.

[33] See Haveman (1970), Gramlich (1981) or Sassone and Schaffer (1978) for additional exposition.

approximation can be obtained through the use of long-run unemployment rates (perhaps twenty-five year average rates) amended by information about investment and growth in the affected region.

The estimated unemployment rate will include an element that is sometimes termed "frictional unemployment," the "nonaccelerating inflation rate of unemployment" (NAIRU), and more generally, the "natural rate of unemployment." This natural rate reflects the expectation that at any one time there will always be a segment of the population that is in transition between jobs, perhaps looking for a new job or to acquire new skills. Recent estimates of the natural rate of unemployment range from 4.7 to 6.5 percent (although, in principle, they can vary by occupation and region).[34] Consequently, many economists describe a fully employed economy as one in which the unemployment rate is in this range. Persistent unemployment rates that are above this range reflect a shadow price (social cost) of labor services that is less than the market wage.

A unifying representation of the potential role of employment benefits is embodied in the recognition that in any labor market, there is some probability between zero and one that a worker who is hired will be drawn from the pool of previously unemployed workers, and some probability that the worker will be drawn from other existing employment. In the latter case, there is a probability that someone to fill the worker's old job will be drawn from the pool of previously unemployed workers, and some probability that, again, the worker will be drawn from another existing job. After this chain of possibilities is played out, there is a probability that a new worker was ultimately drawn from the pool of previously idle workers, or that some old job was eliminated from the economy. The probability that a worker in the previous chain of events is drawn from the pool of previously idle workers is viewed as a function of the unemployment rate. A representation of such a probability distribution was introduced by Haveman and Krutilla (1967) and is represented in ORNL/RFF (1994a, Part V). We note that this general relationship would be expected to differ among different sectors of the economy, hence a family of probability distributions is used to allow for sensitivity analysis. In addition, we again note that one would not expect the probability of drawing a worker from the pool of previously unemployed to rise above zero until the unemployment rate rises above the identified natural rate of unemployment.

If some percentage of the newly employed workers is expected to be drawn from the pool of previously idle workers, the market wage will be an overestimate of the social opportunity cost of employment. This difference is the net new employment benefit that we seek to measure. A preliminary estimate of the employment benefits associated with each expenditure in a primary industry is obtained by multiplication of the total earnings using earnings multipliers by the probability that workers are drawn from the pool of previously unemployed

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[34] See Johnson and Layard (1986). The range of estimates results from different theoretical formulations of the labor market. However, there is broad agreement that there has been a secular increase in the natural rate of unemployment since the early 1950s.

workers.[35] Finally, this estimate must be adjusted to reflect the opportunity cost of time for unemployed workers. Unemployed individuals also attach a positive value to their time, even if it is not spent in the workplace. Some individuals may be providing productive services such as child care, others may be enjoying leisure.

10.16.2 Employment Benefits

Using the methods developed fully in ORNL/RFF (1994a, Part V), we get an MID estimate of benefits across all industries due to all spending associated with the project to be 0.58 mills/kWh for the Southeast Reference environment and 0.31 mills/kWh for the Southwest Reference environment. These numbers are our preferred midpoint estimates of net new employment benefits according to our analysis. The estimate for the Southeast Reference environment in particular is large due to persistent high unemployment in the New Construction in the East South Central region relative to other parts of the country.

We have calculated estimates based on alternative assumptions in order to determine the sensitivity of results to each assumption and to provide a judgmental ninety percent confidence interval for this benefit estimate. The assumption about the opportunity cost of an unemployed person's time may be most critical. The next most critical assumption is the identification of a natural rate of unemployment. The third most critical assumption is the identification of the relevant labor market. In order to construct a reasonable confidence interval for the point estimate of employment benefits, one can not in general combine reasonable conservative or generous assumptions for each relevant parameter and feed these into the model. The actual level of confidence that is generated by combinations of assumptions depends in a complicated way on the nature of the underlying probability distributions.

In the Southeast, the range of the 90% confidence interval from 0.31 to 1.47 mills/kWh should be taken as a measure of the uncertainties that are embedded in this analysis. On the other hand, this range and our identified midpoint estimate of 0.58 mills/kWh indicate our confidence that employment benefits are significant. Similarly, in the Southwest the 90% confidence interval between 0.16 and 1.17 mills/kWh, and the midpoint estimate of 0.31 mills/kWh, indicate that the true value is greater than zero.

10.16.3 Externalities from Employment

Most of the institutional and economic factors that would appear to intervene between an opportunity cost estimate of employment benefits provided above and estimates of externalities have been accounted for already in the previous

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[35] Krutilla and Haveman (1968, p. 75) cite Marglin (1962) on this point. "[The] appropriate shadow wage rate is the marginal opportunity cost of the force actually drawn from alternative employment [the market wage rate] multiplied by the percentage which this force forms of the total labor employed in this category..." (p. 51).

methodology. An additional factor might include contributions to unemployment insurance that would be reflected in production costs.

In this study we do not report these estimates as externalities in the summary chapter. The primary reason for not doing so is the degree of uncertainty surrounding the definitions of relevant labor markets, long term and expected employment rates, the natural rate of unemployment in specific local labor markets, the probability functions that were described, etc. This estimation of potential employment benefits is hampered by the need for additional research and analysis. However, we do not report a zero number either because to do so would be to implicitly assume full employment in the relevant labor markets, which is rather contentious. We do believe the methodology presented here can be replicated in a meaningful manner in specific contexts, including analysis by State agencies, to arrive at reliable estimates of employment benefits that would be a useful basis for policy analysis.

11. SUMMARY AND CONCLUSIONS

This final chapter summarizes the results and discusses the conclusions of the study. Section 11.1 summarizes the step-by-step process that was implemented to demonstrate the damage function approach. Section 11.2 summarizes the *emissions* (interpreted in the broadest sense), the *changes in concentrations* of pollutants, and other changed conditions in the environment as estimated for the benchmark natural gas-to-electricity fuel cycles. Sections 11.3 through 11.5 summarize the range of marginal damages and benefits that were estimated for the natural gas-to-electricity fuel cycle at the two reference sites for the study. Section 11.3 summarizes the findings about the marginal *ecological* impacts from the fuel cycle associated with the single gas plant. Section 11.4 summarizes the findings about the marginal *health* impacts. Section 11.5 discusses the marginal damages and benefits. Section 11.6 discusses the conclusions.

11.1 SUMMARY OF STUDY OBJECTIVES AND THE STEP-BY-STEP APPROACH

This study had three main objectives. The first objective was to *demonstrate* the application of the methodological concepts which were developed in the Background Document (ORNL/RFF 1992). This study addressed this objective by demonstrating the application of the damage function approach to two natural gas-to-electricity fuel cycles. In this demonstration, the assumed benchmark technology was the gas-fired combined-cycle electric power plant. The analysis was applied to two sites, one in the southeastern United States and the other in the southwestern United States.

The second major objective of the study was to develop, given the time and resources, the best range of estimates of the marginal *damages and benefits* associated with selected impact-pathways from the two fuel cycles at these two specific sites. The analysis that addressed this objective was presented in Chapters 4 through 10.

The third major objective was to support the continued development of the National Energy Strategy by assessing the state of the information which is available to support energy decision making and the estimation of externalities, and by so doing, to assist in identifying *gaps in knowledge* and in setting future research agendas. Information about the limitations of the knowledge base and in the accuracy of our estimates was presented in several ways—in the ranges of values given in the numerical results; in the discussions of the analyses; in the papers presented in the Appendices; and in Section 11.7. Additional discussion is presented in Sections 11.2 to 11.5.

An overwhelming conclusion from the discussions in Chapters 4 to 10 is that while the approach is simple in concept, it is not in its *initial* implementation. Rather, it consists of a considerable amount of analysis characterizing the fuel cycle, the technologies, and their emissions; data collection; the application of atmospheric transport models; and the analysis and utilization of the ecosystems, environmental impacts, epidemiology, public health, and economics literatures. The procedure can be summarized as consisting of the following steps:

(1) Select a particular technology(s) (which is, in our case, a power plant using gas-fired turbines) and site (including sites of the upstream activities).

(2) Characterize the nature of the major activities and processes of the total fuel cycle in terms of the potentially (or known) major sources of emissions. Obtain estimates of the major emissions or other residual output from each type of activity. The type of activity could be defined as a general category such as natural gas pipeline transportation.

(3) Select the higher priority impact-pathways on which the analysis is to focus.

(4) Identify and use the appropriate atmospheric (and aquatic, if appropriate) transport models to estimate the change in concentrations and deposition of residuals in the surrounding area.

(5) Identify the types of ecological, health and other impacts that potentially arise from exposure to the changed conditions; and identify appropriate dose-response relationships, as permitted by the scientific literature.

(6) Scale or adjust the estimates of changes in concentrations into the spatial and temporal units required by the dose-response relationships.

(7) Use the dose-response relationships to estimate the impact(s) of the changes in concentration or changed condition of the environment (with environment interpreted in the broadest sense).

(8) Use the economic valuation functions obtained from the literature to estimate the marginal economic damages and benefits of the fuel cycle, and express these values as mills/kWh and on an annual (levelized) basis.

More research is needed to develop improved methods for the application of atmospheric transport models to the impacts of a single plant. As more empirical information is developed on exposure-response and valuation relationships, the estimates of the costs and benefits of fuel cycles will improve in accuracy and precision. If some of the above steps become automated through a computerized information system, then the computational and other requirements on analysts will decrease.

Because of the objectives of this study, the discussion within this section should not be considered as representing a complete picture of the natural gas-to-electricity fuel cycle. Rather it reflects a contribution to the state of knowledge about energy externalities. A complete analysis is beyond the scope of this study. *Consequently, the reader should not use results of this study to draw conclusions about the total externalities of this or of alternative fuel cycles.* Yet, much has been learned and will prove valuable to understanding health and environmental interactions within the natural gas-to-electricity fuel cycle, and the perspective in which economic valuation is cast.

11.2 EMISSIONS FROM THE GAS-TO-ELECTRICITY FUEL CYCLE AND CHANGES IN CONCENTRATIONS IN THE ENVIRONMENT

The first step in the damage function approach is a definition of the sources of the impacts. Many of these sources are emissions to the environment. To contribute to an impact assessment, an emissions rate from a specific part of the fuel cycle must be characterized. Then, depending on whether it is released to the air or water, a lengthy process begins of tracking that emission to the point of impact. For example, in the case of releases to the air, incremental additions to the existing baseline load of ambient pollutants were analyzed in the immediate environment of the reference plant. A summary of the pollutant emissions, concentrations, or other changed conditions for the Southeast and Southwest reference sites are presented in Tables 11.2-1 and 11.2-2.

An important emission transport issue identified in this study is related to the need for a simple yet accurate model to estimate ozone concentration from a point-source over a longer-term time period.[1] A major secondary pollutant, ozone is formed at some point beyond the plant. Formation depends on a wide range of factors, many of which depend on regional air quality. While the model used to predict ozone concentration, OZIPM-4, was not designed to predict impacts from a single point-source, it may be applied to this study provided special attention is given to the limitations and assumptions of the model (for example, emission fluxes must be used to estimate emissions from the power plant). Alternative models, such as the Urban Airshed and Reactive Plume Models, require significantly greater resources in terms of information and manpower. In addition, these models are designed to predict ozone concentrations under short-term episodic conditions lasting one to two days. Clearly, *more work is called for here in the development of an economical ozone model which can be used to predict impacts from point-sources over longer time periods.*

The EPA AP-42 1993 emission factors were used to estimate emissions for this report.

[1]Air emissions were based on 1993 EPA AP-42 data.

Table 11.2-1. Pollutant emissions, concentrations, or other changed conditions for the Southeast reference site: natural gas fuel cycle

Fuel cycle stage and emission	Inform. quality	Emissions or Changed Concentration		
		Quantity	Unit	Comments
		Gas Production		
Offshore (1990)				
Water surface use	●	2,000	acres	18-well platform, includes 1-mi fishing buffer
Land use	-	c	acres	Onshore support activities
Coastal erosion	-	c	tons/year	Navigation support activities
Produced water	●	268	bbl/day/well	Average for Gulf of Mexico
Total suspended solids	●	67.5	mg/L	Concentration in produced water
Oil and grease	●	41.3	mg/L	Concentration in produced water
Benzene	●	4.93	mg/L	Concentration in produced water
Bis(2-ethylhexyl-phthalate)	●	0.10	mg/L	Concentration in produced water
Ethylbenzene	●	0.67	mg/L	Concentration in produced water
Naphthalene	●	0.34	mg/L	Concentration in produced water
Phenol	●	5.77	mg/L	Concentration in produced water
Toluene	●	4.06	mg/L	Concentration in produced water
Zinc	●	0.67	mg/L	Concentration in produced water
Drilling muds	●	6,000	bbl/well	Gulf of Mexico
Drill cuttings	●	1,280	bbl/well	Gulf of Mexico
Air emissions	-	c	lbs/MMcf	Drilling equipment, venting and flaring

Table 11.2-1. Pollutant emissions, concentrations, or other changed conditions for the Southeast reference site: natural gas fuel cycle

Fuel cycle stage and emission	Inform. quality	Emissions or Changed Concentration: Quantity	Unit	Comments
Onshore (2010)				
Land use	●	420-640 3.5-5.3	acres/120 well field acres/well	Average for gas wells
Coastal erosion	-	c	tons/year	Navigation support activities
Produced water	●	14.88	bbl/10^6 cf	Louisiana wells
Arsenic	●	0.012	mg/L	Concentration in produced water
		0.028	g/10^6 cf	Amount produced
Benzene	●	0.02	mg/L	Concentration in produced water
		0.06	g/10^6 cf	Amount produced
Boron	●	5.94	mg/L	Concentration in produced water
		14.1	g/10^6 cf	Amount produced
Sodium	●	470	mg/L	Concentration in produced water
		1,110	g/10^6 cf	Amount produced
Chloride	●	365	mg/L	Concentration in produced water
		864	g/106 cf	Amount produced
Mobile ions	●	115	mg/L	Concentration in produced water
		2,720	g/10^6 cf	Amount produced
Drilling wastes	●	8,254	bbl/well	Louisiana
VOC	○	50-100	tons/yr/well	Fugitive air emissions
Methane	○	21,898	MMcf	Venting and flaring, total for state of Louisiana
Drilling equipment:				
NO_x	●	469	lb/1000 gal	Diesel equipment
SO_x	●	31.2	lb/1000 gal	Diesel equipment
CO_2	●	102	lb/1000 gal	Diesel equipment
HC	●	37.5	lb/1000 gal	Diesel equipment
Particulates	●	33.5	lb/1000 gal	Diesel equipment

Table 11.2-1. Pollutant emissions, concentrations, or other changed conditions for the Southeast reference site: natural gas fuel cycle

Fuel cycle stage and emission	Inform. quality	Emissions or Changed Concentration		
		Quantity	Unit	Comments
Aldehydes	●	7.04	lb/1000 gal	Diesel equipment
Field separation treatment:				
BOD	●	0.00342	$lb/10^3$ cf	Water emission
COD	●	0.0224	$lb/10^3$ cf	Water emission
Oil and grease	●	0.06854	$lb/10^3$ cf	Water emission
Chromium	●	0.00018	$lb/10^3$ cf	Water emission
Zinc	●	0.00006	$lb/10^3$ cf	Water emission
TDS	●	0.914	$lb/10^3$ cf	Water emission
Sulfate	●	0.13708	$lb/10^3$ cf	Water emission
Chloride	●	0.17136	$lb/10^3$ cf	Water emission
		Processing Plant		
Land use	●	22.6	acres	Plant size: 250 x 10^6 ft^3/day
VOC	Θ	1,630	lb/yr.	Fugitive emissions
THC	Θ	4,240	lb/yr.	Fugitive emissions
		Pipeline Transportation		
Land use	●	12,000	acres	600 miles of pipeline
Methane	○	0.5	percent	% of total production
NO_x	Θ	3,400 300	$lb/10^6$ scf $lb/10^6$ scf	Reciprocating engines Gas turbines
HC	Θ	1,400 23	$lb/10^6$ scf $lb/10^6$ scf	Reciprocating engines Gas turbines
CO	Θ	430 120	$lb/10^6$ scf $lb/10^6$ scf	Reciprocating engines Gas turbines
SO_2	Θ	0.6 0.6	$lb/10^6$ scf $lb/10^6$ scf	Reciprocating engines Gas turbines
		Generation		
Land use	●	89	acres	Plant size: 500 MW
CO - 1990 - 2010	●	1.17 0.59	g/sec g/sec	Emission rate

Table 11.2-1. Pollutant emissions, concentrations, or other changed conditions for the Southeast reference site: natural gas fuel cycle

Fuel cycle stage and emission	Inform. quality	Emissions or Changed Concentration		
		Quantity	Unit	Comments
NO_x - 1990 - 2010	●	46.89 16.88	g/sec g/sec	Emission rate
SO_2 - 1990 - 2010	●	neg. neg.	g/sec g/sec	Emission rate
Hydrocarbons	-	c		
Ozone - 1990	●	1.3	ppb	Maximum annual average increase
Acid deposition	Δ	b		
Particulates - 1990	●	1.95	g/sec	Emission rate
Particulates - 2010	●	1.95	g/sec	Emission rate
Peroxyacetyl nitrate (PAN)	Δ	b,c		Modeling needed to determine concentrations
Inorganics	Δ	c		Modeling needed to determine concentrations
Cooling system - blowdown	Δ	c		Modeling required to determine concentrations
Wastewaters	Δ	c		Modeling required to determine concentrations
Ash	-	c	tons/yr	Emissions

Legend:
- -, no data;
- Δ, qualitative data;
- O, marginal quality of quantitative data;
- Θ, quality of quantitative data could be improved;
- ●, quality of quantitative data good.

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of the science; i.e, new models needed.
c. Data limited by lack of site specific studies

Table 11.2-2. Pollutant emissions, concentrations or other changed conditions for the Southwest reference site: natural gas fuel cycle

Fuel cycle stage and residuals	Inform. quality	Emissions or Changed Concentration		
		Quantity	Unit	Comments
			Gas Production	
Land use	●	420-640	acres/120 well field	Average U.S. gas wells
		3.5-5.3	acres/well	
Produced water	●	14.9	bbl/10^6 cf	New Mexico
Arsenic	●			
1990		0.02	mg/L	Concentration in produced water
		0.047	g/10^6 cf	Amount produced
2010		0.012	mg/L	Concentration in produced water
		0.028	g/10^6 cf	Amount produced
Benzene	●			
1990		0.47	mg/L	Concentration in produced water
		1.11	g/10^6 cf	Amount produced
2010		0.02	mg/L	Concentration in produced water
		0.06	g/10^6 cf	Amount produced
Boron	●			
1990		9.9	mg/L	Concentration in produced water
		23.4	g/10^6 cf	Amount produced
2010		5.94	mg/L	Concentration in produced water
		14.1	g/10^6 cf	Amount produced
Sodium	●			
1990		9,400	mg/L	Concentration in produced water
		22,224	g/10^6 cf	Amount produced
2010		470	mg/L	Concentration in produced water
		1,112	g/10^6 cf	Amount produced
Chloride	●			
1990		7,300	mg/L	Concentration in produced water
		17,275	g/10^6 cf	Amount produced
2010		365	mg/L	Concentration in produced water
		864	g/106 cf	Amount produced
Mobile ions	●			
1990		23,000	mg/L	Concentration in produced water
		54,428	g/10^6 cf	Amount produced
2010		115	mg/L	Concentration in produced water
		2,721	g/10^6 cf	Amount produced
Drilling wastes	●	6,774	bbl/well	New Mexico
VOC	○	50-100	tons/yr/well	Fugitive air emissions

Table 11.2-2. Pollutant emissions, concentrations or other changed conditions for the Southwest reference site: natural gas fuel cycle

		Emissions or Changed Concentration		
Fuel cycle stage and residuals	Inform. quality	Quantity	Unit	Comments
Drilling equipment: NO_x	●	469	lb/1000 gal	Diesel equipment
SO_2	●	31.2	lb/1000 gal	Diesel equipment
CO_2	●	102	lb/1000 gal	Diesel equipment
HC	●	37.5	lb/1000 gal	Diesel equipment
Particulates	●	33.5	lb/1000 gal	Diesel equipment
Aldehydes	●	7.04	lb/1000 gal	Diesel equipment
Field separation treatment:				
BOD	●	0.00342	$lb/10^3$ cf	Water emission
COD	●	0.0224	$lb/10^3$ cf	Water emission
Oil and grease	●	0.06854	$lb/10^3$ cf	Water emission
Chromium	●	0.00018	$lb/10^3$ cf	Water emission
Zinc	●	0.00006	$lb/10^3$ cf	Water emission
TDS	●	0.914	$lb/10^3$ cf	Water emission
Sulfate	●	0.13708	$lb/10^3$ cf	Water emission
Chloride	●	0.17136	$lb/10^3$ cf	Water emission
			Processing	
Land use	Θ	22.6	acres	Plant size: 250 x 10^6 ft^3/day
VOC	Θ	1,630	lb/day	Fugitive emissions
THC	Θ	4,240	lb/day	Fugitive emissions
			Pipeline Transportation[1]	
Land use	-	c	acres	
Methane	○	0.0034	percent	% of total production
			Generation	
Land use	●	89	acres	Plant size: 500 MW
CO - 1990 - 2010	●	1.17 0.59	g/sec g/sec	Emission rate

Table 11.2-2. Pollutant emissions, concentrations or other changed conditions for the Southwest reference site: natural gas fuel cycle

		Emissions or Changed Concentration		
Fuel cycle stage and residuals	Inform. quality	Quantity	Unit	Comments
NO_x - 1990	●	46.89	g/sec	Emission rate
- 2010		16.88	g/sec	
SO_2 - 1990	●	neg.	g/sec	Emission rate
Hydrocarbons	-	c		
Ozone	-	a		Modeling required to determine atmospheric concentrations
Acid deposition	-	a		
Particulates	●	1.95	g/sec	Maximum annual average increase
Particulates-10	●	1.95	g/sec	Maximum annual average increase
Peroxyacetyl nitrate (PAN)	-	b,c		Field data and modeling needed to determine concentrations
Inorganics	-	c		
Cooling system - blowdown	Δ	c		Effluents to evaporation ponds
Wastewaters	Δ	c		Effluents to evaporation ponds
Ash	-	c		Emission rate

[1]No compressors located on pipeline at this site

Legend:
- -, no data;
- Δ, qualitative data;
- O, marginal quality of quantitative data;
- Θ, quality of quantitative data could be improved;
- ●, quality of quantitative data good.

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of the science; i.e, new models needed.
c. Data limited by lack of site specific studies

Table 11.2-3. Emission factors for electric utility turbines (lbs/million cubic feet of natural gas)

	NO_x	HC	CO	PM	SO_2
1990 EMISSIONS					
Uncontrolled emissions	449	24.5	112	19.7	neg.
Controlled emissions	122.5	NT[a]	82.0	5.1	neg.
2010 EMISSIONS					
Dry Low NO_x	44.1	neg.	82.0	5.1	neg.

[a] Not tested.

11.3 MARGINAL ECOLOGICAL IMPACTS OF THE NATURAL GAS FUEL CYCLE

This evaluation of the ecological impacts of the natural gas fuel cycle is based on a very specific set of parameters which place limits on the range of possible impacts and on the magnitude of these impacts. The major limiting factors in this assessment are the size and location of the facilities, the location of gas production and processing and the method of transport of gas. The size determines the magnitude of point source emissions from the power plant, as well as the incremental amount of wastes and discharges from drilling, processing, and transportation. Location of the power plant and the processing plants is important in determining whether the emissions from a single facility (which in themselves may be too small to have significant impacts) would contribute, on an incremental basis, to cumulative impacts caused by other sources. Therefore, the conclusions discussed below must be considered in terms of the size (500-MW) and location of the power plant.

Table 11.3-1 presents a summary of the ecological impacts associated with specific resource categories. For each emission examined, this table identifies ecological impacts that: (1) are believed to be negligible, (2) can be quantified from the existing knowledge base, or (3) can not currently be quantified (see also Tables 11.4-1 and 11.4-2).

Under the scenario created for this study, the phase of the natural gas fuel cycle that is likely to have the greatest potential for ecological impacts is discharge (offshore) or disposal (onshore) of wastewaters. The impact of chronic discharges of wastewaters to the marine environment from offshore gas production is localized and pre-drilling surveys are not available. However, the causes for the general decline in the Gulf area commercial fisheries, particularly off the coast of Louisiana, attributed to overfishing, needs further clarification. Even localized and small increments of pollutants to an already stressed ecosystem may be significant. In coastal areas, where wastewaters are directly discharged to surface waters and dredging and pipelines operations take place, natural resources such as beaches, wetlands, fish nursery areas, bird sanctuaries, etc., may be impacted. Commercial shellfish and shrimp fisheries would be at risk, as well as recreational fishing. The aesthetic quality of the area would be impacted.

Onshore, wastewaters may be directly discharged to tidally-affected surface waters, resulting in impacts to freshwater and estuarine organisms and saltwater intrusion into surface drinking water sources. At the Southwestern Reference site, there is the potential for improperly stored wastewaters to migrate to surface waters or to leach to groundwaters. The resulting impacts to drinking water and freshwater biodiversity occur on a case-by-case basis and no general conclusions concerning the ecological impacts of drilling and production can be made.

Potential air emissions from the natural gas-fired power plant, which were evaluated only for the 1990 technology at the southeastern site, were projected to have no direct ecological impacts. At this stage of the fuel cycle, emissions of NO_x and SO_2 from the stack do not result in ambient atmospheric concentrations that exceed currently identified toxicity thresholds for plants or animals. However, NO_x and SO_2 can be dispersed over wide areas, and can contribute to regional impacts such as acid deposition. These potential impacts are discussed in Appendix D. At present, regional assessments of acid deposition on aquatic resources are possible for only a few well-characterized regions. Systematic national environmental monitoring programs that could facilitate future regional assessment studies include the Environmental Protection Agency's Environmental Monitoring and Assessment Program, the National Oceanic and Atmospheric Administration's National Status and Trends Program, and the Geological Survey's National Water Quality Assessment Program.

Releases of NO_x and hydrocarbons from the power plant stack contribute to the formation of atmospheric ozone, which, in turn, can have adverse effects on plants and crop production. Quantitative estimates of the impact of ozone on crop yield indicate that the incremental effect of the power plant would represent about a 0.7% decrease in soybean production, 0.75% for wheat, 0.39% for corn, and 0.52% for tobacco.

Emissions of particulates, NO_x, and water vapor, together with the secondarily formed acid aerosols and ozone, may cause reductions in atmospheric visibility. Changes in visibility are not associated with specific ecological impacts, but can have impacts in terms of diminished aesthetics. In addition, localized reductions in visibility may create traffic hazards in the area. Atmospheric modeling is required to estimate visual range reductions caused by the operation of the power plant.

The concentration of sulfur in the gas is assumed to be very low and therefore the contribution of the power plant to acid deposition is negligible. Emission of NO_x contributes to the formation of atmospheric ozone which results in a small incremental impact on crop yield (when added to high ambient levels of ozone that already stress the system).

Releases of wastewater and cooling system water from the power plant were not expected to have major ecological impacts because of the use of a closed recycling cooling system, and high dilution of effluents in the receiving water body.

11.4 MARGINAL EFFECTS OF A NATURAL GAS-TO-ELECTRICITY FUEL CYCLE ON HEALTH

The emissions and impact-pathways which were evaluated in this study (see Table 11.4-1) probably represent most of the adverse health effects related to the natural gas-to-electricity fuel cycle. Notwithstanding, these impact-pathways represent a partial listing of potentially important sources of adverse impacts. For example, for human health impacts, only the air inhalation pathway was considered. Consideration in the future should be given to transport through the environment to and through the food-chain. Likewise, effluent releases to the aquatic pathway were not fully addressed because of the lack of a sufficient knowledge base. Finally, occupational disease and accident rates were not specific to the technology except for offshore accidents, and these must be considered tentative.

Table 11.3-1 Summary table for key ecological impacts associated with resource categories

	Crops	Forests	Commer. Fishing	Recre. fishing	Rec. parks	Bio-diversity
Production offshore:						
Wastewaters: Produced water, Drilling fluids, Drill cuttings	n.a.	n.a.	□[1]	□[1]	n.a.	xx
Production onshore:						
Wastewaters: Produced water, Drilling fluids, Drill cuttings	n.e.	n.e.	n.e.	n.e.	n.a.	xx
Air emissions[2]	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Production support facilities and activities: onshore and offshore						
Gas separation, Navigation, Dredging, Pipelines	n.a.	xx	n.e.	n.e.	n.a.	xx[3]
Refinery:						
Air emissions,[2] Water emissions	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
Transportation:						
Pipeline methane emissions[2]	□	n.e.	n.a.	n.a.	n.a.	□
Compressor emissions[2]	n.e.	n.e.	n.a.	n.a.	n.e.	n.e.
Power generation:						
Air Emissions:[2] CO_2, NO_x, SO_2, Hydrocarbons, Particulates, Acid deposition	n.e.	n.e.	n.e.	n.e.	n.e.	xx
Ozone	■	n.e.	n.a.	n.a.	n.e.	n.e.
Water Emissions:[2] Wastewater, Cooling water	n.e.	n.a.	n.e.	n.e.	n.a.	□

[1]Impacts negligible with current data
[2]These impacts are discussed in Appendix D; in general, quantitative data were lacking for impact analysis.
[3]Biodiversity impacted as a result of erosion, hydrology changes, and land-use changes.

■ = Impact quantified in this report
xx = Impact qualitatively described, but not quantifiable given current knowledge base
□ = Negligible impact
n.a. = Impact not applicable
n.e. = Impact not examined

The emissions examined were chosen either to demonstrate a particular facet of the methodology, to highlight a technology stage, or to capture a sizeable fraction of the anticipated health effects. Data presented in Table 11.4-1 indicates that a small proportion of both health and ecological impacts are rated as having a high quality of information about them. Future efforts will, no doubt, demonstrate similar conditions with other effluents and pathways. Some of these would include characterization of the hydrocarbons, broken down at least into toxicological classes and characterization of the food-chain and aquatic pathways.

Table 11.4-1. Health and environmental impacts for the Southeast Reference site: natural gas fuel cycle

		Annual impact		
Fuel cycle stage and impact pathway	Inform. quality	Quantity	Unit	Comments
		Production		
Occupational health:				
Fatal accidents	O	0.63	Deaths	
Injuries	O	3,000	Lost work days	
Produced water drinking water biodiversity, fisheries	Δ	b,c		Modeling required for dilutions of specific compounds
Drilling fluids biodiversity	Δ	b,c		Modeling required for dilutions of specific compounds
Drill cuttings biodiversity	Δ	b,c		Modeling required for dilutions of specific compounds
		Processing		
Occupational health				
Deaths:	Θ	a,c	Deaths/GWe-y	
Injuries	Θ	a,c	Injuries/GWe-y	
Water emissions biodiversity	Δ	b,c		
Air emissions biodiversity	Δ	b,c		Insufficient data on specific compounds, concentrations and dose-response functions

Table 11.4-1. Health and environmental impacts for the Southeast Reference site: natural gas fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact: Quantity	Unit	Comments
		Transportation		
Accidents				
Deaths	●	0.0039	Deaths	
Injuries	●	0.0142	Injuries	
Occupational health				
Deaths:	Δ	b,c		
Injuries	Δ	b,c		
Priority pollutant air emissions (diesel): biodiversity	○	b,c		
Methane (pipeline emissions): biodiverstiy	○	b,c		
		Generation		
Occupational health				
Deaths	○	a,c	Deaths/GWe-y	
Injuries	○	a,c	Injuries/GWe-y	
CO_2 - global warming	Δ	b		Regional and global impacts on climate
CO_2 - plant growth	Δ	b		Dose-response functions not available
NO_x biodiversity	●	0	Loss of wildlife/crops	Resulting ambient concentrations below threshold levels for direct ecological impacts
NO_2 - morbidity:				
Phlegm days	Δ	1595	Symptom days	No economic valuation

Table 11.4-1. Health and environmental impacts for the Southeast Reference site: natural gas fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact: Quantity	Unit	Comments
SO_2 biodiversity	●	0	Loss of wildlife/crops	Resulting ambient concentrations below threshold levels for direct ecological impacts
SO_2 - morbidity				
Children cough-days		neg.	Symptom days	
Adult chest discomfort		neg.	Symptom days	
Hydrocarbons biodiversity	Δ	b,c		Insufficient data on specific compounds, concentrations and dose-response functions
Ozone crops	●	0.39-0.75	Percent	Lost productivity in major crops
Ozone - morbidity:	Δ			
Minor respiratory restricted activity days		3,500	Symptom days	
Any-symptom day		8,300	Symptom days	
Asthma-attack day		430	Symptom days	
Eye-irritation day		11,000	Symptom days	
Cough day		4.3	Symptom days	
Cough		26	Symptom days	
Shortness of breath		15	Symptom days	
Pain upon inspiration		15	Symptom days	
Acid deposition - crops	Δ	b		No effect anticipated
Particulates - air	Δ	a,c		Modeling required to determine effects on visibility
Particulates (PM_{10}) mortality	Θ	0.027	Deaths	
Particulates (PM_{10}) morbidity:	Θ			
Respiratory hospital admissions	Θ	0.8	Symptom days	

Table 11.4-1. Health and environmental impacts for the Southeast Reference site: natural gas fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact Quantity	Unit	Comments
Emergency room visits	Θ	1.86	Symptom days	
Restricted activity days	Θ	323	Symptom days	
Respiratory symptoms	Θ	12,100	Symptom days	
Chronic bronchitis in children	Θ	3.2	Symptom days	
Chronic cough in children	Θ	3.7	Symptom days	
Asthma attacks	Θ	132	Symptom days	
Chronic bronchitis in adults	Θ	0.35	Symptoms	
Peroxyacetyl nitrate (PAN) - air	Δ	b,c		Field data and modeling needed to assess impacts
Inorganics - biodiversity	Δ	c		Field data and modeling needed to assess impacts
Cooling system blowdown - water quality	Δ	c		Modeling required to determine concentrations
Wastewaters - water quality	Δ	c		Modeling required to determine concentrations
Ash - biodiversity	-	b,c		

Legend:

-, no data;
Δ, qualitative data;
O, marginal quality of quantitative data;
Θ, quality of quantitative data could be improved;
●, quality of quantitative data good.

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of the science; i.e, new models or dose-response functions needed.
c. Data limited by lack of site specific studies

Table 11.4-2. Health and environmental impacts for the Southwest Reference site: natural gas fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact: Quantity	Unit	Comments
		Production		
Occupational health:				
Fatal accidents	Θ	0.63	Fatalities	During drilling (not annual)
Injuries	Θ	3,000	Work days lost	During drilling (not annual)
Produced water drinking water biodiversity	Δ	c		
Drilling fluids land, water quality, biodiversity	Δ	c		
Drill cuttings	Δ	c		
		Processing		
Occupational health				
Deaths:	Θ	a,c	Deaths/G We-y	
Injuries	Θ	a,c	Injuries/G We-y	
Water emissions biodiversity	Δ	b,c		
Air emissions biodiversity	Δ	b,c		Insufficient data on specific compounds, concentrations and dose-response functions

Table 11.4-2. Health and environmental impacts for the Southwest Reference site: natural gas fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact: Quantity	Unit	Comments
		Transportation		
Accidents				
Deaths	●	0.0039	Deaths	
Injuries	●	0.0142	Injuries	
Diesel emissions biodiversity	○	b,c		
Methane emissions biodiversity	○	b,c		
		Generation		
Occupational health				
Deaths	○	a,c	Deaths/GWe-y	
Injuries	○	a,c	Injuries/GWe-y	
CO_2 - global warming	Δ	b		Regional and global impacts on climate
CO_2 - plant growth	Δ	b		Dose-response functions not available
NO_x - air quality	Δ	a		
NO_2 - morbidity:				
Phlegm days	Δ	84	Symptom days	
SO_2 - air quality	Δ	a		
SO_2 - morbidity:				
Children cough-days	Δ	neg.	Symptom days	
Adult chest discomfort	Δ	neg.	Symptom days	
Hydrocarbons - air quality	Δ	b,c		Insufficient data on specific compounds, concentrations and dose-response functions

Table 11.4-2. Health and environmental impacts for the Southwest Reference site: natural gas fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact: Quantity	Unit	Comments
Ozone - 1990 2010 crops	Δ	a	Percent	Lost productivity in major crops
Acid deposition - crops	Δ	b		No effect anticipated
Particulates - air quality, crops	Δ	a,c		Modeling required to determine effects on visibility
Particulates (PM_{10}) - mortality:	Θ	0.0014		
Particulates (PM_{10}) - morbidity:				
Respiratory hospital admissions	Θ	0.043	Admissions	
Emergency room visits	Θ	0.1	Visits	
Restricted activity days	Θ	17.4	Days	
Respiratory symptoms	Θ	652	Symptoms	
Chronic bronchitis in children	Θ	0.172	Added children	
Chronic cough in children	Θ	0.199	Symptoms	
Asthma attacks	Θ	7.1	Days	
Chronic bronchitis in adults	Θ	0.008	Symptoms	
Peroxyacetyl nitrate (PAN) - crops, air quality	Δ	b,c		Field data and modeling needed to assess impacts
Inorganics - biodiversity	Δ	c		
Cooling system blowdown - water quality	Δ	c		Evaporation ponds used

Table 11.4-2. Health and environmental impacts for the Southwest Reference site: natural gas fuel cycle

		Annual impact		
Fuel cycle stage and impact pathway	Inform. quality	Quantity	Unit	Comments
Ash land, water quality	-	c		

Legend:
- -, no data;
- Δ, qualitative data;
- O, marginal quality of quantitative data;
- Θ, quality of quantitative data could be improved;
- ●, quality of quantitative data good.

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of the science; i.e, new models or dose-response functions needed.
c. Data limited by lack of site specific studies

11.5 MARGINAL ECONOMIC DAMAGES AND BENEFITS

In this report, we estimate impacts for each priority pathway associated with the gas-fired power plant being located in each of two reference environments. Then we obtain willingness to pay (WTP) estimates specific to a particular impact (or sub-impact) and use them to obtain an estimate of damage for that pathway. The main purpose of this section is to highlight these estimates of the marginal damages and benefits. As emphasized numerous times in this report, the numerical values should ***not*** be interpreted as the externalities of the natural gas-to-electricity fuel cycle.

However, it must be recognized that this approach is conceptually limited. In reality, were a new plant to be built, the individual would be offered a package of both positive and negative impacts. Thus, many impacts would be experienced simultaneously. For our approach to be completely valid, we must assume that the WTP for (or to avoid) a given impact is independent of that for (or to avoid) any other impact. That is, we must assume that the WTP to avoid the sum of these impacts equals the sum of the WTP to avoid each impact.

In fact, there is a growing body of economic literature suggesting that adding independently measured WTP estimates across different commodities (i.e., impacts) may overestimate total damage. The reasoning is that money spent on avoiding one impact cannot be spent on avoiding another. Consequently, estimates of the willingness to pay to avoid a single impact will be less constrained by income than such estimates for a set of impacts together. In addition, to the extent that environmental commodities are complements (like good health and recreation), reducing the quality of one will make the quality of the other less valuable to preserve. Thus, adding separate WTP estimates for avoiding these two changes would overestimate damage. At the same time, some environmental commodities may be seen as substitutes. If, for example, two different but substitutable types of recreation sites are degraded, WTP estimates taken from each site separately would take the quality of the other site as given and assume that the other site would be available as a substitute. Degrading both sites together would reduce substitution options and result in a higher WTP to avoid the simultaneous impacts than the WTP to avoid each impact separately, i.e., on this account, our approach would underestimate damage.

To further appreciate the conceptual limitations of our approach to valuing marginal damages, it is helpful to consider an ideal study as a benchmark. An example of an ideal study would be a "perfectly designed" contingent valuation study that addressed how much more a person would be willing to pay to avoid a new gas-fired power plant being located in a particular region against an alternative (hypothetical) source of power with no externalities. These people could be those physically or economically affected or the general population that might hold existence values for natural resources that might be affected. This survey would detail all of the impacts predicted for this gas-to-electricity fuel cycle, their time phasing, etc., presenting them as a package. These effects would then be evaluated as a package, with WTP to avoid the gas power plant emerging directly. Any interdependencies in people's preferences over the elements of the package would, in theory, be taken into account in their WTP responses.

Whether the full set of environmental commodities are more generally complements, substitutes, or unrelated in the individual's utility function is unknown, although the complement case seems more compelling. In any event, the limitations on WTP imposed by an income constraint argues that our damage estimates, were they complete (i.e., for all damage/benefit categories), would overestimate total damage.

It cannot be overemphasized that aggregate damage estimates are empirically limited in several respects. First, and foremost, even with perfect damage estimates (i.e., with all cells filled in with credible estimates), one would not, in general, be justified in treating these damages as externalities, or as "adders" onto the market or bid price of electricity. As shown in the Background Document, the portion of damage that may legitimately be treated as an externality would depend on the types of policies in effect to internalize the externalities.

Second, the damage estimates presented below are only for the natural gas fuel cycle, while the salient damage estimates are those for *differential damages* between fuel cycles (including conservation). This distinction is crucial in light of the finding that the employment benefits (which *are* appropriately treated as externalities) associated with a new gas power plant being built and operated are large relative to the estimates of environmental and road damage.[2] Yet, any large project to generate an equivalent amount of electricity will result in significant employment benefits. Thus, when estimating differential damages between the natural gas and any other similarly sized fuel cycle, the employment benefits registered for the former will tend to be canceled out by employment benefits in the latter, leaving environmental and other damage differentials largely determining external cost differentials among the alternative fuel cycles.

Table 11.5-1 and 11.5-2 summarize the annual damages (in total damages and mills/kWh, in 1989 dollars) associated with the operation of the specified gas plant at the two reference sites. The list of pathways presented is limited to the "priority" pathways identified early in this project. Low, midpoint, and high estimates are presented where such estimates can currently be made with the existing base of knowledge.

As our main goal was to demonstrate methods for estimating damages, we chose to demonstrate methods relevant to additional pathways rather than to duplicate analyses for both reference environments. However, in many of the impact-pathways no estimates are possible, either because of missing knowledge base or an effect too small to estimate or value.

[2]In part this is due to the limited, if major, set of damage pathways investigated. But, mostly this is due to the large employment benefits.

Table 11.5-1. Estimated damages for 1990 natural gas fuel cycle in the Southeast Reference site

Stage	Pathway	Damages (10^3 \$s)			(mills/kWh)		
		Low	Med	High	Low	Med	High
Production	Occupational health:						
	Fatal accidents	a,c	a,c	a,c	a,c	a,c	a,c
	Injuries	a,c	a,c	a,c	a,c	a,c	a,c
	Produced water biodiversity, fisheries	b,c	b,c	b,c	b,c	b,c	b,c
	Drilling fluids biodiversity	b,c	b,c	b,c	b,c	b,c	b,c
	Drill cuttings biodiversity	b,c	b,c	b,c	b,c	b,c	b,c
Processing	crops, biodiversity	b,c	b,c	b,c	b,c	b,c	b,c
Transportation	Accidents						
	Deaths	a,c	a,c	a,c	a,c	a,c	a,c
	Injuries	a,c		a,c			
	Wildlife, crops						
Generation	Occupational health						
	Deaths	a,c	a,c	a,c	a,c	a,c	a,c
	Injuries	a,c	a,c	a,c	a,c	a,c	a,c
	CO_2 - global warming	b	b	b	b	b	b
	CO_2 - plant growth	b	b	b	b	b	b
	NO_x biodiversity	c	c	c	c	c	c
	NO_2 - morbidity:						
	Phlegm days	b	b	b	b	b	b
	SO_2 biodiversity	c	c	c	c	c	c
	SO_2 - morbidity	neg.	neg.	neg.			
	Hydrocarbons biodiversity	b,c	b,c	b,c	b,c	b,c	b,c

Table 11.5-1. Estimated damages for 1990 natural gas fuel cycle in the Southeast Reference site

Stage	Pathway	Damages (10^3 \$s)			(mills/kWh)		
		Low	Med	High	Low	Med	High
	Ozone crops					0.06	
	Ozone - morbidity:	89	160	240	0.027	0.049	0.074
	Total respiratory restricted activity days	0	61	130	Part of total	Part of total	Part of total
	Any-symptom day	3.6	37	83	"	"	"
	Asthma-attack day	2.7	9.2	18	"	"	"
	Eye-irritation day	24	51	94	"	"	"
	Cough-day	4.4	16	37	"	"	"
	Acid deposition - crops	b	b	b	b	b	b
	Particulates (PM_{10}) mortality	11	34	70	0.0052	0.016	0.033
	Particulates (PM_{10}) morbidity:	75	120	190	0.023	0.038	0.058
	Respiratory hospital admissions	0.13	5.2	11	Part of total	Part of total	Part of total
	Emergency room visits	0.026	0.34	0.62	Part of total	Part of total	Part of total
	Restricted activity days	3.5	17	29	Part of total	Part of total	Part of total
	Respiratory symptoms	34	78	140	Part of total	Part of total	Part of total
	Chronic bronchitis in children	0.069	0.42	0.79	Part of total	Part of total	Part of total
	Chronic cough in children	0.0028	0.02	0.048	Part of total	Part of total	Part of total
	Asthma attacks	0.62	3.9	8.1	Part of total	Part of total	Part of total
	Adult chronic bronchitis	4.1	22	40	Part of total	Part of total	Part of total
	Peroxyacetyl nitrate (PAN) - air	b,c	b,c	b,c	b,c	b,c	b,c
	Inorganics - biodiversity	c	c	c	c	c	c

Table 11.5-1. Estimated damages for 1990 natural gas fuel cycle in the Southeast Reference site

Stage	Pathway	Damages (10^3 $s)			(mills/kWh)		
		Low	Med	High	Low	Med	High
	Cooling system blowdown - water quality	c	c	c	c	c	c
	Wastewaters - water quality	c	c	c	c	c	c
	Ash - biodiversity - 1990 - 2010	b,c	b,c	b,c	b,c	b,c	b,c

Legend:

Information quality is a joint measure of the quality of the dose-response function and its application to the specific impact measure.

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of science; i.e., new models or dose-response functions needed.
c. Data limited by lack of site specific studies.

[1]Discussion of calculations are analogous to those in ORNL/RFF (1992) and will be provided in the revised draft of this report.

Table 11.5-2. Estimated damages for 1990 natural gas fuel cycle in the Southwest Reference site

Stage	Pathway	Damages (10^3 $s)			(mills/kWh)		
		Low	Med	High	Low	Med	High
Production	Occupational health:						
	Fatal accidents	a,c	a,c	a,c	a,c	a,c	a,c
	Injuries	a,c	a,c	a,c	a,c	a,c	a,c
	Drilling fluids land, water quality, biodiversity	c	c	c	c	c	c
	Drill cuttings	c	c	c	c	c	c
Processing	Occupational health						
	Deaths	a,c	a,c	a,c	a,c	a,c	a,c
	Injuries	a,c	a,c	a,c	a,c	a,c	a,c
	Hydrocarbons biodiversity	b,c	b,c	b,c	b,c	b,c	b,c
Transportation	Accidents						
	Deaths	a,c	a,c	a,c	a,c	a,c	a,c
	Injuries	a,c	a,c	a,c	a,c	a,c	a,c
Generation	Occupational health						
	Deaths	a,c	a,c	a,c	a,c	a,c	a,c
	Injuries	a,c	a,c	a,c	a,c	a,c	a,c
	CO_2 - global warming	b	b	b	b	b	b
	CO_2 - plant growth	b	b	b	b	b	b
	NO_x air quality	a	a	a	a	a	a
	NO_2 - morbidity:						
	Phlegm days	b	b	b	b	b	b
	SO_2 - air quality	neg.	neg.	neg.			
	Hydrocarbons - air quality	b,c	b,c	b,c	b,c	b,c	b,c

Table 11.5-2. Estimated damages for 1990 natural gas fuel cycle in the Southwest Reference site

Stage	Pathway	Damages (10^3 \$s)			(mills/kWh)		
		Low	Med	High	Low	Med	High
	Ozone	a	a	a	a	a	a
	crops	0	0	0	0	0	0
	health	0	0	0	0	0	0
	Acid deposition - crops	b	b	b	b	b	b
	Particulates - mortality	2.0	5.8	12	0.0006	0.0018	0.0036
	Particulates - air quality, crops	a,c	a,c	a,c	a,c	a,c	a,c
	Particulates (PM_{10}) - morbidity	3.9	6.6	9.8	0.0012	0.002	0.003
	Respiratory hospital admissions	0.002	0.28	0.55	Part of total	Part of total	Part of total
	Emergency room visits	0.66	0.018	0.034	"	"	"
	Restricted activity days	0.25	0.93	1.6	Part of total	Part of total	Part of total
	Respiratory symptoms	1.8	4.2	7.5	"	"	"
	Chronic bronchitis in children	0.0051	0.023	0.041	"	"	"
	Chronic cough in children	0.00018	0.001	0.0025			
	Asthma attacks	0.034	0.22	0.46			
	Adult chronic bronchitis	0.20	1.1	1.9			
	Peroxyacetyl nitrate (PAN) - crops, air quality	b,c	b,c	b,c	b,c	b,c	b,c

Table 11.5-2. Estimated damages for 1990 natural gas fuel cycle in the Southwest Reference site

Stage	Pathway	Damages (10^3 $s)			(mills/kWh)		
		Low	Med	High	Low	Med	High
	Cooling system blowdown - water quality	c	c	c	c	c	c
	Wastewaters - water quality	c	c	c	c	c	c
	Ash - 1990 - 2010 land, water quality	c	c	c	c	c	c

Legend:

Information quality is a joint measure of the quality of the dose-response function and its application to the specific impact measure.

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of science; i.e., new models or dose-response functions needed.
c. Data limited by lack of site specific studies.

neg.: negligible

[1]Discussion of calculations are analogous to those in ORNL/RFF (1992) and will be provided in the revised draft of this report.

11.6 CONCLUSIONS

11.6.1 Scope of the Study

It should be emphasized that the primary objective of the study was to ***demonstrate methodology***. Thus, the numerical results are in no respect definitive, universal estimates of total fuel cycle externalities. The sites considered were for illustrative purposes. They are not representative of all, or even likely, sites in the U.S. The idea of the study was **not** to estimate damages and benefits that could be applied throughout the U.S., or even to other sites in the same region. Nor are these sites actual options. They are so numerous and different in their site characteristics that no single study could pretend to encompass all options.

In practice, analysis of every fuel-cycle activity, emission, and impact is impossible. Practical implementation of the damage function approach requires selecting some, but not all, of the impacts for detailed analysis. This selection is based on an informed *a priori* assessment of the more important impacts in terms of the magnitude of their damages or benefits. Not all impacts are addressed. However, since the primary objective of the study was to demonstrate methodology, whenever time or resource constraints required a tradeoff between analyzing more impact-pathways, but for only one site, versus fewer impact-pathways assessed for both sites, a decision was frequently made to consider more impact-pathways, but for only one site.

11.6.2 Usefulness of the Damage Function Approach

This study has demonstrated that the damage function approach is an operational method for estimating many of the damages and benefits of a gas-to-electricity fuel cycle. Also, as more studies are done using this approach, it will be easier and less costly to implement. Insofar as many Public Utility Commissions in the United States, as well as many other countries, are considering ways of internalizing the external damages of fuel cycles, it seems all the more important to invest in thorough assessments. Regulatory burdens imposed on utilities and others are very costly. They should be justified by thorough study. By the same token, the external damages to health and to the environment should be accounted for and reflected in energy prices. The method demonstrated in this study represents an important step in this direction. Thus, ***in spite of its limitations and the gaps in the base of scientific knowledge, the results gained from studies using this approach would add to the base of knowledge*** to support informed decisions about energy.

Of the impacts that were quantified, the ***major sources of damage from the gas fuel cycle are particulates and ozone, at least in areas with high baseline concentrations***. Damages from the expected increase in premature mortality and morbidity were estimated to be 0.033 mills/kWh and 0.038 mills/kWh, respectively. Acid aerosols from NO_x emissions are also thought to be major factors, but their impacts were not qualified. Based on inspection of data on ambient ozone concentrations in the rural Southeast, high ozone concentrations are not uncommon. High ozone concentrations are associated with elevated rates of respiratory illnesses. For the 1990 scenario, estimated damage to the population within 1,000 miles of the plant at the Southeast Reference site was 0.07 mills/kWh.

Since most of the quantified damages were health-related, if the gas power plant were situated in a region with 10 million people nearby, rather than only one million, as in the Southeast Reference site, then the quantified damages would be about an order of magnitude greater -- assuming that meteorological conditions, topography, population density, and demographic characteristics are comparable at the two sites. This approximation follows directly from: (a) the near-linear relationships between emissions and changes in concentrations, and (b) the linear (or linear approximation) dose-response functions that were used throughout our analysis. In general, the ***size of the nearby population is a major determinant of the level of damages from the gas power plant.***

Estimates of damages are highly uncertain, and are project- and site-specific. The estimates should not be summed and then compared, either between the two regions or technologies, or among alternative fuel cycles. There was generally a lack of quantitative information on ecological exposure-response functions. Also, some impacts were quantified at one site, but not at the other. The same differences are true among the different fuel cycle studies (e.g. biomass, oil, and coal). It **is**, however, informative to compare **individual** impact-pathways -- between sites, technologies, or fuel cycles.

The results show that there are ***significant differences in damages, and thus externalities, among different sites.*** Estimates of emissions vary, even for the near-term technology. For example, estimates of NO_x emissions used in our analysis were taken from the EPA's AP-42 data (EPA 1993). The NO_x emission data from this source is 10-15% lower than that from typical gas turbine power plants constructed in 1990. Consequently, estimates ***using the turbine emissions data reflecting 1990 technology would have resulted in increased ozone-related damages***.

The gas-fuel cycle has ***low net emissions of CO_2*** compared to other fossil fuel cycles, but still has greater emissions than renewable energy sources.

Finally, note that the relative size of damages in these various categories may not be indicative of the relative size of the externalities associated with these damages. Further analysis is required to make this determination with due regard to the policy setting, tax rates, and other factors particular to the pollutant or activity generating the damage/benefit and its location (see Freeman, Burtraw, Harrington, and Krupnick 1992 for a full discussion).

11.6.3 Information Needs

A major conclusion of this study is that while the scientific base of knowledge is reasonably good in some areas, it is certainly lacking in others. The paucity of quantitative estimates of ecological impacts is particularly striking, all the more so for regional and global impacts that extend well beyond the local site of a gas-fired power plant. The many interacting factors in ecological systems make it difficult to identify well-defined functions describing the impacts of changes in pollutant concentrations on ecosystems. ***Given the current state of knowledge, it will generally be very difficult to develop quantitative estimates of ecological damages caused by fuel cycles.***

In the health effects area, the air inhalation pathway was considered in some detail. However, some of the more important health-effects estimates rely on a few or sometimes individual studies. The ***lack of health-effects studies is an obvious weakness which can be overcome with additional research.*** The lack of information about the effects of effluents on aquatic ecosystems and effects related to solid wastes have not been addressed. The ingestion of pollutants through the food-chain is another area where the knowledge base is lacking. Also, priorities should be established to ***develop better atmospheric transport models,*** especially for secondary pollutants, that are reasonably accurate and that are also inexpensive to use in terms of their demands on data.

In economics, a major issue in this area of research is the accuracy and precision of estimates of individuals' willingness to pay (WTP) to avoid certain ecological impacts or health risks. In using estimates of ***WTP, significant issues arise in the transferability issue*** — the application of results obtained in one location or context to another. Other major issues are aggregation and non-use value. Aggregation refers to the practice of how to best add damages and benefits to obtain an overall measure. Non-use value refers to individuals' willingness to

Finally, all of the caveats regarding the interpretation of the numerical results bear repeating:

- The analyses were performed on a number—but not all—of the possible effluents and impacts.
- Limitations in the knowledge base precluded quantitative estimates on most ecological impacts.
- The analyses are project- and site-specific.
- Because of these and related limitations in the analyses, the numerical results should not be used in any definitive comparison of externalities from alternative sources of energy.

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APPENDIX A

OIL AND GAS INDUSTRY REGULATIONS

OIL AND GAS INDUSTRY REGULATIONS

1.1 Regulations of Wastewaters from Oil and Gas Production

The wastes produced during oil and gas well drilling and extraction are regulated by state and federal agencies. Most oil and gas producing states have regulations on reserve pit design, construction, and operation; reserve pit closure and waste removal; design and construction of produced water pits; surface discharge of produced water; construction of produced-water injection wells; and abandonment and plugging of wells (for a review of requirements in individual states, see EPA, 1987b).

At the federal level, there are three primary federal programs that regulate oil and gas production wastes: the Underground Injection Control (UIC) program under Part C of the Safe Drinking Water Act (SDWA), the effluent limitation guidelines authorized by Clean Water Act, and the regulations of the Bureau of Land Management of the U.S. Department of Interior on oil and gas production activities in federal and Indian lands through notices to lessees (NTLs) and through issuing permits.

The 1980 RCRA (Resource Conservation and Recovery Act) which identifies and regulates hazardous wastes categorizes drilling fluids, produced waters, and other wastes associated with well drilling and oil and gas extraction as "special wastes" because of their unusually high volume. The high volume of these wastes could make the application of some RCRA regulatory requirements technically infeasible or impractical. Consequently, solid wastes generated from oil and gas production are not considered as hazardous wastes.

The Clean Water Act (CWA) authorizes EPA to regulate the discharge of water pollutants to U.S. waters through technology-based effluent limitations. The CWA requires the achievement of effluent limitations for different discharge sources based on the best available control technology currently available (BACTCA), best available technology economically achievable (BATEA), best practicable control technology currently available (BPCTCA), and the new source performance standards (NSPS) that reflect the greatest degree of effluent reduction to be achieved by the application of the best available demonstrated control technologies, processes, operating methods, or other alternatives. The BACTCA effluent limitations must be achieved by July 1, 1977. The BATEA effluent limitations must be achieved by July 1, 1983. The BPCTCA and NSPS are applied to new sources (EPA, 1976).

Different point source subcategories of the oil and gas development and extraction category are established for the purpose of regulating water pollutant discharges. The oil and gas extraction point source category includes those facilities engaged in field exploration, drilling, well production, and well treatment in the oil and gas extraction industry. Based on production location, production methodology, and waste characteristics, this category is further divided into five subcategories: offshore subcategory, onshore subcategory, coastal subcategory, agricultural and wildlife water use subcategory, and stripper subcategory. Currently, effluent limitations for each of the subcategories have been established based on the application of the best practicable control technology currently available (CFR, 40, Part 435).

The offshore subcategory includes those oil and gas production facilities which are located seaward of the inner boundary of the territorial seas. The effluent limitations of oil and grease discharges from produced water, deck drainage, drilling muds, drill cuttings, well treatment, sanitary wastewater, and domestic wastewater have been established based on the application of the best practicable control technology currently available.

The onshore subcategory includes those oil and gas extraction facilities located landward of the inner boundary of the territorial seas, except those facilities included in the coastal, agricultural and wildlife water use, and stripper subcategories. Based on the application of the best practicable control technology currently available, the effluent limitation for the onshore subcategory requires that no wastewater pollutants be discharged from onshore production facilities into navigable waters.

The coastal subcategory includes those facilities located in any body of water landward of the territorial seas or any wetlands adjacent to such waters. The effluent limitation for oil and grease established for the coastal subcategory is similar to that established for the offshore subcategory.

The agricultural and wildlife water use subcategory includes those facilities whose produced water is used in agriculture or wildlife propagation when discharged into navigable waters. The effluent limitations require that no water pollutants be discharged into navigable waters from any source other than produced water. A daily maximum oil and grease limitation of 35 mg/liter for produced water has been established.

The stripper subcategory includes those onshore facilities which produce ten or less barrels of crude oil per well daily. Currently, there is no effluent limitation for this subcategory.

Recently, EPA proposed offshore effluent limitations defined by the best available control technology economically achievable (BAT) and/or best conventional pollutant control technology (BCT) for existing sources, and NSPS for new sources (EPA, 1991a).

The BPT limitation of onshore oil and gas production requires a zero discharge of wastewaters into surface water bodies. Thus, no pollutant discharges are supposed to be released to water bodies. The zero discharge requirement for onshore oil production forces oil producers to dispose of wastewaters through underground injection and evaporation of water in ponds or pits. Wastewaters to be injected into underground formations must be treated to remove some pollutants in order to reduce their effects on underground water resources. The evaporation of wastewaters leaves pollutants as solid wastes. Thus, pollutants in wastewaters eventually become solid wastes.

1.2 The Clean Air Act and Air Emission Regulations

In 1963, Congress passed the Clean Air Act (CAA) to ask federal and state governments to oversee polluters' actions in reducing air pollution. In 1967, Congress passed the Air Quality Act of 1967 which detailed the time frame for achieving given air quality goals. The act required the Department of Health, Education, and Welfare (HEW) to establish criteria for major pollutants. Individual states were required to file with the HEW to indicate that they would establish emission standards for individual pollutants.

In 1970, Congress adopted the Clean Air Act Amendments, intending to quickly clear the nation's air. The 1970 act and its implementing regulations, which are issued by EPA, obligate owners and operators of air pollution sources to achieve NAAQS and maintain ambient air quality, and ensure that the best technologies for controlling air pollution are developed and used.

The act gives EPA the authority and responsibility for promulgating National Ambient Air Quality Standards (NAAQS) for seven criteria pollutants: particulates, SO_2, NO_2, HC, ozone, CO, and lead. Within nine months of the promulgation of NAAQS, each state must submit a state implementation plan (SIP) to EPA that provides for meeting, maintaining, and enforcing NAAQS within the state's air quality control regions. The SIP must contain enforceable emission limits for pollution sources, necessary compliance schedules for installing the control equipment required to meet those limits, and any work practice or equipment standards necessary to achieve and maintain compliance. An SIP must also set forth the state's provisions for monitoring ambient air quality, issuing construction permits for new pollution sources, and implementing the plan.

EPA has promulgated New Source Performance Standards (NSPS). The NSPS requirement includes limits on the emissions of criteria pollutants and non-criteria pollutants, as well as certain monitoring, testing, and reporting requirements. State and local agencies as well as EPA have the authority to implement NSPS. A federal program on the Prevention of Significant Deterioration (PSD) of air quality has been established. The goal of PSD is to prevent the air quality of "clean" areas from deteriorating. States are required to include PSD measures in their SIPs.

The 1970 CAA required NAAQS to be met by May 1975. Yet, individual states had only nine months to prepare their SIPs after EPA established the NAAQS. Because the requirements in the CAA were extremely stringent, few areas had met the NAAQS even by 1977. Consequently, Congress had to amend the act and, thus, created the 1977 Clean Air Act Amendments. The 1977 Amendments extended the deadline for meeting the NAAQS to December 1982 for most of the nation's areas and to December 1987 for some worst-air-quality areas. In the Amendments, the emission control technology categories of best available control technology (BACT), lowest achievable emission rates (LAER), and reasonable available control technology (RACT) for stationary sources were specified. The BACT must be deployed in new or substantially modified sources. The LAER must be applied to new sources in non-attainment ares. All RACTs must be implemented.

By 1989, about ninety-six U.S. urban areas still failed to meet the federal ozone standard, and forty-one areas failed to meet the CO standards. Attempting to clean the air in most urban areas, Congress has adopted the 1990 Clean Air Act Amendments. To help attain the NAAQS, especially the ozone standard, in a reasonable time frame, the 1990 CAA specifies five categories of non-attainment areas, based on the severity of air pollution. The most severe air-pollution areas are required to implement more control measures but are allowed more time to attain the NAAQS than the less severe areas.

2.3 The Clean Water Act and Effluent Limitations

The first Federal Water Pollution Controls Act was enacted in 1948 and was amended five times prior to the passage of the 1972 amendments. The 1948 Act encouraged interstate compacts and assigned states the primary responsibility for preventing, reducing, and eliminating water pollution. The Act adopted a "water-quality-standard" approach to water pollution control, meaning that pollution regulation would be based on the intended use for a body of water and that waste quality standards would express how much pollution could be put into the body of water.

Another forerunner to modern water pollution control legislation in the U.S. was the Rivers and Harbors Appropriations Act of 1899. Unlike the 1948 Act with its dependence on water quality standards, the 1899 law relied on the "effluent limitations" approach, meaning that effluent standards prescribed the amount of water pollution which could be legally discharged from an individual source, without regard to the water quality of the receiving water body.

The 1972 amendments to the Federal Water Pollution Control Act represent an entirely new law to call for the reduction and even elimination of the flow of water pollution from both municipal sewage systems and industrial facilities. Based largely on the effluent standard approach, the Act established strategies intended to achieve the national goal of a zero-discharge of water pollution by 1985. The Act established three phases of effluent limitations for industrial dischargers: (1) industrial dischargers were to achieve best practicable technology (BPT) by July 1, 1977; (2) industrial dischargers were to achieve a more stringent best available technology (BAT) by July 1, 1983, and (3) new industrial sources were to achieve new source performance standards (NSPS).

The 1977 Water Act Amendments changed the name of the Federal Water Pollution Control Act to the Clean Water Act. The Act specified three sets of effluent limitations to be met by certain deadlines: (1) best conventional technology (BCT) had to be achieved by July 1, 1984, by sources discharging the kinds of conventional pollutants generally found in domestic discharges; (2) best available technology economically achievable (BATEA) had to be achieved by July 1, 1984, by dischargers of priority toxic pollutants; and (3) BAT had to be achieved no later than July 1, 1978, for dischargers of nonconventional pollutants (i.e., neither conventional nor toxic priority pollutants). The Act established requirements for sources to pretreat wastes prior to discharging those wastes to treatment works.

The regulation of water pollutant discharges is accomplished by developing and enforcing the national categorical effluent limitations guidelines and standards. These limitations are established for all facilities which discharge or may discharge directly into U.S. waterways or into publicly owned treatment works (POTWs).

Since 1972, the regulatory process of establishing effluent limitations has focused on the subcategorization of the industries, usually by products, processes or waste characteristics. EPA has promulgated effluent limitations for over fifty industrial categories (EPA, 1991b).

The initial implementation of the Clean Water Act in 1972 focused on controlling conventional pollutants, such as BOD, TSS, and a small number of metals. After an agreement made between the Natural Resources Defense Council (NRDC) and EPA in 1976 for a lawsuit by NRDC, EPA established a new regulatory priority to develop best available technology-based effluent limitations for specific toxic pollutants. Since then, there have been 129 toxic pollutants identified.

Development of effluent limitation guidelines and standards involves categorizing industrial sectors, selecting types of pollutants to be regulated, determining level of technology-based limitations and standards, and conducting economic analysis of the proposed limitations and standards. There are three groups of industrial pollutants for which effluent limitations, standards, and guidelines are established: conventional, toxic, and nonconventional. Conventional pollutants include BOD, TSS, fecal coliform bacteria, pH, and oil and grease. Toxic pollutants include the 129 priority pollutants and the classes of pollutants considered to be toxic (three of which have been deleted). Nonconventional pollutants are any pollutant or pollutant parameter that is not identified as either conventional or toxic.

Four levels of technologies have been selected to determine technology-based limitations for direct dischargers: best practicable technology currently available (BPT), best available technology economically achievable (BAT), best conventional pollutant control technology (BCT), and new source performance standards (NSPS). The BPT level represents the average of the best existing performances of plants of various ages, sizes, processes, or other common characteristics for controlling similar pollutants. The BAT level represents the best economically achievable performance of plants varying in age, size, processes, or other characteristics. BCT is not an additional limitation, but rather replaces BAT for the control of conventional pollutants. BCT is more stringent than BPT. NSPS is applied to new industrial sources. The basis for this level is the best available demonstrated technology aimed to reduce pollution to the maximum extent.

2.4 Hazardous Wastes Regulations

The Solid Waste Disposal Act (SWDA), enacted in 1965, was the first piece of federal legislation to address the waste management problem. The Act was amended significantly by the Resource Conservation and Recovery Act (RCRA) in 1976 and by the Hazardous and Solid Waste Amendments of 1984 (HSWA). These three acts, which are collectively referred to as RCRA, regulate hazardous wastes, solid wastes (nonhazardous wastes), and underground storage tanks that hold petroleum products and hazardous substances.

The RCRA regulates nonhazardous solid wastes and solid waste management facilities, such as nonhazardous industrial surface impoundments, construction/demolition debris landfills, municipal landfills, and "town dumps." The act establishes a voluntary program through which participating states receive federal financial and technical support to develop and implement solid waste management plans and operation standards for facilities.

The RCRA regulates hazardous wastes "from the cradle to the grave." The act requires EPA to establish minimum acceptable requirements for all aspects of hazardous wastes for generators and transporters as well as for treatment, storage, and disposal facilities.

The determination of a waste as a RCRA hazardous waste is the most important, and by far the most complex, step in regulating hazardous wastes. The RCRA defines hazardous wastes as those solid wastes with at least one of the four hazardous characteristics (i.e., ignitability, reactivity, corrosiveness, and toxicity), and requires EPA to identify hazardous wastes. The act explicitly excludes some wastes. Two of the excluded wastes related to petroleum fuels are fly ash waste, bottom ash waste, slag waste, and flue-gas emission control waste generated primarily from the combustion of coal or other fossil fuels; drilling fluids, produced waters, and other wastes associated with the exploration, development, and production of crude oil, natural gas, and geothermal energy; and petroleum-contaminated media from tank cleaning.

The RCRA assigns the responsibility for meeting its regulations to each of the primary hazardous-waste managers: generators, transporters, treaters, storers, and disposers. The requirements designed for generators ensure proper record-keeping and reporting; use of the Uniform Hazardous Waste Manifest system to track shipments of hazardous waste; use of proper labels, markings, and containers; proper storage; and the delivery of the waste to a permitted treatment, storage, or disposal facility.

A transporter must obtain an EPA identification number to transport hazardous wastes. Transporters must complete a Uniform Hazardous Waste Manifest for each shipment, and the manifest must accompany the shipment all times. Any person who treats, stores, or disposes of hazardous waste is considered an owner or operator of a treatment, storage, or disposal facility. The owner or operator is required to meet the requirements of the general facility standards, groundwater monitoring, and closure activities. The general facility standards include notification and record-keeping, general waste handling, preparedness and prevention, contingency plan and emergency procedures, and a manifest system.

Proper facility maintenance and monitoring as well as the use of new techniques to minimize wastes are required for facilities which generate hazardous wastes. Generally, it is not the process that is regulated per se, but rather the type of unit through which the process occurs. The hazardous waste management units addressed by the RCRA include container storage units; tank systems; surface impoundments; waste piles; land treatment areas; landfills; incinerators; thermal treatment units; chemical, physical, and biological treatment units; and underground injection wells.

The HSWA of 1984 prohibits the continued land disposal of hazardous wastes. It requires EPA to set levels or methods of hazardous waste treatment. Wastes that meet treatment standards are not prohibited from land disposal.

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as the Superfund, provides the federal government with broad authority to respond to emergencies involving uncontrolled releases of hazardous substances, develop long-term solutions for the most serious hazardous waste sites, and arrange for the restoration of damaged natural resources. The Superfund provides EPA with the authority and funding to initiate cleanup activities or to require others to undertake immediate cleanup without first having to determine who is liable. If the responsible party cannot be found or is bankrupt, money from the Hazardous Substance Response Trust Fund (the Superfund) can be used. If the responsible party refuses to clean a site, EPA can do so with federal monies and sue the responsible party for damages. The monies for the Superfund are generated from a tax on specified feedstock chemicals. The Superfund Amendments and Reauthorization Act of 1986 (SARA) extended the Superfund beyond 1985, changed the cleanup approach and standards, and allowed for more public involvement throughout the cleanup process.

The Superfund requires the reporting of any release of a hazardous substance into the environment at or above the designated reportable quantity. Currently, there are 720 Superfund hazardous substances. Interestingly, petroleum is specifically excluded from the definition of a hazardous substance under the Superfund. However, the Clean Water Act specifically requires the reporting of certain oil spills, such as petroleum, fuel oil, and sludge.

It is important to note that, unless specifically exempted from the Superfund, a party responsible for the release of a hazardous substance is liable for the costs of cleaning up that release and for any natural resource damages caused by the release, even if the release is not subject to reporting requirements.

Drilling fluids, produced waters, and other wastes associated with the exploration, development, or production of crude oil and natural gas are exempted by the RCRA. The exemption is due to the large amount of wastes produced from these activities and their low level of apparent environmental hazard (based on the information available at that time).

2.5 State Regulations for New Mexico and Texas

The gas production sites for the natural gas fuel cycle study are located in New Mexico and Louisiana (both onshore and offshore). Some features of the regulations for oil and gas production are unique to these states and are included for comparison with the national regulations.

APPENDIX B

PHOTOCHEMICAL MODELING OF POLLUTANTS FROM ELECTRIC POWER PLANTS: APPLICATION TO A GAS TURBINE POWER PLANT

1. INTRODUCTION

The Environmental Protection Agency's (EPA) Ozone Isopleth Plotting Mechanism, (OZIPM-4) model (EPA, 1989a and 1989b) and the Mapping Area-wide Predictions of Ozone, (MAP-O_3) model (McIlvaine 1994) were used to predict ozone concentrations within the vicinity of the hypothetical 500 MW gas turbine power plant. The modeling methodology is described in detail in ORNL/RFF (1994a) and McIlvaine (1994). The MAP-O_3 model predicts area-wide ozone concentrations over the ozone season, by combining ozone concentrations predicted with the OZIPM-4 model with plume trajectories calculated from wind speed and direction measurements. The MAP-O_3 model is also used to predict seasonal average ozone concentrations, as well as, daily peak ozone concentrations over the ozone season throughout the study area.

The effect of power plant NO_x emissions on ozone concentrations is a complex function of meteorological conditions, hydrocarbon concentrations (due to manmade and/or natural hydrocarbon emissions), as well as, ambient concentrations of ozone and ozone precursors. Since the various combinations of these conditions is unique for each day, the task of predicting ozone concentrations over a period of several months is complex and time-consuming. One alternative to modeling each unique day of the ozone season is to model a few days which represent the range of conditions expected to occur over the time period of interest. This approach was chosen for this analysis.

A range of parameters that are characteristic of conditions which result in low, median and high ozone concentrations were identified from a case analysis of ambient ozone monitoring data and the corresponding meteorological observations. These parameters were used in the OZIPM-4 model to predict existing ozone concentrations at the Southeast Reference site (without the power plant) for three composite base case days. These three base case scenarios were then used in the OZIPM-4 model to predict ozone concentrations expected to occur as the result of the power plant NO_x and non-methane organic compounds (NMOC) emissions on high, median and low ozone days. The difference between the base case simulations and the plant simulations is the increment of ozone due to the plant emissions under high, median and low ozone conditions.

Each day of the ozone season was identified as either a 'high', 'median' or 'low' ozone day according to the peak daily ozone concentration that was measured at a nearby monitoring station on that day. This typing scheme, together with the hourly ozone **concentrations** due to the plant emissions, predicted for each of three composite ozone days, resulted in predicted hourly ozone concentrations for each hour of each day of the ozone season. The MAP-O_3 model was used to predict the location of each ozone concentration predicted with the OZIPM-4 model and to calculate the longer-term ozone concentrations needed for this analysis. The MAP-O_3 model calculates the path of the power plant plume (trajectory) from meteorological surface observations of wind speed and direction, for each day of the ozone season. The plume trajectories are combined with the hourly ozone concentrations to provide a map of ozone concentrations occurring in the vicinity of the power plant. The MAP-O_3 model also calculates the peak one-hour ozone concentration for each day of the ozone season and the seasonal average 9 a.m. to 9 p.m. ozone concentration.

Results from the MAP-O_3 model are transferred to an isopleth plotting routine (e.g., SURFER, Deltagraph or others) which generates isopleth maps showing the distribution of ozone concentrations (both above and below ambient ozone concentrations) due to emissions of NO_x and NMOC from the power plant.

This appendix presents the pollutant emission rates (including the calculation of NO_x and NMOC emissions fluxes used as input to the OZIPM-4 model) and the results of the MAP-O_3 modeling. This appendix is intended to provide details of the ozone modeling that are specific to the gas fuel cycle. All other details of the ozone modeling are as described ORNL/RFF (1994a) and McIlvaine (1994).

2. DATA USED IN THE COMPUTER MODELING

2.1 EMISSIONS FLUXES

Once the base case simulations for the Southeast Reference site are run, the power plant emissions are entered in the OZIPM-4 model in the form of an hourly emissions flux. Unlike Gaussian dispersion models which accept emissions from point sources as an emission rate (e.g., grams/second), the OZIPM-4 model accepts emissions of NO_x and NMOC as an emissions flux in units of kilograms per square kilometer per hour (kg/km ^{2}-hr). Both the OZIPM-4 model and Gaussian type models predict pollutant concentrations, typically in units of grams per cubic meter, (g/m ^{3}) or ppb. The simulated column of air in the OZIPM-4 model is assumed to extend from the earth's surface through the mixed layer and the air within the column is assumed to be uniformly mixed at all times. As the column of air passes over the power plant, the column is 'initialized' with a quantity of NO_x and NMOC emissions from the plant.

In the OZIPM-4 model, the column of air is transported at some wind speed (u) along a trajectory (Lagrangian coordinate system). Output from the model is in the form of pollutant concentrations that occur, within the column, after some period of time (travel time or downwind distance assuming some wind speed). In order to use the OZIPM-4 model to calculate ozone concentrations due to a point source, an emissions flux must be calculated and entered into the model, that will result in a concentration within the column (i.e. the plume) equal to that which would occur from the plant emissions after traveling downwind for one hour. The one-hour time period is chosen because that is the normal temporal resolution achieved with the OZIPM-4 model. That is, OZIPM-4 is typically used to calculate (instantaneous or average) ozone concentrations, hour by hour. Therefore, all input conditions such as emissions are one-hour averages.

The emissions flux, F, used as input to the OZIPM-4 model and derived in ORNL/RFF (1994a) and McIlvaine (1994) is given by:

$$F = \frac{8Q}{\pi u^2 t_t t_d} (0.2778) \qquad (1)$$

where,

F = the emissions flux which has units of kg/km ^{2}-hr,
Q = the emission rate of pollutant from the plant in units of g/s,
u = the wind speed which has units of m/s,
t_t = the travel time of the plume in hours and
t_d = the duration of emissions in hours (this value will always be one hour when the OZIPM-4 model is used to simulate a point source emission).

This is the emissions flux that will result in a NO_x concentration in the power plant plume, after one hour of travel time (i.e. one hour of dispersion) from the stack. This method of calculating flux is not appropriate for tame periods less than one hour. This calculation assumes no chemical conversion during the first hour. During this time, NO_x concentrations from the plant are expected to be predominantly NO and very high (relative to ambient). Any chemical reactions occurring would most likely be the conversion of some NO to NO_2 by ambient ozone. After this time, NO_x concentrations in the column are expected to be dominated by photochemical reactions and vertical mixing of the atmosphere, as it is subsequently simulated by the OZIPM-4 model.

The emissions flux calculated with this method is a function of the pollutant emission rate (Q in g/s), duration of the emission, (t_d), travel time of the plume, (t_t) and the wind speed, (u). The NO_x emission rate for the gas turbine power plant at the Southeast reference site of 46.9 g/s was used to calculate the NO_x emissions flux. The non-methane hydrocarbon emission rate is negligible. Duration of the emission (t_d) is always one hour for the OZIPM-4 simulations, since the column of air receives emissions, in units of kg/km ^{2}-hr, from the stack as it is transported over the power plant plume.

The travel time of the plume (t_t) is the number of hours that the plume travels before mixing to the ground. Prior to 10 a.m., under typical summertime conditions, the mixing height, (which may be thought of as a lid which prevents further vertical mixing) is stall below the effective stack height. (The effective stack height is the combined height of the stack and the height that the plume has risen due to effects of momentum and buoyancy). Until the mixing height exceeds the effective stack height, the plume is essentially trapped above the mixed layer and may be transported some distance before the mixing height rises sufficiently to allow the plume to be mixed to the ground. Due to the effects of the mixing height on plume mixing, it is assumed that no plume is mixed to the ground prior to 10 am. Any plume which originates between 10 a.m. and 8 p.m. is assumed to mix to the ground within an hour of travel time. Plumes which originate prior to this time are assumed to be transported aloft until 10 a.m., after which time solar heating is sufficient to produce vertical mixing. Since sunlight and temperature are not sufficient to promote photochemical activity during early morning hours, the most likely effect from early morning emissions is to increase concentrations of NO_x aloft, until such time, as they are mixed to the ground and can react with NMOC emissions.

The flux calculation for hours prior to 10 a.m. is adjusted to account for the fact that the plume has undergone additional dispersion prior to mixing to the ground. To account for the additional dispersion which occurs in plumes which originate prior to 10 a.m., the flux for each of these hours is defined as a function of the 10 a.m. flux. Plumes which have traveled two hours (dispersed two hours) are assumed to have half the flux of a plume which has traveled one hour ($F_{9a\,m} = F_{10a\,m} / 2$) and plumes which have traveled three hours are assumed to have one third the flux of a plume which has traveled one hour ($F_{8\,a.m.} = F_{10\,a.m.} / 3$) and so on. In other words, the flux for hours prior to 10 a.m. is calculated with Equation [1] above with t_t = the travel time of the plume prior to mixing to the ground (i.e. the number of hours prior to 10 a.m. plus one hour to account for 10 - 11 a.m.)

Tables [1], [2] and [3] show the wind speed data used in calculating the NO_x and NMOC emissions flux for the gas turbine power plant under low, median and high ozone conditions. The 10-meter wind speeds are the 10-day average observations described in ORNL/RFF (1994a) and McIlvaine (1994) for each composite day. Since wind speed varies with height (wind speeds at the earth's surface are slower due to frictional effects of surface roughness), the stack top wind speed was calculated from the 10-meter wind speed using the stability class and the power law expression (Wark and Warner, 1981):

$$\frac{u}{u_1} = \left(\frac{z}{z_1} \right)^p \qquad (2)$$

where, u is the wind speed at altitude z,

u_1 is the wind speed at altitude z_1, and

p is the positive exponent which is a function of stability class.

Default rural wind profile exponents from the Industrial Source Complex (ISC) Dispersion Model User's Guide were used (EPA, 1986). The stack height of the gas turbine power plant is 65 meters.

In calculating the emissions flux, a 24-hour average representative wind speed was developed for each composite base case scenario. The combined 24-hour average of both the 10-meter and stack top wind speeds was computed for the flux calculation. This average wind speed was selected to dampen some of the hourly variability seen in both wind speeds and to account for the fact that the actual wind speed is, in fact, unknown and may actually be higher than the surface wind speed and lower than the calculated stack top wind speed. The average wind speeds for the high, median and low ozone conditions were 2.2, 2.9 and 3.6 m/s, respectively.

The 24-hour, average wind speeds described here were used to calculate the emissions flux for the plant under high, median and low ozone conditions during the hours from midnight to 9 p.m. Due to the uncertainty regarding the location of the mixing height, with respect to the plume, during the evening hours (9 p.m. to midnight) and to the fact that emissions from the plant during this time are not expected to have an appreciable impact on ozone concentrations during the following day, ozone concentrations were not predicted for plumes which originate between 9 p.m. and 1 1 p.m.

The NO_x and NMOC emissions flux for each hour are shown in Tables [1], [2] and [3]. These values were input to the OZIPM-4 model in order to predict the ozone concentrations expected to occur as the result of power plant plumes that originate at certain hours (birth hour) and travel for some period of time (plume age). Results of these OZIPM-4 model plant simulations were subtracted from the corresponding base case simulations to obtain the incremental ozone concentration due to the plant emissions as a function of birth hour and plume age under high, median and low ozone conditions.

3. RESULTS

3.1 CROP EFFECTS RESULTS

The crop effects analysis portion of the gas fuel cycle requires an estimate of the seasonal 9 a.m. to 9 p.m. average ozone concentrations due to the plant emissions. These results are shown in Fig. [1] and [21. The power plant is shown in the center of each isopleth map with a triangle marker. The scale of each figure is in kilometers from the plant. Ozone concentrations are reported in ppb (by volume). Results are presented separately for two cases; one with and one without ozone depletion. (Ozone concentrations above base case will be referred to as ozone bulges and ozone concentrations below base case will be referred to as ozone depletions).

Figure [1] shows the predicted impact of the gas power plant emissions on the seasonal 12-hour average ozone concentrations due to ozone bulges only. These results do not account for ozone scavenging. As seen in Fig. [1], the highest 12-hour seasonal average ozone concentration (based on bulges only) is 0.8 ppb (the smallest isopleth line) and occurred approximately 30 kilometers from the plant in the east northeast direction. The lowest isopleth plotted in Fig. [1] is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 260 kilometers from the plant in the northeast direction and 170 kilometers in the southwest direction.

Figure [2] shows the predicted impact of the gas turbine power plant emissions on the seasonal 12-hour average ozone concentrations due to both ozone bulges and depletions. The highest 12-hour seasonal average ozone concentration is 0.60 ppb (the smallest isopleth line) and occurred approximately 20 kilometers from the plant in the east northeast direction. The lowest positive isopleth plotted in Fig. [2] is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 240 kilometers from the plant in the northeast direction and 160 kilometers in the southwest direction. The results shown in Fig. [1] and [2] are very similar since emissions from the gas turbine power plant do not cause significant ozone depletion on a seasonal average.

In addition to the results seen in Fig. [1] and [2] the seasonal average baseline ozone concentration was obtained from monitoring station data. The 9 a.m. to 9 p.m. seasonal average ozone concentration for a rural monitoring station (Rutlege Pike, Knoxville) approximately 60 kilometers from the hypothetical plant site, for the period from May 1990 to September 1990, was calculated from hourly ozone concentrations in the U.S. EPA AIRS database. The five-month seasonal average background ozone concentration is 53 ppb.

3.2 HEALTH EFFECTS RESULTS

Estimates of the peak daily one-hour average ozone concentration, due to the plant, for each day of the ozone season are required for the health effects analysis. Results from the MAP-O_3 model for the health effects portion are in tabular form and are too lengthy to include here. The peak daily ozone increment due to the power plant, as well as the daily peak background ozone concentration are reported at each location in a polar grid (each downwind distance and sector) for each day of the ozone season (provided the combined total of the background and increment due to the plant was greater than or equal to 80 ppb). This criteria was met (and results reported) for 33 days during the 1990 ozone season. One of the 33 days was in the month of May, eight of the days were in June, ten were in July, and seven days each were in August and September.

As stated above, results for the health effects analysis are in tabular form and correspond to 33 days of the ozone season. (If the actual results used in the health effects study were presented here graphically it would require 33 figures, one for each day). Alternatively, Fig. [3] is provided here, simply to illustrate the spatial distribution of daily peak ozone concentrations during the 1990 ozone season at the Southeast Reference site. The power plant is shown in the center of each isopleth map with a triangle marker. The scale of the figure is in kilometers from the plant. Ozone concentrations are reported in ppb (by volume).

The ozone concentrations shown in Fig. [3] are the maximum daily peak ozone concentrations at each location in the receptor grid. As seen in Fig. [3], the highest daily peak ozone concentration due to the power plant emission, during the ozone season, was 11 ppb, occurring from 115 kilometers in the northeast direction to 25 kilometers in the southwest direction. A daily peak ozone concentration of 1 ppb was seen, as far away as 190 kilometers in the northeast direction and 110 kilometers in the southwest direction.

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Table 1. Hourly meteorological parameters for the 10-highest ozone days during 1990 at Knoxville used to calculate emissions fluxes for the gas-fired power plant.

Begin Hour	10-meter Wind Speed* (m/s)	Stack Top Wind Speed* (m/s)	Stability, Class	NOx Flux** (kg/km^2-hr)	NMOC Flux** (kg/km^2-hr)
0	1.0	2.9	7	0.60	0.00
1	1.1	3.2	7	0.66	0.00
2	1.2	3 5	7	0.73	0.00
3	0.5	1.3	7	0.83	0.00
4	0.9	2.5	7	0.94	0.00
5	0.8	2.2	7	1.10	0.00
6	0.6	1.6	6	1.32	0.00
7	1.0	1.9	5	1.65	0.00
8	1.3	1.8	4	2.20	0.00
9	2.2	2.7	3	3.30	0.00
10	2.4	2.7	2	6.60	0.00
11	2.2	2.5	2	6.60	0.00
12	2.8	3.2	1	6.60	0.00
13	2.8	3.2	1	6.60	0.00
14	2.3	2.6	1	6.60	0.00
15	2.8	3.2	2	6.60	0.00
16	2.3	2.6	2	6.60	0.00
17	2.3	2.7	3	6.60	0.00
18	2.1	2.4	2	6.60	0.00
19	2.5	3.0	3	6.60	0.00
20	2.1	2.8	4	6.60	0.00
21	2.1	4.1	5	6.60	0.00
22	1.4	3.9	6	6.60	0.00
23	1.2	3.5	6	6.60	0.00

* 24-hr average of stack height & surface wind speed: 2.2 m/s
** Flux based on the 24-hr average stack height and surface wind speed; flux for hours 0 to 9 is adjusted for spreading of plume

Table 2. Hourly meteorological parameters for the 10-median ozone days during 1990 at Knoxville used to calculate emissions fluxes for the gas-fired power plant.

Begin Hour	10-meter Wind Speed* (m/s)	Stack Top Wind Speed* (m/s)	Stability Class	NOx Flux** (kg/km^2-ltr)	NMOC Flux** (kg/km^2-hr)
0	1.3	3.6	6	0.37	0.00
1	1.2	3.5	7	0.40	0.00
2	1.3	3.6	6	0.45	0.00
3	1.0	2.7	6	0.50	0.00
4	1.6	4.5	7	0.58	0.00
5	1.4	3.9	6	0.67	0.00
6	1.3	2.6	5	0.81	0.00
7	1.3	1.7	4	1.01	0.00
8	1.4	1.8	4	1.35	0.00
9	1.9	2.3	3	2.02	0.00
10	1.8	2.1	2	4.04	0.00
11	2.8	3.4	3	4.04	0.00
12	3.6	4.1	2	4.04	0.00
13	3.1	3.5	2	4.04	0.00
14	3.1	3.5	2	4.04	0.00
15	2.8	3.2	2	4.04	0.00
16	2.5	3.0	3	4.04	0.00
17	3.0	3.7	3	4.04	0.00
18	3.1	4.2	4	4.04	0.00
19	2.4	3.1	4	4.04	0.00
20	2.4	4.7	5	4.04	0.00
21	2.4	6.6	6	4.04	0.00
22	1.9	5.3	6	4.04	0.00
23	2.2	6.2	6	4.04	0.00

* 21-lb average of stack height & surface wind speed: 2.9 m/s
** Flux based on the 24-hr average stack height and surface wind speed:
flux for hours 0 to 9 is adjusted for spreading of plume

Table 3. Hourly meteorological parameters for the 10-low ozone days during 1990 at Knoxville used to calculate emissions fluxes for the gas-fired power plant.

Begin Hour	10-meter Wind Speed* (m/s)	Stack Top Wind Speed* (m/s)	Stability Class	NOx Flux** (kg/km^2-hr)	NMOC Flux** (kg/km^2-hr)
0	2.8	5.4	5	0.23	0.00
1	2.6	7.4	6	0.25	0.00
2	2.3	4.4	5	0.28	0.00
3	2.1	5.9	6	0.31	0.00
4	2.0	3.8	5	0.36	0.00
5	2.0	5.6	6	0.32	0.00
6	1.8	2.4	4	0.50	0.00
7	2.3	3.1	4	0.63	0.00
8	2.4	3.2	4	0.83	0.00
9	3.1	4.1	4	1.25	0.00
10	3.5	1.6	4	2.50	0.00
11	3.5	4.6	4	2.50	0.00
12	3.5	4.6	4	2.50	0.00
13	3.7	4.9	4	2.50	0.00
14	3.9	5.2	4	2.50	0.00
15	4.1	5.4	4	2.50	0.00
16	3.8	5.0	4	2.50	0.00
17	3.4	4.5	4	2.50	0.00
18	3.4	4.5	4	2.50	0.00
19	2.7	3.6	4	2.50	0.00
20	2.3	3.0	4	2.50	0.00
21	2.4	3.1	4	2.50	0.00
22	3.1	4.2	4	2.50	0.00
23	2.1	1.0	5	2.50	0.00

*21-hr average of stack height & surface wind speed: 3.6 m/s

** Flux based on the 24-hr average stack height and surface wind speed: flux for hours 0 to 9 is adjusted for spreading of plume

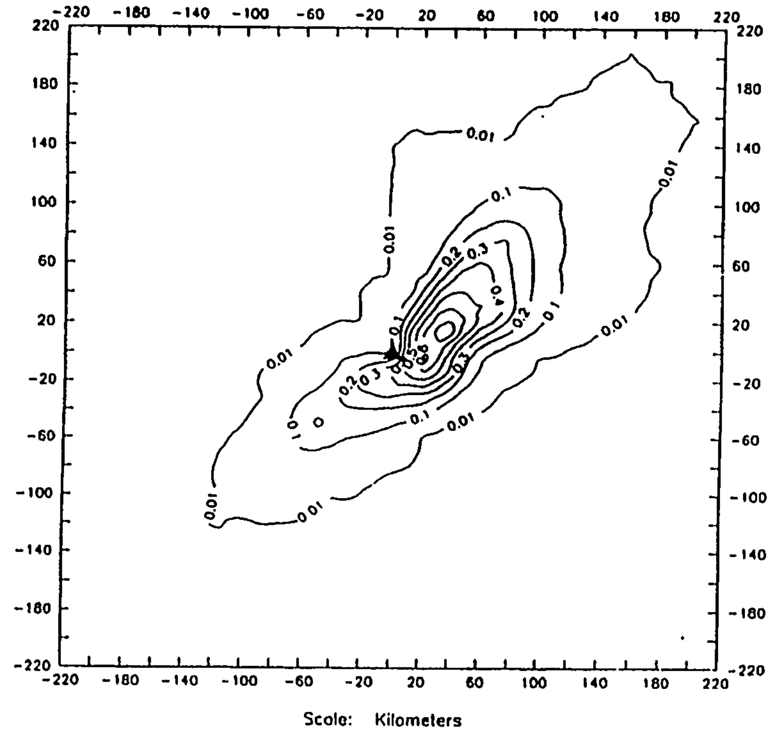

Fig. 1 Positive incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the gas-fired power plant located at the Southeast reference site (positive concentrations are above ambient).

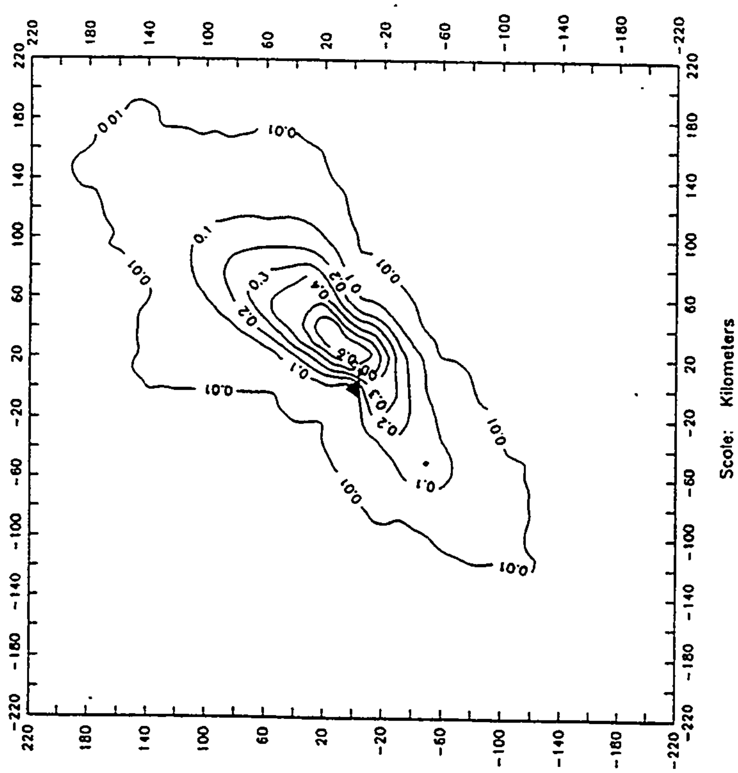

Fig. 2 Total incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the gas-fired power plant located at the Southeast reference site (total concentrations include both positive and negative incremental concentrations).

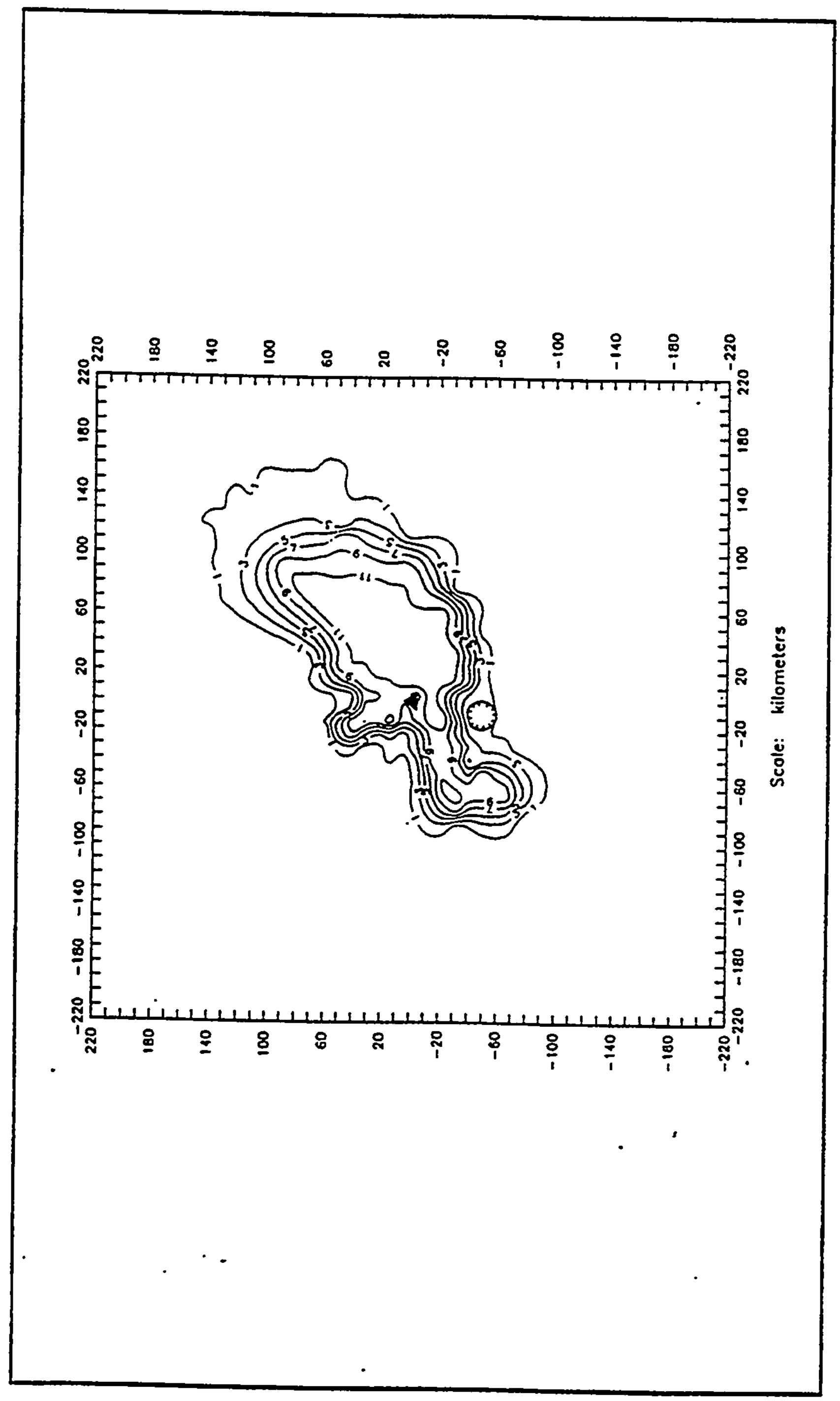

Fig. 3 Maximum daily peak incremental ozone concentrations (ppb) (one-hour average) for May to September 1990 due to emissions from the gas-fired power plant located at the Southeast reference site.

APPENDIX C

AIR DISPERSION MODELING OF PRIMARY POLLUTANTS FROM ELECTRIC POWER PLANTS: APPLICATION TO A GAS TURBINE POWER PLANT

1. INTRODUCTION

The ground-level pollutant concentrations that could be expected to occur as the result of the operation of a 500 megawatt (MW) gas turbine power plant were predicted using atmospheric dispersion modeling. An atmospheric dispersion model is a set of mathematical equations used to characterize the dilution of pollutants by the wind. Some models also account for the chemical transformation of pollutants over time.

Using stack information, (i.e., stack diameter, exit gas velocity, and exit gas temperature) the model predicts the release height of pollutants to the atmosphere. Wind direction, wind speed and other meteorological measurements made in the vicinity of the stack are used to predict the dimensions (i.e., vertical and horizontal spread) of the plume and its travel path downwind. The model calculates pollutant concentrations at receptor locations which are defined by a system of grid points.

The air pollutants resulting from the operation of a power plant may be classified as primary (emitted directly from the plant) or secondary (formed in the atmosphere from primary pollutants). The primary pollutants of interest in this modeling study are nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter. This appendix presents the source characteristics, the pollutant emission rates and the results of the primary air pollutant dispersion modeling for the hypothetical 500 MW gas turbine power plant located at both the Southeast Reference site and the Southwest Reference site. This appendix is intended to provide details of the primary pollutant modeling that are specific to the gas fuel cycle. All other details of the modeling study are described in ORNL/RFF (1994a).

2. DATA USED IN THE COMPUTER MODELING

2.1 SOURCE CHARACTERISTICS

For the operation stage of energy production for a gas turbine power plant, there is one source of air emissions: the exhaust gas stack. The source information needed to perform the air dispersion modeling includes the pollutant emission rate, stack height, exit gas temperature, exit gas velocity and stack tip(internal) diameter. The emissions used in the modeling are presented in the next section.

The hypothetical gas turbine power plant was modeled with a stack height of 65 meters (213 feet) [Chapter 5]. The exhaust stack was modeled with an exit gas temperature of 398 Kelvin (257 degrees F), an exit gas velocity of 19.6 meters per second (3,850 feet per minute) and an internal stack diameter of 7.92 meters (26 feet). Refer to Chapter 5 for a discussion of these source characteristics.

2.2 EMISSIONS

Air pollutant emissions from the operation of the gas turbine power plant used in the modeling study are given in Table 1. A detailed description of the emissions estimates is given inChapter 5. Emission rates of 46.9 grams per second (g/s) nitrogen oxide (NO_x) and 1.95 g/s PM-10 were used in this analysis. PM-10 is particulate matter with an aerodynamic diameter less than 10 micrometers and all the particulate matter emitted from the gas turbine is less than 10 micrometers.

3. RESULTS

The Environmental Protection Agency (EPA) Industrial Source Complex Long-Term (ISCLT) model (EPA 1986) was used to predict annual average pollutant concentrations expected to occur in the vicinity of the power plant. The EPA SCREEN model (Brode, 1988) was used to predict the highest one-hour average pollutant concentrations expected to occur at 24 downwind distances from the power plant. One-hour average pollutant concentrations predicted with the SCREEN model were multiplied by a persistence factor of 0.4 (Brode, 1988) to obtain the highest 24-hour average concentration. Both models were run with an emission rate of 1 g/s. The results from these model runs represent the annual, one-hour and 24-hr average concentrations expected to occur from a unit emission rate. Finally, these concentrations were multiplied by the emission rates, in grams per second, of each of the pollutants of interest.

The ISCLT model was used to predict concentrations at 384 receptor locations (16 directions times 24 downwind distances). The highest concentration at each downwind distance is presented here for the sake of brevity. Concentrations predicted for each receptor location were used in the calculation of impacts in the fuel cycle analyses. The SCREEN model predicts the highest concentration at each receptor along a single radial.

3.1 UNIT CONCENTRATIONS

The highest annual average unit concentration for 24 downwind distances, at the Southeast and Southwest Reference sites are presented in Table 2. The highest of these concentrations for the Southeast site is 0.003 micrograms per cubic meter $\mu g/m^3$, occurring 2 kilometers from the plant. The highest of these concentrations for the Southwest site is 0.002 $\mu g/m^3$, occurring from 2 kilometers to 40 kilometers from the plant.

The highest 24-hour and highest one-hour average unit concentrations for 24 downwind distances are presented in the second and third columns of Table 2. At both sites, the highest 24-hour average concentration is 0.15 $\mu g/m^3$ and the highest one-hour average concentration is 0.38 $\mu g/m^3$, both occurring 2 kilometers from the plant. Differences in annual average unit concentrations (ISCLT) between the two sites are due to different meteorological conditions at each site.

3.2 POLLUTANT CONCENTRATIONS

The maximum pollutant concentrations of PM-10 and NO_x predicted to occur at 24 downwind distances from the power plant at the Southeast site for 1990 are presented in Table 3. The corresponding results for the Southwest site are presented in Table 4. These concentrations were determined by multiplying the unit concentrations in Table 2 by the emission rate (grams per second) in Table 1 for each pollutant.

The highest annual average incremental concentration of PM-10 for 1990, at both sites is 0.005 $\mu g/m^3$. The highest annual average incremental concentration of NO_x is 0.13 $\mu g/m^3$ and 0.11 $\mu g/m^3$ for *the* Southeast and Southwest sites respectively. The highest 24-hour and one-hour average incremental concentrations of PM-10 at both sites is 0.29 $\mu g/m^3$ and 0.730 $\mu g/m^3$, respectively. The highest 24-hour and one-hour average incremental concentrations of NO_x at both sites is 7.03 $\mu g/m^3$ and 17.6 $\mu g/m^3$, respectively.

3.3 COMPARISON TO NAAQS

Under current federal law, National Ambient Air Quality Standards (NAAQS) have been established for sulfur dioxide, nitrogen dioxide, lead, carbon monoxide, ozone and inhalable particles (PM-10). Tables 5 and 6 present a comparison of the total concentration (the sum of the incremental concentration due to the power plant plus the background concentration) and the NAAQS for PM-10 and NO_2 at both sites, for 1990. As shown in Tables 5 and 6, the total ambient concentration of these pollutants is below the NAAQS. (For regulatory purposes the highest, second highest receptor concentration is added to the background concentration and compared to the NAAQS.

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Table 1(a). Natural gas power plant emissions for NO_x and NMOC

Pollutant	Natural gas (lb/MMBtu)	Natural gas (gm/sec)
NO_x	0.12	46.89
CO	0.0003	1.17
NMOC	neg.	-
TOC	0.001 methane	0.39
CO_2	154.3	60,286.
SO_2	neg.	-
PM	see note	-
PM_{10}	0.005	1.95

Table 1(b). Natural gas power plant stack parameters

Parameter	Value	Units
Capacity	500	MW
Exit Temperature	257	°F
Velocity	3850	ft/min.
Diameter	26	feet
Flow rate	2,044,000	cf/min.
Stack height	213.3(65)	feet (meters)
Efficiency	41	%
Capacity factor	74.5	%

Table 2. Maximum unit concentrations at downwind distances from the gas turbine power plant stack at the Southeast Reference site (micrograms/cubic meter).

Downwind Distance From Stack (km)	Maximum Unit Concentration		
	24-hr Avg. SCREEN	1-hr Avg. SCREEN	Annual Avg. ISCLT
1	0.123	0.307	0.000
2	0.150	0.375	0.003
3	0.115	0.288	0.002
4	0.093	0.233	0.002
5	0.082	0.205	0.002
6	0.082	0.204	0.002
7	0.076	0.190	0.002
8	0.069	0.174	0.002
9	0.063	0.158	0.002
10	0.058	0.145	0.002
15	0.054	0.134	0.002
20	0.053	0.133	0.002
25	0.056	0.139	0.002
30	0.057	0.142	0.002
35	0.057	0.142	0.002
40	0.056	0.141	0.001
45	0.054	0.136	0.001
50	0.052	0.131	0.001
55	0.038	0.094	0.001
60	0.036	0.090	0.001
65	0.034	0.085	0.001
70	0.033	0.082	0.001
75	0.031	0.078	0.001
80	0.030	0.075	0.001

Table 2 (cont.). Maximum unit concentrations at downwind distances from the gas turbine power plant stack at the Southwest Reference site (micrograms/cubic meter).

Downwind Distance From Stack (km)	Maximum Unit Concentration		
	24-hr Avg. SCREEN	1-hr Avg. SCREEN	Annual Avg. ISCLT
1	0.123	0.307	0.001
2	0.150	0.375	0.002
3	0.115	0.288	0.002
4	0.093	0.233	0.002
5	0.082	0.205	0.002
6	0.082	0.204	0.002
7	0.076	0.190	0.002
8	0.069	0.174	0.002
9	0.063	0.158	0.002
10	0.058	0.145	0.002
15	0.054	0.134	0.002
20	0.053	0.133	0.002
25	0.056	0.139	0.002
30	0.057	0.142	0.002
35	0.057	0.142	0.002
40	0.056	0.141	0.002
45	0.054	0.136	0.001
50	0.052	0.131	0.001
55	0.038	0.094	0.001
60	0.036	0.090	0.001
65	0.034	0.085	0.001
70	0.033	0.082	0.001
75	0.031	0.078	0.001
80	0.030	0.075	0.001

Table 3. Maximum pollutant concentration (microgramslcubic meter) at downwind distances from the gas turbine power plant stack at the Southeast Reference site for 1990.

Downwind Distance From Stack (km)	Maximum NO_x Concentration			Maximum PM-10 Concentration		
	24-hr Avg. SCREEN	1-fur Avg. SCREEN	Annual Avg. ISCLT	24-hr Avg. SCREEN	1-fur Avg. SCREEN	Annual Avg. ISCLT
1	5.75	14.38	0.022	0.239	0.598	0.001
2	7.03	17.57	0.130	0.292	0.730	0.005
3	5.40	13.50	0.108	0.225	0.561	0.004
4	4.38	10.94	0.104	0.182	0.455	0.004
5	3.84	9.61	0.103	0.160	0.399	0.004
6	3.83	9.57	0.104	0.159	0.398	0.004
7	3.57	8.92	0.105	0.148	0.371	0.004
8	3.26	8.14	0.106	0.135	0.339	0.004
9	2.97	7.43	0.106	0.124	0.309	0.004
10	2.73	6.82	0.106	0.113	0.284	0.004
15	2.51	6.28	0.099	0.104	0.261	0.004
20	2.49	6.22	0.091	0.103	0.259	0.004
25	2.62	6.54	0.084	0.109	0.272	0.003
30	2.67	6.66	0.078	0.111	0.277	0.003
35	2.67	6.67	0.072	0.111	0.277	0.003
40	2.64	6.60	0.067	0.110	0.274	0.003
45	2.55	6.37	0.063	0.106	0.265	0.003
50	2.46	6.15	0.059	0.102	0.256	0.002
55	1.76	4.41	0.056	0.073	0.183	0.002
60	1.68	4.20	0.053	0.070	0.175	0.002
65	1.60	4.00	0.050	0.067	0.167	0.002
70	1.53	3.83	0.048	0.064	0.159	0.002
75	1.47	3.67	0.045	0.061	0.152	0.002
80	1.41	3.52	0.044	0.058	0.146	0.002

Table 4. Maximum pollutant concentration (micrograms/cubic meter) at downwind distances from the gas turbine power plant stack at the Southwest Reference site for 1990.

Downwind Distance From Stack (km)	Maximum NO_x Concentration 24-hr Avg. SCREEN	1-hr Avg. SCREEN	Annual Avg. ISCLT	Maximum PM-10 Concentration 24-hr Avg. SCREEN	1-hr Avg. SCREEN	Annual Avg. ISCLT
1	5.75	14.38	0.027	0.239	0.598	0.001
2	7.03	17.57	0.070	0.292	0.730	0.003
3	5.40	1 3.50	0.082	0.225	0.561	0.003
4	4.38	10.94	0.102	0.182	0.455	0.004
5	3.84	9.61	0.110	0.160	0.399	0.005
6	3.83	9.57	0.111	0.159	0.398	0.005
7	3.57	8.92	0.107	0.148	0.371	0.004
8	3.26	8.14	0.102	0.135	0.339	0.004
9	2.97	7.43	0.096	0.124	0.309	0.004
10	2.73	6.82	0.095	0.113	0.284	0.004
15	2.51	6.28	0.099	0.104	0.261	0.004
20	2.49	6.22	0.097	0.103	0.259	0.004
25	2.62	6.54	0.091	0.109	0.272	0.004
30	2.67	6.66	0.086	0.111	0.277	0.004
35	2.67	6.67	0.080	0.111	0.277	0.003
40	2.64	6.60	0.075	0.110	0.274	0.003
45	2.55	6.37	0.070	0.106	0.265	0.003
50	2.46	6.15	0.066	0.102	0.256	0.003
55	1.76	4.41	0.062	0.073	0.183	0.003
60	1.68	4.20	0.059	0.070	0.175	0.002
65	1.60	4.00	0.056	0.067	0.167	0.002
70	1.53	3.83	0.053	0.064	0.159	0.002
75	1.47	3.67	0.050	0.061	0.152	0.002
80	1.41	3.52	0.048	0.058	0.146	0.002

Table 5. Summary of 1990 modeling results and monitoring data for a gas turbine power plant located at the Southeast Reference Site (micrograms per cubic meter).

	Particulate		PM-10		NOx
	24-hour	Annual	24-hour	Annual	Annual
Maximum Incremental Impact of the Faciltly	0.29	0.005	0.29	0.005	0.13
Background Concentration*	108	47	71	37	23
Total Concentration	108	47	71	37	23
Primary NAAQS**	None	None	150	50	100

* From 1990 EPA AIRS database McMinn Co. TN monitoring station (Site I.D. 47-107-0101); 2nd highest 24hour average and annual mean concentrations.

**. For regulatory purposes the highest second highest receptor concentration is added to the baseline concentration and compared to the National Ambient Air Duality Standard (NAAQS).

Table 6. Summary of 1990 modeling results and monitoring data for a gas turbine power plant located at the Southwest Reference site (micrograms per cubic meter).

	Particulate		PM-10		NOx
	24-hour	Annual	24-hour	Annual	Annual
Maximum Incremental Impact of the Faciltly	0.29	0.005	0.29	0.005	0.11
Background Concentration*	66	42?	64	24	15
Total Concentration	66	42	64	24	15
Primary NAAQS**	None	None	150	50	100

· From 1990 EPA AIRS database San Juan Co. NM monitoring stations; 2nd highest 24 hour average and annual mean concentrations.

·. For regulatory purposes the highest second highest receptor concentration is added to the baseline concentration and compared to the National Ambient Air Duality Standard (NMOS).

? Indicates that the mean does not satisfy AIRS summary criteria.

APPENDIX D

ECOLOGICAL IMPACTS
OF THE NATURAL GAS FUEL CYCLE

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ECOLOGICAL IMPACTS OF THE NATURAL GAS FUEL CYCLE

1. INTRODUCTION

The purpose of this appendix is to summarize the approach used to characterize the ecological effects of the natural gas fuel cycle. The general approach for the overall project is an accounting framework designed as a series of matrices that map each phase of the fuel cycle to a suite of possible emissions, each emission to a suite of impact categories, and each impact category to an external cost or benefit. This appendix defines the ecological impact categories, summarizes the impacts for all phases of the natural gas fuel cycle, and identifies which of those are considered key impacts.

2. DEFINITIONS OF IMPACT CATEGORIES

This section defines the impact categories to be used in the accounting framework (i.e., the column headings in the matrices that map emission and disturbance impacts). The categories are determined by resources or conditions valued by society, rather than by the medium or path. A particular resource such as agriculture can be affected by multiple emissions and by multiple environmental pathways (e.g., both through direct effects of air pollutants on plants and on indirect effects of degraded soil quality). Impact categories associated with the procurement, processing, transport, and use of fuels for electric power generation can be characterized according to whether they relate to (1) natural biological systems, (2) man-made systems, and (3) nonbiological environmental conditions. Depending on the preexisting conditions and on the fuel cycle and energy technology utilized, the impacts discussed under each category (Table D-1) may be adverse or beneficial.

2.1 NATURAL BIOLOGICAL SYSTEMS

Natural biological systems can be affected by energy technology in three ways: (1) by changes in biodiversity, (2) by impacts on commercially important resources; and (3) by impacts on recreationally important resources.

Table D-1. Summary of impact categories

Impact Categories	Impact Pathways	Definition
	Natural Biological Systems:	
Biodiversity	Impaired air, water, soil quality; habitat destruction or disturbance; physical destruction	Impacts on plants and animals; loss of species; altered community structure and function
Commercial fishing	Impaired water quality; habitat loss; physical destruction	Diminished production or contamination above regulatory standards
Recreational fishing	Impaired water quality; flow reduction; habitat loss; physical destruction	Diminished opportunity due to reduced production or contamination
Hunting	Habitat/landscape destruction or disturbance; physical destruction	Diminished opportunities to hunt
Timber	Altered land use; soil contamination; plant contamination or uptake	Diminished yield due to reduced tree growth or reduced acreage
Recreational land and water use	Habitat/landscape destruction or disturbance; impaired air/water quality; reduced visibility	Diminished opportunities for touring, hiking, swimming, etc.
	Man-made Systems:	
Crops and sub-urban landscape	Altered land use or quality; contaminant deposition on plants; uptake by plants; soil contamination, irrigation water contamination	Diminished crop yield
Livestock	Altered land use; contaminant deposition on plants; soil contamination	Diminished productivity due to impaired production or availability of pasture
Buildings and materials	Deposition of particles, aerosols or contaminated rainwater	Enhanced weathering of exposed metal or stone
	Nonbiological Environmental Conditions:	
Land	Altered land use; disturbance; impoundment; contamination	Depression of land values; loss of archeological and historic sites
Water	Runoff; spills; atmospheric deposition	Changes in availability, clarity, taste, potability; diminished aesthetics
Air	Dust or haze; odors; noise	Reduced visibility; diminished aesthetics

2.1.1 Biodiversity

Biodiversity refers to (1) the genetic diversity of species and populations, (2) the species diversity of biological communities (i.e., number of species of plants and animals); and (3) habitat diversity at a local, regional, or global scale. The genetic diversity of species and populations can be altered by changes in environmental parameters; by environmental contamination with xenobiotic substances (e.g., development of hydrocarbon-resistant species); or by the intentional or inadvertent introduction of new gene pools (i.e., hybrid plants or introduced species of animals). Changes in species diversity can result from habitat alterations, extinction of native species, or the introduction of non-native species. Habitat diversity is largely affected by altered land use/land cover patterns. Habitat diversity is especially important for species of animals that require different types of habitats for different life stages or activities (i.e., feeding, shelter, nesting) and for plants that may be dependent on insect pollinators that rely on other habitats (Ranney et al. 1991). Habitat patch size and spatial location is also important, not only in determining animal population size and reproductive success, but in defining microhabitats, as is the case for animal species which survive only in the interior of large forests or certain desert areas.

In general, the greater the biodiversity of desired species the greater the ecological richness and stability of an area. However, changes in biodiversity at a local level are not necessarily followed by identical changes at the regional or global level. Extinction of native species of plants and animals and their replacement by a greater number of non-native species might be viewed as a local increase in biodiversity but on a regional or global scale this would represent a decline in biodiversity (Ranney et al. 1991). Threats to biodiversity were recently discussed in the proceedings of the National Forum on Biodiversity (Wilson 1988).

In the context of this report, ecological impacts of fuel technologies on habitats, species, and/or populations, which are not directly related to commercial exploitation or recreational use of natural resources, are considered impacts on biodiversity. Habitat alterations often cause the greatest impacts on biodiversity because numerous species can be affected. In addition, small unique habitats, which may be of limited scenic or recreational value, but which may be considered valuable for commercial development, may contain rare or endangered species of small population size and limited geographic distribution. Specific impacts which are of concern include those on threatened or endangered species, legally protected areas (e.g., Wild and Scenic Rivers), and other ecologically valued natural systems (e.g., wetlands, pine barrens, riparian areas, bogs, coastal areas, estuaries). These impacts may come about as a result of (1) altered land use; (2) local or regional changes in environmental parameters; or (3) the introduction of toxic substances which may adversely affect the growth or survival of populations.

Although heavily modified by man's activities, the southeastern United States supports a number of endangered and threatened species as well as relict examples of a number of previously common ecosystem types. The southwest has also been heavily modified by man. In this region, riparian habitats are especially important reservoirs of biodiversity. Offshore gas drilling activities and associated navigation activities needed to support offshore development have impacted coastal wetlands.

2.1.2 Commercially Valuable Natural Resources

Commercially valuable natural resources such as fisheries and timber can be affected at various stages of a fuel cycle. Fisheries resources can be affected by physical habitat destruction or alteration (e.g., dewatering of streams) or changes in water quality which can result in the loss of commercially valuable fish and shellfish populations due to direct kills, reductions in productivity (growth, population size or reproductive success), or by the accumulation of contaminants at levels above regulatory standards. Water quality parameters of importance in fisheries are temperature, pH, dissolved oxygen, suspended sediments, plant nutrients (phosphates and nitrates), and toxic substances. Water quality can be affected by wastewater disposal, surface runoff, dredging or other disturbances of substrate, and atmospheric deposition. The latter pathway has recently been identified as the principal source of PCBs, dioxin, and heavy metals in many water bodies; however, no quantitative estimates of biological impacts from this source are available at this time.

Commercial fishing in the Gulf of Mexico is an important economic component of the United States. Economically-important species are shrimp, oysters, blue crabs, menhaden, yellowfin tuna, groupers and scamp, black mullet, red snapper, swordfish, bluefin tuna, black drum, shark, spotted seatrout, and vermilion snapper. Both finfish and shellfish resources are dependent on the estuaries of the Gulf of Mexico. Commercial fishing is not an important industry near the southeastern and southwestern reference sites, although there is a small mussel industry (primarily for pearl production) in the southeastern area, and aquaculture for trout and catfish is common. Commercial fishing would not be an economic consideration at the two refinery sites.

The timber industry may be affected by the development of a specific energy technology as a result of the deposition of air contaminants on foliage causing direct phytotoxicity or reduced growth or by soil contamination leading to leaching of soil nutrients. Extensive stands of pines are grown in the southeast for pulp production, and national forests in the area are utilized for hardwood production. Commercial timber harvesting is negligible in the southwest.

2.1.3 Recreationally Valuable Natural Resources

Forests, parks, streams, lakes, rivers, beaches, and other public or private outdoor areas that may be used for fishing, hunting, camping, nature studies, birdwatching, swimming, boating, hiking, and other recreational activities may be affected by environmental changes associated with a given stage of a fuel cycle or energy technology. Changes in forest composition, wildlife abundance, water quality, and air quality may alter the use of such resources. All rivers and reservoirs in the southeast support intensive recreational use. Recreational fishing for sport or consumption is common throughout the area and is often associated with electric generating facilities such as in the tailwaters below hydroelectric dams and in the cooling water effluents from fossil fuel and nuclear power plants. The most important recreational fisheries in warmwater reservoirs, rivers, and ponds involve the families Centrarchidae (largemouth and smallmouth bass, bluegills, and crappie), Ictaluridae (catfishes), Percidae (perches, walleye, and sauger) and Serranidae (white bass and striped bass). Coldwater streams in the southern Appalachians and on the Cumberland Plateau support fisheries for rainbow, brown, and brook trout. Although the area surrounding the southwestern site is semiarid, the San Juan River supports both a cold-water fishery including rainbow and brown trout and warm-water species including carp, catfish, and suckers. There are no recreational fisheries at the refinery sites. The Gulf of Mexico coastal area is an important site of offshore marine recreational fishing and scuba diving, both associated with oil and gas production platforms which serve as artificial reefs.

Hunting refers to the noncommercial harvesting of game birds and mammals. These animals can be affected by air and water pollution and by physical disturbances (habitat destruction and noise) related to energy production. Hunting is common on private and public lands throughout the southeast. In recent years areas adjacent to the southeastern site have been used for deer hunting.

National forests and the Great Smoky Mountains National Park near the southeastern site are important recreational resources. The number of visitors to the latter was about 8.6 million in 1991 (National Park Service). Recreational resources at the New Mexico site include sightseeing, camping, hiking, and picnicking.

2.2 MAN-MADE SYSTEMS

2.2.1 Agricultural, Silvicultural and Horticultural Industries

Fuel cycles and energy technologies may affect the agricultural, silvicultural, and horticultural industries by reducing the amount of land available for such use, or by reducing crop yields as a result of direct exposure to phytotoxic air contaminants or soil contamination following deposition or irrigation with contaminated water.

Common crops in the southeastern United States include corn, soybeans, and tobacco. Within a 75-mile radius of the southeastern reference site, about 115,300 acres are utilized for corn and about 123,200 acres for soybeans, 14,700 acres for other row crops (tobacco etc.), and 34,200 acres for closecrops such as wheat. Most of the land at the southwestern reference site is semiarid, with vegetation consisting of grasses and shrubs. Lesser amounts of sand wash and saline lowland and badland vegetation are also present in the area. Some native plants are used by Native Americans.

2.2.2 Livestock Industry

Elimination of land for pasture and deposition of contaminants on plant surfaces followed by grazing may have impacts on livestock productivity or commercial value. Livestock includes animals and poultry raised for meat or dairy products as well as animals raised for other commercial purposes such as show horses. Ambient air pollution levels in rural areas are usually far below levels that could cause significant direct effects on animals, and no data demonstrating such direct impacts are available. Cattle and poultry are the principal livestock raised in the southeast. Approximately 76,570 acres within a 75-mile radius of the southeastern reference site is used as pasture and about 19,480 acres for hay production. Vegetation at the southwestern reference site is used for grazing and browsing by domestic livestock and wildlife.

2.2.3 Archeological and Historical Sites

Various aspects of the alternative energy technologies, including utilization of land for construction of roads, power plants, and transmission lines as well as impoundment of streams and rivers may result in the loss of valuable archeological and historically important sites. The southwestern site is in the San Juan Basin, an area rich in paleontological resources. The site would also occupy an area of historic and religious importance to Native Americans. The Bisti and De-na-zin

Wilderness Study Areas and Chaco Culture National Historical Park are located only a few miles from the proposed power plant.

2.2.4 Buildings, Roads, and Materials

Air emissions generated at different points in a fuel cycle can have potential impacts in terms of enhanced weathering of exposed metal, wood, and stone. Acidic depositions can erode limestone and tarnish metals. Additional roads for access to pipelines and refinery sites would be needed.

2.3 NONBIOLOGICAL ENVIRONMENTAL CONDITIONS

Included in this category are general aesthetic considerations such as physical alterations to the landscape and natural bodies of water, changes in visibility due to increases in moisture content, hydrocarbons, or particulate concentrations in the air, the release of noxious odors from stacks or motor vehicles, changes in water clarity, taste and potability due to surface runoff or the addition of process or wastewater effluents, and increases in noise due to machinery and vehicles. Water availability can also be affected by power generating facilities, and can be a major issue in areas where water resources are limited.

3. OVERVIEW OF ENVIRONMENTAL IMPACTS OF THE NATURAL GAS FUEL CYCLE

Gas drilling and production, gas processing, energy generation from natural gas, and transportation and storage of natural gas can have a variety of impacts on aquatic and terrestrial resources. Large amounts of wastes and wastewaters associated with gas extraction and refining must be disposed of in an ecologically acceptable manner. Air emissions in the form of methane from drilling and pipelines and particulates, hydrocarbons, SO_2, NO_x, CO, and CO_2 from power generation, well drilling equipment, and compressors used for distribution add to atmospheric pollutants. These latter emissions may add incrementally to regional and global effects of atmospheric pollutants such as acid deposition and ozone depletion. Maintenance of waterways and construction of pipelines and on-shore facilities for transportation and storage may impact coastal resources such as wetlands. Noise associated with drilling and production operations and the construction of roads is generally a local problem.

3.1 GAS DRILLING AND PRODUCTION

The natural gas supplied to the southeastern reference site in 1990 would be produced and processed in the Gulf of Mexico off the coast of Louisiana whereas that in 2010 would be produced onshore in southern Louisiana. Natural gas for the southwestern power plant site would be produced and processed in the San Juan Basin of northwestern New Mexico in both 1990 and 2010.

The three major wastes from both onshore and offshore natural gas drilling and extraction are "produced" water (water associated with the oil or gas reservoir), drilling fluids, and drill cuttings. The constituents of these three wastes vary from well to well, geographically, and over time. The amounts of produced water also vary over time. These three types of waste are combined, solid material is separated, and then they are treated by the same processes. Offshore, treated wastewaters are discharged directly overboard. Onshore, most produced water is disposed of by reinjection into the well. Treated produced water and drilling wastes are also discharged into coastal areas or stored in pits where they can enter surface waters or leach into groundwater. Both Louisiana and New Mexico have experienced groundwater contamination. Groundwater is a major source of drinking and irrigation water in New Mexico; approximately 88% of the New Mexico population relies upon groundwater for their water supply (New Mexico Water Quality Control Commission 1990).

3.1.1 Offshore Drilling

Because natural gas and oil are often produced from the same well, the impacts of emissions from either source cannot be separated. Impacts to coastal areas and marine environmental resources such as fisheries and endangered species at offshore drilling sites can result from discharge of produced water and drilling fluids and cuttings. Well blowouts may occur, but these are of little ecological impact. Oil spills are considered as part of the oil fuel cycle. Pre-construction seismic surveys and the construction and operation of platforms and pipelines can interfere with commercial, recreational, and subsistence fisheries. The construction of pipelines and navigation channels through intertidal zones and wetlands can permanently destroy aquatic areas which serve as nursery areas for fish and habitat for birds and other wildlife. In addition, onshore construction of support facilities can have potential adverse economic effects on tourism, recreation, and fishing (Neff et al. 1987). Major activities that may impact coastal and marine areas during development and operation of an offshore natural gas/oil facility are listed in Table D-2. The major types of onshore gas service and support facilities include gas processing plants, navigation channels, pipelines and

Table D-2. Major activities in the development of an offshore oil and gas field and their potential effects on marine and coastal environments

Activities	Potential Effects
Evaluation	
Seismic surveying	Noise effects on fishes and mammals
Exploration	
Rig emplacement	Seabed disturbance due to anchoring
Drilling	Discharge of drilling fluids and cuttings; risk of blowouts
Routine rig operations	Deck drainage and sanitary wastes
Rig servicing	Discharges from support vessels and coastal port development
Development and production	
Platform fabrication	Land use conflicts and increased channelization in heavily developed areas
Platform installation	Consturction of coastal navigation channels; seabed disturbance resulting from placement and subsequent presence of platform
Drilling	Larger and more heavily concentrated discharges of drilling fluids and cuttings; risk of blowouts
Completion	Increased risk of oil spills
Platform servicing	Dredges and coastal port development; discharges from vessels
Separation of oil and gas from water	Intermittent or chronic discharges of petroleum and other pollutants
Fabrication of storage facilities and pipelines	Coastal use conflicts
Offshore emplacement of storage facilities and pipelines	Seabed disturbances; effects of structures
Transfer to tankers and barges	Increased risk of oil spills; acute and chronic inputs of petroleum
Construction of on-shore facilities for transportation and storage	Coastal use conflicts; alterations of wetlands in pipeline corridors
Pipeline operations	Oil spills; chronic leaks

From Neff et al. 1987.

pipeline landfalls, pipecoating and storage yards, platform fabrication yards, service bases, and terminals. These facilities are concentrated in the coastal areas of Louisiana and eastern Texas (U.S. Department of Interior 1991).

The Gulf of Mexico continental shelf is an important winter spawning ground for sport and commercial fishes such as menhaden, Atlantic croaker, and mullet and invertebrates such as brown and white shrimp. It is also the year round habitat for ocean sunfish, oarfish, swordfish, king mackerel, and whales (Gates 1985). Other important commercial fisheries are yellowfin tuna, groupers and scamp, black mullet, red snapper, swordfish, bluefin tuna, black drum, shark, spotted seatrout, and vermilion snapper (U.S. Department of Interior 1991). Marine mammals and sea turtles are present offshore; shorebirds inhabit the wetlands. Most species of finfish and shellfish are dependent on estuarine areas at some time during their life history. Estuary-dependent species of importance include menhaden, shrimps, oyster, crabs, and sciaenid fish. The coast of Louisiana consists of vast areas of esturaine wetlands interlaced with many streams and channels; the wetlands extend from the shore for 5 to 30 miles inland. There is very little beach area.

Although baseline studies of the physical oceanography and ecology of the Gulf of Mexico Outer Continental Shelf have been ongoing (National Research Council 1990, 1992) there is a paucity of information on distribution of species and composition of communities before onset of oil or gas drilling. The natural variability of ecosystems makes quantification of changes in the quantity and composition of marine communities difficult. Animals and plants near the edge of their range or utilizing marginal habitats would be the most susceptible to reduction in numbers. Although local effects in the area of drilling platforms have been noted, overall effects on biodiversity are probably slight. Chronic pollution of the marine environment is widespread but difficult to quantify. Ecological impacts, particularly from a small incremental increase in pollution, are even more difficult to assess. Models of the fate and effects of chronic discharges may be useful but require further development.

The catch of fish off the coast of Louisiana has decreased concomitantly with the development of the petroleum industry. However, the decrease has been attributed to overfishing (U.S. Department of the Interior 1991). Landings data from the Louisiana coast for several important commercial fisheries - shrimp, red snapper, and blue crab - indicated consistently lower catch-per-unit-effort than for the rest of the Gulf of Mexico. Since >88% of the offshore platforms are located in this area, the impact from drilling could be significant (Petrazzuolo et al. 1985). However, natural variations of fish populations and the presence of contaminants from other sources make it difficult to detect or quantify potential impacts from gas production.

According to the U.S. Department of Interior (1991), no permanent degradation of water quality is expected in the offshore coastal environment. Rapid dilution of discharged materials is expected to limit the extent of water quality degradation to within a few hundred meters of the source. However, if produced water is discharged into isolated coastal areas such as shallow salt marsh environments with limited circulation, localized degradation of water quality may take place as long as the discharges continue.

3.1.1.1 Wastewater Emissions

3.1.1.1.1 Produced Water

Produced waters contain oil and grease which are removed before disposal, water soluble hydrocarbons, other organic chemicals, high salt concentrations, and trace metals. Radioactivity in the form of radium-226 and radium-228 has been associated with some produced waters. On offshore platforms, produced water is treated by gravity separation and gas or air flotation before discharge overboard. These processes generally reduce the free oil present by more than 90%. Based on a 30-platform study in the Gulf of Mexico, the U.S. EPA set the mean values from the study as Best Practicable Treatment (BPT) limits for oil and grease, priority organics, and priority metals in offshore produced waters (U.S. EPA 1991). Limits were set for both oil only and oil and gas producing platforms (Table D-3). Best Available Technology (BAT) limits based on membrane filtration were also calculated. The BPT guidelines are currently in effect. In an earlier survey of oil and gas platforms in the Gulf of Mexico, Lysyj (1982) found four organic priority pollutants (benzene, toluene, xylenes/ethylbenzene and phenol) and two metal priority pollutants (chromium and lead) in all treated effluents. Naphthalene, zinc, beryllium, cadmium, copper, silver, and nickel were found intermittently. The dissolved organic carbon averaged 436 mg/L. The composition of the treated water was complex; components originated from the oil and gas as well as from demulsifiers, defoamers, and flocculation reagents used to facilitate treatment.

Neff (1987) reviewed the toxicity of produced water to estuarine and marine crustaceans and fish from the Gulf of Mexico. For whole produced water (hydrocarbon concentration 17.9 ppm), more than 88% of LC_{50} values were above 10,000 mg/L and all were above 1,000 mg/L. The most toxic produced water samples had been treated with biocides. The most sensitive organism was the brown shrimp (*Penaeus aztecus*) with a 48-hour LC_{50} of 8,000 mg/L. By most toxicity classifications, produced water can be considered practically nontoxic and would not have an adverse impact on organisms in the water column around platforms. Chronic studies with produced water have not been undertaken.

Table D-3. BPT effluent concentrations for produced waters (mg/L)

Constituent	Gas Platforms	Oil and Gas Platforms
Total suspended solids	67.5	67.5
Oil and grease	28	92
Benzene	6.05	1.797
Bis(2-ethylhexyl)phthalate	0.101	0.106
Ethylbenzene	0.736	0.533
Naphthalene	0.410	0.136
Phenol	7.456	0.814
Toluene	4.965	1.533
2,4-Dimethylphenol	0.720	0
Cadmium	0	0.032
Copper	0	0.193
Lead	0	0.384
Nickel	0	0.145
Silver	0	0.060
Zinc	0.154	2.574

Source: U.S. EPA 1991

Water Quality Criteria have been set for acute and chronic exposures of saltwater organisms to many of the organic and trace metal constituents of produced water (U.S. EPA 1992b) (Table D-4). These limits are close to or lower than BPT limits for offshore produced water discharges. However, a comparison of the BPT concentrations with the Water Quality Criteria after 10,000-fold dilution 100 meters downcurrent of the discharge (see Section 3.1.1.1.2 for dilution factors) shows that all constituent concentrations would be below the acute and chronic criteria levels.

Table D-4. Water quality criteria of produced water constituents for saltwater organisms (mg/L)

Constituent	Acute	Chronic
Benzene	5.1[a]	0.7[a]
Bis(2-ethylhexyl)phthalate (as phthalate ester)	2.9[a]	0.0034[a]
Ethylbenzene	0.4[a]	-
Naphthalene	2.35[a]	-
Phenol	5.8[a]	-
Toluene	6.3[a]	5.0[a]
2,4-Dimethylphenol	-	-
Beryllium	-	-
Cadmium	0.043	0.0093
Chromium (III)	10.3[a]	-
Chromium (VI)	1.1	0.05
Copper	0.0029	-
Lead	0.220	0.0085
Nickel	0.075	0.0083
Silver	0.0023	0.00092[b]
Zinc	0.095	0.086

[a]Insufficient data to develop criteria. Value presented is the lowest-observed-effect level.
[b]Proposed criterion.

3.1.1.1.2 Drilling Fluids

Drilling fluids are slurries composed primarily of barite (barium sulfate), clays, lignosulfonates, and lignites. Used drilling fluids are usually recovered and reused during drilling activities; spent drilling fluids, referred to as muds, become wastewater and are discharged intermittently into the ocean during well drilling. U.S. EPA (1991) estimates that, on the average, 6,926 barrels per well (268 barrels per day) of water-based drilling fluid may be discharged during the first 100 days of well drilling in the Gulf of Mexico.

Discharges of water-based drilling fluids are regulated by the Environmental Protection Agency. Although mineral oil or diesel oil is commonly used intermittently as a lubricant during drilling, discharges of oil-based drilling fluids into marine waters is prohibited. The free oil "no discharge" limitation is implemented by requiring no oil sheen to be present upon discharge (U.S. EPA 1991). After treatment for removal of oil and grease, drilling fluids are discharged directly into the ocean. These drilling muds contain a high BOD and chemical oxygen demand (COD) which may have a detrimental effect on aquatic organisms. Several metals of environmental concern because of their potential toxicity and/or abundance are found in drilling fluids: arsenic, barium, chromium III, cadmium, copper, iron, lead, mercury, nickel, and zinc.The metals found at concentrations significantly higher than in natural marine sediments include barium, chromium, lead, and zinc (Neff et al. 1987). Effluent limitations of 1 mg/kg dry weight for cadmium and mercury in whole drilling fluid have been proposed (U.S. EPA 1991).

Payne et al. (1987) among others (Neff 1987; U.S. Department of the Interior 1991) reviewed dispersion models and field studies of the fate of drilling fluids and cuttings. Dispersion models for drilling fluids and drill cuttings adequately described short-term dispersion. In contrast, because of insufficient data on transport rates, current patterns and the long-term behavior of discharge constituents, models have not been successful in adequately predicting the long-term dispersion of discharges from platforms.

Field studies were also undertaken at platforms. These studies showed only localized effects; far-field effects or long-term accumulations were restricted by the high dilution and dispersion rates. Despite different hydrologic parameters at different sites, plume dilution rates were fairly consistent, and the measured levels of suspended solids and particulate trace metal constituents were typically reduced to background concentrations within a few hundred meters of the discharge. The barite and associated metals (aluminum, iron, chromium) tended to settle out of the discharge plume in the vicinity of the well, depositing in the sediment. The lighter materials in the upper part of the plume were transported with the prevailing currents; suspended solids reached background levels 1,000 to 2,000 meters downcurrent of the discharge and within 2 to 3 hours of discharge. Based on the several field dispersion studies, discharged drilling fluids are diluted 1,000-fold or greater within one to three meters of discharge and trace metals are diluted 10,000-fold 100 meters downcurrent from the discharge. At high discharge rates in the Gulf of Mexico, the greatest area of influence ranged up to one kilometer; the measured parameter was light transmittance. Sediments enriched in heavy metals were found around some platforms.

Drilling fluids are of low acute toxicity. Petrazzuolo (1981, 1983) and the National Research Council (1983) reviewed the toxicity of 70 water-based drilling fluids to 70 species of marine organisms including phytoplankton, copepods, isopods, amphipods, gastropods, decapods, bivalves, echinoderms, mysids, polychaetes, and finfish. More than 95% of the tests had LC_{50} values >1000 ppm. None of the drilling fluids were acutely toxic at <100 ppm. The most sensitive species were the estuarine copepod *Acartia tonsa*, the marine copepod *Centropages typicus*, larvae of the dock shrimp *Pandalus danae*, pink salmon fry *Onchorhynchus gorbuscha*, larvae of the lobster *Homarus americanus*, juvenile ocean scallops *Placopecten magellanicus*, and mysid shrimp (*Mysidopsis* sp., *Neomysis* sp., *Acanthomysis* sp., and *Mysis* sp.). The most toxic drilling fluids were those that contained hexavalent chromium, diesel fuel or surfactant.

Studies of chronic or sublethal effects are better indicators of environmental impact than acute studies. Neff (1987) reviewed the sublethal effects of drilling fluids on marine organisms under chronic exposures. Several of the drilling fluids contained diesel fuel. Sublethal effects included altered chemosensory responses and behavior patterns, abnormal development, decreased viability, decreased feeding and food assimilation, altered respiration, and other physiological effects. These effects were observed at concentrations as low as 10-100 ppm. Dilution of the drilling fluids to less than 10 ppm within three hours (an extremely short exposure time compared to chronic exposures) would render them nontoxic under chronic field-exposure conditions.

Water Quality Criteria have been set for acute and chronic exposures of marine organisms to many of the constituents of drilling fluids (U.S. EPA 1992b) (Table D-5). As noted for produced water constituents, a 10,000-fold dilution 100 meters downcurrent of the discharge would result in safe levels of drilling fluid constituents for chronically exposed saltwater organisms.

Table D-5. Water quality criteria of drilling fluid constituents for saltwater organisms (mg/L)

Constituent	Acute	Chronic
Aluminum	–	–
Antimony	1.5[a]	0.5[a]
Arsenic (III)	0.069	0.036
Arsenic (V)	2.3[b]	-
Barium	-	-
Beryllium	-	-
Cadmium	0.043	0.0093
Chromium (III)	10.3[b]	-
Chromium (VI)	1.1	0.05
Copper	0.0029	-
Iron	-	-
Lead	0.220	0.0085
Mercury	0.002	0.000025
Nickel	0.075	0.0083
Selenium	0.3	0.071
Silver	0.0023	0.00092[a]
Thallium	2.13[b]	-
Zinc	0.095	0.086

[a]Proposed criterion.
[b]Insufficient data to develop criteria. Value presented is the lowest-observed-effect level.

3.1.1.1.3 Drill Cuttings

Drilled formation solids and silt are separated from fluids by a shale shaker screen and hydrocyclone and discharged. Drill cuttings are discharged only during the initial phase of drilling. They are released directly to the sea floor (Menzie 1982), leading to potential sediment alteration and burial of benthic organisms (Petrazzuolo 1985). An estimated 1,471 barrels of drill cuttings per well are produced. Depending on quantities discharged and hydrographic conditions, drill cuttings may settle out rapidly near the platform forming piles several meters high and 100-200 meters in diameter or may be dispersed immediately or following resuspension (U.S. Department of Interior 1991). Drill cuttings are generally considered nontoxic.

3.1.1.2 Air Emissions

Air emissions from gas extraction and treatment in the field include volatile organic compounds (VOCs), NO_x, SO_x, CO, and CO_2. The sources and amounts of these emissions are reviewed in Appendix B. Emissions of VOCs are caused by leakage of gas during extraction and treatment, evaporative emissions from wastewater pits and storage tanks, and combustion of diesel fuels used to provide power for gas production and treatment. Emissions of NO_x, SO_x, CO, and CO_2 are primarily from combustion of diesel fuel and natural gas in large internal combustion engines that supply power for drilling.

The primary source of air emissions during drilling and production are the large internal-combustion engines that supply power for drilling. Emission factors, as determined by EPA (1992), for portable well drilling equipment for hydrocarbons, NO_x, SO_x, CO, aldehydes, and particulate matter are 72.8, 910, 60.5, 197, 13.7, and 65 grams per hour, respectively. Emission factors for large diesel engines used in drilling and other activities, in pounds per thousand gallons, are 50 (particulates), 500 (NO_2), 130 (CO), 14 (volatile organic compounds), and 60 (SO_2). For natural gas engines that use a small amount of diesel fuel, emission factors, in pounds per thousand horsepower, are 18 (NO_2), 5.9 (CO), 6.2 (volatile organic compounds), and 0.7 (SO_2). Modeling was not conducted to determine atmospheric concentrations. Emissions from drilling would be diluted before they reach shore and are not expected to cause any national or state air quality standards to be exceeded or to impact aquatic or terrestrial biota.

Gas may require separation and treatment steps at the well site prior to refining or processing at a gas plant. These processes include heating, separation, and dehydration. Emission factors for gas/liquid separators, glycol regenerators, and heater treaters at field sites are not available (U.S. EPA 1992a).

Venting and flaring in order to prevent a well blowout could cause short-term increases in volatile organic carbon concentrations near the site, but these would be of short duration. Venting and flaring emissions data for offshore wells were not located.

3.1.1.3 Other Impacts

Construction activities can impact ocean floor and coastal areas. Dredging for pipeline channels can produce benthic disturbances. Salt marshes may be degraded by construction of pipelines, receiving terminals, and disposal of wastes. A small amount of coastal wetlands (<200 hectares) may be lost to erosion caused by navigation activities needed to support offshore development (U.S. Department of the Interior 1991). The construction of platforms and support activities may interfere with commercial fishing activities. On the other hand, the presence of offshore platforms may enhance recreational fishing in some areas as fish and other marine organisms are attracted to platforms. Offshore platforms may detract from coastal aesthetics (U.S. Department of the Interior 1991).

3.1.2 Onshore Drilling

3.1.2.1 Wastewater Emissions

Drilling wastes in the form of produced water, drilling muds, and drill cuttings were defined in Section 3.1.1.

Onsite treatment of drilling wastes includes underground injection (injection of produced water into underground pits is extensively practiced by the petroleum industry and accounts for 90% of all wastes) evaporation in surface pits or ponds, or treatment and discharge to surface waters. Drilled formation solids and silt are separated from fluids by a shale shaker screen and hydrocyclone and disposed of in landfills, by landspread, by roadspread, or by pit burial. Reserve pits (one per well) are used to accumulate, store (prior to recycling), and dispose of spent drilling fluids, cuttings, and associated wastes. More recently, mud tanks have been used for storage and recycling and pits for disposal. About 63% of reserve pits are unlined and, as a result, seepage of liquid and dissolved solids into shallow freshwater aquifers may occur (U.S. EPA 1987).

In Southern Louisiana, gas production areas are located in or near coastal wetland areas on barge platforms or small coastal islands. Operators dredge canals and esturaries to gain access to sites. Gas and oil producers operating near the Gulf Coast are allowed to discharge treated produced water as well as other drilling-associated wastes into tidally affected surface streams; in other cases wastewater is disposed of in pits. "In this area, reserve pits are constructed out of the materials found on coastal islands, mainly from peat, which is highly permeable and susceptible to damage after exposure to reserve pit fluids. Reserve pits on barges are self-contained, but are allowed to be discharged in particular areas if levels of certain constituents in wastes are below specified limits. If certain constituents are found in concentrations above these limits in the waste, they must be injected or stored in pits" (unlined on coastal islands) (U.S. EPA 1987). Many operators in this area discharge produced water directly to adjacent water bodies; it is estimated that roughly 1.8 to 2.0 million barrels of produced water are discharged daily. Often, the receiving water bodies are freshwater. The Louisiana Department of Environmental Quality now requires operators to apply for permits for these discharges.

New Mexico's San Juan Basin gas field is located in the northwest corner of the state. New Mexico still permits the use of unlined pits for disposal of produced water, but because of groundwater contamination from oil production in the northwestern part of the state, the amount of produced water discharged into unlined pits is limited to five barrels per day (U.S. EPA 1987). Oil and gas wastes are also deposited at centralized disposal facilities. Because of leaching of constituents to groundwater at these sites, current New Mexico regulations prohibit use of unlined commercial disposal pits (U.S. EPA 1987). In one case, it was found that leaching from unlined pits at a commercial landfill that received liquid wastes associated with the oil and gas industry contributed to groundwater contamination by volatile organic compounds (U.S. EPA 1987).

The U.S. EPA (1987) has documented the following cases of environmental impacts from oil and gas production. Incidences in which monetary damages were collected include (1) groundwater contamination following leaching from unlined waste disposal and reserve pits and from improperly operated injection wells, and (2) surface water and sediment contamination from the direct discharge of produced water and drilling mud and the disposal of oily water. Barium, sodium, iron, chlorides, and other ions have migrated into groundwater. These practices have led to contaminated domestic wells, degradation of wetlands, endangerment of oyster beds and crayfish fishery, damage to crops, buildup of polycyclic aromatic hydrocarbons (PAHs) in stream and estuarine sediments, declines in fish populations and other populations of aquatic organisms, and fishkills downstream of operations. Drilling cuttings deposited in shallow waters have extended above the water surface. Most of these impacts were associated with oil production. A damage case involving natural gas was documented in Louisiana: an abandoned gas well blew out sending gas through fault zones and permeable formations to land surface resulting in a potential hazard to drinking water wells in the area.

Onshore produced water has been successfully treated using gravity separators, gas flotation cells, and retention ponds to separate the oil and other constituents from the water. Information concerning concentrations of constituents of onshore produced water was not available, but effluent concentrations of produced water from offshore drilling are expected to be similar (See Table D-3).

Based on sampling data from onshore oil and gas extraction waste streams and disposal facilities, U.S. EPA (1987) identified benzene, phenanthrene, antimony, arsenic, barium, fluoride, and lead as constituents of environmental concern. On the basis of mobility, sodium, cadmium, hexavalent chromium, boron, chloride and total mobile ions were added to the list. Median concentrations (defined as "best-estimate" waste characterizations) for arsenic, benzene, boron, sodium, chloride, and mobile ions (chloride, sodium, potassium, calcium, magnesium, and sulfate) were 0.02, 0.47, 9.9, 9,400, 7,300, and 23,000, mg/L, respectively. Water Quality Criteria for acute exposures of freshwater organisms to constituents of produced water are listed in Table D-6 (EPA 1992b).

Table D-6. Water quality criteria of produced water constituents for freshwater organisms (mg/L)

Constituent	Acute	Chronic
Benzene	5.3[a]	-
Bis(2-ethylhexyl)phthalate (as phthalate ester)	0.94[a]	0.003[a]
Ethylbenzene	0.32[a]	-
Naphthalene	2.3[a]	0.62[a]
Phenol	10.2[a]	2.56[a]
Toluene	17.5[a]	
2,4-Dimethylphenol	2.12[a]	-
Beryllium	0.13[a]	0.0053[a]
Cadmium	0.0039[b]	0.0011[b]
Chromium (III)	1.7	0.21[b]
Chromium (VI)	0.016	0.011
Copper	0.018[b]	0.012[b]
Lead	0.083[b]	0.0032[b]
Nickel	1.4[b]	0.160[b]
Silver	0.00092[c]	0.00012
Zinc	0.120[b]	0.11[b]

[a]Insufficient data to develop criteria. Value presented is the lowest-observed-effect level.
[b]Hardness dependent; tested at 100 mg/L $CaCO_3$
[c]Proposed criterion.

3.1.2.2 Air Emissions

The primary sources of emissions during drilling and production are the large internal-combustion engines that supply power for drilling. See Appendix B and Section 3.1.3 for a discussion of air emissions from wells. Modeling was not conducted to determine atmospheric concentrations. Emission factors were also not available for heating, separation, and dehydration treatment steps which may take place at the well site prior to transport to processing plants.

Venting and flaring in order to prevent a well blowout could cause short-term increases in volatile organic carbon concentrations near the site, but these would be of short duration. By the 1980s, the amount of gas vented or flared in the fields amounted to approximately 0.6% of the gross production (Hillard 1980). According to permits from the Texas Railroad Commission, in 1989, 99.95% of this gas was flared; however, venting activities of less than 24 hours duration do not require a permit, so the venting percentage could be higher (U.S. EPA 1992a). Flaring results in a 98% destruction efficiency for particulate matter and a 99.9% destruction efficiency for total organic gases (California Air Resources Board 1989, as cited in U.S. EPA 1992a).

3.1.2.3 Other Impacts

As previously discussed, drilling activities can impact coastal areas and wetlands. Saltwater, estuarine, and freshwater marshes may be degraded by dredging of access channels, construction of pipelines and receiving terminals, and disposal of wastes.

3.2 NATURAL GAS PROCESSING

Natural gas for the southeastern reference site will be processed in southern Louisiana; natural gas for the southwestern reference site will be processed at the Conoco Company plant in San Juan county, New Mexico. Processing plants require land for their plant and process facilities including settling ponds, water treatment plants, and disposal sites for wastewaters.

Natural gas contains gases and liquids such as water, hydrogen sulfide, carbon dioxide, and various hydrocarbons (ethane, propane, butane) that have to be removed prior to transmission.

3.2.1 Wastes and Wastewaters

Information on the amounts of waste and wastewater produced during processing was not located. The discharge of wastewaters from refineries is regulated by the National Pollutants Discharge Elimination System (NPDES) and state programs. Hazardous wastes are disposed of by land treatment, landfills, impoundments, or landspreading. Condensate stripper bottoms disposal is of environmental concern (U.S. DOE 1983). The water table around the New Mexico refinery site is less than 200 feet below the surface (New Mexico Water Quality Control Commission 1990), making the aquifer vulnerable to leaching of toxic constituents to groundwater.

3.2.2 Air Emissions

Air emissions from natural gas purification plants include particulate matter, NO_x, SO_2, CO_2, hydrocarbons, CO, and aldehydes (U.S. DOE 1983). If present in significant amounts, sulfur and natural gas liquids such as propane and butane are recovered and sold as byproducts. A gas purification plant (process undefined) that handles 250×10^6 ft^3 of natural gas per day (heat content = 1000 Btu per ft^3) emits the following amounts of pollutants per year: particulates, 13.3 tons; NO_x, 3.35×10^3 tons; SO_2, 0.443 tons; hydrocarbons, 29.5 tons; CO, 0.295 tons; and aldehydes, 2.21 tons (U.S. DOE 1983). Modeling was not conducted to determine atmospheric concentrations and thus incremental increases in atmospheric concentrations of primary pollutants for the two processing plants were not available at this time.

3.3 POWER GENERATION

The 500-MW power plants at both sites will have gas turbine units. In 1990 the technology centers on the combined-cycle gas turbine; in 2010 the technology will be the integrated gasification-combined-cycle configuration.

The generation of power by gas-fired power plants will impact the environment through the replacement of existing land resources by the generating facilities and associated support facilities and by the release of gaseous and wastewater emissions. The existing land uses are forest, pasture, and crop production at the southeastern site and grazing territory at the southwestern site. The building of roads to the remote southwestern site would bring increased public access resulting in greater recreational use and greater fishing and hunting (mule deer) pressure. Paleontological resources, Native American cultural and religious resources, and wilderness and recreational resources are located near the southwestern site (U.S. Department of Interior 1982).

3.3.1 Potential Impacts

3.3.1.1 Air Emissions

Combustion of the natural gas contributes hydrocarbons, particulate matter, SO_2, NO_x, CO and CO_2 to the atmosphere. Information on emission rates and incremental increases in atmospheric concentrations of primary pollutants is given in Appendix C. Emission rates are highest for NO_x. According to U.S. Department of Energy (1983), emission rates for the above pollutants are generally lower than for other fossil fuel technologies and emissions for many trace elements are below the limit of detection.

Air pollution can damage plant tissue and cause decreases in production of crops and native vegetation. The extensive literature on the effects of air pollutants on plants has been summarized by Shriner et al. (1990). Gaseous and particulate emissions can also decrease visibility over vast areas. Aesthetic quality at parks in the Southeast and Southwest has been adversely affected by pollution-caused decreases in visibility.

The soil at the southwestern power plant site does not qualify as agricultural land (U.S. Department of Interior 1982), so no impact on crops from air pollution is considered to occur at this site. Therefore, the following discussion will be restricted to the southeastern reference site.

3.3.1.1.1 Carbon Dioxide

Carbon dioxide is the most important greenhouse gas implicated in global warming. General ecological impacts of global warming are discussed in ORNL/RFF (1992). As noted in that report, elevated atmospheric temperatures are likely to result in regional changes in climate and precipitation patterns which will be difficult to predict and may be beneficial or detrimental depending on prior conditions in a given area. Although any source of CO_2 will contribute to these effects, there is at present no way of adequately identifying and quantifying the impacts from a single source.

Increases in atmospheric CO_2 can also stimulate photosynthesis, increase the growth of plants, and enhance the accumulation of carbon in the biosphere. This increase in plant growth is a potential ecological benefit of fossil fuel combustion. However, dose-response functions are not available to quantify this effect, and other factors, such as interactions with fluctuating water and nutrient supplies, competition, and changes in predator-prey relationships are not adequately known to predict impacts. Further discussion of this subject is given in ORNL/RFF (1992).

3.3.1.1.2 Hydrocarbons

Hydrocarbons are emitted from the power plant stack during the combustion process. In natural gas, the primary hydrocarbon is methane. The hydrocarbon emission factor used in this study is 0.01 lb/10^6 Btu or 4.64 grams per sec (Appendix C). Modeling was not conducted to determine atmospheric concentrations. In general, there is a lack of evidence that current ambient levels of hydrocarbons have direct ecological impacts (Amdur, 1986; Heck et al. 1986). However, combustion-derived organic compounds released in the stack emissions do have the potential for indirect impacts due to their reaction with NO_x in the presence of sunlight to form ozone and peroxyacetyl nitrate (PAN). PAN is discussed in Section 3.3.1.1.3 and ozone in Section 3.1.1.1.4.

3.3.1.1.3 NO_x and Other Nitrogen Compounds

The NO_x emission factors used in this study are 0.2 lb/10^6 Btu (75 grams per second) for the 1990 technology and 0.1 lb/10^6 Btu (35.7 grams per second) for the 2010 technology (Appendix C). At these emission rates the maximum annual average increase in NO_x concentration over a 50-km area due to the power plant was calculated to be 0.293 $\mu g/m^3$ in 1990 and 0.140 $\mu g/m^3$ for 2010. In comparison, the average annual ambient concentration of NO_x at the southeastern site was reported to be 23 $\mu g/m^3$ (about 12 ppb NO_2). NO_x emissions from the hypothetical 500-MW natural gas-fired power plant therefore represent about a 1.3% increase in the annual average in 1990 and 0.6% in 2010.

Information on the effects of NO_x on animals is limited to laboratory studies on NO_2 (Table D-7). Nitrogen dioxide is a deep lung irritant capable of producing pulmonary edema if inhaled in sufficient concentrations (Amdur 1986). It can not only cause significant alterations in pulmonary function, but can increase susceptibility to respiratory infection by bacterial pneumonia or influenza virus. The lowest concentrations causing adverse effects (primarily biochemical and structural changes in the respiratory system) generally range from 250 to 1000 ppb. These toxicity thresholds are all above the predicted maximum ambient concentrations resulting from the operation of the 500-MW natural gas-fired power plant. Assuming that wild animals have the same tolerance levels as laboratory animals, it can be concluded that ambient NO_x concentrations would not have direct toxic effects on the local fauna.

There is no evidence that concentrations of NO_x below 50 ppb have direct toxic effects on plants. Concentrations above 50 ppb may produce signs of reduced growth in some species (ORNL/RFF, 1992, Appendix D), and levels of 500 ppb and above may cause foliar injury (Taylor and Eaton 1966).

Table D-7. Effects of Nitrogen Dioxide on Laboratory Animals

Species	Exposure	Effects	Reference
Rat	1 ppm for 4 hours	Lipid peroxidation in lung	Thomas et al. 1968
Rat	166 ppm for 1 hour	LC_{50}	Amdur 1986
Rat	88 ppm for 4 hours	LC_{50}	Amdur 1986
Rat	0.5 ppm for 4 hours or 1 ppm for 1 hour	Damage to mast cells (repaired within 24 hours)	Mueller and Hitchcock 1969
Rat	10 or 25 ppm for 16 weeks	Emphysema-like lung damage	Freeman et al. 1972
Rat	0.8 or 2 ppm for life	Concentration-related cellular alterations in bronchiolar epithelium; 2 ppm induced moderate tachypnea, bloating, increased air retention, and 20% weight increase in lungs	Freeman et al. 1972
Mouse	1.5 ppm for 18 hours; 14.5 ppm 2 hours	25% and 65% increase in mortality (1.5 and 14.5 ppm, respectively) following exposure to *Streptococcus pyrogenes*	Coffin et al. 1976
Mouse	0.5 ppm, 6 or 18 hours/day for 6 months; 0.5 ppm continuously for 3 months	Increased mortality following exposure to *Klebsiella pneumoniae*	Ehrlich and Henry 1968
Guinea pig	5-13 ppm for 2-4 hours	Changes in pulmonary function	Murphy et al. 1964
Rabbit	0.25 ppm, 4 hours/day for 6 days	Alterations in lung collagen	Mueller and Hitchcock 1969
Dog	25 ppm for 6 months	Emphysema-like lesions	Riddick et al. 1968
Squirrel monkey	10-50 ppm for 2 hours	Concentration-related lesions in alveoli and changes in pulmonary function; frank edema at 50 ppm (function recovered 24-48 hours post exposure	Henry et al. 1969
Squirrel monkey	5 or 10 ppm for 1-2 months; 50 ppm for 2 hours	Increased mortality following exposure to *K. pneumoniae*	Henry et al. 1970

In the atmosphere, NO_x reacts with strong oxidizing agents such as O_3, OH, and H_2O_2 to form HNO_3. Deposition of HNO_3 in forests may have an indirect effect on forest health by modifying soil chemistry and thereby affecting plant nutrient status, symbiotic relationships, functions associated with the root system, and susceptibility to disease and damage due to other environmental pollutants such as ozone. Recent studies have indicated that high nitrogen deposition rates in high-elevation forests in the eastern U.S. exceeded nitrogen requirements for growth and may cause nitrate leaching, soil acidification, and loss of essential soil cations such as calcium and magnesium (Van Miegroet and Cole 1984; Ulrich et al. 1980). Occurring over the long life cycle of the forest, this alteration in soil chemistry would outweigh any short-term benefits resulting from the fertilization effect of nitrogen inputs to the soil (Brandt 1987; Abrahamsen 1980).

NO_x emissions from a natural gas-fired power plant can also contribute to the formation of ozone (see Section 3.3.1.1.4) and peroxyacetyl nitrate (PAN). PAN can be toxic to plants and animals. It causes silvering or bronzing of the underside of the leaves of broadleaf plants, yellow to tan bleached bands in the blades of grasses, and needle blight with chlorosis or bleaching in conifers (Heck and Anderson 1980). Concentrations which cause foliar injury depend on the species, exposure time, and other environmental variables. In one study, foliar damage occurred in bean plants exposed for 1 hr to 140 ppb or for 8 hr to 20 ppb (Jacobson 1977). Sigal and Taylor (1976) reported that of eight crops tested, lettuce and swiss chard showed yield reductions after intermittent long-term exposure to 40 ppb. Animals appear to be less sensitive to PAN. In mice, a 13-wk exposure to 1,000 ppb caused only a slight irritation to the mucous membranes of the nasal cavity, but 200 ppb produced no signs of adverse effects (Kruysse and Feron 1977).

Information on ambient and incremental increases in PAN at the southeastern reference site was not available for evaluation.

3.3.1.1.4 Ozone

Ozone is a secondarily derived air pollutant formed by the reaction of hydrocarbons and NO_x in the presence of sunlight. Maximum ozone formation occurs at a C:NO_x ratio of 15:1 (Arnts 1981). Because background levels of hydrocarbons in the atmosphere range from 40 to 100 ppb in rural areas and are even higher in urban and industrial areas (Arnts and Meek 1980), ozone formation is largely controlled by the incremental increase in NO_x. The peak 1-hr average increase in ozone within an 50-km radius of the hypothetical gas-fired power plant at the southeastern reference site was calculated to be 21.2 ppb, and the average monthly increase in the 12-hr average was estimated to be 1.3 ppb (Appendix C). The background concentration of ozone at the southeastern reference site was reported to be 55 ppb (annual average).

Ozone damages plants and affects growth and yield. Broadleaf plants exhibit red-brown spots, bleached tan to white flecks, irregular necrotic areas and chlorosis; grasses exhibit necrotic flecks or streaks and interveinal chlorosis; and conifers exhibit brown-tan necrotic needle tips and chlorotic mottling (Heck and Anderson 1980). The effects of ozone on plants depends on many factors including concentration, exposure time, species, cultivar genetics, growth stage, environmental variables (soil conditions, meteorology, temperature, humidity) and pollutant interactions (SO_2, acid deposition, and NO_2) (ORNL/RFF 1992). Concentration and exposure time are the two most critical factors. For relatively short-term exposures, damage to plants can be seen at ozone concentrations of 50 to 100 ppb. For example, a concentration of 80 ppb, 7 hr/day, five days/wk (intermittent, for a total of 420 hr) caused foliar damage and reduced growth of seedlings of four species of hardwood trees (black cherry, red maple, northern red oak, and yellow poplar) (Davis and Skelly 1992); a concentration of 100 ppb, 4 hr/day, 5 days/wk for six weeks suppressed growth of seedling white and green ash (Chappelka et al. 1988); concentrations of 40-80 ppb, 5 hr/day, 16 days, reduced seed yield in soybeans (Reich and Amundson 1984); and concentrations exceeding 50 ppb damaged tobacco plants (Heggestad and Menser 1962, as reported in Menser and Heggestad 1966).

In the presence of other pollutants such as SO_2, NO_x, and PAN, effects on plants can be additive, synergistic, or antagonistic. Available information on the combined effects of ozone and other primary air pollutants on plants is summarized in ORNL/RFF (1992, Appendix D).

Reduction in crop yields due to incremental increases in atmospheric ozone concentrations is considered a potential key impact of a gas-fired power plant. Dose-response functions are available to quantify this impact for major crop species (see Section 5.4). However, information is not available for estimating the response of whole trees or tree stands. Consequently, empirical models and conclusive quantitative estimates of such responses do not exist. Existing process models relate to responses of tree seedlings and branches. These models are currently being modified to provide preliminary estimates of whole tree responses, which could then be used to extrapolate to responses for entire stands of trees.

Ozone can also adversely affect animals (Table D-8). Chronic bronchitis, bronchiolitis, fibrosis, and emphysematous changes have been observed in several species of laboratory animals exposed to ozone concentrations slightly above 1 ppm, and extrapulmonary effects (i.e., reduced activity, chromosomal aberrations, increased neonatal mortality, and jaw abnormalities in offspring of exposed mice) have been observed at concentrations as low as 200 ppb (Amdur, 1986). These concentrations are above the maximum average annual ambient levels predicted for the hypothetical 500-MW gas-fired power plant (56.3 ppb).

Table D-8. Effects of Ozone on Laboratory Animals

Species	Exposure	Effects	Reference
Rat	0.2 ppm for 3 hours	Degenerative changes in type I alveolar cells	
Rat	0.25-0.5 ppm for 6 hours	Threshold for edema formation	Alpert et al. 1971
Rat	0.2, 0.5, or 0.8 ppm 8 hours/day on 7 consecutive days	Mild, but significant morphologic lesions at lowest concentrations. With continuous exposure, lesions reached a peak in 3-5 days and diminished. After 90 days at 0.8 ppm there was obvious damage, but less severe than at 7 days.	Dungworth 1976
Rat	0.5 to 0.9 ppm for up to 3 weeks	Morphologic lesions in respiratory bronchioles, in distal portions of the terminal bronchiolar epithelium, and in the alveolar duct and alveoli	Stephens et al. 1974
Rat	0.3 ppm for 1 hour	Tolerance - protection against subsequent exposure to otherwise lethal concentrations. Tolerance lasted 4-6 weeks and protected against pulmonary edema but not against alterations in pulmonary function.	Stokinger 1965
Rat	0.2, 0.5, or 0.8 ppm continuously for 7 days	Increased metabolic (enzyme) activity in lung tissue. Levels returned to normal when exposure ceased	Mustafa et al. 1983
Mouse	20 ppm for 3 hours	LC_{50}	Stokinger 1965
Mouse	0.3 ppm for 1 hour	Tolerance - protection against subsequent exposure to otherwise lethal concentrations. Tolerance lasted up to 14 weeks and protected against pulmonary edema but not against alterations in pulmonary function.	Stokinger 1965
Mouse	0.08 ppm for 3 hours	Enhanced mortality from subsequent exposure to a bacterial aerosol of streptococcus (Group C)	Coffin and Blommer 1967
Guinea pig	50 ppm for 3 hours	LC_{50}	Stokinger 1965
Guinea pig	0.34-1.8 ppm for 2 hours	Decreased tidal volume, increased flow resistance (both reversible); concentration-related reductions in compliance	Murphy et al.. 1964; Amdur et al. 1978
Cat	0.25, 0.5, or 1.0 ppm for 4-6 hours	Dose-related desquamation of the ciliated epithelium of all airways; alveolar damage, including swelling and denudation of the cytoplasm of type I cells	Boatman et al. 1974

Table D-8. Effects of Ozone on Laboratory Animals

Species	Exposure	Effects	Reference
Dog	1-3 ppm, 8, 16, or 24 hours/day for up to 18 months	Concentration-dependent thickening of the terminal and respiratory bronchioles (accompanied at highest conc. by infiltration of cells that reduced the diameter of the small airways)	Stephens et al. 1973
Monkey	0.2, 0.5, or 0.8 ppm 8 hours a day on 7 consecutive days	Mild, but significant morphologic lesions at the lowest concentrations.	Dungworth 1976

3.3.1.1.5 Sulfur Dioxide

The sources of natural gas for this hypothetical scenario were reported to have low concentrations of sulfur (Appendix B); consequently, emissions of SO_2 from the power plant stack are expected to be relatively low. The SO_2 emission factor used in this study is 0.221 gram per second for the 1990 technology (Appendix C). The resulting maximum 1-hr and 24-hr average increases in SO_2 were calculated to be 0.202 and 0.024 $\mu g/m^3$ (Appendix C). The maximum annual average increase was calculated to be 0.001 $\mu g/m^3$. The reported annual average ambient concentration of SO_2 near the southeastern reference site is 25 $\mu g/m^3$ (9.54 ppb) (Appendix C). The addition of SO_2 from a single 500-MW natural gas-fired power plant would represent about a 0.004% increase in the annual average.

Information on the toxicity of SO_2 is limited to studies on laboratory animals (Table D-9). The reported toxicity thresholds are all above the predicted maximum ambient concentrations resulting from the operation of the 500-MW natural gas-fired power plant. Assuming that wild animals have the same tolerance levels as laboratory animals, it can be concluded that ambient SO_2 concentrations would not have direct toxic effects on the local fauna.

Sulfur dioxide can damage plants and reduce crop yields. Lichens, one of the most sensitive plant groups, can be adversely affected by a concentration of about 50 $\mu g/m^3$ (19 ppb) (Gilbert 1965, 1970; Barkman 1969; both as reported in Bradshaw 1973). Soybeans are stressed by 130 $\mu g/m^3$ (50 ppb) (Gupta et al. 1991), and a concentration of 261 $\mu g/m^3$ (100 ppb), 4
hr/day for 5 days, caused a 13% reduction in photosynthesis, a 28% reduction in specific root nodule nitrogenase activity, and a 23% reduction in foliar nitrogen (Sandhu et al. 1992). Growth of rye grass was reduced 50% by an SO_2 level of about 200 $\mu g/m^3$ (76 ppb) (Bell and Clough 1973), and a

TABLE D-9. Effects of SO_2 on Laboratory Animals

Species	Exposure	Effects	Reference
Rat	10 ppm, 18-67 days, inhalation	Thickening of mucous layer of trachea	Dalhamn 1956
Rat	12 ppm, 4-6 minutes, direct exposure to trachea	Cessation of ciliary beat; recovery a few minutes after exposure ceased	Dalhamn 1956
Rat	25, 50, 100, 200, and 300 ppm, ten periods of 6 hours each	Dose-related effects on trachea. At 300 ppm, notable epithelial damage and complete destruction of goblet cells. At 25 ppm, increased goblet cells and increased acid phosphatase activity in alveolar macrophages	Mawdesley-Thomas et al. 1971
Rat	0.1, 1.0, or 20 ppm for 70 to 170 hours	Interference with clearance of inert particles. "The most marked effects were seen with lower doses administered over a longer period of time"	Ferin and Leach 1973
Guinea pig	0.1 to 5.0 ppm for up to one year or more	No pulmonary pathology	Alarie et al. 1972; 1975
Guinea pig	0.13, 1.01, or 5.72 ppm continuously for a year	No evidence of adverse effects on mechanical properties of the lung (t. vol., resp. rate, num. vol., flow resist., and work of breathing)	Alarie et al. 1970
Dog	1 ppm for 1 year	Slowing of tracheal mucous transport	Hirsch et al 1975
Dog	5 ppm, 21 hours/day for 225 days	50% increase in resistance; 16% decrease in compliance	Lewis et al. 1969
Dog	0.5 ppm sulfur dioxide and 0.1 mg/m^3 sulfuric acid 16 hours/day for 18 months	No impairment in pulmonary function	Vaughan et al. 1969
Monkey	0.1 to 5.0 ppm for up to one year or more	No pulmonary pathology	Alarie et al. 1972; 1975
Monkey	0.14, 0.64, or 1.28 ppm continuously for 78 weeks; one group accidentally exposed for one hour to approximately 200 to 1000 ppm	No detrimental alterations in pulmonary function detected in low conc. groups; accidental exposure resulted in deterioration in pulmonary function	Alarie et al. 1972

concentration of 80 ppb, 4 hr/day, 5 days/wk for six weeks, suppressed the growth of seedling green ash (Chappelka et al. 1988).

In a review of the available literature, Heck et al. (1986) found that soybean yields were reduced by periodic exposures to total SO_2 doses of 10-15 ppm-hours (mean concentrations 0.12-0.13 ppm, 2.5 to 4.5 hours per exposures and 19-25 exposures); however, doses in the 5 ppm-hour range were either stimulatory or inhibitory. Heck et al. (1986) noted that field experiments indicated that ambient SO_2 levels in the range of 10 ppb were not likely to reduce crop yields. Roberts (1984) analyzed a large amount of data for various plants and found a liner correlation between increasing SO_2 levels from about 20 to 180 ppb and decreasing crop yield; however, at levels below 40 ppb some of the data indicated increases in yield. Similarly, Murray and Wilson (1990) reported that low levels of SO_2 stimulated the growth of barley plants. Because of this variability in response at low concentrations, ecological impacts of small increases in SO_2 are difficult to quantify; however, it is unlikely that the predicted ambient SO_2 levels (<10 ppb) associated with a gas-fired power plant would cause reductions in crop yield.

Interactions with other air pollutants can alter the response of plants to SO_2. Concomitant exposure to 450 ppm CO_2 compensated for the negative effect of 261 $\mu g\ SO_2/m^3$ on soybean plants (Sandhu et al. 1992). In contrast, a concentration of 240 ppb SO_2 and 30 ppb O_3 damaged tobacco plants, but either substance alone did not (Menser and Heggestad 1966). Similarly, Dochinger et al. (1970) found that the interaction of SO_2 (100 ppb) and ozone (100 ppb) produced symptoms of chlorotic dwarf disease in sensitive ramets of eastern white pine (*Pinus strobus*), but the same concentrations separately had little or no effect.

Atmospheric emissions of SO_2 can affect regional air quality due to reactions with oxidizing agents (e.g., O_3, OH, and H_2O_2) and the resulting formation of H_2SO_4. H_2SO_4 (and HNO_3 formed from NO_x) can be transported over long distances before being removed from the atmosphere by dry and wet deposition (acid rain). Acid deposition is discussed in Section 3.3.1.1.7

3.3.1.1.6 Particulates

Particulate emission rates for the hypothetical 500-MW natural gas-fired power plant using 1990 technology were set at 0.01 lb/10^6 Btu (5.15 grams per second). The resulting atmospheric concentrations at the southeastern site were calculated to be 4.21 $\mu g/m^3$ for a maximum 24-hr average, and 0.02 $\mu g/m^3$ for a maximum annual average (Appendix C). Ambient particulate concentration in the study area has been reported to be 108 $\mu g/m^3$ for a 24-hr average (2nd highest) and 47 $\mu g/m^3$ for an annual average (Appendix C). Operation of the power plant would result in an increase of about 0.04 % in the maximum annual average concentration.

There is very little experimental data on the ecological effects of high particulate concentrations. Generally, suspended or deposited particulate matter is not toxic to plants at existing atmospheric concentrations unless it contains large amounts of certain toxic components such as heavy metals (Heck et al. 1986). However, in one study it was found that deposition of particulate matter on the leaves of oak trees indirectly caused a loss of leaf chlorophyll (Williams et al. 1971). The particles clogged leaf stomatal pores which allowed a greater uptake and retention of SO_2. The SO_2 decreased pH levels within the leaf and resulted in hydrolysis of chlorophyll *a* to phaeophytin. Deposits of particulate matter on the leaf surface causing these effects ranged from 4 to 175 $\mu g/cm^2$. Deposition rates for ambient particulate matter and estimates of the fraction of ambient and incremental deposition resulting in contamination of foliar surfaces are needed to assess impacts from a single point source; however, it is unlikely that the small amount of particulate matter released from a gas-fired power plant would have adverse effects on nearby plants.

In the vicinity of the power plant site, emissions of particulates and secondary aerosols may cause atmospheric haze, particularly during unfavorable meteorological conditions. Quantitative estimates of localized impacts are, however, not available. On a regional scale, visual range reduction caused by haze is a major form of visibility impairment throughout the United States. Visually important recreational areas located near the southeastern reference site include the Great Smokey Mountains National Park, Cherokee National Forest, and Nantahala National Forest. According to monitoring studies conducted by the National Park Service at Look Rock, TN, the average annual visual range in the Great Smokey National Park was 55 kilometers during 1980-1983 (Reisinger and Valente 1985). Haze is generally considered to be caused by multiple emission sources (U.S. EPA 1988). A single 500-MW natural gas-fired power plant is unlikely to have direct visibility impacts on distant recreational areas.

3.3.1.1.7 Acid Deposition

In the atmosphere NO_x and SO_2 react with strong oxidizing agents such as O_3, OH, and H_2O_2 to form HNO_3 and H_2SO_4. These compounds can be transported over long distances before being removed from the atmosphere by dry and wet deposition. This acid deposition occurs over a wide area and may impact both aquatic and terrestrial systems. Terrestrial studies of acid deposition have focused mainly on impacts on vegetation.

As discussed in ORNL/RFF (1992), acid precipitation does not appear to have significant impacts on crop yield (Shriner et al. 1990). No consistent reduction in yield was found in crops, in the eastern U.S., that were exposed to levels of acid rain representing average ambient levels (pH 4.1-5.1) or rain events with relatively high acidity (pH 3.0-4.0). The levels of acid deposition required to impact crop yield are for the most part between 10- and 100-fold greater than average ambient levels. Therefore, it is unlikely that a single power plant would contribute significantly to reductions in crop yield through acid deposition; however, it should be noted that each incremental addition of atmospheric pollutants increases the probability of cumulative effects.

Acid deposition is known to have ecological impacts on aquatic resources as a consequence of changes in lake and stream pH levels. In general, regional scale modeling is required for the evaluation of incremental impacts of single point sources. Such modeling was undertaken as part of the 10-yr National Acid Precipitation Assessment Program (NAPAP 1991; see also Baker, et al. 1990; Turner et al. 1990; Thornton et al. 1990). The models that were developed consisted of watershed chemistry models relating acid deposition to longterm changes in surface water quality, and biotic response models relating fish population status to acid-base chemistry. The output of the combined models was an estimate, on a regional basis, of the fraction of streams or lakes with long-term acid-base chemistry suitable for fish survival under different scenarios of future sulfur deposition. Responses differed by regions because of differences in watershed chemistry and fish sensitivity. In general, changes in fish densities were not modeled in these studies.

As discussed in ORNL/RFF (1992), the NAPAP models are useful for making general regional comparisons for different projected acid deposition rates, but they are not considered useful in quantifying specific impacts because of uncertainties associated with the watershed chemistry and dose-response models and in the estimates of acid deposition on a local as well as regional scale.

Most of the streams and reservoirs within a 50-km radius of the hypothetical 500-MW natural gas-fired power plant at the southeastern reference site are well-buffered by carbonate rock and would not be affected by acidic deposition (ORNL/RFF 1992). However, many small streams draining the ridges in the area originate in highly weathered soil with little buffering capacity and, during storms, these streams show pulses of acid runoff (Elwood and Turner 1989; Mulholland et al. 1990). In addition, a small number of streams on the Cumberland Plateau to the west and within 50 km of the site have a low acid neutralizing capacity (ANC) and are also potentially at risk from acid deposition. No streams within the study area were identified as being currently affected by acid deposition to the extent that significant ecological changes were occurring. Therefore, the small incremental increase in acid deposition due to a single natural gas-fired power plant is not expected to have a major ecological impact.

3.3.1.2 Water Emissions

Potential water emissions from a natural gas-fired power plant include cooling system water, boiler water discharges, and general utility wastewater. Potential ecological impacts on surface water and groundwater are dependent on the type of waste treatment and disposal system used at the facility. At the southwestern reference site the nearest river of sufficient size for discharge of power plant wastewaters is located about 40 miles away; consequently, waste treatment, recycling, and/or disposal in evaporation ponds are likely to be the methods used. Spills, leaks, overflows and leaching from ponds may result in the loss of pollutants to the soil and subsequent groundwater contamination, but the incidence of these occurrences is likely to be small. At the southeastern reference site the proximity of a large river system would probably result in direct discharges of treated wastewaters to the river.

3.3.1.2.1 Cooling systems

The condenser cooling water system designed for both the 1990 and 2010 technologies used at the southeastern reference site is a mechanical draft wet cooling tower. Corrosion inhibitors, biocides, and dissolved solids would be released into the receiving water body, the Clinch River, in cooling tower blowdown. Cooling tower blowdown ranges from 0.5 to 3% of the average condenser flow rate. Makeup water must be continuously added to compensate for blowdown, evaporation, and drift (DOE 1983). For mechanical draft cooling towers makeup water amounts to 1.5-4.5% of average condenser flow rate which is about 228 acre-ft per 10^{12} Btu (DOE 1983). For a 500-MW facility (25.6 x 10^{12} Btu/yr), this would amount to about 88-264 acre-ft, or 2.9-8.6 x 10^7 gal per year. Blowdown would be 1-4.3 x 10^7 gal per year. The Clinch River has an average flow of 4,561 cfs (about 2 million gpm or about 1.1 x 10^{12} gal/yr) (Project Management Corporation 1975-77); therefore, makeup water would account for 0.003-0.01 % of river flow and blowdown 0.001-0.005 %. River flow velocity is controlled by turbine operation at Melton Hill dam. Discharges during low or no-flow periods could have very localized environmental impacts. Site-specific information on frequency and volume of the blowdown and concentrations of the component chemicals is needed to fully assess ecological impacts. Overall, the high rates of dilution are expected to minimize impacts.

3.3.1.2.2 Wastewater

Boiler-associated wastewater from a fossil-fuel power plant originates from two major sources, feedwater preparation and boiler blowdown (DOE 1983). Chemicals contained in wastewater consist of those added to the boiler makeup water to avoid problems with deposits and corrosion. The extent of pretreatment of makeup water depends on the chemical characteristics of the intake water. Suspended solids are usually removed by coagulation and filtration and, if necessary, water hardness is reduced by an ion exchange process which replaces calcium and magnesium with sodium (from sodium chloride). Additional chemicals which may be added to the boiler water for oxygen scavenging, phosphates and caustic soda for corrosion control and chelates to limit boiler fouling.

Wastewaters from a natural gas-fired power plant are expected to contain varying pH, high dissolved solids, COD and BOD and metals such as iron and copper. Technologies are available for zero-discharge waste treatment systems; however, it is likely that at the southeastern reference site treated wastewaters will be discharged into the Clinch River. As noted above for cooling tower blowdown, site-specific information on the volume of the wastewater discharges and concentrations of the component chemicals is needed to fully assess ecological impacts, but the high rates of dilution with the river water are expected to minimize impacts.

3.3.2 Potential benefits

NO_x and SO_2 emissions from a natural gas-fired power plant can react in the atmosphere with strong oxidizing agents such as O_3, OH, and H_2O_2 to form the acids H_2SO_4 and HNO_3. Depending on atmospheric conditions, these acids may be transported over long distances before being removed from the atmosphere by dry and wet deposition. Although acid deposition can have adverse ecological effects (see Section 3.3.1.1.5), when deposited on soils and vegetation, these compounds can also represent sources of sulfur and nitrogen which may be utilized as nutrients by some plants. Several field studies have documented that sulfur additions to the soil, either directly or through acid rain may be beneficial for plant growth. Jones and Suarez (1980) reported that corn showed a positive response to sulfur additions to soil (9 kg/ha), and Irving (1986) reported a similar positive response when timothy hay and red clover were treated with simulated acid rain. Furthermore, Noggle (1980) reported that soybeans growing near a point source of atmospheric sulfur obtained 10 to 50% of their sulfur requirement from the atmosphere.

As discussed in ORNL/RFF (1992), natural forests are not likely to benefit from atmospheric deposition of sulfur because deposition rates (>10 kg/ha/yr in polluted regions) are substantially higher then forest requirements for growth (1-2 kg/ha/yr). However, atmospheric deposition rates for nitrogen (5-25 kg/ha/yr) may be within the range of forest requirements in some instances (1-5 kg/ha/yr), and therefore, may be beneficial to forests especially in areas where soils are deficient in nitrogen (Shriner et al. 1990).

Exposure-response functions are not available to quantity the impact of emissions of NO_x and SO_2 from a single power plant on agricultural crops or forests.

3.4 TRANSPORTATION AND STORAGE

Production wells and refineries are connected to consumers by a complex network of buried pipelines consisting of gathering lines, transmission lines, and distribution mains. The main trunk transmission line from Louisiana ends in Nashville; distribution lines to the southeastern reference area are probably in place, but a line directly to the Clinch River site would have to be constructed. A pipeline of up to 35 miles from the Chaco, New Mexico, gas processing plant to the southwestern power plant site would have to be constructed. Pipeline construction would result in temporary, localized, minor environmental impacts.

Methane leakage from pipelines is estimated to be 1% of total production (Appendix B). Although releases are generally due to structural failure rather than slow leaks, no impact to local vegetation or wildlife would be expected. (Methane acts as a simple asphyxiant in enclosed spaces, but is dispersed in the atmosphere.) The contribution of methane to the greenhouse effect has not been quantified.

The major pollutant from natural gas transmission is the release of NO_x at compressor stations which are located at approximately 75 mile intervals. Reciprocating engines and gas turbines respectively emit 3,400 and 300 lb of NO_x per million standard cubic feet of natural gas (24 and 2.9 pounds per thousand horsepower). Information on ambient and incremental increases in NO_x at each of these point sources were not available for evaluation.

Information on emissions of natural gas during storage were not located.

3.5 SUMMARY AND SELECTION OF KEY IMPACTS

Although quantitative information on many of the potential environmental impacts of the natural gas fuel cycle is limited, some general qualitative conclusions can be made based on the available data. Impacts from the production stage of the fuel cycle include effects of wastewater emissions on aquatic resources at both offshore and onshore sites and effects of construction activities and navigation channeling on wetlands. Impacts at the power plant site include the potential changes in crop yield from ozone formation from power plant emissions of hydrocarbons and NO_x.

4. QUANTIFICATION METHODS

Methods for deriving quantitative relationships between levels of environmental stress and ecological impacts are reviewed in ORNL/RFF (1992, Appendix D). These methods can be divided into three general categories, (1) empirical modeling using statistical analysis of measured data, (2) mechanistic (or process) modeling which predicts steady-state conditions or dynamic fluxes from known physical, chemical, or biological relationships, and (3) expert judgement based on field and laboratory data. All three approaches are required to assess the ecological impacts of alternative fuel technologies. Reasonably well understood impacts such as the effects of ozone on crops, can be partially quantified using both types of models as well as expert judgement. Other impacts are very site-specific, and mechanistic models can not be used.

Impacts on ground water require models to predict partitioning of the chemical in environmental media, rates of degradation, information on hydrology, changes in aquifer concentration, and the number of area wells in which water quality standards may be exceeded.

5. EVALUATION OF KEY IMPACTS

5.1 EFFECTS OF OFFSHORE GAS DRILLING AND PRODUCTION ON COMMERCIAL FISHERIES

Commercial fishing in the Gulf of Mexico is an important economic component of the United States. Commercial landings of all fisheries in the Gulf of Mexico during 1989 totaled nearly 1.8 billion pounds and were valued at about $649 million (U.S. DOC/NOAA/NMFS 1990). This was an 18 percent decrease in landings and a 7 percent decrease in value from 1988 landings. Although losses of fisheries resources are difficult to distinguish from natural variation, there has been a general decrease in landings in the Gulf of Mexico since the development of the petroleum industry. The decrease has been attributed to overfishing.

Discharges of produced water, drilling fluids, and drill cuttings from drilling platforms continuously add solid material, hydrocarbons, and metals to the sediments and hydrocarbons to the water column over the life of the well. These materials are diluted in the water, but can potentially produce sublethal effects on sensitive stages of aquatic organisms. Dispersion models for platform wastewaters adequately describe short-term dispersion; in contrast, because of insufficient data on transport rates, current patterns, and the long-term behavior of discharged constituents, models have not been successful in adequately predicting the long-term dispersion of discharges from platforms. Dilution factors of 1,000 within one to three meters of the discharge and 10,000 within 100 meters downcurrent of the discharge have been measured in field studies. The combination of discharges of produced water, drilling fluids and cuttings, and oil from natural gas platforms would produce only chronic ecological impacts in a local area (within 1,000-2,000 meters of each well site) and result in an extremely small incremental impact on commercial fisheries of the Gulf. However, the contribution of these pollutants should be of concern in an area experiencing decreased fisheries landings and increased oil and gas development.

5.2 IMPACTS OF OZONE ON AGRICULTURAL CROPS

The effects of air pollutants on crops has been reviewed and summarized by Shriner et al. (1990). Adequate data for the evaluation of crop yield reductions are available only for ozone. Reductions up to 56% have been reported depending on crop species, location, and ozone level.

The response of plants to ozone depends on many factors including concentration, species, cultivar genetics, growth stage, environmental variables (soil conditions, meteorology, temperature, humidity) and pollutant interactions (SO_2, acid deposition, and NO_2) (ORNL/RFF 1992). Because of the lack of data for many of these variables, uncertainties exist in the reliability of the available exposure-response functions for all possible scenarios. Choice of an exposure parameter may also be a critical factor. Exposure of plants to ozone is usually reported in terms of 7-hr or 12-hr seasonal mean concentrations. The mean values represent daily periods during the growing season which are thought to correspond to the periods of highest plant sensitivity and highest ozone levels. However, there is some evidence that a seasonal mean of daily 1-hr maximums may be a more appropriate measure of exposure (ORNL/RFF 1992).

Ozone-induced incremental changes in crop yields resulting from the operation of the hypothetical 500-MW natural gas-fired power plant were calculated using the same methodology described in ORNL/RFF (1992). This analysis utilized literature-derived ozone exposure-plant growth response functions, reported ambient ozone levels, and estimations of the incremental increases in ozone which could be attributed to the operation of the power plant. The same methodology could be used to assess this impact for the southwestern reference site; however, baseline emissions data were not available to run the ozone model (see Appendix C).

As discussed in ORNL/RFF (1992), the ozone exposure-plant response functions used in this analysis were those developed by Heagle et al. (1988) from field data generated from the National Crop Loss Assessment Network (NCLAN) (see also Heck et al., 1988; Shriner et al., 1990). These studies provided crop yield losses for major cultivars for five seasonal mean ozone concentrations representative of the range of ambient ozone levels in the United States (Table D-10).

Table D-10. Crop yield losses estimated to result from various ozone concentration (in percent)

	Mean ozone concentration during the growing season (ppb)				
Crop	40	50	60	70	80
Soybeans (Average of 22 experiments with about 10 cultivars)	5.6	10.1	15.5	21.5	28.4
Tobacco (Average of 2 experiments)	5.0	9.0	13.0	18.0	23.0
Wheat (Average of 5 experiments with 3 cultivars)	9.0	15.0	20.8	26.8	33.2
Corn (Average of 3 experiments with mixtures of 5 cultivars	1.7	3.7	6.7	10.3	15.7
Hay (Red clover, the main type of hay grown in the study area)	9	19	31	44	59

For a given predicted increase in ozone, the percent decrease in yield for a particular cultivar can be estimated by interpolation of the data presented in Table

D-10. For the southeastern reference site the existing ambient ozone level within the region was determined to be 55 ppb (12-h seasonal average, 9 a.m. to 9 p.m., May through September), and the incremental increase in the 12-h seasonal ozone level associated with the power plant was calculated to be 1.3 ppb (see Appendix C). Applying the ambient and predicted ozone levels during plant operation to the exposure-response functions given in Table D-10 gave the results shown in Table D-11.

Table D-11. Percentage decrease in crop yield due to increased ozone (1990 southeastern reference site)

Crops	Reduction in crop yield (%)	Reduction in yield due to power plant (%)
Soybeans		
existing ambient	12.80	
predicted	13.50	0.70
Tobacco		
existing ambient	11.00	
predicted	11.52	0.52
Wheat		
existing ambient	17.90	
predicted	18.65	0.75
Corn		
existing ambient	5.20	
predicted	5.59	0.39

The approach used to estimate area-wide crop losses from the percent decrease in yield was the same as that developed in ORNL/RFF (1992). Losses in crop production were calculated for the counties surrounding the plant. Data for entire counties and an infinite number of sites within each county was assumed. This procedure avoided the need to deal only with portions of counties falling within the 50-km perimeter of the study area; it provided results which are more generally representative of the reference site; and it allowed for the easy computation of the hypothetical crop losses in any county within the region (ORNL/RFF, 1992). Counties having half or more of their area within 50 km of the site were selected. Crop loss for each county was estimated, and then total losses for all counties was determined (Table D-12).

Table D-12. Crop production and the estimated crop losses (1990 southeastern reference site)

County	Acres	Soybeans (1,000s bu)	Wheat (1,000s bu)	Corn (1,000s bu)	Tobaccco (1,000s lb)
Anderson	185,200				
production		*a*	*a*	15	170
loss				0.059	0.884
Blount	347,516				
production		38	186	345	798
loss		0.266	1.395	1.346	4.150
Campbell	253,373				
production		*a*	*a*	32	593
loss				0.125	3.084
Knox	228,969				
production		6.3	16.5	89	587
loss		0.044	0.124	0.347	3.052
Loudon	142,247				
production		14	51	80	730
loss		0.098	0.383	0.312	3.796
Morgan	342,810				
production		20	13.2	84	78.3
loss		0.140	0.099	0.328	0.407
Roane	172,533				
production		*a*	*a*	28	297
loss				0.109	1.544
Anderson, Roane, and Campbell[a]					
production		3.98	7.84		
loss		0.028	0.059		
Total loss		0.576	2.06	2.626	16.917

[a] Soybean and wheat production statistics for these counties were not reported by the Tennessee Department of Agriculture (1990) because less than 500 acres of the respective crop were planted. Total production for all non-reported counties in district #6, to which these counties belong, was: 19,900 bu of soybeans for 15 non-reported counties and 18,300 bu wheat for 7 counties - these data were used to obtain the rough estimates given.

The crops listed in Table D-12 are those for which county-level production data were available for the southeastern reference site (Tennessee Department of Agriculture, 1990). Data for 1988 was used to estimate ozone-induced crop losses for all crops except corn, because production of these crops in 1989 [the latest year reported by the Tennessee Department of Agriculture (1990)] was poor. Corn production data for 1989 were used because this year appeared to be representative of average conditions for corn.

The total acreage occupied by the seven counties reported above is 1,672,648, compared to the larger acreage of 1,940,761 acres within 50 km of the power plant site.

The numerical values of the crop losses within these seven counties must be increased proportionally to calculate crop losses within a 50-km radius of the power plant at the southeastern site. These estimated losses are show in Table D-13.

Table D-13. Estimated crop losses due to increased ozone (1990 southeastern reference site)

	Soybeans (1,000s bu)	Wheat (1,000s bu)	Corn (1,000s bu)	Tobacco (1,000s lb)
Total loss in 7 counties	0.576	2.060	2.626	16.917
Loss within a 50-km radius of the powerplant	0.668	2.390	3.047	19.629

5.3 CONCLUSIONS

This evaluation of the ecological impacts of the natural gas fuel cycle is based on a very specific set of parameters which place limits on the range of possible impacts and on the magnitude of these impacts. The major limiting factors in this assessment are the size and location of the facilities, the location of gas production and refining and the method of transport of gas. The size determines the magnitude of point source emissions from the power plant, as well as the incremental amount of wastes and discharges from drilling, refining, and transportation. Location of the power plant and the refineries is important in determining whether the emissions from a single facility (which in themselves may be too small to have significant impacts) would contribute, on an incremental basis, to cumulative impacts caused by other sources. Therefore, the conclusions discussed below must be considered in terms of the size (500-MW) and location of the power plant.

Under the scenario created for this study, the phase of the natural gas fuel cycle that is likely to have the greatest potential for ecological impacts is discharge (offshore) or disposal (onshore) of wastewaters. The impact of chronic discharges of wastewaters to the marine environment from offshore oil production are localized and pre-drilling surveys are not available. However, the causes for the general decline in the Gulf area commercial fisheries, particularly off the coast of Louisiana, attributed to overfishing, needs further clarification. Even localized and small increments of pollutants to an already stressed ecosystem may be significant. In a coastal area, natural resources such as beaches, wetlands, fish nursery areas, bird sanctuaries, etc., may be impacted by drilling and wastewater discharges. Commercial shellfish and shrimp fisheries would be at risk, as well as recreational fishing. The aesthetic quality of the area would be impacted. Potential air emissions from the oil-fired power plant, which were evaluated only for the 1990 technology at the southeastern site, were projected to be quite small and no direct ecological impacts were identified. The concentration of sulfur in the oil is very low and therefore the contribution of the power plant to acid deposition is negligible. Emission of NO_x contributes to the formation of atmospheric ozone which results in a small incremental impact on crop yield (when added to the high ambient levels of ozone that already stress the system). The amount of ozone predicted from the 2010 technology is one-tenth that of the 1990 technology.

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