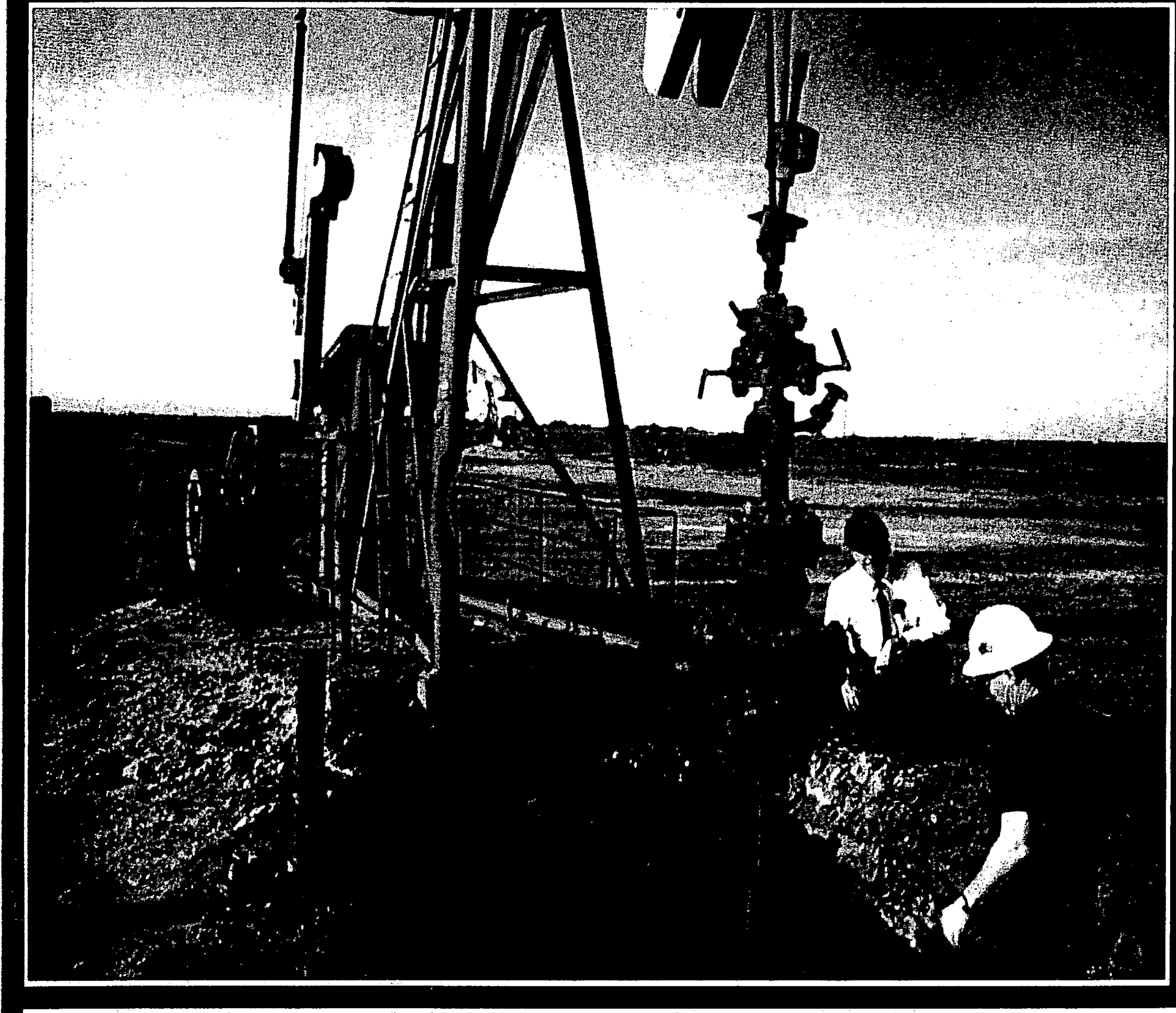
## Report 5

# Estimating Externalities of Oil Fuel Cycles



Prepared by Oak Ridge National Laboratory
and Resources for the Future

Report Number 5 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

# ESTIMATING EXTERNALITIES OF OIL FUEL CYCLES

## OAK RIDGE NATIONAL LABORATORY
## AND
## RESOURCES FOR THE FUTURE

**Report No. 5 on the**
**EXTERNAL COSTS AND BENEFITS OF FUEL CYCLES:**
**A Study by the**
**U.S. Department of Energy**
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August 1996

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# PREFACE

This report provides guidance on how to estimate the externalities of oil fuel cycles, in which oil is used to generate electric power. The report considers a number of possible health, environmental, and other impacts associated with these activities and provides information on their possible externalities. The report is part of a series of reports on a joint U.S.-European Commission (EC) study of fuel cycle externalities.

One reviewer of a draft of this report commented that it answered a question that no one had asked. The underlying basis of his comment was that oil is used to generate only 2.5% of the electric power generated in the United States and that an oil-fired power plant has not been constructed in this country since about 1981. So why publish a report on oil fuel cycle externalities?

One reason for this report is that there are countries where oil is still an important fuel for generating electricity. The concept of externalities is relevant worldwide. Indeed, recent regulatory and policy concerns about externalities and environmental protection have been much greater in Europe and elsewhere, compared to the United States, where interest has been focused on reducing financial costs through industry restructuring.

Another reason for this report is that the methods in this report are also relevant to estimating externalities associated with the use of gasoline and other refined oil products. From a life cycle perspective, these products involve extraction and transport of crude oil to refineries, activities that are common to all refined products, including residual oil which is used in electricity generation. Thus, some of the methods in this report can be used in, for example, studies of the externalities of gasoline use.

Notwithstanding the relevance of studying oil fuel cycles, this study was still a hypothetical exercise in which a new oil-fired power plant is constructed in the year 1990. The study assumes that very effective pollution abatement technologies would be installed. Consequently, the emissions from the power plant, and the subsequent externalities, turn out to be much less than many people would expect from an oil-fired power plant. This result reflects the importance of the efficiency of a power plant, and of the equipment installed in it, on the externalities from that plant, irrespective of the type of fuel used.

There has been a bit of a hiatus since the publication of the previous report in this series. Since that time, the methodological approach, the major purpose of which the U.S.-EC study was to develop, is rapidly becoming a worldwide standard. This is evidenced by recent studies in the States of New York and Minnesota; in Europe with the EC's ExternE program (the successor to the U.S.-EC study); the Research Coordination Programmes at the International Atomic Energy Agency; and many other studies.

This report benefitted from a review by the Fuel Cycle Peer Review Panel, which was commissioned by the Secretary of Energy's Advisory Board (SEAB) and chaired by J. Christopher Bernabo. Panel members Richard M. Adams, Gardner M. Brown, Jr., Donald C. Haney, Joseph S. Meyer, Paulette Middleton, Edward S. Rubin, Carl M. Shy, John M. Skelly, and Leonard H. Weinstein provided useful review comments on a previous draft. In addition, we thank staff in DOE's EP-51 office; Hilary Smith, Richard Dye, and Nancy Johnson of DOE; and Howard Shafferman (then of the Federal Energy Regulatory Commission) for their reviews of the first draft. We also thank those who provided us with data and other useful information. The U.S. Department of Energy (DOE) provided financial support for this study. Hilary Smith and, later, David Meyer, were the DOE contracting officer's technical representatives. Finally, we again thank family and others who provided us with much appreciated moral support during this endeavor.

Russell Lee

Oak Ridge, Tennessee
July 1996

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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 oil fuel cycle, in which oil is used to generate electricity.

## ES.2 PURPOSE OF STUDY

This report demonstrates the collection, assessment, and application of existing literature to estimate selected damages and benefits from the oil fuel cycle in which oil is produced, refined, and used to generate electric power. The major objectives of this study were:

(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 oil fuel cycle (the Background Document provided a common conceptual framework for studying all of the fuel cycles; but different fuel cycles have unique characteristics, residual discharges,

impacts, and regulating issues that need to be addressed using different scientific and economic information and models);

(2) to use existing data and other information to develop, given the time and resources, a range of estimates of marginal damages and benefits associated with selected impacts due to a new oil-fired power plant, using a 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 are the most important objective of this study.*** This demonstration provides an illustrative example for those who will, in the future, undertake "actual" studies of "real" options at "real" sites. Although real data are used in the numerical examples in this study, the reference sites are only hypothetically considered as sites for the power plants. In reality, oil-fired plants would likely never locate at these sites. They were used in the study solely for the purpose of demonstrating the methodologies. 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 were 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. Readers should not regard the hypothetical oil-fired power plant, that this study considers, to be a typical plant, or even one that is economically viable.

(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

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 was considered in this study involves the construction and operation of a new oil-fired power plant. The transportation infrastructure, refineries, and other infrastructure that would be required to supply the power plant are assumed to already exist. That is, the addition of an oil-fired power plant does not result in any incremental damages associated with the construction of oil production, refining, or transportation facilities. If additional facilities were needed, than the damages from constructing these facilities would be included as part of the incremental damages of the oil fuel cycle. 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 was used to estimate the social costs and benefits of the oil fuel cycle. The damage function approach combines natural science and economics to estimate the changes in both environmental and nonenvironmental conditions that stem from an incremental investment to provide electrical power (building and operating an oil-fired power plant). The damage function approach is the most detailed and thorough approach for this purpose -- though past applications of this method prior to 1994 have been very limited because of the extensive data requirements and the level of effort involved (ORNL/RFF 1994b).

Figure ES-1 is a flow chart that illustrates the damage function approach. 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) the economic value that is placed on these impacts; and (5) the distinction between the social costs and benefits that are internalized within the market and those that remain as externalities.

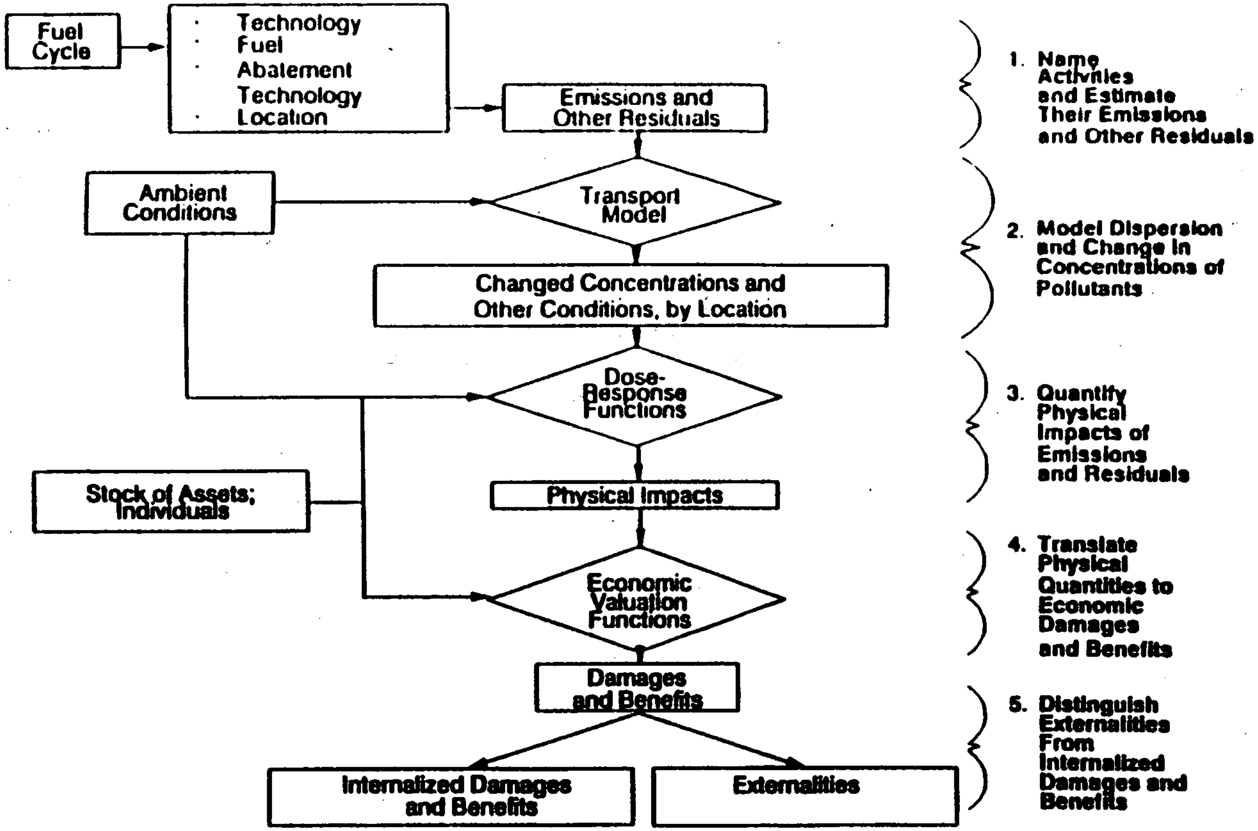

**Figure ES-1. Impact pathway implementation of damage function approach.**

The concept of impact pathways is used 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 then identifies: a particular emission, discharge, or other source of environmental stress from an activity; the transport and the possible chemical and physical transformation of that emission; the resulting change in its concentration in the 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 an economic valuation of that impact.

The impacts that this study addresses are the marginal or incremental effects on the environment. It is important to note the distinction between the marginal effects and the average effects. The marginal effects can be attributed to the incremental increase in fuel cycle activity. The average effects are the total effects divided by total electricity production from oil-fired power plants nationwide.

Economic valuation in this study reflects the extent that individuals are willing to pay to avoid (the risk of) negative impacts or to obtain positive impacts --the so-called willingness to pay (WTP) criterion in economics that underlies modern benefit-cost analysis. Emissions or other residuals from the oil fuel cycle result in health, environmental, and other impacts. In this study, the estimation of marginal damages and benefits from a new oil-fired plant and from its supporting fuel cycle activities utilizes the results of past economic studies that have estimated the WTP to avoid different types of impacts.

## ES.4 OIL TECHNOLOGIES AND EMISSIONS

The benchmark technology that was used in the analysis of the oil fuel cycle is an oil-fired steam boiler electric generating plant. The analysis in this study focused on the impacts and damages (and benefits) associated with this fuel cycle.

A benchmark baseload technology was selected for analysis. A 300 MW oil-fired steam boiler plant having a lifetime of 40 years was selected for each of the two reference sites examined. We assume an 80% capacity factor for this power system which would generate $2.1 \times 10^9$ kWh per year. A 35% conversion efficiency was used, resulting in a daily consumption of approximately 8,900 barrels of No. 6 residual oil or 3.26 million barrels per year.

For each of the two time frames that we consider, the power plants are built to meet or exceed environmental standards. The primary pollutants emitted by the power plants are particulate matter (PM), $NO_2$, and $SO_2$. For the power plants built in 1990, we assume the following emission control technologies: for PM -- baghouse and wet scrubbers; $SO_2$ -- wet scrubbers; and $NO_2$ -- low-$NO_x$ burners and ammonia injection. We do not assume control technologies for CO and VOC emission control because these emissions from power plants are not a major concern.

For the power plants built in 2010, we assume the same emission control technologies as 1990, but with more effective control. In addition, selective catalytic reduction devices are included with 90% control effectiveness. The damage function approach was used with the 1990 scenario. Emissions data for the 2010 scenario were provided for comparison.

Table ES.4-1 contains some of the primary air emissions data. We used EPA's AP-42 emissions factors to calculate emissions per $10^3$ barrels of residual oil input to oil-fired power plants with steam boiler technology. We used the same emission values for both of the reference power plant sites (in practice, the emission values are normally expected to exhibit regional variation depending on the location of the power plants). Examples of variations in oil-fired power plant emissions are shown in Section 2.2.

**Table ES.4-1. Air Emission Rates of Oil-Fired Power Plants**

**(lbs/$10^3$ bbl of oil input)**

| | PM | $SO_2$ | CO | $NO_x$ | VOC |
|---|---|---|---|---|---|
| Uncontrolled Emissions | 546 | 6594 | 210 | 2814 | 43.7 |
| Controlled emissions: 1990 | 27 | 659 | 210 | 844 | 43.7 |
| Controlled emissions: 2010 | 11 | 330 | 210 | 84 | 43.7 |

## ES.5 SELECTED IMPACT PATHWAYS

Total fuel cycle externalities include those associated with the oil-fired electric power plant itself, the "upstream" activities that take place to supply residual oil to the plant, and the secondary activities that must take place for the oil plant to be built. Secondary activities are associated with the manufacturing of the materials and components used by the plant. Previous analysis showed that, in fossil fuel cycles, the emissions from secondary activities are likely two or three 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 oil fuel cycle.

Many activities, processes, and emissions are associated with the oil fuel cycle. Due to time and budget constraints, three major factors guided a setting of priorities in selecting pathways for analysis: (1) impacts that were considered to be most important in terms of their potential external costs or benefits (based on the existing literature and informed assessments); (2) impacts in different stages of the fuel cycle (so that we have a basis for comparing externalities in different stages); and (3) and impacts and damages (or benefits) that were more likely to be expressed in quantitative terms. The existing literature and preliminary screening analysis were used to suggest impacts and damages that were important and likely to be quantified. The following impact pathways were selected for more detailed analysis.

Impacts from crude oil production:

- contamination of surface and groundwater from onshore drilling
- effects on marine organisms due to wastewaters from offshore drilling
- effects on aquatic or marine organisms due to crude oil spills from offshore drilling platforms
- injuries from offshore production activities

Impacts from refining crude oil:

- ecological and health effects of emissions and other wastes from refineries

Impacts from crude and residual oil transportation:

- effects on aquatic of marine organisms due to crude and residual oil spills from barges or tanker trucks
- road deterioration

Priority impacts for the power plant stage of the cycle:

- 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.

Impacts are generally site- (as well as project-) specific. In this study, impacts were 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 were selected as case study environments. Figure ES-2 is a map of the locations of the two reference sites. Some of these impacts are internalized in that their damages are reflected in market decisions. However, the extent to which these types of damages are internalized is usually not clear-cut.

Fig. ES.2. Locations of the Southeast and Southwest Reference sites.

## ES.6 MARGINAL ECOLOGICAL IMPACTS OF AN OIL FUEL CYCLE

Some of the potentially significant ecological impacts from oil fuel cycles are: (1) effects of wastewater and discharges from offshore drilling on local biota and regional fisheries, (2) effects of possible crude oil spills, either from a platform or from a pipeline, on marine and coastal resources, (3) changes in crop yield from ozone formation from power plant emissions of hydrocarbons and $NO_x$, (4) damage to coastal wetlands and marine resources from potential spills of residual oil during barge transport along coastal areas, and (5) damage to freshwater aquatic resources from potential spills of residual oil during barge transport through inland waterways. Most of the quantitative data, which are available for the reference sites, are on the potential impacts of oil spills on marine and coastal resources and the impacts of ozone on crop yields at the Southeast Reference site. Under the scenario created for this study, the parts of the oil fuel cycle that are likely to have the greatest *potential* for ecological impacts are large oil spills, though these are infrequent.

Appropriate models provided the basis for quantifying these impacts. Injuries to marine and coastal resources of the Gulf of Mexico from hypothetical crude and residual oil spills were estimated using the U.S. Department of the Interior's Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME). The model provides estimates of injuries to adult and larval fish, mollusks, decapods (shrimp, prawns, crabs, and crayfish), and birds for a given type of oil, size of spill, site, and season. The impact to the marine environment of chronic discharges of produced water and other wastes from offshore oil production are qualitatively described.

Several qualifications should be kept in mind regarding ecological impacts. First, site-specific impacts are often not generalizable to other sites. Second, impact categories such as biodiversity are difficult to quantify because there is no consensus among ecologists on the definition of biodiversity for assessment purposes. Third, impacts that are distributed over large regions are inherently difficult to quantify. 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.

## ES.7 MARGINAL EFFECTS OF AN OIL FUEL CYCLE ON HEALTH

The emissions and impact pathways that were evaluated in this study probably represent most of the adverse health effects related to the oil 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 sufficient information. Finally, occupational disease and accident rates were not specific to the technology except for offshore accidents, and these estimates must be considered tentative.

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 indicate that a small proportion of both health and ecological impact information is rated as high quality. 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.

## ES.8 CONCLUSIONS

### ES.8.1 Scope of the Study

The primary objective of the study was to ***demonstrate methodology*** that can be applied to estimate externalities of oil fuel cycles. Thus far, only selected damages and benefits have been addressed.

A major objective of the methodology is to develop quantitative estimates of damages and benefits, i.e., numerical estimates. However, the numerical results are in no respect definitive, universal estimates of the total externalities of oil fuel cycle. The sites considered were for illustrative purposes. They are not representative of all, or even likely, sites in the U.S. or elsewhere in the world. 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. The options are so numerous and different in their site characteristics that no single study can encompass them all.

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 an oil fuel cycle, for an individual site. Also, as more studies are done using this approach, it will be much easier and less costly to implement. Future studies will be able to draw on the information, methods, results, and lessons learned from previous studies.

Because many countries are currently, and many Public Utility Commissions in the United States have in the past, considered ways of internalizing the external damages of fuel cycles, it seems all the more important to invest in thorough assessments. Regulatory burdens imposed on electric 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, results gained from studies using this approach add to the base of knowledge*** to support informed decisions about energy. Such results certainly extend beyond numerical estimates. They include estimates of the uncertainty and quality of the estimates, various analytical tools, dose-response functions, valuation functions, and information about impacts that are not quantified.

### ES.8.3 Marginal Damages and Benefits[1]

Much of the damage, and particularly the benefit, of using oil is internalized in its price, and in the price of the products that use it. However, some damages are not internalized. But the ones that are potentially the greatest are also those that are the most controversial. There are many questions about their magnitude and even about whether they exist at all. The most controversial impacts are global climate change from $CO_2$ (and other greenhouse gas) emissions, the effects of using imported oil on a country's energy security, and the ecological effects of catastrophic oil spills. Each is discussed below.

The discussion in this report on climate change was written before publication of the Second Assessment of the Intergovernmental Panel on Climate

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[1] All values are in 1989 dollars.

Change.[1] But our discussion is still basically relevant. Average global temperature is expected to increase about 3 degrees C over the next 100 years. Damages and benefits will be highly variable across regions. Analysts are still uncertain about their magnitude. Overall, global damage from marginal increases in $CO_2$ emissions from oil-fired power plants could be 4-5 mills/kWh, but estimates range by an order of magnitude or more. Even if they could be quantified, the incremental impacts of greenhouse gases from a *single* power plant on climate change would be difficult to estimate. But the cumulative impact of many power plants may have a great impact.

In the scenarios constructed for this study, imported oil is not used. Thus, there are no energy security impacts. In any event, the addition of a single oil-fired power plant does little to affect a country's energy security. But the overall effect of *all* end-users of imported oil (including of course automobiles) probably affects energy security to some degree. However, the magnitude of this effect is highly contentious. The two main positions in the literature on energy security are that it is either very small (close to zero), or sizeable. If sizeable, then there is still uncertainty about its magnitude. Based on a range calculated in the literature (i.e., \$2.25-\$5.65/barrel of oil), if there are sizeable energy security effects, then the externalities are in the range of 2-8 mills/kWh.

In the reference cases that this study considered, oil tankers were not used for transporting crude oil. All of the oil was assumed to be from domestic sources. Thus, no tanker spills -- in particular, Valdez-scale spills -- were considered. These catastrophic spills are infrequent and are largely internalized through insurance coverage. Nevertheless, the risks of these spills remain an issue of the oil fuel cycle. Much of the controversy, as well as source of potentially very large damages, are non-use effects. These are effects on individuals who will never use any of the ecological resources damaged in an oil spill, but whose sense of well-being is still adversely affected by it. The magnitude, and even the "legitimacy,"

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[1] Houghton, J.J., Filho, L.G.M., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (eds.) (1996) *Climate Change 1995 – The Science of Climate Change*. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Watson, R.T., Zinyowera, M.C., Moss, R.H. (eds.) (1996) *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Bruce, J., Lee, H., Haites, E. (eds.) (1996) *Climate Change 1995 – Economic and Social Dimensions of Climate Change*. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

of non-use values are the subject of ongoing debate among environmental economists and others.

Based on the analysis in this report, most of the other damages expected from oil fuel cycles appear to be much less than the possible values that are associated with the impacts mentioned above. As emphasized throughout this report, however, most externalities are highly dependent on geographic factors -- the location of the source of the emissions, the population density, and other characteristics in the surrounding region -- as well as on the technology. In our study of oil fuel cycles, we selected advanced pollution abatement technologies. As a result, the emissions from the oil-fired power plant are less than those from any existing plant; but such low levels are possible, even if they are not economically viable.

With the assumed level of emissions, and with the rather low populations in the two reference sites, health and ecological damages are small. Of the impacts that were quantified (other than possible global climate or energy security effects), the major source of externalities is damage to public roads, when residual oil is transported in tank trucks over some (e.g. 30 mile) distance. The damages were estimated to be 0.10 mills/kWh, of which 0.092 mills/kWh is an externality.[1] The other externalities calculated for the Southwest Reference site were much less, the next greatest one being 0.0011 mills/kWh for effects of particulate matter on premature mortality (0.00054 mills/kWh, if a health impact threshold is assumed). Other impacts are given in Table ES.8-1.

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[1] These externalities pertain only to the Southwest Reference scenario. The Southeast Reference scenario involved barge transport.

**Table ES.8-1. Summary of externalities estimated for the Southeast and Southwest Reference sites (mills/kWh in 1989 dollars)**

| Type of Impact | Southeast | Southwest |
|---|---|---|
| Highway damage from tank trucks carrying residual oil to the power plant | not applicable | 0.092 |
| Ozone effects on health (all morbidity endpoints) | 0.074 | almost 0 |
| Ozone effects on crops | 0.06 | almost 0 |
| Occupational injuries during offshore oil drilling[a] | 0.021 | not applicable |
| $SO_2$ damage to materials[b] | 0.019 | 0.00064 |
| Particulate effects on mortality risk (primary emissions only) | 0.016 (0.033 without threshold) | 0.00054 (0.0011 without threshold) |
| Particulate effects on morbidity (primary emissions only) | 0.015 (0.028 without threshold) | 0.0016 (0.002 without threshold) |
| $SO_2$ effects on morbidity (primary emissions only)[b] | 0.0048 | 0.00016 |
| Barge accidents in river system[c] | 0.0043 | not applicable |
| Barge accidents offshore[c] | 0.0017 | not applicable |

[a] Largely internalized by workers' wages.

[b] Some portion internalized by trading of emissions permits.

[c] Largely internalized by the Oil Pollution Act.

For the Southeast Reference site, the greatest marginal health impacts are from ozone, at least in areas with high baseline concentrations above the assumed threshold of 80 parts per billion. High ozone concentrations are associated with elevated rates of respiratory illnesses. Based on inspection of data on ambient rural concentrations in the rural Southeast, high ozone concentrations are not uncommon. Estimated externalities to the population within 1,000 miles of the power plant were estimated to be 0.074 mills/kWh. Estimates of other health-related externalities are given in Table ES.8-1.

If the oil plant were situated in a region with 10 million people within, say 50 miles, rather than only one million, as in the Southeast Reference site, then the damages would be significantly greater – assuming that meteorological conditions, topography, population distribution, demographic characteristics, and baseline ambient conditions are comparable at the two hypothetical sites. In general, **the level of emissions and the size of the nearby population are major determinants of the externalities from oil-fired power plants, especially in areas with high baseline ozone concentrations.** Simply put, the greater the emissions and the greater the number of people exposed to a pollutant, the greater the expected health impacts.

As found in analysis of other fuel cycles, there is generally a lack of quantitative information on ecological exposure-response functions. This situation does not mean that ecological impacts are unimportant. Indeed it suggests the need for a broad approach for assessing externalities that uses the damage function approach, together with other methods that account for ***qualitative*** information on the impacts of oil fuel cycles.

### ES.8.4 Information Needs

A major conclusion of this study is that although 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 an oil 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 ***limited number of health-effects studies can be augmented 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 information is lacking. Also, priorities should be established to ***develop better atmospheric transport models, especially for ozone and sulfates,*** that are reasonably accurate and that are also inexpensive to use in terms of their demands on data.

In economics, a major issue 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 these conditions themselves. This issue is probably the most important point of contention in developing the Arctic National Wildlife Refuge. Neither of the reference scenarios in this study uses oil from Alaska. Thus, these types of non-use damage issues were not addressed.

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 residuals and impacts.
- Limitations in the knowledge base precluded quantitative estimates on most ecological impacts.
- The analyses are project- and site-specific.
- The analyses estimate economic damages and benefits, not necessarily externalities.
- 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.

# 1. INTRODUCTION

## 1.1. BACKGROUND

This report considers the oil fuel cycle, which involves the use of oil to generate electric power.[1] While it is highly unlikely that any oil-fired power plants will be built in the future in the United States, there are about 82,000 MW of oil-fired capacity. Worldwide, there is still considerable reliance on oil for generating electricity. When in operation, these power plants (and the associated fuel cycle activities) emit pollutants and have other residual effects that directly result in externalities.

*While it is highly unlikely that any oil-fired power plants will be built in the future in the United States, there are about 82,000 MW of oil-fired capacity.*

Externalities are effects on the well-being of third parties that are not taken into account by the producers and consumers (of electricity). Within the concept of social accounting, externalities are real costs, just like capital, labor and other costs, except that externalities are to third-parties and usually have no market value.

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.[2] 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 reflected in market transactions but that, nevertheless, have value). External costs and benefits include the value of environmental quality and health, as well as nonenvironmental considerations.

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[1] Within the U.S., oil is used mostly for gasoline. The processes (and the resulting externalities) involved in producing electricity and gasoline from oil are the same up to the point where crude oil is refined into petroleum products.

[2] 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.

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) and the production processes and technologies at each stage of the fuel cycle (especially including emissions and other residuals); (2) the deposition of these residuals in the environment; (3) the incremental consequences, or impacts, that result from the change in pollutant concentrations, or from other physical changes, in the environment; (4) the magnitude to which these impacts are valued by individuals as economic damages, or as benefits; and (5) factors that distinguish externalities from 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 a specific type of emission is traced from its source to its ultimate damage or benefit. 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).

The lack of high-quality information about external costs and benefits is a handicap to making good decisions about energy. This problem is apparent both at the Federal level, in terms of allocating energy research and development budgets, and at the State Public Utility Commission (PUC) level, in terms of choices among supply and demand resources that are necessary to meet the projected demand for electric power. Both sets of decisions have large implications for the nation's energy future. The European Union 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 the U.S. Department of Energy (DOE) and the Commission of the European Communities (EC) agreed 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. Lead responsibilities for the fuel cycles were distributed between the U.S. and EC research teams as follows:

- both teams were to undertake the coal fuel cycle;
- the United States was to lead on oil, biomass, natural gas, and small hydroelectric energy; and
- the EC was to lead on the nuclear, photovoltaic energy, and wind cycles.

- conservation options were later addressed by the EC.

Complete analysis of the external costs and benefits ultimately requires an equally balanced assessment of abatement technology and costs. This assessment is planned for future phases of this study. Such an assessment is crucial to evaluating the cost of abatement against the damage from unabated impacts. If the marginal cost of control is less than the external costs, then it would be efficient, from the standpoint of society as a whole, to reduce emissions and other residuals (or to have equivalent offsets). On the other hand, if the marginal cost of control is greater than the external costs, then it would be economically inefficient to reduce the externalities. In fact, there would be over-control. What action is taken to address the residual impacts (and externalities) is a policy issue.

## 1.2. STUDY PRIORITIES AND CAVEATS

This report documents the analysis of the oil fuel cycle, in which oil is produced, transported to refineries, refined into petroleum products and used to generate electricity.[3]

The major objectives of this oil fuel cycle study are three-fold:

(1) to apply the general methodological concepts which were developed in the Background Document (ORNL/RFF 1992) of this study to the specific analysis of oil fuel cycles; different fuel cycles have, in many cases, unique characteristics, residuals, discharges, impacts, and issues that need to be addressed in different ways, using different scientific and economic information;

(2) to develop, given the time and resources, a range of estimates of externalities associated with a new oil-fired power plant, using a benchmark technology, at two reference sites in the United States; and

(3) to assess the state of the information available to support 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 contribution of this study.*** It provides an

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[3] Because the report is intended to be self-contained, some of the material in this report overlaps with material in the reports on the other fuel cycles.

illustrative example for those who undertake energy planning and who are interested in developing quantitative estimates of externalities. While "real" data are used in the numerical examples in this study, the reference sites are only hypothetically considered as sites for the power plants. In reality, oil-fired plants would likely never be located at these particular sites. They were used in the study for the purpose of demonstrating the methodologies.

In fact, there are several reasons why ***it is not appropriate to apply directly the numerical results of this study to all oil projects:***

(1) All of the potentially important impacts were not necessarily addressed because of limited scientific and economic knowledge or because of study priorities with 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, to the extent possible, 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.

This study makes a number of assumptions for the purpose of analysis, while the study avoids by design, any particular policy context, the assumptions that define the scope of the analysis make it more relevant to certain policy contexts than to others. ORNL/RFF (1994b, Ch. 2,3) devotes considerable discussion to these issues. Below we note some of the most important assumptions.

## 1.3. SCOPE OF THE ANALYSIS

### Fuel-Cycle Assumptions:

- The U.S.-EC studies are based on the life cycle concept of fuel cycles, in which fuel is extracted, transported, converted, and used 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 not classified as being part of the fuel cycle. They are highly varied, and may be important sources of externalities that should be addressed in future study.

- The study focused on the following stages of activities: crude oil production, crude oil transportation, refining crude oil into products, 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 oil is assumed to be from plausible domestic sources close to refineries, which themselves are assumed to be nearby the power plant. Oil production, transportation, refining, and other infrastructure required to supply the power plant with fuel were assumed to exist already unless they were unlikely to exist without the oil 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—are not addressed in this study.

> ***Oil production, transportation, refining, and other infrastructure required to supply the power plant with fuel were assumed to exist already unless they were unlikely to exist without the oil plant.***

- 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 substantially different information to examine pollution emissions and other effects. The operations view, which is broader, 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, on the other hand, limits the analysis to characterizing emissions, impacts, and damages associated with the increment to output, holding the rest of the power system constant. This approach is appropriate, for example, in the context of new resource selection by State regulatory commissions.

- Similarly, it is more consistent with existing literature to frame the analysis in terms of the incremental fuel cycle requirements of a new power plant than those of a new extraction process. Thus, incremental activities performed within other stages of the fuel cycle are assumed to reduce underutilized capacity, unless that activity is dedicated to the new plant.

**Scenario Assumptions:**

- A benchmark technology was considered. The technology represents a current technology, if a plant were built for operation in 1990. This benchmark technology generally has lower emissions than the older oil-fired plants that are currently in operation. Technical data are also given for a power plant representing a future technology, one available in the year 2010. For the current timeframe, we assume that oil-fired power plants use steam boiler technology fired with No. 6 residual oil. We assume that the oil-fired plant built in 2010 uses a combined-cycle technology with No. 6 residual oil. Since impacts are project specific, however, different power plant specifications will change the magnitude of the residual damages and benefits. The methodology that this study develops is illustrated for only the 1990 technology. Analogous calculations can be carried out for the 2010-technology (or any other).

- 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]

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[4] Of course, some plants, particularly gas-fired ones, are in the range 50 to 300 MWe.

The scale set for the benchmark oil plant for both timeframes (1990 and 2010) was a 300 MWe capacity. This benchmark plant was assumed to achieve a 80% capacity factor producing about 2,100 GWh of electricity per year for 40 years.

- Since impacts may have varied temporal distributions, the corresponding damages and benefits must reflect their occurrence 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 oil 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, 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 extreme uncertainty and scientific disagreement about the linkage between emissions and measurable physical changes. This study does not develop new estimates of global warming damages or benefits. Instead, the more prominent studies are summarized in ORNL/RFF (1994), and a range of values is given, based on past studies.

- 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 oil fuel cycle analysis, regional reference environments were defined for the Southeast (Clinch River site, Tennessee) and Southwest (near Farmington, New Mexico). See Section 4.2 for the description of the regional reference environments.

**Study Approach:**

- The U.S. and EC research teams selected the Damage Function Approach (DFA) as the basic methodology. The DFA attempts to combine natural science and economics to identify the changed conditions which stem from an incremental investment. In our study the investment is building and operating an oil-fired power plant. Figure 1.2-1 shows a flow chart that illustrates the DFA. It consists of a sequence of analyses that are described

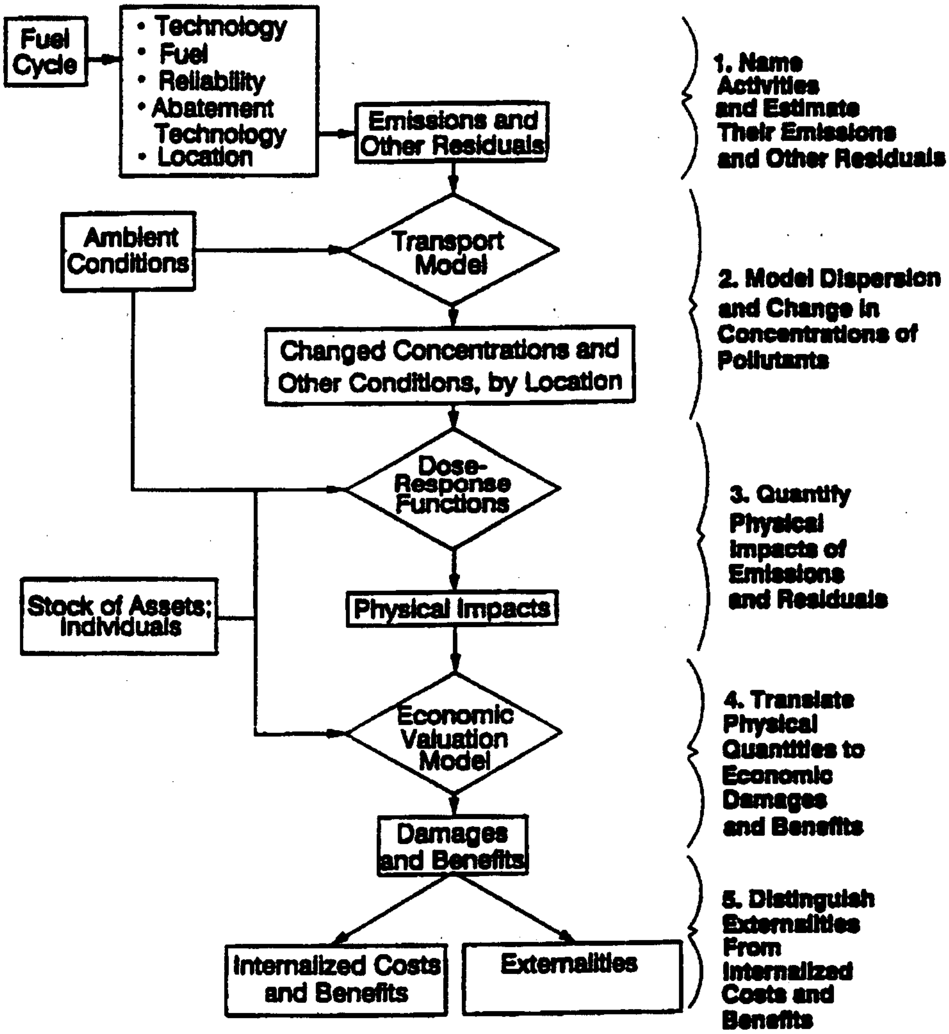

**Figure 1.2-1. Impact-pathway implementation of the damage function approach**

further in Section 1.4 in the Background Document ORNL/RFF (1992), and in ORNL/RFF (1994b).

A major departure from other approaches, which provide information about residual emissions and impacts, is the use of economic methods to estimate the economic value of 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 economic *value* of these impacts.

- Given the extreme challenges posed by dynamic modeling at the given level of knowledge, in terms of both the 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.

## 1.4. OVERVIEW OF THE 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 life-cycle 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 is a methodology that uses the existing scientific literature on ecological and health impacts associated with fuel cycles 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 oil fuel cycle can be found in Appendix D. Some of the health impacts are discussed in ORNL/RFF (1994a).

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 on the one hand and on the other hand the social costs and benefits which are internalized within the market. ORNL/RFF (1992, 1994) provide further discussion of this damage function approach.

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, traces the transport and/or chemical and physical transformation of that emission, identifies the resulting changes in its concentration in the environment, and notes 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 starting point for an economic valuation of the impact, what we call the 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.

## 1.5. ECONOMIC VALUATION

A dictionary might define "value" as a quantity considered to be a suitable equivalent for something else, or the worth in terms of the usefulness or importance to the possessor (Morris 1976). This definition contains several key concepts. First, value is *quantitatively* measured in terms of a suitable *equivalent* to something else. Thus, value is substitutable and is expressed in a common metric. Second, value is measured in terms of its *worth* to a *possessor*, i.e., to an *individual(s)*. These concepts are fundamental to the paradigm of economics.

**Table 1.3-1. Impact-pathway mappings**

| Broad-Level Mappings | | |
|---|---|---|
| Fuel cycle stages | → | activities |
| Activities | → | emissions and other residuals |
| Emissions | → | transport and changed 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 startpoints |
| Valuation startpoints | → | damages and benefits |
| Damages and benefits | → | external costs and external benefits |

Thus, this study utilizes the economic approach because it is well suited to valuation.

In economics, 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 oil 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 oil 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 nonmarketed 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 value changes in welfare may be used when damages arise 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, however, 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 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 nonmarketed 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 nonmarketed 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

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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.

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.

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 indivuduals; treatment of nonlinearities in damage functions; matching physical endpoints with economic startpoints; and treatment of the temporal perspective, including discounting/levelization. These issues are addressed in some detail in the Background Document ORNL/RFF (1992).

The issue of non-use values, while not an issue special to this report, is nonetheless particularly relevant to the oil fuel cycle. 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 describes the collection, assessment, and application of existing literature to estimate selected damages and benefits from the oil fuel cycle. In Chapter 2, a brief review of other recent attempts to accomplish this goal is provided for contextual background. Chapter 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 Chapters 4 through 10 -- the intent being a detailed demonstration of the methodology. Chapter 4 provides a technical characterization of the oil fuel cycle. Chapter 5 summarizes the major emissions and other residuals of the oil fuel cycle. Chapter 6 presents the priority pathways selected for more in-depth analysis, discussed in greater detail in Chapters 7 to 10. Chapter 7 presents analysis of some of the major impacts and damages associated with drilling and production of the oil. Chapter 8 discusses impacts from crude oil refining activities. Chapter 9 presents impacts and damages from the transportation and storage stages of the fuel cycle. Chapter 10 presents impacts and damages from oil combustion. Chapter 11 presents a summary of the results and key conclusions.

Externalities are generally project- and site-specific. Thus, the specific numerical results in this report are not generic to the oil fuel cycle. It is desirable to implement the analytical methods, that this report compiles, within a decision support software system. This would ease the computational burden.

Appendices A through D provide additional discussion. Appendix A provides supplementary information on refining technologies and oil industry regulations. Appendix B discusses the effects of power plant $NO_X$ emissions on ozone concentrations. Appendix C presents results of the atmospheric transport modeling. Appendix D reports on the ecological impacts related to the oil fuel cycle.

# 2. PRIOR STUDIES OF DAMAGES AND BENEFITS FROM THE OIL FUEL CYCLE

This chapter reviews some previously published studies of damages and benefits from the oil fuel cycle. These studies include *Environmental Costs of Electricity* by the Pace University Center for 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, *America's Energy Choices* published by the Union of Concerned Scientists, and *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity* by M. A. DeLuchi (1991). The following sections briefly summarize the studies.

## 2.1. PACE REPORT

The Pace (1990) report is path-setting and often-cited, though highly controversial in terms of the accuracy of its numerical estimates. The intent of the Pace 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 caused these impacts to be excluded from the tabulations of economic damages.

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 is 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.

These steps are essentially identical to the first four steps of the damage function approach that this study takes (our study combines Pace's steps 3 and 4 into one step). However, there are two significant differences between our studies in the implementation of the approach. The first difference is that our modeling and analysis in each step of the methodology is consistent with the initial characterization of the technology and site. Pace, on the other hand, applies the results of other pollutant-dispersion and impact studies, without regard to their being consistent with the assumed technology and locational parameters of the power plant. The second difference is that our study reflects a more up to date and thorough assessment of the scientific and economics literature than Pace was able to undertake, with the resources available for their study.

The Pace report considers the effects of electricity generation on humans, flora and fauna, materials, and social assets (e.g., climate, recreation, and visibility). The study does not, however, include front-end costs from the upstream stages of the fuel cycle. The damage estimates for $SO_2$ and $NO_X$ are based primarily on health effects calculated from ECO Northwest's *Generic Coal Study* (1986). Dose-response relationships used for $SO_2$ were linear. Pace (1990) points out that these may not be valid relationships 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 a statistical life are based on hedonic wage studies. The health effects costs for $NO_X$ and $SO_2$ are heavily dependent on population density. This observation is frequently overlooked in many interpretations of Pace's work.

Particulate damages result primarily from visibility degradation (ECO Northwest 1984) and from health effects (ECO Northwest 1987). Visibility effects of particulates are based on estimates of visibility impairment (person-kilometers of visibility lost) and their associated economic value; ECO Northwest (1984) selected an economic value for 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 (and is thus *not* a damage-cost estimate). Table 2.1-1 shows the tabulation of damage estimates in the Pace (1990) report.

Data are provided for boilers burning residual No. 6 fuel oil at 0.5, 1.0 and 2.2 percent sulfur composition and a combustion turbine burning distillate (#2) oil with sulfur content of 1 percent. No data are provided on water emissions, dust, sludge, or iron oxides. Emission rates and valuations are given in Table 2.1-1.

Table 2.1-1. Emission rates and valuations in Pace (1991).

| | No. 6 oil[1] (0.5% S) | | No. 6 oil (1% S) | | No.6 oil (2.2% S) | | Combustion Turbine No. 2 oil (1% S) | |
|---|---|---|---|---|---|---|---|---|
| | emission tn/GWh | valuation mills/kWh | emission tn/GWh | valuation mills/kWh | emission tn/GWh | valuation mills/kWh | emission tn/GWh | valuation mills/kWh |
| $SO_2$ | 2.808 | 11.400 | 5.616 | 22.801 | 12.376 | 50.182 | 1.088 | 4.417 |
| $NO_X$ | 1.856 | 3.044 | 1.492 | 2.448 | 1.856 | 3.044 | 3.386 | 5.554 |
| Part. | 0.286 | 0.680 | 0.468 | 1.114 | 0.905 | 2.153 | 0.245 | 0.583 |
| $CO_2$ | 878.8 | 11.951 | 878.8 | 11.952 | 878.8 | 11.95 | 1094.8 | 14.889 |
| **Total** | | **27.074** | | **38.314** | | **67.330** | | **25.443** |

*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.

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[1] No. 6 Residual Fuel Oil

## 2.2. TELLUS REPORT

The Tellus report (1990) develops estimates of the social costs of air emissions using an abatement cost approach. This method is different from the damage-cost approach followed in this report and in Pace (1990) [though, as discussed in the previous section, our implementation of the damage-cost approach is quite different from Pace's]. Abatement costs are viewed as an indicator of what Tellus calls "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 p. 4-5). 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.

The revealed preference approach is used by Tellus 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 regulatory standards. The basis that Tellus uses for the revealed preferences are Federal standards and the South Coast Air Quality Management District's (SCAQMD) regulations.

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 Tellus computes the costs of pollutants on a dollars per pound basis regardless of the fuel cycle. For any given pollutant, however, the costs of controlling the emissions should vary, depending on the fuel and technology involved.

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 marginal 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. See Krupnick and Burtraw (1992) for a full discussion.

Tellus departs from its revealed political preference rationale when it comes to global climate change. The pollutants $CO_2$, $CH_4$, $N_2O$, CO, and $NO_X$ are referred to as 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 come into effect in the future. Externality costs for $CO_2$ are based on the mitigation cost of tree planting (as in Pace). 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 the effect of 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.

**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* |
| Carbon dioxide ($CO_2$) | *a* | *a* | 0.011 |
| | *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.

## 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). Damages from greenhouse gas emissions were taken into account (Table 2.3-1) as were other airborne emissions. Estimates were obtained from other researchers, primarily Wicke (1986). 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 of other studies cited, a judgement about these damage estimates cannot be made.

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.

Additionally, 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.

## 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;

### 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 compounds (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.

### Table 2.3-2. Damages in the Federal Republic of Germany 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) 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). The objective of the study was to examine 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 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, 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 oil technologies are listed in Tables 2.5-1 and 2.5-2 below. Table 2.5-1 is based on data from the EPA's National Emissions Data System and takes into account regional differences in environmental constraints and control technologies. This table lists the current average emissions of residual oil steam and distillate combustion turbine (CTDST) plants 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 distillate oil combustion turbine technology having steam injection for 70 percent removal of $NO_X$. The study does not assume any regional differences for this technology.

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, existing

**Table 2.5-1. Current average oil utility emissions factors (lb/MMBtu).**

| | $NO_X$ | $SO_2$ | $CO_2$ | $CH_4$ | CO | TSP | VOC |
|---|---|---|---|---|---|---|---|
| Residual oil steam | | | | | | | |
| North Central | 0.66 | 0.95 | 173 | 0.0016 | 0.041 | 0.080 | 0.008 |
| Northeast | 0.39 | 1.29 | 173 | 0.0016 | 0.035 | 0.068 | 0.006 |
| South | 0.38 | 1.22 | 173 | 0.0016 | 0.035 | 0.072 | 0.004 |
| West | 0.19 | 0.18 | 173 | 0.0016 | 0.025 | 0.024 | 0.009 |
| CTDST | | | | | | | |
| North Central | 2.23 | 0.86 | 162 | 0.0016 | 0.39 | 0.076 | 0.058 |
| Northeast | 0.46 | 0.17 | 162 | 0.0016 | 0.12 | 0.040 | 0.039 |
| South | 2.09 | 2.34 | 162 | 0.0016 | 0.43 | 0.20 | 0.064 |
| West | 2.15 | 0.63 | 162 | 0.0016 | 0.24 | 0.085 | 0.088 |

*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 |
|---|---|---|---|---|---|---|---|
| CTDST | 0.20 | 0.212 | 164 | 0.0016 | 0.116 | 0.035 | 0.036 |

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

and proposed environmental regulations are assumed to reflect the 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.

*America's Energy Choices* also provides a levelized cost of 0.69 to 2.41 cents/kWh for residual oil steam turbine plants. This range of values is based upon both the Tellus emissions externalities values and regional differences. In

**Table 2.5-3. Monetary values for air emissions externalitites (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 $/lb)**

| 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.

addition, the UCS study's Environmental and Climate Stabilization scenarios account for the risks to national security of relying on oil by incorporating an oil security externality value ($2.50 per barrel) in energy prices that would add about 0.4 cents/kWh to oil-fueled plants' externality costs.

## 2.6. DELUCHI'S REPORT

M. A. DeLuchi's (1991) *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity* is a report on a study that aims to 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 greenhouse gas emissions for a variety of transportation and electricity generation fuel cycles. These estimates are developed for each of several scenarios that differ in a number of assumptions such as those about power plant efficiencies. The study also compares each of the fuel cycles' global warming contributions by converting the estimates for non-$CO_2$ emissions into $CO_2$-equivalent terms.

The DeLuchi study takes into account emissions from feedstock recovery and fuel production, 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 considers 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 estimates for the oil-to-power fuel cycle in terms of grams of $CO_2$-equivalent emissions per kWh of generated electrical energy are tabulated in Table 2.6-1 for the study's base scenario. 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 from the EPA's *Compilation of Air Pollutant Emission Factors* (AP-42) and other sources, as well as from analyses of the carbon and energy contents of oil. 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 (Shine et. al. 1990). The table lists the emissions values for both the fuel cycle's upstream processes (feedstock recovery, fuel production, etc.) and for the power-generation stage. The power plant values are based on the assumption that the efficiency of electricity distribution and transmission is 92% and that the oil fuel burner has an efficiency, or heat rate, of 32%. With regard to $NO_x$ DeLuchi assumes that in the year 2000 such oil-fired plant emissions will be reduced to 25% below uncontrolled levels. All fuel oil is assumed to be No. 6 residual oil.

**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 | Residual Fuel Oil Boiler |
|---|---|
| $CH_4$ | 7.9 |
| $N_2O$ | 5.3 |
| NMOCs | 3.3 |
| CO | 1.5 |
| $NO_x$ | 20.6 |
| $CO_2$ | 141.8 |
| Upstream Total | 180.5 |

| Power Plant | |
|---|---|
| $CH_4$ | 0.2 |
| $N_2O$ | 0.0 |
| NMOCs | 0.3 |
| CO | 0.5 |
| $NO_x$ | 71.0 |
| $CO_2$ | 875.9 |
| Power Plant Total | 957.9 |

Table 2.6-2 lists the total $CO_2$-equivalent emissions for the oil fuel cycle for the 100-year time period, as well as for 20 and 500-year periods. These totals can be obtained by summing the $CO_2$ 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 his report, 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 2.6-2 Total $CO_2$-equivalent emissions for the oil fuel cycle in g/kWh delivered to end user**

| | Residual Fuel Oil Boiler |
|---|---|
| 100-year case | 1138 |
| 20-year case | 1416 |
| 500-year case | 1067 |

## 2.7 MORE RECENT STUDIES

After the completion of this chapter, the National Renewable Energy Laboratory [NREL] (1994), ICF (1994), Leiby et al. (1994) and RCG/Hagler-Bailly issued a number of noteworthy reports. NREL (1994) completed a life cycle analysis of the emissions and other residuals from the reformulated-gasoline life cycle. The upstream (i.e., production and crude oil transportation) stages of that life cycle are common to the oil fuel cycle that this study addresses. NREL (1994) identifies the life cycle processes and emissions in detail, but does not attempt to estimate their impacts, damages, or externalities. ICF (1994) summarizes the major oil life cycle activities and their emissions, drawing on an early draft of this chapter, as well as on other sources for its information. Leiby et al. (1994) develop some order-of-magnitude estimates of externalities based on: an analysis of the literature, data on oil spills and on other sources of impacts on the environment, and the regulatory requirements of State Public Utility Commissions (in the context of integrated resource planning). RCG/Hagler-Bailly (forthcoming) develops and implements a damage function methodology, much like this study, with emphasis on the generation stage of the fuel cycle.

# 3. ORGANIZATION AND INTERPRETATION OF RESULTS

This chapter describes the organization of the results that follow, particularly in Chapters 7 through 10. 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 oil-to-electricity 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 oil fuel cycle externalities.

Chapter 4 gives information on the reference sites, oil feedstock operations, and conversion technology. Chapter 5 identifies the major emissions and other residuals from the oil-to-electricity fuel cycle. Chapter 6 summarizes the major impact pathways and identifies those addressed in greater detail in this study.

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

Chapters 7 through 10 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 and oil production stage of the fuel cycle. Chapter 8 takes account of crude oil refining activities. Chapter 9 concerns the oil transportation and storage stages of the fuel cycle. Chapter 10 pertains to the electricity generation stage.

### 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 within 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 steam boiler technology using No. 6 residual oil as the benchmark for the current year (i.e. 1990) for oil-fired electric power generation. The future technology (in the year 2010) is the same except for significantly improved pollution control. Data are also given for the advanced combined-cycle gas turbine technology, fired with residual oil; but no analysis is done using this technology.

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 crude oil, the transportation routes, and the refineries associated with each of these two reference power plant sites differ as well.

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 necessarily to all combinations

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

**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 |
|---|---|---|---|---|---|
| Drilling/ wastewater/ aquatic organisms | 7.1 | ■ | ■ | ■ | ■ |
| Drilling/ oil spills/ aquatic organisms | 7.2 | nd | ■ | nd | nd |
| Oil production/ accidents/ injuries | 7.3 | nd | ■ | nd | nd |
| Refining/ residuals/ health and ecology | 8.1 | ■ | ■ | ■ | ■ |
| Transportation/ coastal barge oil spill/ aquatic organisms | 9.1 | na | ■ | na | na |
| Transportation/ river barge residual oil spill/ aquatic organisms | 9.2 | na | ■ | na | na |
| Transportation/ truck traffic/ road pavement deterioration | 9.3 | na | na | ■ | ■ |
| Generation/ozone/crops | 10.1 | ■ | ■ | neg | neg |
| Generation/ozone/health | 10.2 | ■ | ■ | neg | neg |
| Generation/$SO_2$/health | 10.3 | ■ | ■ | ■ | ■ |
| Generation/$NO_x$/health | 10.4 | ■ | ■ | ■ | ■ |
| Generation/particulates/health | 10.5 | ■ | ■ | ■ | ■ |

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

of sites and technologies. 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 oil-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. Sections 3.3 and 3.4 discuss the methods used to describe systematically the uncertainty in calculations and the quality of the knowledge base.

## 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 oil-to-electricity 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 two particular oil conversion technologies were analyzed in detail for each of the two timeframes. The oil feedstock 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). The economic values derived in this study should be interpreted as the marginal damages and marginal benefits associated with the addition of the oil plant and of the feedstock operations needed to support the oil 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. The numerical estimates should not be applied directly to other project and siting decisions.

### 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 oil plant would sum up to the total present value of the damage or benefit.

Damage to the region surrounding oil 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 OIL FUEL CYCLE

Section 4 gives an overview of the boundary assumptions required for estimating emissions and impacts for an oil fuel cycle. A current and a future time period are considered for the hypothetical power plants at two reference sites. Section 4.1 gives a general description of the oil fuel cycle stages and activities. In addition, potential emissions, pathways, and impacts are presented.

Section 4.2 describes in detail the oil technology that was used as the foundation for the analysis reported in Sections 5 through 10. The section also presents information on the types of emissions from oil production, crude oil transportation, refining, and the oil-fired electric generating plant. Information is also presented on a different oil technology that may be utilized in 2010.

Section 4.3 provides summary data on the two reference sites that were selected to demonstrate the application of the impact-pathway damage function approach. In addition, impacts on the population and environment due to the transport of emissions to areas surrounding the reference power plants are summarized.

Section 4.4 describes the oil technology assumed for our benchmark analyses at the reference sites. Data are also given for the upstream activities.

## 4.1 OVERVIEW OF OIL FUEL CYCLE, EMISSIONS, PATHWAYS, AND IMPACTS

The oil fuel cycle involves five major stages -- crude oil extraction from on- and offshore drilling, transportation of crude oil from production sites to refinery storage terminals, refining the crude oil to residual fuel oil, transportation of the residual oil to the power plant site and storage there, and generation of electricity.

For the oil fuel cycle, priority impact pathways were selected primarily on the basis of their significance in terms of the potential for externalities [refer to ORNL/RFF (1994b) for a more detailed description of the screening procedure]. These priority impact pathways are discussed in detail in section 6, and include impacts from 1) crude oil production, 2) crude and residual oil transportation, and

3) electricity generation from oil-fired power plants. In this section, we have identified and discuss in detail ten sources of environmental pollution from the oil fuel cycle, most of which are important enough to be included in the priority impact pathways. Some of the ten sources of environmental pollution were not included in the priority impact pathways since their consequences on the environment were not judged to be as severe as those that were included.

The ten sources of environmental pollution include 1) wastewater from oil well drilling and oil extraction, 2) hazardous wastes from oil well drilling and oil extraction, 3) air emissions from oil well drilling and oil extraction, 4) water pollutants from crude refining, 5) hazardous wastes from crude refining, 6) air emissions from crude refining, 7) air emissions from oil-fired power plants, 8) water pollutants from oil-fired power plants, 9) hydrocarbon air emissions from crude and fuel oil transportation and storage, and 10) oil spills during oil transportation and storage.

The wastes and emissions noted in the ten sources listed above have potential for adverse ecological impact. Some of the wastes and emissions may have health and safety impacts, for example, the emissions from electricity generation -- carbon monoxide (CO), nitrogen oxide ($NO_X$), sulfur oxide ($SO_X$), particulate matter (PM), and carbon dioxide ($CO_2$). Accidents are also associated with some stages of the oil fuel cycle. There are also potential socioeconomic impacts with the oil fuel cycle. These impacts would include employment and income growth and energy security, although the extent of all of these impacts is highly controversial (ORNL/RFF 1994a,b). Table 4.1-1 shows the oil fuel cycle emissions and the potential resource categories that may be impacted (those resource categories that are italicized are priority or key impacts that are discussed further in section 6. The impacts not in italics have not been quantified and some of these are discussed in Appendix D).

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

| Emissions | Sources | Impacts |
|---|---|---|
| | *Air Emissions* | |
| Carbon dioxide ($CO_2$)<br>Carbon monoxide (CO) | Releases from mechanical equipment, vehicles, and power plant stack | *All impact categories* |
| Nitrogen oxides<br>Sulfur dioxide | Releases from refinery, vehicles, and power plant stack | Biodiversity; crop production; tree growth |

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

| Emissions | Sources | Impacts |
|---|---|---|
| Acid aerosols | Formation in atmosphere from $NO_x$ and Sulfur Dioxide ($SO_2$); long range transport, acid deposition | Recreational fishing; crop production; tree growth; biodiversity |
| Ozone | Formation in the atmosphere | *Morbidity; mortality; change in crop production* |
| Hydrocarbons | Refinery emissions, air emissions, combustion products | Biodiversity |
| Particulates,<br>Acid aerosols | Power plant emissions (haze formation) | *Morbidity; mortality;* recreational use of parks |
| Peroxyacetyl nitrate (PAN) | Formation in the atmosphere from $NO_x$ and HC | Biodiversity |
| Inorganics | Power plant emissions | Biodiversity |
| | ***Water Emissions*** | |
| Produced water<br>Drilling fluids<br>Drill cuttings | Emissions from offshore drilling platforms | *Commercial fisheries; recreational fishing; biodiversity* |
| Wastes and wastewater | Refineries, power plant | Aquatic impacts |
| Crude oil | Spills from drilling rigs and pipelines in coastal and estuarine areas | *Commercial fisheries; recreational fishing; biodiversity* |
| Residual oil | Spills from barges in freshwater systems | *Recreational fishing; biodiversity* |
| Residual oil | Spills from barges in marine systems | *Recreational fishing; commercial fishing, 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 contaimination impacts |

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

| Emissions | Sources | Impacts |
|---|---|---|
| | ***Other Burdens*** | |
| Land use | Production fields, refinery, power plant | Biodiversity |
| Drilling platforms | Construction | Commercial fishing, recreational fishing |
| Dredging | Offshore construction of pipelines | Commercial fishing |
| Erosion | Shoreline activities associated with offshore production | Recreational use |

The five major stages in the Oil Fuel cycle are discussed in section 4.2.

## 4.2 OIL FUEL CYCLE STAGES, ACTIVITIES, AND TECHNOLOGY

### 4.2.1 Crude Oil Exploration

Exploratory drilling is performed to determine if oil and/or gas is present in a promising formation[1]. The exploration process consists of mapping the area of the potential oil/gas deposit, and conducting seismic, gravimetric, and magnetic surveys to determine if the geologic structure is suitable for a potential oil 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 1992].

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

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[1] In this oil fuel cycle study we assume that existing crude oil formations, both on- and offshore, have previously been located so that exploratory activities are unnecessary. We include the discussion in section 4.2 to describe the process if exploration were needed.

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 (a detailed description of the drilling wastes are found in Section 5.1).

### 4.2.2 Onshore Drilling

In onshore drilling, cuttings are removed from the drilling mud at the surface. They are then deposited in a reserve pit next to the rig. The reclaimed drilling fluid is then recirculated back to the well. Drilling mud must be disposed of when excess mud is collected, when changing down-hole conditions require a whole new type of fluid, or when the well is abandoned. If the well is a dry hole, the drilling mud may be disposed down-hole upon abandonment.

There are an estimated 1,200,000 abandoned oil and gas wells in the U.S. To avoid degradation of ground water and surface water, abandoned wells are plugged. Plugging involves placing cement over portions of a well bore to permanently seal formations containing hydrocarbons or high-chloride waters. The majority of produced water and other wastes associated with oil production are injected back into depleted underground oil reservoirs.

If a well is not plugged, the native brines of the injected wastes associated with oil production may migrate to freshwater aquifers through the well bore, and contaminate fresh ground water. State regulations enforce the plugging of once active wells now becoming inactive, but have not eliminated entirely the problem of contamination due to older abandoned wells.

Air emissions from well drilling are mainly due to burning diesel fuels, natural gas, and gasoline in internal combustion engines and to using electricity imported from the electric utility grid. Major air pollutants from these sources include $NO_x$, $SO_x$, hydrocarbons (HC), PM, CO, and $CO_2$. Although the use of electricity does not directly produce emissions in oil fields, the generation of electricity produces emissions at the power plant site. Air emissions may be produced from the evaporation of light organic compounds in the reserve pit where spent drilling fluids and wastewater are stored; they may also be caused from the de-gassing of drilling mud.

*Note: For this study, we categorize emissions due to use of electricity for oil production as secondary emissions. We do not consider secondary emissions because they and their impacts are minimal.*

Wastewater and solid wastes are also caused by drilling activities. An estimated 0.0482 acre-feet of water is consumed in the form of drilling fluids per $10^{12}$ Btu energy produced (U.S. Department of Energy 1983). Constituents such as cadmium, cyanide, mercury, organic carbon, suspended solids, and dissolved solids are found in varying concentrations in drilling muds and can contaminate ground water and surface water. Currently, wastewater discharge from onshore oil production is regulated by EPA.

Drilling mud, drilling cuttings, spent fracturing and acidizing fluids, completion and workover fluids, and hydrocarbon-bearing soil are produced in close proximity of oil-drilling facilities (Environmental Protection Agency 1987a). The largest volume of drilling-related wastes are generated in the form of spent drilling fluids. The composition of modern drilling fluids can vary widely from one geographical area to another, and even from one depth to another, in a particular well. Therefore, the type of waste generated depends on the composition of drilling fluids. Solid wastes from onshore oil well drilling and oil extraction are restricted by state regulatory agencies.

Completion and workover fluids are placed in the well bore during completion or workover and will control the flow of native formation fluids such as oil, water, and gas. Various additives such as salts, organic polymers, and corrosion inhibitors are added to the water-based fluid. These materials have the potential to become solid wastes.

Other wastes include rig-wash materials, pipe dope, sanitary sewage, trash, and lubricating oil.

The wastes generated from well drilling activities are usually stored in a reserve pit next to the drilling rig. Usually one reserve pit is constructed per drilling site. Current regulations require pits constructed above unconfined groundwater aquifers to be lined. This will limit reserve pit constituents leaching into and contaminating groundwater.

Pollution discharges into U.S. navigable waters has been compiled by the U.S. Coast Guard (1989) for the 1986–1989 period. The Coast Guard information categorized spills into three groups: oil, hazardous substances, and other. The data is presented in tables by general area, type of oil spilled, source of the spill (type of vessel, land vehicle, or land facility), type of incident causing the spill, and a frequency distribution of oil spill sizes. The data is not summarized by frequency distribution, vessel, and location, which would be useful for this analysis. Consequently, it is impossible to assign the oil spill frequency distribution data to oil tankers and barges.

### 4.2.3 Offshore Drilling

Offshore drilling technology is similar to onshore drilling technology, except that a supporting platform is needed for offshore drilling rigs. Different platforms have been developed for offshore drilling; these include barges, drilling ships, jack-up drilling rigs, semi-submersible rigs, and others.

Drilling ships are used extensively for offshore drilling and are self-propelled. These ships maintain positions by an anchor and chain system or by a dynamic positioning system. These dynamic positioning systems often consist of a series of propellers or thrusters coupled to sensors which detect and compensate for movement.

A jack-up drilling rig is equipped with tubular or derrick legs that support the platform deck and hull. A jack-up rig is towed or propelled to a location with its legs up. While positioned over the drilling site, the bottoms of the legs rest on the ocean floor. The legs are then firmly positioned on the ocean floor, and the deck and hull height are adjusted and leveled.

A semi-submersible drilling rig is a floating offshore drilling structure that has hulls submerged in the water but not resting on the sea floor. Semi-submersible rigs are either self-propelled or towed to a drilling site and are either anchored and/or dynamically positioned over the site. Semi-submersibles are more stable than drilling ships and are used extensively to drill wells in rough waters.

The major environmental concerns regarding offshore drilling center around its impacts on marine biological species, such as fish, marine mammals, and birds. The environmental consequences of oil spills from offshore production are of special concern to the public. Significant oil spills related to offshore production are infrequent, but can occur due to well blowouts, fires, storms, hurricanes, and leaks of the pipeline system used to transport crude from oil platforms to onshore storage facilities. Virtually all of the offshore oil produced in the Gulf of Mexico and the California coastal areas is transported onshore through pipelines. Oil leaks from underwater pipelines may result from corrosion outside or inside pipelines; some leaks may be difficult to detect.

Offshore drilling activities produce air pollution, wastewater, and solid wastes similar to onshore drilling activities. The amount of air emissions, wastewater, and solid wastes per barrel of crude produced from offshore drilling is larger than that from onshore drilling because of the intensive activities involved in offshore drilling. For example, energy consumption for offshore oil production is six times as high as that for onshore oil production (U.S. Department of Energy 1983). However, the effects of these emissions from offshore drilling are probably minimal because a large body of ocean water acts as a sink for wastewater and solid wastes, and because few humans are exposed to the air pollution.

During offshore operations, water from the geological formations is often ejected. These waters may contain mineral salts such as iron, calcium, magnesium, sodium, and chloride and often contain small amounts of oil. The effects of this discharge is dependent on a variety of factors such as distance from shore, water currents, and water depth.

### 4.2.4 Oil Extraction

Upon the completion of drilling a well, if tests show that commercial quantities of oil and gas are present, the well must be prepared for production. To do so, production casing is first run into the hole and cemented permanently into place. Then, strings of production tubing are set in the hole, productive intervals are isolated with packers, and surface equipment is installed. During these operations, drilling fluid may be modified or replaced by specialized fluids, called completion fluids, to control flow from the formation. Completion fluid may consist of a brine solution modified with petroleum products, resins, polymers, and other chemical additives. When the well produces oil, the completion fluid may be reclaimed or treated as a waste product and disposed of.

Two types of extraction methods are employed to extract oil from under the ground to the surface: conventional extraction methods and enhanced oil recovery methods. These two methods create different intensities of environmental pollution.

#### 4.2.4.1 Conventional Extraction Methods

In conventional extraction methods, oil and gas are extracted from a reservoir by using the natural pressure of underground oil reservoirs or artificial lift methods, such as surface or subsurface pumps and gas lift, to bring oil out of the formation and up to the surface.

Oil wells generally produce a wide variety of hydrocarbon compounds ranging from methane gas to very heavy oils. Crude oil is often produced under high pressures and high temperature. Fugitive emissions and spills, attributable to poor housekeeping, high pressures, and the corrosive environment, produce air pollution.

Wastes from oil extraction include hydrocarbon solids, hydrates, and other deposits removed from piping and equipment; pigging wastes from gathering lines; basic sediments, water, and other tank bottoms from storage facilities and separators; produced water; constituents removed from produced water; accumulated materials (e.g., hydrocarbons, solids, sand, and emulsion) from production separators, fluid-treating vessels, and production impoundments that are not mixed with separation or treatment media; and materials ejected from a production well during a blowout (Environmental Protection Agency 1987a). Materials such as benzene, phenanthrene, lead, barium, arsenic, fluoride, and antimony are found in various concentrations in these wastes. Consequently, the effects on the local environment may vary.

### 4.2.4.2 Enhanced Oil Recovery (EOR) Extraction Methods

Some deposits of crude oil consist mainly of thick, highly viscous crude oils which require an EOR method to modify them before they can be extracted from the ground. It is estimated that two-thirds of the oil left underground is due to high viscosity and unfavorable reservoir geology (California Energy Commission 1991). Some of this oil can be recovered with EOR methods.

An EOR method employs a secondary method in addition to the primary method used in conventional extraction. Three general EOR secondary methods can be used: thermal recovery, chemical flooding, and gas displacement.

In the *thermal recovery* method, heat is applied to the reservoir by injecting it with steam. The steam is generated by burning fuel oil or natural gas, which produces air pollutants. The high-pressure injection of water into reservoirs and the subsequent disposal of wastewater could contaminate surrounding aquifers.

In the *chemical flooding* method, a mixture of chemicals and water is injected into a reservoir in order to generate fluid properties that are more favorable for oil extraction. Groundwater contamination can be caused by the chemicals injected into the reservoir. The subsequent disposal of chemical wastes may cause surface and groundwater contamination.

In the *gas displacement* method, gases (mainly $CO_2$) are injected into a reservoir to sweep oil toward a production well. Injected gases may cause groundwater contamination.

The land consumption, water consumption, and energy consumption of EOR extraction methods are very high relative to the conventional extraction method. For example, in thermal recovery, one unit of energy is needed for every three units of energy produced (California Energy Commission, 1991). In contrast, one unit of energy is needed for every 70 units of energy produced through the conventional extraction method (DOE, 1983). Therefore, the amount of air emissions, wastewater, and solid wastes generated per barrel of crude produced through EOR methods is larger than that produced through the conventional method.

The EIA estimates that oil production from EOR methods in 1990 was about 0.66 million barrels per day, about 9% of the total oil produced (Energy Information Administration 1991b). Oil production through EOR methods is expected to increase considerably through the year 2010 (Energy Information Administration 1991c).

### 4.2.5 Treatment and Storage of Crude at Production Sites

#### 4.2.5.1 Crude Treatment in Production Fields

Crude oil is brought to the surface with a mixture of oil, water, and gas. In the U.S., about 20% of the natural gas produced is a co-product of oil production (Energy Information Administration 1991b). As producing reservoirs are depleted, their water/oil ratio may increase considerably, resulting in higher water content in the mixture. Water can account for amounts ranging from less than 10% to greater than 50% of the total fluids produced from a single well. Virtually all water in the mixture must be removed before the oil can be transferred to a pipeline (the maximum allowed water content in oil delivered to pipelines is about 1% by weight). Thus, it is necessary to separate oil, gas, and water. This separation is accomplished by on-site crude treatment facilities.

An on-site crude treatment facility usually includes an oil/gas separator, an oil/water separator (heater treater), oil storage tanks, and produced water storage tanks. During the separation process, the oil/gas/water mixture is first fed into the oil/gas separator, where gas is separated from the mixture. Since some oil/water mixtures can be separated by their gravity, the separation of water from oil is done in settling tanks. When emulsions are difficult to break, heat is usually applied in the "heater treater," or de-emulsifying agents are applied to the mixture. The separated oil is then stored in oil storage tanks until it is transported to central storage terminals. Impurities contained in crude, such as salt and sand, are also removed during the treatment process.

A large quantity of produced water is generated from the separation process. The API estimates that 20.9 billion barrels of produced water were generated in 1985 from crude production sites (Environmental Protection Agency 1987a). Most produced water is strongly saline. If chloride levels and the levels of other constituents are low enough, produced water may be used for beneficial purposes such as agricultural irrigation or livestock watering. Produced water also contains petroleum hydrocarbons and metals.

Produced water can be disposed of through the use of annular injection into producing wells (although only a small percentage of produced waters is disposed of by this method). This method has the potential to adversely affect underground sources of drinking water if not properly monitored. Produced water can also be disposed of in injection wells. This method has the potential to degrade groundwater in the vicinity if these injection wells are inadequately designed, constructed, or operated. Nation-wide, 95% of all produced water is injected for disposal or used in enhanced recovery methods (Environmental Protection Agency 1987b).

Low-volume production-related wastes include many chemical additives, production tank bottoms, and scrubber bottoms. These wastes can be managed through on-site or off-site management methods. Currently, the EPA and states regulate the construction and operations of class II oil and gas wells. On-site waste management methods include subsurface injection; evaporation and percolation pits; and discharge of produced waters to surface water bodies (Environmental Protection Agency 1987b). Off-site waste management methods include the use of solids from waste treatment which can be used as materials for road pavement or other land pavement (such as parking lot pavement).

The sludges and liquids that settle out of the oil as tank bottoms throughout the separation process must be collected and disposed of. Tank bottoms are usually hauled away from the production site for disposal.

Both crude oil and natural gas may contain $H_2S$. $SO_2$ emissions are generated at plants where $H_2S$ is removed from natural gas. $H_2S$ dissolved in oil does not pose a danger, but when it is produced at the wellhead in gaseous form, it poses occupational risks.

Volatile organic compounds (VOCs) may be released from leaks in production equipment or from pressure vents on separators and storage tanks. VOC emissions may also be caused by the evaporation of hydrocarbons from wastewater reserve pits.

#### 4.2.5.2 Crude Storage at Production Sites

The treated oil is stored at production sites until it can be transported to central storage terminals. The storage of crude oil in storage tanks and the transfer of crude to and from storage tanks generate HC evaporative emissions. The cleaning of storage tanks produces sludges and, therefore, results in water pollution and solid wastes.

### 4.2.6 Crude Transport from Production Sites to Central Storage Terminals

Crude oil from numerous producing sites is transported to central storage terminals to provide storage for segregation, batching, blending, and inventory necessary for mass-scale, long-distance transportation. Central storage terminals are usually located at water ports or at the end of long-distance pipelines.

Tank trucks or small pipelines are usually used to transport crude from production wells to central storage terminals. The transport distance depends on the locations of ports, pipeline ends, and production sites.

When tank trucks are used to transport crude, air emissions are caused by tank vapors being displaced as crude is loaded into the tanks. Air emissions from truck tailpipes also contribute to transport emissions. The cleaning of tanks may cause surface and ground water contamination and produces sludges. When crude is transported through pipelines, air emissions are negligible.

### 4.2.7 Crude Storage in Central Storage Terminals

Crude is stored in central storage terminals for mass-scale, long-distance transportation. The types of storage terminals include inland pipeline terminals, marine shipping terminals, onshore marine receiving terminals, offshore marine receiving terminals, barge shipping terminals, and barge receiving terminals.

Five types of storage tanks are used for storing crude and refining products (Environmental Protection Agency 1985): 1) fixed-roof tanks consisting of a cylindrical steel shell with a permanently affixed roof, 2) external floating-roof tanks consisting of a cylindrical steel shell equipped with a roof which floats on the surface of the stored liquid, rising and falling with the liquid level, 3) internal floating-roof tanks equipped with both the permanently fixed roof, and a deck inside which rises and falls with the liquid level, 4) pressure tanks equipped with a pressure/vacuum vent that is set to prevent venting loss from boiling and breathing loss from daily temperature changes, and 5) variable vapor-space tanks equipped with expandable vapor reservoirs to accommodate vapor volume fluctuations attributable to temperature changes. Floating-roof-type storage tanks are widely used in the U.S. due to evaporative emission regulations and tank safety concerns.

HC evaporative emissions released during crude storage are a major concern. There are three sources of HC emissions during crude storage: breathing losses (i.e., evaporation during crude storage in the tank), filling losses, and emptying losses. Breathing losses are due to daily temperature changes; filling losses are due to vapors displaced from transportation tanks during loading; and emptying losses are due to vapors displaced from storage tanks during unloading.

The amount of evaporative emissions generated is a function of the type of tanks, the true vapor pressure of the crude, temperature changes in the tanks, tank outages, tank diameters, schedules of filling and emptying, mechanical conditions of tanks and seals, types of paint applied to the outer surface of tanks, and types of tank seals.

Evaporative emissions can be controlled effectively by the use of floating-roof tanks, vapor recovery systems such as vapor/liquid absorption and vapor/solid adsorption, and thermal oxidation. Thermal oxidation in which an air/vapor mixture is injected through a burner manifold into the combustion area of an incinerator can be used to burn down HC evaporative emissions. Other pollutants of less concern during crude storage include $SO_X$, $NO_X$, CO, PM, and $CO_2$. These pollutants are generated from space heating, fuel combustion for pumping, and dust.

Solid wastes such as tank bottoms are not usually generated at a storage terminal if the crude storage tanks are kept well mixed and all of the contents are transported to a refinery for processing. Crude shipping facilities (i.e., marine tankers and barges), however, may generate wastewater and solid wastes from the treatment of disposed ballast water.

Slop oil is produced in storage terminals. It is the oil/water emulsion which is normally collected in a tank as the residue of tank cleaning operations.

A major task in storage terminals is to treat wastewater contaminated by oil, ballast water, and sanitary water prior to discharge. The treating methods for oil-contaminated wastewater employ the use of API separators, CPI (corrugated plate interceptor) separators, or other types of gravity separators.

### 4.2.8 Crude Transport to Refineries

In the U.S., most crude oil is produced in the Gulf Coast region and in Alaska. For example, in 1990, the Gulf Coast region produced 45% of the domestically produced crude, and Alaska produced 24% (Energy Information Administration 1991a, p. 44). In addition, imported crude accounts for about 40% of the total crude supplied to U.S. refineries. Crude is transported through marine tankers, barges, pipelines, rail tankers, and tank trucks.

The bulk of imported crude oil is delivered by marine tankers. Pipeline deliveries from Canada account for about 12% of the total imported crude oil (National Petroleum Council 1989). Foreign crude oil may be in transit for up to forty-five days after loading (assuming it is transported from the Middle East region to the Gulf Coast region). More than 75% of foreign crude oil is transported to and refined in Petroleum Administration for Defense Districts (PADDs) I and III (see attached map for each of the PADDs) (Fig. 4.2.1.).

Most domestic crude oil is refined in the same region in which it is produced. Inter-PADD crude movements are mainly accomplished through pipelines. A negligible amount of crude oil is transported to refineries by railroad tankers.

There are four major activities involved in crude transportation: crude loading, crude transportation, crude unloading, and cleaning of tanks. These activities and the pollution produced by each are described in the following paragraphs.

*There are four major activities involved in crude transportation: crude loading, crude transportation, crude unloading, and cleaning of tanks...*

### 4.2.8.1 Crude Loading

During crude loading, HC emissions are caused by the displacement of vapor space of storage cargo by crude. The amount of emissions produced from loading crude depends on the physical and chemical characteristics of the previous cargo, the method of loading the new cargo, and the physical and chemical characteristics of the new cargo.

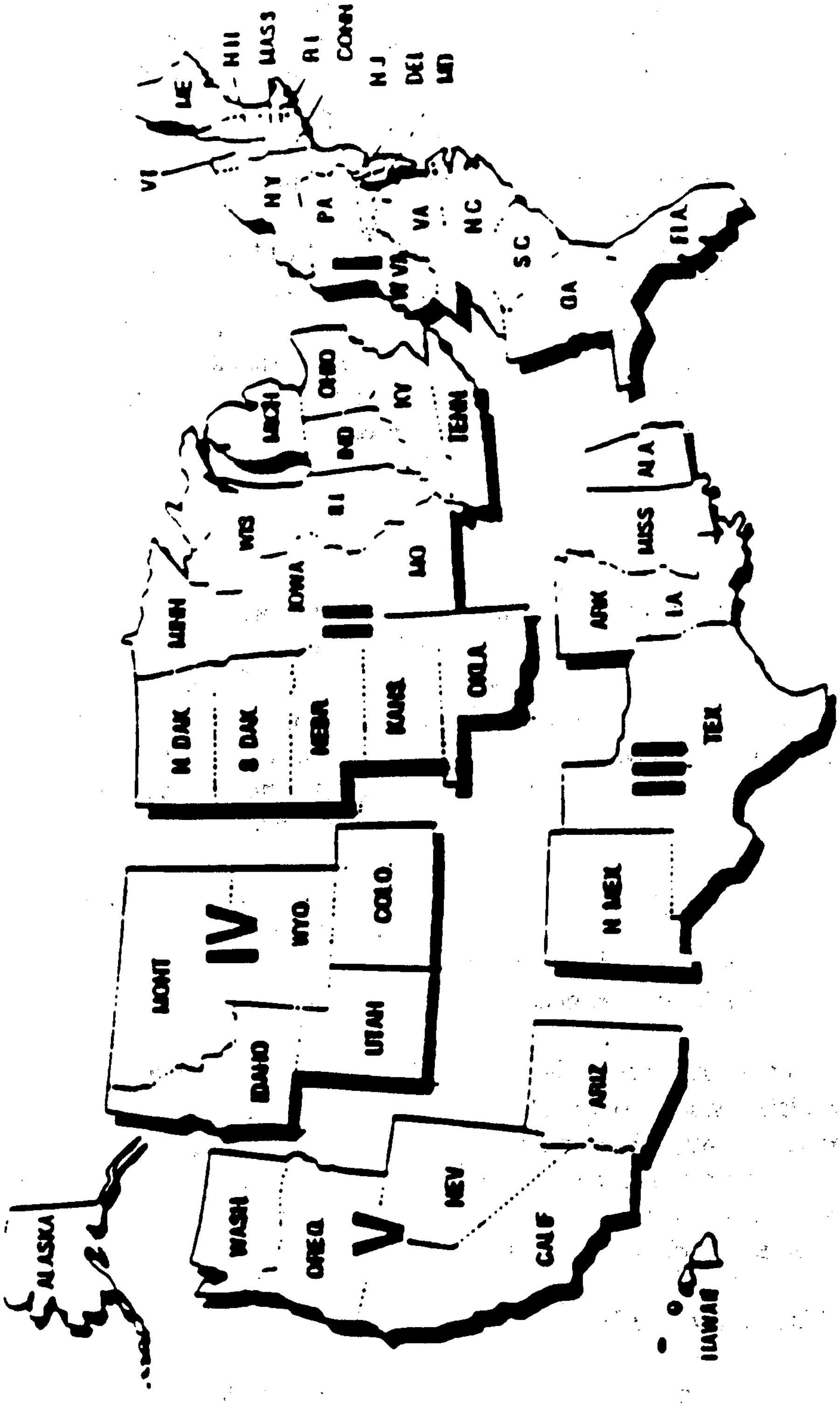

Fig. 4.2-1. Petroleum administration for defense districts (EIA 1991a)

Ballast water is applied to barges and tankers to maintain vessel stability during the trip back to storage terminals. The amount of ballast water required to stabilize a vessel depends on the ship design, its operation, and the regulations governing the discharge of ballast water. Usually, about 15%-40% of the cargo capacity is filled with ballast water to maintain vessel stability during the return trip (Environmental Protection Agency 1985). The ballast water discharged from tankers is contaminated by the previous contents of the compartments. Therefore, the amount of oil in ballast water can be reduced by cleaning the compartments before they are filled with water. Recently, ships have been designed with dedicated ballast water compartments to eliminate the mix of crude or crude products with remaining ballast water in the compartment and to control water contamination by crude or products. Thus, ballast water contamination caused by ballast water displacement of crude storage compartments will decrease in the future.

#### 4.2.8.2 Crude Transportation

Steam boilers used as vessel engines produce air emissions of HC, CO, $NO_X$, $SO_X$, PM, and $CO_2$ due to the combustion of diesel fuels and/or bunker fuel. However, these emissions are minimal on a per-barrel-of-crude-transported basis. If pipelines are the transport mode, air emissions are produced by burning diesel fuels for pumping and heating. Still, the amount of emissions may be less than those from vessels (primarily because less energy is consumed per barrel of crude transported through pipelines than per barrel transported by vessels).

Oil tankers and tank trucks are generally empty during return trips (DeLuchi, Wang, and Greene 1991). Therefore, the emissions of both the trip to refineries and the return trip to storage terminals should be accounted for when calculating the emissions produced from transporting crude and oil products.

HC transit losses occurring during the cargo transit are similar to breathing losses associated with petroleum storage. The amount of transit emissions depends on the extent of venting from cargo tank during transit, which, in turn, depends on the vapor tightness of the tank, the pressure-relief-valve settings, the pressure in the tank at the start of the trip, the vapor pressure of the crude being transported, and the degree of fuel vapor saturation of the space in the tank.

#### 4.2.8.3 Unloading Crude

Unloading crude creates HC emissions in the storage tanks located in refineries due to vapor space displacement similar to the HC emissions released from storage tanks in crude terminals. Ballast water is usually filled in some storage compartments of a vessel. The displacement of HC vapors by ballast water also causes HC emissions. In ozone non-attainment areas, ballasting emissions are regulated and, therefore, controlled by discharging the vapors during ballasting into a cargo tank being simultaneously unloaded. Vessels in the storage terminals of attainment areas may emit vapors directly into the atmosphere. Some vessels are designed with dedicated ballast water compartments. The use of dedicated ballast water compartments for vessels helps reduce HC emissions due to vapor displacement.

#### 4.2.8.4 Tank Cleaning

The inner surface of a cargo tank is rough, uneven, and pock-marked with thousands of minute pore openings, causing a considerable amount of oil to adhere to the side of the tank. It has been found that about 0.3% of the crude in the tank of a tanker adheres to the inner surface of the tank. Thus, the adhered oil must be washed out regularly.

Non-dedicated tanks which are used to transport different petroleum cargoes must be cleaned after every trip. For example, about 22% of rail tanks and tank trucks are not in dedicated service (Environmental Protection Agency 1985). Dedicated tanks which are used to transport one type of fuel must be cleaned prior to repair or testing.

Tank cleaning is mainly conducted at shipping and receiving terminals, where the waste goes to the waste treatment system. Steam, water, detergents, and solvents are used as cleaning agents. These agents cause water contamination during cleaning. The cleaning activities generate solid wastes as well. The average amount of residual material cleaned from a rail tank car with a capacity of 10,000-34,000 gallons is estimated to be 550 lbs (Environmental Protection Agency 1985). Vapors from cargo cleaning not flared or dissolved in water are dissipated into the atmosphere as air emissions.

#### 4.2.8.5 Oil Spills

Oil spills occur during crude and product storage and transport. Oil spills cause ground and surface water contamination, beach contamination, air emissions, and fire hazards, all of which have large adverse impacts on ecosystems (e.g., destroying or limiting marine life, ruining wildlife habitat, killing birds, etc.). During the period from 1984 through 1986 considerably more crude oil was spilled by accidents to vessels than offshore oil production incidents. For example, in 1986, approximately 3.4 million gallons of oil were spilled by oil carrying vessels in U.S. waters (2,819 incidents) compared with approximately 12 thousand gallons spilled due to offshore drilling activities (260 incidents).

Small-scale spills or leaks occur very often. These spills are mainly caused by equipment failures. Proper design, inspection, and maintenance of general facilities are important to prevent these spills. Oil storage tank materials and construction should be compatible with the oil stored and the storage conditions (e.g., pressure and temperature) to prevent oil leaks.

Extremely large accidental spills occur less often. For example, the 1989 Exxon Valdez accident spilled 10.08 million gallons of crude. Most large marine tanker spills occur within fifty miles of land. Most spills result from groundings, rammings (i.e., the vessel hits a fixed structure), or collisions.

#### 4.2.8.5.1 Spill Prevention and Control

It has been reported that 88% of the total number of accidental oil spills can be attributed to human errors (Sittig 1974). Reduction of human errors is, therefore, critical to limiting accidental oil spills. Precautions such as equipping plants with spill-containment features and alarms, designing workable and efficient contingency plans, employing trained spill control personnel, and using adequate spill control equipment are effective in preventing and controlling accidental spills in storage terminals.

An important factor in the cause of spills by vessels is the stopping ability of the tankers under crash-stop conditions. It has been reported that the most important factor in connection with collision and stranding is crash-stop ability (Sittig 1974). Unfortunately, the ability of tankers to come to a crash stop decreases as their size increases. Thus, larger tankers have both a higher probability of having accident-related spills as well as the potential for larger scale spills.

Also, the use of double hulls on oil tankers tends to reduce the probability of oil spills. Thus, the Oil Pollution Liability and Compensation Act of 1990 requires all new tankers operating in U.S. waters to have double hulls (Energy Information Administration 1991b). Single-hulled tankers must be phased out during 1995-2000.

#### 4.2.8.5.2 Oil Spill Liability Issue

The Oil Pollution Liability and Compensation Act of 1990 imposes limited federal liabilities on vessels and facilities (onshore and offshore facilities as well as ports) for oil spill cleanup and damage repair, allows states to impose unlimited liability, and establishes a federal oil spill cleanup fund (Energy Information Administration 1991b). Thus, the act in some degree internalizes the damage of accidental oil spills in a private company's operation activities.

### 4.2.9 Crude Storage in Refining Plants

Crude must be stored in refineries to facilitate continuous refining operations. The storage capacity for crude oil at a refinery depends mainly on the capacity of the refinery and transportation mode for the crude (e.g., pipeline-supplied refineries need less storage capacity than tanker- or barge-supplied refineries due to pipeline's steady supply of crude). In 1990, the storage capacity for crude oil in U.S. refineries was 204 million barrels (Energy Information Administration 1990). Of this 204 million barrels of storage capacity, some may be as unavailable ullage or be occupied by tank bottoms. We assume that 10% of the total capacity is not available for storing crude. Since the average crude input of U.S. refineries is about 13.4 million barrels per day, assuming 90% of the total storage capacity available, the average loading interval of storage capacity is about 13.7 days.

Floating-roof tanks are usually used for crude storage at refineries because of safety and emission regulations. Floating-roof storage tanks cause less HC emissions than fixed-roof storage tanks. The air emissions released from storing crude in refineries are mostly comprised of HC emissions caused by vapor space displaced during loading and by breathing losses due to daily temperature changes.

During storage, water and suspended solids contained in crude oil tend to settle out to form a water layer at the tank bottom. This is typically in the form of a sludge which usually contains foul smelling sulfur compounds and high dissolved solids concentrations. Sludge withdrawn from storage tanks also includes some emulsified oil.

Storage tank cleaning operations, which are required intermittently, produce a significant amount of oily wastewater. The wastewater from cleaning operations is typically high in oil and total suspended solids (TSS) and has a high chemical oxygen demand (COD).

### 4.2.10 Crude Treatment in Refineries

Crude is usually washed to remove salt and brines before it is refined. The so-called desalting process is typically performed by either chemical or electrostatic desalters, although the latter method is becoming universally adopted. In chemical desalting, a chemical demulsifying agent and a water-soda ash mixture are used. Heat is provided to promote contact between water and brine droplets. The emulsion is then broken down in a long coalescing section, allowing water droplets to coalesce. The oil and water then separate into layers in a settling drum.

In electrostatic desalting, a wash-water and crude oil mixture is applied at high temperature to provide thorough contact between entrained salt and the wash-water. A water-in-oil emulsion is formed, and this emulsion is destabilized by applying an electrostatic field to the mixture, which causes the water droplets to agglomerate and separate.

Wastewater containing various removed impurities is discharged into the waste stream while clean desalted crude oil flows from the upper portion of the holding tank. The wastewater stream from the desalting process contains emulsified and, occasionally, free oil, ammonia, phenol, sulfides, and suspended solids. These pollutants produce a relatively high $BOD_5$ (biological oxygen demand) and COD. The wastewater also contains chlorides and other dissolved materials that contribute to the dissolved solids. There are also potential thermal pollution problems because the temperature of the wastewater produced from the desalting process often exceeds 95°C (Environmental Protection Agency 1974).

The desalting process produces sludge containing oil and small quantities of hazardous compounds such as trace elements. The quantity of sludge produced depends on the quality of the crude oil. The wastewater produced contains emulsified and free oils, ammonia, phenols, sulfides, suspended solids, and dissolved solids.

### 4.2.11 Crude Refining

Although refineries are located all over the U.S., 56% of the U.S. refining capacity is concentrated in three states: Texas which has a capacity of 4.0 million barrels per stream day; Louisiana which has a capacity of 2.2 million; and California which has a capacity of 2.2 million (Argonne National Laboratory 1990). (A stream day is an operating day on a process unit, including a calendar day and an allowance for downtime.) A large refining plant may have a capacity of over 100,000 bbl/sd.

*Note: We assume that the fuel oil for the proposed power plant in East Tennessee is from the Gulf Coast, and we further assume that the Gulf Coast refinery plant is located in Harris County, Texas. We assume that the fuel oil for the proposed power plant in Northwest New Mexico is from a refinery in Southeast New Mexico.*

### 4.2.11.1 Refining Products

In 1990, the total production of all refining products was 5,392 million barrels (Energy Information Administration 1991a). The production of refining products is presented in Table 4.2-1.

Refining plants are designed to produce a mix of various products so that crude feedstocks can be utilized economically. To respond to the change in demand for certain products, the mix of products can be changed to some degree by changing the type of crude feedstock used and the refining processes employed.

A question facing the oil fuel cycle project is how to allocate environmental pollution from a refinery to various refining products. Our approach is to use the shares of products from the refinery as the weighing factor for allocating environmental pollution among products, with consideration of dedicated processes for certain products. We will not include pollution from these processes that do not produce fuel oil.

### 4.2.11.2 Refining Processes

The number and type of refining processes involved in a refinery are essentially determined by the compositions of petroleum feedstocks and the chosen petroleum products. Refining processes are usually classified into three general categories: physical separation, chemical reaction, and treating processes.

Physical separation processes separate crude oil into its major fractions according to their boiling points. (A fraction is a mixture of hydrocarbons with a particular boiling range.) The process vessel for the physical separation is usually a fractionating tower. Fractions with different boiling points are removed at different levels of the fractionating tower.

**Table 4.2-1. U.S. refining products: 1990**
**(Source: Energy Information Administration, 1991a)**

| Product Category | Amount Produced (million barrels) | Products Included |
|---|---|---|
| Motor Fuels | 3,092 | Motor Gasoline<br>Aviation Gasoline<br>Jet Fuels |
| Distillate Fuel Oils | 1,083 | Nos. 1, 2, & 4 Fuel Oils<br>Nos. 1, 2, & 4 Diesel fuels<br>Kerosene |
| Residual Fuel Oils | 374 | Nos. 5 & 6 Residual Oils |
| Asphalt | 163 | Asphalt |
| Lubricants | 61 | Lubricants |
| Other Products | 646 | Petrochemical feedstocks<br>(naphtha, liquefied gases, aromatics)<br>LPG<br>(methane, ethane, propane, butane)<br>Petroleum Coke<br>(sponge coke and needle coke)<br>Sulfur |
| Total Products | 5,392 | |

Two types of distillation are employed for physical separation: atmospheric distillation and vacuum distillation. The latter usually follows the former. As of January 1991, U.S. refineries had a 15.7 million barrel per day combined atmospheric distillation capacity and a 7.3 million barrel per day combined vacuum distillation capacity (Energy Information Administration 1991a).

Atmospheric Distillation. In atmospheric distillation, crude oil is distilled by heating it at near-atmospheric pressure. Pre-heated crude enters a pipe-still furnace, where it is heated. A foaming stream of petroleum leaves the furnace and passes to a fractionating tower, which is a vertical cylinder or column with trays. Different components of crude are separated by the trays based on their boiling points. The separated fractions are condensed, and the liquid products are cooled using cooling water or other heat exchange processes.

Pipe-still furnaces are fired with gas or oil. Due to the high temperatures involved, undesired cracking reactions can occur in pipe stills, resulting in coke deposits. Periodical cleaning of coke deposits from pipe stills generates sludges.

A substantial amount of energy is required for heating crude. It is estimated that energy consumption for heating crude is about 2% of the energy throughput in a refinery if oil is used for heating (Neumann and Rahimian 1984). Consequently, the combustion of gas or oil produces air emissions of HC, CO, $NO_x$, $SO_x$, PM, and $CO_2$. Currently, air emissions of $NO_x$, $SO_x$, and PM from furnaces in refineries are regulated.

Vacuum Distillation. The reduced crude withdrawn from the bottom of the atmospheric fractionating tower is composed of high-boiling-point fractions. When distilled at atmospheric pressure, these fractions may decompose and polymerize. They must be distilled in a vacuum tower at a very low pressure in a steam environment. This distillation process is called vacuum distillation. Petroleum fractions withdrawn from the vacuum distillation tower include lube distillates, vacuum oil, asphalt stocks, and residual oils. The vacuum in the vacuum distillation tower is normally maintained by the use of steam ejectors or vacuum pumps.

The primary air emissions produced from vacuum distillation are associated with the use of steam ejectors and vacuum pumps. The majority of the vapors withdrawn from the vacuum distillation tower are condensed in condensers. The non-condensable part of the vapors may be vented into the atmosphere. It is estimated that about 50 lbs of non-condensable hydrocarbon vapors are generated per 1,000 barrels of topped crude processed by vacuum distillation. Another source of air emissions is combustion products from the process heater. Fugitive hydrocarbon emissions from leaking seals and fittings also occur during vacuum distillation.

Control methods applicable to non-condensable emissions include venting the non-condensable vapors into blowdown systems or flue-gas systems, and incinerating them in furnaces or waste heat boilers.

The wastewater from both atmospheric and vacuum distillation generally comes from various sources. Condensers and heat exchangers are used to condense vapors and cool liquids. Circulating water in a cooling tower then absorbs the heat from the steam discharged from condensers and heat exchangers. Some of the cooling water from cooling towers evaporates into the atmosphere. Because cooling water eventually becomes contaminated by solids build-up, the circulated cooling water must be periodically de-sludged and replaced by fresh water. The discharge of the replaced water contains toxic compounds, heat, and oil.

Another wastewater source is the water drawn off from overhead accumulators prior to the recirculation or transfer of hydrocarbons to other fractionating towers. This source is a major source of sulfides and ammonia. This wastewater also contains significant amounts of oil, chlorides, mercaptans, and phenols. A minor source of wastewater is the discharge from oil sampling lines. This may form emulsions in the sewer. A wastewater source usually unique to vacuum distillation is the very stable oil emulsions formed in the barometric condensers used to create reduced pressures in the vacuum distillation units. However, when barometric condensers are replaced with surface condensers, oil vapors do not come in contact with water. Consequently, emulsions do not develop.

### 4.2.11.3 Auxiliary Facilities

#### 4.2.11.3.1 Boilers for Generating Steam

Steam is used for heating and separating hydrocarbon streams and for generating power through steam-driven turbines, compressors, and pumps. When used for heating, steam usually heats feedstocks indirectly in heat exchangers, and then returns to the boiler. In direct contact operations, steam can serve as a stripping medium or a process fluid. Steam may be used in vacuum ejectors to produce the vacuum needed for some refining processes.

The steam circulation system in a refinery discharges some condensate as blowdown and requires the addition of boiler make-up water. Refinery gases, natural gas, and residual oils are used for steam boilers. Thus, emissions of HC, CO, $NO_X$, $SO_X$, PM, and $CO_2$ are produced by steam boiler combustion. The emissions of $NO_X$, $SO_X$, and PM are currently regulated.

#### 4.2.11.3.2 Wastewater Treatment Plants

Wastewaters are generated from various refining processes. The discharge of wastewater is subject to regulations under the federal Clean Water Act. Therefore, wastewaters are treated in refineries before discharge. Wastewater treatment plants in refineries generally include neutralizers, oil/water separators, settling chambers, clarifiers, dissolved air floatation systems, coagulators, aerated lagoons, and activated sludge ponds.

Air emissions from wastewater treatment plants include fugitive emissions and dissolved gases that evaporate from the surfaces of wastewater residing in open process drains, wastewater separators, and wastewater ponds. The control of air emissions involves covering wastewater systems, such as API separators and settling basins, and removing dissolved gases from wastewater streams with sour water strippers and phenol recovery techniques.

#### 4.2.11.3.3 Sulfur Recovery Plants

Sulfur recovery plants convert $H_2S$ generated from various processes to elemental sulfur. Emissions from the sulfur recovery unit include $SO_2$, hydrogen sulfide, other reduced sulfur compounds, CO, and VOC (Environmental Protection Agency 1985). Emissions of $SO_2$ and $H_2S$ from sulfur recovery plants are regulated under New Source Performance Standards requirements.

#### 4.2.11.3.4 Cooling Towers

Cooling towers cool water circulated over the tower by moving a predetermined flow of ambient air through the tower with large fans. The air-water contact causes a small amount of the water to evaporate. The remaining circulated water is cooled. Besides evaporation loss, water losses are also caused by drift and blowdown. The blowdown causes heat pollution in the discharge stream.

Cooling-water circulation rates for refineries range from 0.3 to 3.0 gallons per minute for each barrel per day refinery capacity (Environmental Protection Agency 1985). Air emissions from cooling towers consist of fugitive VOC and gases stripped from the cooling water as the air and water come into contact. $H_2S$ and $NH_3$ are also found in the cooling water. Cooling water emissions are controlled by reducing the contamination of cooling water through proper maintenance of heat exchangers and condensers. The pollution from cooling water systems is allocated according to refining processes and, thus, is not presented here.

#### 4.2.11.3.5 Blow-Down Systems

Most refinery processing units and equipment subject to hydrocarbon vapor discharges are manifolded into a collection unit, called a blow-down system. By using a series of flash drums and condensers arranged in decreasing pressure levels, the blow-down discharges are separated into vapors and liquids. The separated liquid is recycled into the refinery. The vapors can either be flared or recycled.

Emissions from blow-down systems can be controlled by burning the non-condensable vapors in a flare or by a gas recovery system. If flaring was used to control vapors, air emissions would be produced. To obtain complete combustion, steam is injected in the combustion zone of the flare to provide turbulence and to inspire air. Steam injection also reduces $NO_X$ emissions by lowering flame temperature.

### 4.2.11.3.6 Compressor Engines

Compressors are run with reciprocating and gas turbine engines powered by natural gas. However, steam engines and electric motors are increasingly used to drive compressors.

Compressor engine emissions come from combustion products. These emissions include CO, HC, $NO_X$, aldehydes, $NH_3$, and $CO_2$. Emissions from reciprocating engines are higher than those of turbine engines.

### 4.2.11.3.7 Process Heaters (Furnaces)

Process heaters are extensively used to supply the heat necessary to raise the temperature of feedstocks to reaction and distillation levels. The fuels used for process heaters are refinery gas, natural gas, and residual oils.

All criteria pollutants are emitted from process heaters (i.e., HC, CO, $NO_X$, $SO_X$, and PM). $CO_2$ emissions are also produced during combustion. The amount of emissions depends on the type of fuel used and the heat duty of the furnace. $SO_X$ can be controlled by fuel desulfurization or flue-gas treatment. CO and HC can be limited by increasing combustion efficiencies. $NO_X$ can be controlled by combustion modification, fuel modification, furnace design, and flue-gas treatment. Emissions from process heaters are allocated to appropriate processes and are not presented here.

### 4.2.12 Storage of Residual Oils in Refineries

Final refinery products are stored prior to shipment in adjustment to market demands. During this stage, intermittent cleaning of storage tanks can produce large amounts of oil, COD, and suspended solids as well as a minor amount of $BOD_5$.

Loading fuel oils to storage tanks displaces vapor space in tanks and, therefore, causes HC evaporative emissions. Breathing losses due to daily temperature changes are probably minimal because of the lower "Reid vapor pressure" of residual oils and because of the wide use of floating-roof storage tanks in refineries. Oil spillage during storage and loading could be a problem.

In 1990, the storage capacity for residual fuel oils at U.S. refineries was fifty-six million barrels (Energy Information Administration 1990). The available storage capacity is smaller than the total capacity because of unavailable tank ullage and the space occupied by tank bottoms in a tank. We assume that 90% of the total storage capacity is the available capacity. Since the daily production of residual fuel oils in U.S. refineries is about 0.95 million barrels (Energy Information Administration 1991a), the loading interval of residual fuel oils in refinery storage tanks averages about fifty-three days. This implies that residual fuel oils are loaded to and unloaded from storage tanks less frequently than crude. Considering the fact that residual oils are loaded and unloaded less frequently and that fuel oils are less volatile, HC evaporative emissions during residual fuel oil storage may be trivial.

### 4.2.13 Residual Fuel Oil Transportation

The physical characteristics of residual oils make their transportation distinct from that of other products. Residual oils are not normally moved by pipelines because of their high viscosity and tendency to become semi-solid at a low temperature. Statistical data show that in 1990 no residual fuel oils were transported through pipelines (Energy Information Administration 1991a). They are transported by marine tankers, barges, or railroad tank cars. Many of the marine vessels and tank cars carrying residual oils are equipped with heating coils to maintain product fluidity.

The relative high cost of switching and loading rail cars makes rail movement uncompetitive with trucks for distances of less than one hundred miles (National Petroleum Council 1989). For transportation distances of less than one hundred miles, the transportation of residual oils may be accomplished economically by tank trucks.

*Note: We assume that residual fuel oils will be transported from Texas to East Tennessee by railroad cars or barges and from the Southeast New Mexico refinery to the northwest New Mexico oil-fired power plant by tank trucks.*

Air emissions are produced from fuel combustion for transportation facilities. Diesel is mostly used for barge, railroad, and tank truck transportation;

natural gas, electricity, and diesel are used for pipelines. Evaporative emissions from fuel oils from cargo space during transit are probably minimal due to the lower vapor pressure and high viscosity of fuel oils.

Tanker cars are most likely used to ship fuel oil by rail. The cleaning of the tanker cars generates air pollution and water pollution. For purposes of comparison, the average material removed from a 55 gallon drum has been estimated at 4.2 lbs (Environmental Protection Agency 1985). It is plausible to expect the waste material removed from a tanker to be in excess of 100 lbs considering it's volume. Also, oil spills are a potential problem during the transportation of residual fuel oils.

### 4.2.14 Storage of Fuel Oils in Power Plants

Fuel oils must be stored at power plants to maintain a fuel supply for continuous operation. The environmental impacts of storing fuel oil at oil-fired power plants are similar to those of storing fuel oil at refineries.

### 4.2.15 Electricity Generation

#### 4.2.15.1 Generating Technology

> ***The benchmark technology used in this study is a 300 MW oil-fired steam boiler. We assume an 80% capacity factor for these power plants, each generating $57.6x10^5$ kWh per day, or $2.102x10^9$ kWh per year. Assuming a conversion efficiency of 35% for oil-fired power plants, approximately 8,940 barrels of residual oil would be needed daily for each power plant...***

The benchmark technology used in this study is a 300 MW oil-fired steam boiler electric generating plant for each of the two reference sites. This is a reasonable size for a base load plant, based on data on recently-build plants in the U. S. and based on field information. Different types of technologies generally have different size plants. To facilitate comparisons among fuel cycles, externalities are expressed on a per kWh basis. We assume an 80% capacity factor for these power plants, each generating $57.6x10^5$ kWh per day, or $2.102x10^9$ kWh per year. Assuming a conversion efficiency of 35% for oil-fired power plants, approximately 8,940 barrels of residual oil would be needed daily for each power plant (assuming 3,412 Btu/kWh and 6.28 million

Btu/bbl residual oil [EIA, 1991d]). This translates into about 3.26 million barrels of residual oil consumed per year for each of the two plants.

We assume that in future studies the oil-fired electric generating plants may use combined-cycle technology using No. 6 residual oil.

#### 4.2.15.1.1 Steam Boiler Technology

There are four stages involved in the generating unit of steam-boiler electric power plants: fossil fuel combustion in furnaces, turbine and generator rotation driven by steam, steam condensation, and feeding condensed steam into the boiler. In the first stage, fossil fuel is burned in a boiler furnace. The evolving heat is used to produce pressurized and superheated steam. This steam is conveyed to the second stage, the turbine, where it gives energy to rotating blades and, in the process, losses pressure and increases in volume. The rotating blades of the turbine drive the electric generator or alternator which converts the imparted mechanical energy into electrical energy. The steam leaving the turbine enters the third stage, the condenser, where it is condensed to water. The liberated heat is then transferred to a cooling medium, usually water. Finally, the condensed steam is reintroduced into the boiler by a pump.

Steam electric power plants can be fired by fossil fuels (i.e., coal, natural gas, and oil) and by nuclear energy. The conversion efficiency of a new steam-boiler generator can be 35% (Energy Information Administration 1991d). Usually, No. 6 residual fuel oil is used for firing steam boilers in oil-fired power plants.

#### 4.2.15.1.2 Combustion (Gas) Turbine Technology

In combustion turbine power plants (simple cycle), fuel 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 schemes are used to increase overall efficiency. Combustion turbines require little or no cooling water and, therefore, produce no significant effluent. Gas turbines are presently used for peaking capacity with distillate fuel oils, although residual oils can also be used.

#### 4.2.15.1.3 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. 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 as high as 45% (Energy Information Administration 1991d). The technology is believed to generate less environmental pollution than conventional combustion technologies primarily due to the high efficiency of the combined cycle system.

The recovery of waste heat from the combustion turbine exhaust is usually accomplished by heat recovery steam generators (HRSGs). HRSG system designs include unfired, supplementary-fired, and fully-fired heat recovery boilers. Unfired 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 unfired 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 unfired HRSG production rate.

### 4.2.15.2 Environmental Pollution

#### 4.2.15.2.1 Air Emissions

Oil-fired power plants produce emissions of HC, CO, $NO_x$, $SO_x$, PM, and $CO_2$. The amount of PM emissions is dependent on the level of mineral matter in the fuel oil. $NO_x$ emissions come from the oxidation of fuel-bound nitrogen and the thermal fixation of the nitrogen in combustion air. Fuel $NO_x$ is primarily a function of the nitrogen content of the fuel and the available oxygen. Thermal $NO_x$ is largely a function of the peak flame temperature and the available oxygen. Generally, oil boilers produce more fuel $NO_x$ than thermal $NO_x$.

Small amounts of HC and CO are emitted from burning residual fuel oil for steam boilers. Organic compounds present in the flue-gas streams include aliphatic and aromatic hydrocarbons, esters, ethers, alcohols, carbonyls, carboxylic acid, and polycyclic organic matter.

Heavy metals such as arsenic, cadmium, lead, mercury, nickel, manganese, chromium, copper, and vanadium are present in flue gases.

#### 4.2.15.2.2 Water Pollution

Water pollutants include BOD, COD, TSS, TDS (total dissolved solids), oil and grease, chlorine, zinc, copper, and iron. Water quality is also reflected by pH and heat of the wastewater.

A large amount of water is used as cooling water for electric generation. The massive volume of cooling water carries away the heat rejected in the generation of electric power-heat. The rejected heat is dissipated in part by evaporation at a rate dependent upon the cooling facility employed. The methods most commonly used for cooling steam-electric thermal discharges are once-through cooling, evaporative cooling towers, and recirculating cooling ponds (Huston 1975).

Water pollution regulations for steam electric power plants require the use of best practicable technology currently available (BPTCA) and best available technology currently achievable (BATCA) and require new source performance standards, pretreatment standards for existing sources, and pretreatment standards for new sources to be met.

#### 4.2.15.2.3 Solid Wastes

The ash from oil-fired plants is usually in the form of fly ash. Vanadium, sodium, and sulfur may appear in the ash. Sludge is generated from wet scrubbers and spray dryer systems, both for $SO_x$ control. Ash is generated from PM emission control systems. Disposal of ash may be a problem due to trace elements associated with the ash. The solid wastes generated from power plants are not classified as hazardous wastes and, therefore, are not subject to EPA's hazardous waste regulations. The solid waste generated from oil-fired power plants can be disposed of in landfills or on-site.

### 4.2.16 Electricity Transmission

Electricity generated from the two oil-fired power plants is distributed to users through an electric transmission and distribution system. Usually, electricity generated from a power plant is transmitted to an electric grid system through which electricity is distributed to end-users.

Transmission lines need to be built in order to transmit electricity from our two specific oil-fired power plants to regional electric grid systems. A major environmental impact of electric transmission lines is their disturbance of wildlife and the possible adverse health impact of high levels of radiation near transmission lines. Air emissions, water pollutants, and solid wastes associated with building and operating the electric transmission systems are negligible.

## 4.3 REGIONAL REFERENCE ENVIRONMENT AND SCENARIO DESCRIPTION

### 4.3.1 Introduction

This section delineates the locations of the oil-fired plants and the related sites for crude oil production and refineries, and describes the sites in terms of their baseline socioeconomic and environmental characteristics. Two sites were chosen as regional reference environments for the oil 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 in the Southeastern United States and the other in the Southwest.

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.

### 4.3.2 Reference Plant, Oil Production, and Refinery Sites

The site of the oil-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 oil 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 4.3-1 is a map showing the locations of these two reference sites in the United States. As discussed thoroughly in the ORNL/RFF (1994b), these sites are used solely for illustrative purposes. Sites elsewhere in the country could be used, such as in the Northest U. S., but they would not necessarily be representative of all plausible sites even within the Northeast region.[2]

The crude oil for the Southeast Reference site in 1990 was assumed to be produced by wells in a field in southeastern Texas. For the 2010 scenario, oil was assumed to come from wells approximately 50 kilometers offshore in the Texas Gulf coast. For both scenarios, the oil refinery is assumed to be in the metropolitan Houston area, in Harris County, a likely location where oil produced inland would be refined.

The residual oil is assumed to be barged from the refinery to the power plant site. The proposed route would follow the Gulf Coast Intracostal Waterway from Houston, Texas, to Mobile, Alabama. The Tennessee-Tombigbee Waterway would be taken from Mobile to the Tennessee River. The barges would travel the Tennessee River to the Clinch River and along the Clinch River to the plant site. The total distance is about 1,320 miles.

The crude oil for the Southwest Reference site was assumed to be produced by wells in an approximately 3,000 square mile rectangle bounded by the cities of Artesia, Lovington, Hobbs, and Carlsbad in southwest New Mexico. This area encompasses portions of Eddy and Lea Counties. The refinery site for the Southeast Reference environment is in Eddy County, southeastern New Mexico, which is the closest refinery.

The refined oil would travel by highway tank trucks from the refinery to the power plant site. This is a distance of approximately 450 miles. However, since this is an unrealistic distance for petroleum products to be shipped by truck, the calculations of truck-related damages in later chapters are arbitrarily scaled down to a 30 mile (one-way) distance - the same distance as the Southeast case in the coal fuel cycle study (ORNL/RFF 1994b).

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[2] Different externality issues can arise at different sites.

Fig. 4.3-1 Locations of the Southeast and Southwest Reference sites.

### 4.3.3 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 the Y-12 plant site in Oak Ridge, TN were available in specified distance intervals in 16 directions. These population figures were used as a proxy for the Southeast Reference site, which is less than ten miles from the Y-12 plant. These are 1989 data that were projected from 1980 U.S. Bureau of the Census data.[3] The total number of people within 50 miles of the plant was 943,037. Tables 4.3-1 and 4.3-2 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.

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,*

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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 not be included until this report is revised.

## Table 4.3-1 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 | 21,080 | 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 4.3-2 Cumulative 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 | 205 | 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 |

*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 10.16 in this report) for the Southeast Reference site are shown in Table 4.3-3. 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 4.3-3. 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 CRBR EIS 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 NMGS EIS, 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 Agency, 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 CRBR 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.

### 4.3.4 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. There are water quality technical reports that were prepared for both the Southeast Reference site and 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.

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 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 4.3-2. 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 UT-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.

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 in the Coal Document (ORNL/RFF 1994b, Sect. 10.15). An emissions inventory for the southwest was not obtained [refer to Section 6 of the ozone modeling in ORNL/RFF (1994a)].

### 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.

## 4.4 REFERENCE TECHNOLOGIES

### 4.4.1 Assumptions on Site Selection

### 4.4.1.1 Sites of Electricity Generation and Crude Oil Production

Two power plant sites have been selected for the external cost project by DOE and the ORNL research team: one in East Tennessee and another near Farmington, New Mexico (these two sites were discussed in section 4.3). We assume that No. 6 residual oil would be used in base-load power plants, because it is cheaper than any other petroleum-based fuel. We further assume that the No. 6 residual oil used in these proposed power plants would be produced domestically. Although some of the residual oil consumed in the U.S. is imported, we do not consider imported residual oil in this study. Considering available crude-producing sites and transportation distance and facilities for residual oil, for the East Tennessee oil-fired power plant, we assume that crude oil will be produced and refined in Southeast Texas. For the Northwest New Mexico oil-fired power plant, we assume that crude oil will be produced and refined in Southeast New Mexico.

In our study, we have established two target years: 1990 and 2010. We have established different assumptions regarding crude production for these two years. We assume that in 1990 the crude for the East Tennessee power plant would have been produced onshore in Southeast Texas since about 234 thousand barrels of crude per day were produced that year in Southeast Texas (Texas Railroad Commission, 1991). We assume that the crude for the Northwest New Mexico plant would have been produced in Southeast New Mexico since more than

90% of the crude produced in New Mexico is produced in the Southeast New Mexico Basin (New Mexico Energy and Minerals Department, 1992).

The environmental pollution of offshore oil production is considerably different from that of onshore oil production. In 1990, offshore oil production was 0.9 million barrels per day, or about 12% of the total U.S. crude production (EIA 1991b). The share of offshore oil production will be very likely to increase mainly due to continuous decreases in onshore domestic oil production. Currently, most U.S. offshore crude production takes place in the Gulf of Mexico. We assume that in 2010 the crude supplied to a refinery near Houston would be produced offshore in the Gulf of Mexico and would be transported to the refinery through under-ocean pipelines. We assume that in 2010 the crude supplied to the Southeast New Mexico refinery would be produced in the Southeast New Mexico Basin.

#### 4.4.1.2 Crude Refining Sites

Although crude refineries are located all over the U.S., more than half of the U.S. refining capacity is concentrated in three states: Texas, Louisiana, and California. Major refining centers are located along the Texas-Louisiana coast, the California coast, and New Jersey harbor because these sites can be accessed easily by marine vessels (see Fig. 4.4-1 for a regional distribution of the U.S. refining capacity). As of January 1, 1990, 108 refining companies owned 205 operable refineries in the U.S. These refineries had atmospheric crude distillation capacities ranging from 1,000 to over 400,000 barrels per day and had a combined atmospheric crude distillation capacity of 15.6 million barrels per day (EIA, 1991b).

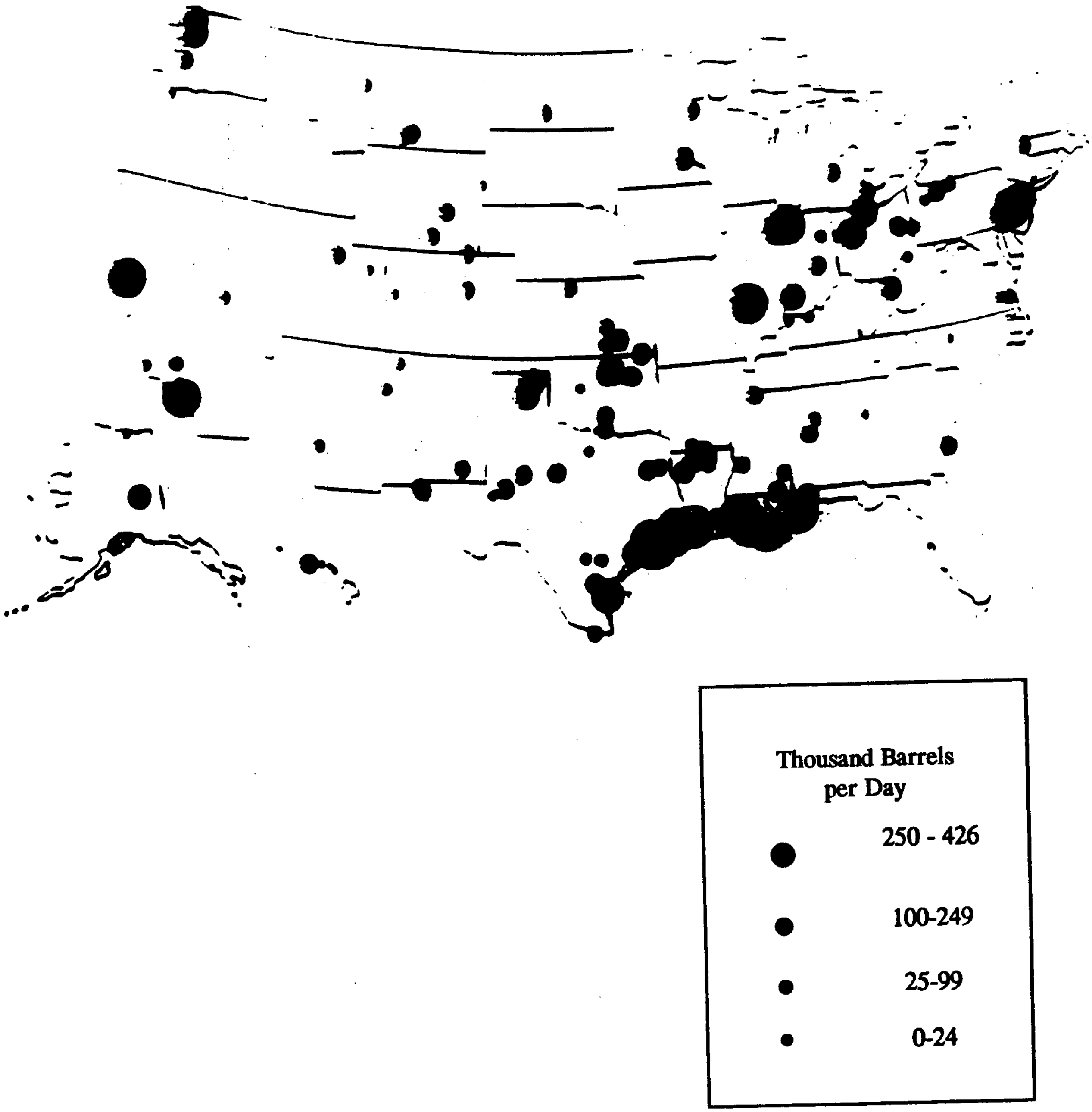

**Fig. 4.4-1.** U.S. refinery atmospheric distillation capacity as of January 1, 1990 (EIA, 1991b).

Since the Gulf Coast region is a net exporter of residual oil, and since the region is not far away from the East Tennessee power plant site, the East Tennessee power plant would be likely to receive residual oil from the Gulf Coast region. Therefore, we assume that the residual oil supplied to the East Tennessee power plant would come from the Gulf Coast region.

Refineries are designed to produce a mix of various products so that feedstocks can be utilized economically. To respond to the change in demand for certain products, the mix of products in a refinery can be changed to some degree by changing the type of crude feedstock used and the refining processes employed. Historically, the share of residual oil produced by refineries has decreased because high crude prices drive refiners to produce high-quality fuels, such as gasoline, to make a profit. To increase the production of high-quality fuels, the design of refineries has become increasingly complex. Currently, residual oil production accounts for about 7% of total refinery production (Wang 1992).

Technically speaking, a refinery with fewer refining processes (e.g., mainly distillation processes and some down-stream finishing processes) can be built to produce residual oil. Such a refinery would have a high output percentage of residual oil and a low output percentage of other high-quality fuels. This type of refinery, dedicated to residual oil production, could be built to provide residual oil for the two oil-fired power plants. However, no one may want to build such a refinery because it would make only a small profit, if any, since the price a refiner pays for crude is greater than the price for which it can sell residual oil. (For example, refiners now pay about $20 per barrel for crude, but they can only sell No. 6 residual oil for about $10-$11 per barrel). For this reason, we do not believe that a residual-oil-dedicated refinery would ever be built.

Instead, we assume that the two power plants would obtain residual oil from existing refineries. If there were an increase in the demand for residual oil, existing refineries could increase residual oil production, to a small degree, to meet the increase in demand. The addition of one or two oil-fired power plants would change the demand for residual oil in the U.S. market by a small percentage. We believe that existing refineries would change their product slates (or product mixes) very little to accommodate the residual oil demand increase due to the addition of the two oil-fired power plants proposed in this study. For our analysis, we assume the selected refinery would not change its product slate to provide residual oil to one of these two power plants.

We have selected a refinery east of Houston, Texas, within its metropolitan area, as the source of residual oil for the East Tennessee power plant. This refinery has an atmospheric distillation capacity of 215,900 barrels per day.

Assuming a 7% residual oil production share, the plant produces roughly 15,100 barrels of residual oil per day. The actual residual oil production from this refinery can range from 20,000 to 30,000 barrels per day (Personal communication with W. Brown 1992). We have selected this refinery for two reasons. First, the refinery has the capacity to produce more than enough residual oil for the East Tennessee power plant. Second, the plant is located in a metropolitan area. This enables us to estimate the environmental impacts of refining crude oil in a densely-populated area.

We have selected a refinery located in Southeast New Mexico to provide residual oil to the power plant located in Eddy County, New Mexico. This refinery has an atmospheric distillation capacity of 60,000 barrels per day. Assuming a 7% residual oil production share, the refinery can produce about 4,200 barrels of residual oil per day. The actual production capacity of residual oil in this refinery is about 5,000 barrels per day (personal communication with D. Blair 1992). In contrast to the refinery near Houston, the New Mexico refinery is located in an area that is less densely populated. Two small refineries are located in Northwest New Mexico, but the capacity of these refineries is inadequate to provide enough residual oil for the Northwest New Mexico power plant.

We assume that crude is transported from nearby oil production fields to the two refineries through small pipelines or by tank trucks.

### 4.4.2 Transportation of Residual Oil

Residual oil is too viscous to be transported through pipelines without extra handling activities. We assume that residual oil would be transported by river barges from the Houston refinery to the Clinch River power plant. The proposed barge route would run along the Gulf Coast Intracoastal Waterway from Houston, Texas, to Mobile, Alabama. From Mobile, the barges would travel through the Tennessee-Tombigbee waterway to its intersection with the Tennessee River. The barges would then travel up the Tennessee River to the Clinch River site. The total distance of this route is about 1,320 miles.

The only transportation mode available for moving residual oil from the New Mexico refinery site to the Farmington plant site is highway tank trucks. No railroad passes through the Farmington area. Thus, we assume that residual oil would be transported by tank trucks to the Farmington power plant. The highway distance from the Southeastern New Mexico refinery to the Farmington plant is about 450 miles. In reality, such long-distance truck transportation is highly unlikely, but it is the only means under the assumed scenario. For the purposes of illustrating the methods for estimating truck traffic-related damages, we use the

450 mile distance, but we scale the results down to a more realistic 30 mile distance.

### 4.4.3 Scale of Power Plants

It has been assumed in the external cost project that the power plants proposed for different fuel cycles serve as base-load facilities. Table 4.4-1 shows the generating capacities of some existing oil-fired power plants. The rated capacity of these oil-fired power plants ranges from 90 MW to 2,600 MW. Considering the amount of residual oil needed for a particular plant and the transportation capacity of moving residual oil to the two power plants, we assume a capacity of 300 MW for each power plant. Base-load power plants may be larger than our proposed 300 MW plants. However, the fuel cost of oil-fired plants would be a major cost component. For a large oil-fired plant, the transportation cost of residual oil and the storage capacity of residual oil in the two power plants would be likely to increase dramatically. Therefore, we assume that a relatively smaller oil-fired power plant with a 300 MW capacity would operate as a base-load facility.

### 4.4.4 Oil-Fired Power Plant Technology

We assume that No. 6 residual oil would be used to generate electricity for the base-load oil-fired power plants, mainly because No. 6 residual oil is the cheapest petroleum fuel for power plants. Steam boiler technology is mostly used to fire No. 6 residual oil in power plants. We assume that in both 1990 and 2010 the oil-fired power plants at the two sites would have been equipped with steam boiler technology (it is conceivable that an oil-gasification turbine system would be used for the electric power plant in 2010, however this option was not selected since emissions data were not available):

Steam Boiler Technology. Steam boiler technology for generating electricity employs the use of boilers to generate steam and use of generators to generate electricity from steam. There are four stages involved in the generating unit of steam-boiler electric power plants: fossil fuel combustion in furnaces, turbine and generator rotation driven by steam, steam condensation, and the injection of condensed steam into the boiler. In the first stage, fossil fuel is burned in a boiler furnace. The evolving heat is used to produce pressurized, superheated steam. This steam is conveyed to the second stage, the turbine, where it gives energy to rotating blades and, in the process, loses pressure and increases in volume. The rotating blades of the turbine drive the electric generator or alternator which converts the imparted mechanical energy into electrical energy. The steam leaving the turbine enters the third stage, the condenser, where it is condensed to water. The liberated heat is then transferred to a cooling medium, usually water. Finally, the condensed steam is reintroduced into the boiler by a pump. Steam electric power plants can be fired by fossil fuels (i.e., coal, natural gas, and oil) and by nuclear energy. Usually, No. 6 residual oil is used for firing steam boilers in oil-fired power plants.

Gas Turbine Technology Using Residual Oil. Advanced combined-cycle gas turbines with different steam injection designs have conversion efficiencies as high as 45%. (In comparison, the conversion efficiency of steam boilers is about 35%.) Currently, virtually all gas turbines are fired with natural gas or distillate fuels. Gas turbines fired with residual oil or crude have been designed and built in the past. Currently, there are some gas turbine units fired with residual oil or crude around the world and a few in the U.S. (Dye 1992). The use of low-quality fuels such as residual oil or crude for gas turbines helps reduce the fuel cost of operating gas turbine units.

Two major gas turbine designs use residual oil: direct-firing and gasification. The direct-firing design employs the combustion of residual oil to generate gases feeding to turbines. With this design, residual oil needs to be preheated for proper atomization in the combustion chamber.

Residual oil contains ash-forming contaminants such as vanadium, sodium, potassium, and calcium. With the direct-firing gas turbine design, these contaminants can cause hot corrosion of blade and vane alloys and/or fouling deposits in the gas turbine hot gas path. During combustion, vanadium contained in residual oil forms a very corrosive oxide which is in liquid form at turbine operating temperature. To prevent the corrosion, magnesium can be added to the vanadium to form a dry non-corrosive ash. The ash deposits that accumulate in the turbine blades need to be removed periodically. Intermittent turbine cleaning such as water washing is used to remove the deposits. Low-combustion-temperature turbines with large external combustors may be used for burning residual oil because some ash constituents become sticky at high combustion temperatures, resulting in increased turbine maintenance and cleaning tasks.

Pretreatment of residual oil is needed to remove vanadium, sodium, potassium, and calcium for direct-firing turbine units. The vanadium content of heavy residual oil may be as high as 300-500 ppm. During residual oil treatment, vanadium may be inhibited in an inhibitor by adding magnesium or other additives. Solids in residual oil may be removed by a filtration system. Sodium and potassium may be removed by fuel washing systems such as electrostatic precipitation vessels or centrifugal units. The fuel washing system generates effluent discharges containing oil/water emulsion and free oil.

## Table 4.4-1 Rated capacity of typical existing oil-fired power plants in the U.S. (EIA, 1991c, 1991e)

| Plant Name | Company | Oil Consumed (1,000 bbl) | Rated Capacity (MW) | No. of Units | First Yr. of Operation[a] | Designed Fuel Type[b] |
|---|---|---|---|---|---|---|
| Canal, MA | Canal Electric Co. | 8,841 | 1,072 | 2 | '68, '75 | F6 |
| Rosenton, NY | Central Hudson G&E Co. | 10,252 | 1,242 | 2 | '74 | F6 |
| Wyman, ME | Central Maine Power Co. | 3,666 | 848 | 4 | '57, '58, '65, '78 | F6 |
| Collins, IL | Commonwealth Edison Co. | 1,464 | 2,648 | 5 | '78-'79 | F6 |
| Devon, CT | CT. Light & Power Co. | 2,317 | 428 | 7 | '42-'58 | F6 |
| Norwalk, CT | CT. Light & Power Co. | 2,621 | 342 | 3 | '60-'63 | F2, F6 |
| Middletown, CT | CT. Light & Power Co. | 2,801 | 856 | 5 | '54-'73 | F6, JF |
| Hudson Ave., NY | Consolidated Edison Co.-NY Inc. | 4,174 | 158 | 6 | '51-'70 | KER, F2, F6 |
| Fort Myers, FL | Florida Power & Light Co. | 4,070 | 1,302 | 14 | '58-'74 | F2, F6 |
| Manatte, FL | Florida Power & Light Co. | 7,378 | 1,726 | 2 | '77-'76 | F6 |
| Northport, NY | Long Island Lighting Co. | 11,506 | 1,564 | 5 | '67-'77 | F2, F6 |
| Port Jefferson, NY | Long Island Lighting Co. | 3,364 | 482 | 5 | '48-'66 | F2, F6 |
| Oswego, NY | Niagara Mohawk Power Corp. | 9,399 | 2,180 | 9 | '40-'80 | F2, F6 |
| Newington, NH | Power Service Co. of NH | 4,068 | 414 | 1 | '74 | F6 |
| Linden, NJ | Public Service E&G Co. | 1,069 | 927 | 9 | '57-'73 | MIXED |
| 59th Street, NY | Consolidated Edison Co.-NY Inc. | 100 | 91 | 4 | '62-'69 | KER, F6 |
| Vienna, MD | Delmarva Power & Light Co. | 439 | 180 | 2 | '68-'71 | F2, F6 |
| Greenwood, MI | Detroit Edison Co. | 352 | 815 | 1 | '79 | F6 |
| Higgins, FL | Florida Power Corp. | 420 | 291 | 7 | '53-'71 | F2, F6 |
| Werner, NJ | Jersey Central Power & Light Co. | 75 | 272 | 5 | '53-'72 | F2, F6 |
| Delaware, PA | Philadelphia Electric Co. | 709 | 391 | 7 | '53-'69 | F2, F6, BIT |
| Schuylkill, PA | Philadelphia Electric Co. | 613 | 233 | 4 | '58-'71 | F2, F6 |
| Benning, DC | Potoma Electric Power Co. | 771 | 580 | 2 | '68-'72 | F4 |
| Burlington, NJ | Public Service E&G Co. | 242 | 725 | 5 | '55-'72 | KER, F6 |
| Kearny, NJ | Public Service E&G Co. | 174 | 830 | 6 | '67-'73 | F6, KER, NG |
| Hookers Point, FL | Tampa Electric Co. | 206 | 233 | 5 | '48-'55 | F6 |

[a] Different generating units in a plant could start to operate in different years, because some generating units were added to the plant later.

[b] F2 = No. 2 fuel oil, F4 = No. 4 fuel oil, F6 = No. 6 fuel oil, JF = jet fuel, KER = kerosene, BIT = bituminous coal, and NG = natural gas.

The gasification gas turbines gasify residual oil first, then the produced oil gases are fed into a gas turbine. The gasification design allows the use of very low-quality residual oils. Shell and Texaco have designed and built residual oil gasification units since the 1950s. The Texaco gasification process is based on the partial oxidation of hydrocarbons to produce a mixture of hydrogen and carbon monoxide called synthesis gas (Quintana 1990). The synthesis gas is then fed into the gas turbine system to generate electricity (Fig. 4.4-2). Gasification of high-sulfur residual oils produces a syngas containing essentially all the sulfur in the form of $H_2S$. $H_2S$ can be recovered as elemental sulfur through sulfur recovery methods. Thus, $SO_X$ emissions from gasification gas turbines can be reduced substantially.

### 4.4.5 The Total Amount of Residual Oil Needed for the Two Power Plants

A capacity of 300 MW has been proposed for each of the two oil-fired power plants. Assuming an 80% capacity factor for these power plants, each plant would generate $57.6*10^5$ kWh per day, or $21.02*10^8$ kWh per year. Assuming a conversion efficiency of 35% for oil-fired power plants, about 8,940 barrels of residual oils would be needed daily for each power plant (assuming 3,412 Btu/kWh and 6.28 million Btu/bbl residual oil [EIA 1991d]). This translates into about 3.26 million barrels of residual oil per year for each of the two plants.

Residual oil would be transported from Houston to Knoxville through the Tennessee-Tombigbee waterway by barge. There are about ten locks along the waterway. These locks limit the size of barges going through the waterway. We assume that barges capable of carrying 70,000 barrels of residual oil would be used. Barges of this size can go through the waterway without problems (as a comparison, some ocean barges may have a capacity of as much as 500,000 barrels). Assuming a capacity of 70,000 barrels per barge, the 300 MW plant at the Clinch River site would require a barge of residual oil every 7.8 days.

We assume that residual oil would be transported from Southeast New Mexico to the Farmington site by tank trucks. Truck sizes are regulated by individual states. In New Mexico, a typical tank truck has a capacity of 200 barrels. To accommodate the daily demand of 8,940 barrels of residual oil, about 45 tank trucks of residual oil per day would be required.

Assuming a 7% residual oil production share, the refinery near Houston can produce about 15,100 barrels of residual oil per day. The refinery actually has the capacity to produce 20,000-30,000 barrels of residual oil per day and, therefore, could meet the Clinch River plant's demand of

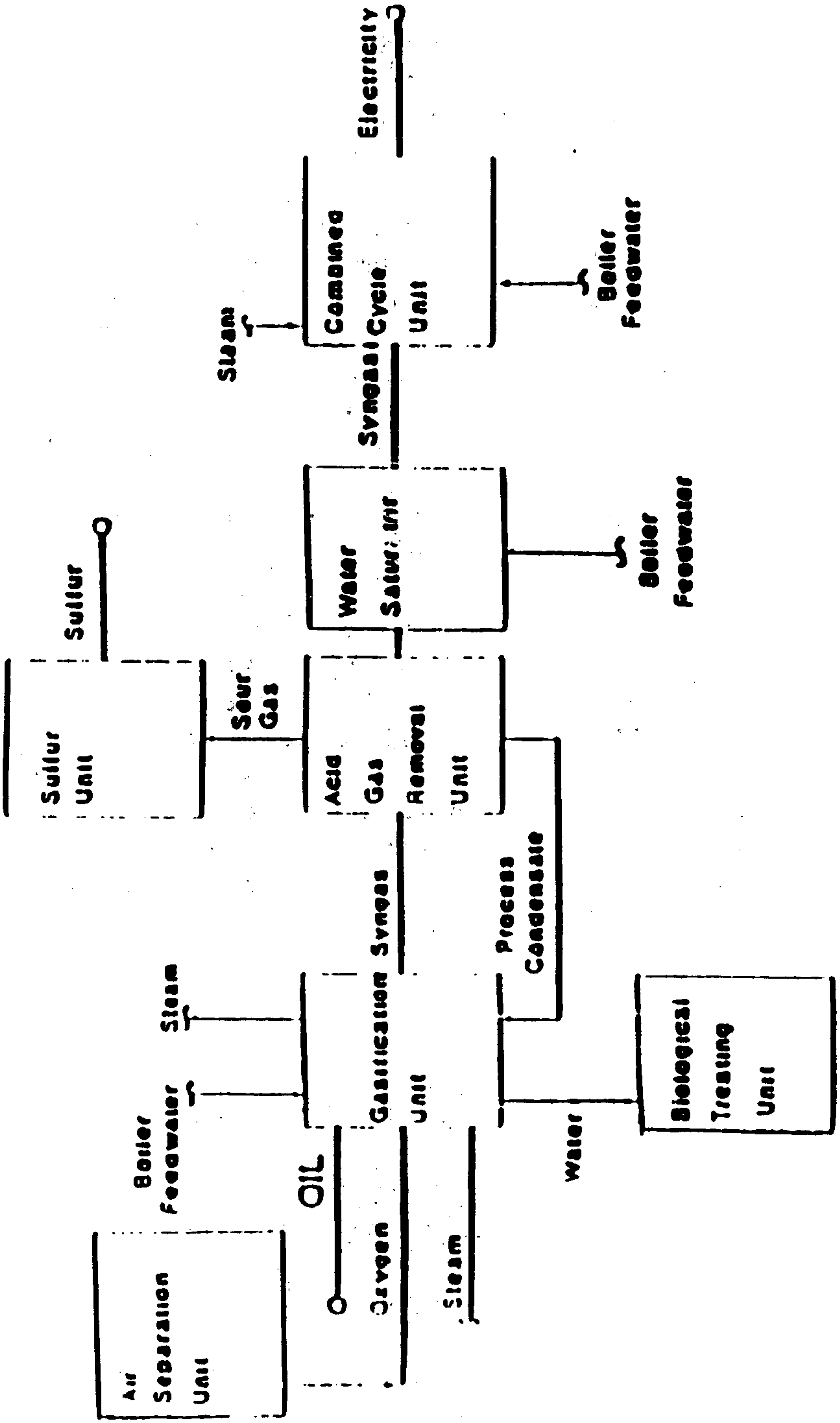

Fig. 4.4-2. Combined-cycle gas turbine with residual oil gasification: simplified flow diagram (Quintana, 1990)

8,940 barrels per day. However, the residual oil currently produced in the southeast Texas refinery has a sulfur content above 3% (personal communication with W. Brown 1992) (problems related to the sulfur content of the residual oil from southeast Texas will be addressed in a later section of this report).

The southeast New Mexico refinery can produce about 4,200 barrels of residual oil per day, assuming that 7% of the production share is allotted to residual oil. The plant has actual production capacity of 5,000 barrels per day of residual oil (personal communication with D. Blair 1992). To meet the Farmington plants demand of 8,940 barrels per day, two refineries the size of the New Mexico refinery would be needed. We assume that these refineries would be located next to each other at the New Mexico refinery site. We assume that these two identical refineries would be located next to each other in order to simplify the analysis of health and ecological impacts of residual oil production. The sulfur content of the residual oil produced in the refinery is about 3.5%.

We assume production of one ton of residual oil requires one ton of crude, simply because of the law of mass conservation. The mass density of domestically produced crude is about 295 lbs/bbl; the mass density of residual fuel oil is about 331 lbs/bbl (API 1991b). Therefore, the 8,940 bbl/day residual oil demand of the power plant translates into a 10,030 bbl/day crude demand. Table 4.4-2 shows crude production per well in New Mexico and Texas. Assuming that wells producing more than 10 bbl/day would produce crude for the two power plants, we estimate that about 241 producing wells would be needed in New Mexico to produce 10,030 barrels of crude per day and that about 449 producing wells would be needed in Texas.

**Table 4.4-2 Crude production per well per day during 1990 (based on data in API, 1991b)**

| | New Mexico | Texas |
|---|---|---|
| **Total Production (bbl/day)** | | |
| All wells | 184,240 | 1,924,000 |
| Stripper wells[a] | 39,167 | 372,189 |
| Regular wells[b] | 145,073 | 1,551,811 |
| **Total Number of Producing Wells** | | |
| All wells | 18,546 | 188,829 |
| Stripper wells | 15,050 | 119,693 |
| Regular wells | 3,496 | 69,136 |
| **Crude Production per Well (bbl/day)** | | |
| All wells | 9.9 | 10.2 |
| Stripper wells | 2.6 | 3.1 |
| Regular wells | 41.5 | 22.4 |

[a] Stripper wells are wells with daily crude production equal to or below 10 barrels.

[b] Regular wells are defined here as wells with daily production above 10 barrels.

# 5. OIL-TO-ELECTRICITY WASTES AND EMISSIONS

This section presents the main activities and emissions from the major stages of the fuel cycle -- extraction, refining, transport, and generation of electricity. Emissions are calculated for each reference site and time period. The section is organized into nine subsections. Each subsection includes a discussion of the wastes and emissions of each significant oil-to-electricity activity and its impact. The priority impact-pathways are summarized in Section 6 and are analyzed in Sections 7 to 10.

## 5.1 WASTES FROM OIL WELL DRILLING, EXTRACTION, AND TREATMENT IN OIL FIELDS

### 5.1.1 Waste Sources

Oil well drilling, oil extraction, and oil treatment in oil 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 ground water) 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, oil extraction, and oil treatment are oil and grease, 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 the 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 field. Generally, the amount of produced water increases as an oil reserve is depleted. Therefore, the ratio of produced water to extracted oil 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 of.

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 5.1-1 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 vise versa carries 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 adheres to the cuttings. Adhered drilling mud can account for as much as 40-60% (by weight) of drill cuttings (EPA, 1991a).

**Table 5.1-1. 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 | 1,588 |
| 3,000-8,000 | 27 | 1,350 | 1,757 |
| 8,000-16,000 | 61 | 3,050 | 1,733 |
| 16,000-20,000 | 30 | 1,900 | 361 |
| **Total** | **135** | **15,000** | **6,739** |

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 barrels of oil produced (EPA, 1976). On shore, these solid wastes are eventually disposed of in landfills, by landspread, by roadspread, or by pit burial.

In estimating the wastes generated during oil 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 oil 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.

## 5.1.2 The Amount of Wastewaters

### 5.1.2.1 Offshore Drilling

In 1990, about 93% of all offshore oil 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 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. 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, and the amount of produced water increases with the age of an oil well. We do not have site-specific information on the amount of produced water. We use the average of produced water to serve the target-year analysis that is conducted for the oil-cycle project. A static approach is used (oil well performance in a given year is used) rather than a dynamic approach (oil well performance during the lifetime of the well). With the static approach, it is more representative to use the life-time average of produced water rather than the amount of produced water from new wells or add wells. Therefore, we assume that the amount of produced water from an oil well is the same as the amount of oil produced from the oil well.

EIA assumes that a 12- or 18-well platform has a maximum crude production of 11,000 barrels per day (EIA, 1990a). This means that each well produces a maximum average of about 733 barrels of crude per day. We assume that 600 barrels of crude is produced daily by each offshore well. Assuming that produced water accounts for half of the extracted mixture, we estimate that 600 barrels of produced water is produced daily by each offshore 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 four (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 oil formations are to be depleted, we do not have any information on the amount of wastewaters from offshore production for 2010.

An oil well produces natural gas in association with oil. In the U.S., about 20% of all gas produced is in the form of so-called associated gas (EIA, 1991b). The above results of waste production are attributable to the production of both oil and associated gas. Thus, produced waste amounts need to be allocated between oil and associated gas. We use the shares of oil production and gas production from oil-producing wells to divide the wastes between the two products. In 1990, about $17.51 \times 10^{12}$ 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 $3.503 \times 10^{12}$ cubic feet. Using a 1,031 Btu/ft$^3$ energy content for natural gas (EIA, 1991d), this represents $3.61 \times 10^{15}$ Btu of natural gas.

In 1990, $2.665 \times 10^9$ barrels of crude were produced in the U.S. Assuming the energy content of 5.8 million Btu/bbl of domestically produced crude (EIA, 1991d), this amount translates into $15.457 \times 10^{15}$ Btu of crude. These results show that a total of $19.067 \times 10^{15}$ Btu of energy ($3.61 \times 10^{15}$ Btu in natural gas and $15.457 \times 10^{15}$ Btu in crude) were produced from oil-producing wells in 1990. Therefore, crude production accounted for 81.06% of all energy produced from oil-producing wells. Consequently, we allocate 81.06% of the total waste produced to crude production. We summarize the calculated wastes due to crude production in Table 5.1-2.

### 5.1.2.2 Onshore Oil 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 5.1-3 presents drilling waste volumes for two states: New Mexico and Texas.

As shown in Table 5.1-4, EPA's estimated waste volume can be ten times as high as API's estimated volume. Due to the inherent limitation of EPA's method, we believe that EPA's method over estimates waste volumes. Thus, we use API's estimated waste volumes.[1]

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[1] Preference of API's estimate over EPA's estimate in this section was based on the fact that EPA's estimate was calculated from total available volume of reserve pits in production sites, while API's estimate was based on an actual survey on total drilling wastes. See footnotes of Table 5.1-3 for details.

The Amount of Produced Water. An EPA study assumed 8.42 barrels of produced water per barrel of crude produced for the Gulf region and 7.31 barrels of produced water per barrel of crude for the southern mountain region, which includes New Mexico (EPA, 1987a). For our 1990 case, we assume 8.42 barrels of produced water per barrel of crude produced for the Gulf Coast region and 7.31 barrels of produced water per barrel of crude for New Mexico. For the 2010 case, the amount of produced water per barrel of crude will certainly increase, mainly due to the depletion of oil reservoirs in these regions. We have no information for 2010. We assume that the amount of produced water per barrel of crude for 2010 to be the same as that for 1990. We allocate 81.06% of the total waste water production to crude production (for detailed discussion of this percentage allocation, see section 5.1.2.1).

**Table 5.1-2. Wastes generated during offshore crude production**

| | Total Wastes | Wastes Due to Crude Production[a] |
|---|---|---|
| Drilling muds (bbl/well) | 6,926 | 5,614 |
| Drill cuttings (bbl/well) | 1,471 | 1,192 |
| Produced water (bbl/bbl of product) | 1 | 0.8106 |

[a] We allocate 81.06% of the total wastes to the wastes due to crude production. See section 5.1.2.1 for discussion.

**Table 5.1-3. Estimated drilling waste volumes produced during 1985 (EPA, 1987a)**

| State | Drilling Waste Volume (bbl/well) | |
|---|---|---|
| | EPA Method[a] | API Method[b] |
| New Mexico | 18,677 | 7,813 |
| Texas | 54,970 | 5,562 |

[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.

**Table 5.1-4. Onshore wastes of crude production**

| Type of Waste | State | Total Waste | Waste Due to Crude Production[a] |
|---|---|---|---|
| Drilling Waste (bbl/well) | New Mexico | 7,813 | 6,332 |
| | Texas | 5,562 | 4,509 |
| Produced Water (bbl produced water/bbl of product) | New Mexico | 7.31 | 5.93 |
| | Texas | 8.42 | 6.83 |

[a] We allocate 81.06% of the total wastes to crude production. See section 3.1.2.1 for discussion.

## 5.1.3 Concentration of Constituents in Wastewaters

### 5.1.3.1 Produced Water

EPA has estimated the effluent concentrations of offshore produced water based on an analysis of produced waters from thirty platforms. The estimated concentrations are presented in Table 5.1-5.

Since BPT (Best Practicable Technology) 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 (Best Available Technology) 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.

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 5.1-6 presents EPA's estimates.

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 5.1-5. For those constituents not presented in Table 5.1-6, we use the offshore concentrations in our estimation.

#### 5.1.3.2 Drilling Muds

EPA has tested the concentrations of the major constituents of some generic drilling fluids. Table 5.1-7 presents concentration results based on EPA's tests.

### 5.1.4 Total Amount of Constituents in Wastewaters

#### 5.1.4.1 Offshore Oil Production

Produced Water. We use the waste production information in Table 5.1-2 and the concentration information in Table 5.1-5 to calculate the amount of constituents per well drilled. The calculated results are presented in Table 5.1-8.

Drilling Muds. We use the information on drilling muds produced during offshore well drilling in Table 5.1-2 and the constituent concentrations of drilling muds in Table 5.1-7 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 5.1-9.

#### 5.1.4.2 Onshore Oil Production

Produced Water. We use the information on the amount of produced waters in Table 5.1-4 and the information on the constituent concentrations of produced water in Table 5.1-6 to calculate the constituent amounts per barrel of oil produced. The calculated results are presented in Table 5.1-10.

Drilling Muds. We use the information on drilling wastes produced during well drilling from Table 5.1-4 and the information of the constituent concentration information from Table 5.1-7 to calculate the constituent amounts in drilling muds. The calculated results are presented in Table 5.1-11.

### 5.1.5 Waste Management Methods

Wastes generated during oil production are regulated by state and federal agencies (see Appendix A for the regulations of wastes generated during oil production). To meet waste regulations, a wide range of on-site treatment technologies have been developed to treat wastewaters produced from oil 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

## Table 5.1-5. Effluent concentrations of offshore produced waters (EPA, 1991a)

| **Pollutant** | **Concentration (mg/liter)** | |
|---|---|---|
| | **BPT Limit**[a] | **BAT Limit**[b] |
| Oil and Grease | 79.2 | 3.96 |
| Benzene | 0.931 | 0.047 |
| Bis(2-ethylhexyl)phthalate | 0.031 | 0.002 |
| Ethylbenzene | 0.066 | 0.003 |
| Naphthalene | 0.090 | 0.005 |
| Phenol | 0.914 | 0.046 |
| Toluene | 0.693 | 0.035 |
| **Priority Metals** | | |
| Copper | 0.107 | 0.064 |
| Nickel | 0.150 | 0.09 |
| Silver | 0.059 | 0.035 |
| Zinc | 0.133 | 0.001 |

**[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. Cooper 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.**

**Table 5.1-6. Constituent concentration of onshore produced water (EPA, 1987a)**

| Constituent | Concentration (mg/liter) | |
|---|---|---|
| | BPT Limit[a] | BAP 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%.

**Table 5.1-7. Constituent concentrations of drilling fluid[a] (EPA, 1991a)**

| Constituent | Concentration (mg/liter) |
|---|---|
| pH | 9.0 |
| BOD | 643.3 |
| TOC | 4,288.8 |
| COD | 11,376.6 |
| Oil and Grease | 1,518.3 |
| **Metals[b]** | |
| Zinc | 9.009 |
| Beryllium | 0.293 |
| Aluminum | 196.970 |
| Barium | 53.675 |
| Iron | 549.727 |
| Cadmium | 0.530 |
| Chromium | 100.648 |
| Copper | 5.704 |
| Nickel | 1.755 |
| Lead | 5.176 |
| Mercury | 0.090 |
| Silver | 0.004 |
| Arsenic | 1.557 |
| 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.

**Table 5.1-8. The amount of pollutants from offshore produced waters (g/bbl)**

| Pollutant | 1990[a] | 2010[b] |
|---|---|---|
| Oil and Grease | 10.20 | 0.51 |
| Benzene | 0.120 | 0.006 |
| Bis(2-ethylhexyl)phthalate | 0.004 | 0.0002 |
| Ethylbenzene | 0.009 | 0.0004 |
| Naphthalene | 0.012 | 0.0006 |
| Phenol | 0.118 | 0.006 |
| Toluene | 0.089 | 0.004 |
| Copper | 0.013 | 0.008 |
| Nickel | 0.018 | 0.011 |
| Silver | 0.007 | 0.004 |
| Zinc | 0.016 | 0.001 |

[a] We use the constituent concentrations of BPT technology in Table 5.1-5 to calculate 1990 constituent amounts.

[b] We use the constituent concentrations of BAT technology in Table 5.1-5 to calculate 2010 constituent amounts.

Table 5.1-9. Constituent amounts of drilling muds

| Constituent | Amount (kg/well) | GM/BBL of Oil Produced |
|---|---|---|
| pH | 9.0 | 0.9 |
| BOD | 574.23 | 57.3 |
| TOC | 3828.29 | 381.7 |
| COD | 10155.05 | 1012.5 |
| Oil and Grease | 1355.27 | 135.1 |
| Zinc | 8.04 | 0.802 |
| Beryllium | 0.26 | 0.026 |
| Aluminum | 175.82 | 17.5 |
| Barium | 47.91 | 4.78 |
| Iron | 490.70 | 48.9 |
| Cadmium | 0.47 | 0.047 |
| Chromium | 89.84 | 8.96 |
| Copper | 5.09 | 0.507 |
| Nickel | 1.57 | 0.157 |
| Lead | 4.62 | 0.461 |
| Mercury | 0.08 | 0.008 |
| Silver | 0.004 | 0.0004 |
| Arsenic | 1.37 | 0.137 |
| Selenium | 0.78 | 0.078 |
| Antimony | 0.24 | 0.024 |
| Thallium | 0.03 | 0.003 |

(i.e., reinjection of produced water for extracting oil) and the recovery and reuse of drilling fluids.

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.

**Table 5.1-10. Constituent amount of produced water (g/bbl oil produced)**

| | 1990[a] | | 2010[b] | |
|---|---|---|---|---|
| Constituent | New Mexico | Texas | New Mexico | Texas |
| Arsenic | 0.019 | 0.022 | 0.011 | 0.013 |
| Benzene | 0.443 | 0.510 | 0.022 | 0.026 |
| Boron | 9.334 | 10.751 | 5.601 | 6.451 |
| Sodium | 8,862.978 | 10,208.4 | 443.149 | 510.42 |
| Chloride | 6,882.951 | 7,927.8 | 344.148 | 396.39 |
| Mobile Ions | 21,686.01 | 2,478.0 | 108.43 | 124.89 |

[a] We use the constituent concentrations of BPT technology in Table 5.1-6 to calculate 1990 constituent amounts.

[b] We use the constituent concentrations of BAT technology in Table 5.1-6 to calculate 2010 constituent amounts.

Table 5.1-11. The amount of pollutants generated from drilling fluid

| | Amount (kb/well) | | GM/BBL of Oil Produced | |
|---|---|---|---|---|
| Constituent | New Mexico | Texas | New Mexico | Texas |
| pH | 9.0 | 9.0 | 0.897 | 0.897 |
| BOD | 647.80 | 461.25 | 64.6 | 46.0 |
| TOC | 4318.82 | 3075.07 | 430.6 | 306.6 |
| COD | 11456.24 | 8157.02 | 1142.2 | 813.3 |
| Oil and Grease | 1528.93 | 1088.62 | 152.4 | 108.5 |
| Zinc | 9.07 | 6.459 | 0.904 | 0.644 |
| Beryllium | 0.295 | 0.210 | 0.029 | 0.021 |
| Aluminum | 198.4 | 141.2 | 19.8 | 14.1 |
| Barium | 54.1 | 38.3 | 5.39 | 3.82 |
| Iron | 553.6 | 394.2 | 55.2 | 39.3 |
| Cadmium | 0.554 | 0.38 | 0.055 | 0.038 |
| Chromium | 101.35 | 72.165 | 10.10 | 7.19 |
| Copper | 5.744 | 4.09 | 0.573 | 0.408 |
| Nickel | 1.77 | 1.26 | 0.176 | 0.125 |
| Lead | 5.21 | 3.71 | 0.520 | 0.370 |
| Mercury | 0.091 | 0.065 | 0.009 | 0.006 |
| Silver | 0.004 | 0.003 | 0.000 | 0.000 |
| Arsenic | 1.568 | 1.116 | 0.156 | 0.111 |
| Selenium | 0.884 | 0.63 | 0.088 | 0.063 |
| Antimony | 0.276 | 0.196 | 0.028 | 0.020 |
| Thallium | 0.029 | 0.021 | 0.003 | 0.002 |

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.

## 5.2 WATER POLLUTION FROM OIL-FIRED POWER PLANTS

### 5.2.1 Sources of Water Pollution

Wastewaters are generated from oil-fired power plants. Water pollutants contained in wastewaters include BOD, COD, TSS, TDS, oil and grease, chlorine, zinc, copper, iron, pH, and heat. There are many sources of wastewaters in power plants. These sources are discussed below.

Once-Through Cooling System. A once-through cooling system withdraws water from a natural water body (e.g., river, lake, estuary, or ocean). The water comes in contact with the heat exchanger, resulting in heat transfer from the condenser to the water. Subsequently, the water is discharged to the receiving water where the excess heat is dissipated. Because this system requires a large, nearby body of water, and because stringent water pollution regulations are now in affect, once-through cooling systems are no longer commonly used. Pollutants contained in once-through cooling water can be attributed to the corrosion of construction materials and the reaction of elemental chlorine as hydrochloride with organics in the intake water.

Cooling Tower Blowdown. A power plant equipped with recirculating cooling water systems uses cooling towers, either forced draft or natural draft, and recirculates cooling water within the plant. A blowdown stream is typically discharged from the recirculating system to control the buildup of dissolved solids in the cooling water. Moreover, the cooling mechanism, evaporation, results in the discharge of waste heat to the atmosphere.

The evaporation of water from a recirculating cooling water system results in an increase in the dissolved-solids concentration of the water remaining in the system. Thus, the dissolved-solids concentration tends to build up over time. The level of dissolved-solids concentration is reduced by the use of a bleed stream. This process is called cooling water blowdown. A portion of the cooling water in the system is discharged via this stream. The discharged water has a higher dissolved-solids content.

Pollutants in cooling tower blowdown may be the result of chlorination, chemical additives, and corrosion and erosion of the pipes, condensers, and cooling tower materials.

Chemical Metal Cleaning Wastes. Metal cleaning wastes include washwater from the chemical cleaning of boiler tubes, air preheater washwater, and boiler fireside washwater. The waste streams from the cleaning contain boiler metals such as iron and copper. Other waste constituents present in spent chemical cleaning solutions include wide ranges of pH, high dissolved-solids concentrations, and significant chemical and biological oxygen demands.

Fly and Bottom Ash Transport Water. Power plants fired by residual fuel oils generate fly ash in large quantities and may generate some bottom ash. These ashes typically contain heavy metals and must be controlled using dry or wet handling. Wet handling produces a waste stream. Plants which use wet removal methods have an ash water stream system. However, few oil-fired plants have wet handling systems.

Low-Volume Wastes. Low-volume wastes include boiler blowdown, waste streams from water treatment, tank bottoms from oil storage tanks, and effluents from floor and yard drains. Boiler blowdown serves to maintain specified limitations for dissolved and suspended solids in the water used to generate steam in boilers. The impurities in the blowdown system result from the intake water, internal corrosion of the boiler, and chemicals added to the boiler system.

Wet Flue-Gas Cleaning Blowdown. Wet flue-gas cleaning processes such as scrubbers can be divided into nonregenerable processes (throwaway) and regenerable processes. Nonregenerable processes generate a large amount of throwaway sludges. These sludges can be stored in an on-site pond to settle out pollutants. After settling, the water from the pond may be recycled back into the scrubber system.

### 5.2.2 The Amount of Water Pollutants

According to the requirements of the NPDES (National Pollution Discharge Elimination System) and state regulations, the amount of wastewater and water pollutants produced from a particular power plant must be reported to either the EPA or a state agency by the plant operator. Data on effluent discharges from oil-fired power plants can be obtained from EPA's regional offices.

## 5.3 VOC EMISSIONS FROM CRUDE AND RESIDUAL OIL TRANSPORTATION AND STORAGE

Crude and crude products evaporate during storage and transportation due to their volatile nature. In this section, we calculate VOC emissions during the storage and transportation of crude and residual oil.

In estimating VOC evaporative emissions, we include crude storage at refineries, residual oil storage at refineries, residual oil transportation to power plants, and residual oil storage at power plants. We do not include long-distance crude transportation because we assume that crude is produced near the two refining sites. We present the calculated VOC emissions in Table 5.3-1.

Table 5.3-1 indicates that evaporative emissions from crude and residual storage are much greater than evaporative emissions from residual oil transportation. It should be noted that these emissions presented in the table occur at different locations.

## 5.4 OIL SPILLS FROM CRUDE AND RESIDUAL OIL TRANSPORTATION AND STORAGE

Oil spills occur during the transportation and storage of crude and crude products. Strict liability for damage from oil spills and hazardous substance releases is provided under various pieces of environmental legislation, including the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), its recent amendments (i.e., Superfund Amendments and Reauthorization Act [SARA]), the Clean Water Act, and the Outer Continental Shelf Lands Act. Responding primarily to the Exxon Valdez oil spill in Alaska, which resulted in 240,000 barrels of spilled crude, Congress enacted the Oil Pollution Liability and Compensation Act of 1990. The act imposes limited federal liabilities on vessels and facilities for oil spill cleanup and damage repair, allows states to impose unlimited liability, and establishes a federal oil spill cleanup fund.

It is necessary to assess the environmental damages of oil spills in order to impose oil spill liability on spillers. In 1981, the Department of Interior (DOI) was assigned the responsibility for developing the Natural Resource Damage Assessment (NRDA) regulations. The DOI regulations include two types of NRDAs: Type A assessments and Type B assessments (DOI, 1987). Type A assessment procedures are standard procedures for simplified assessments requiring

**Table 5.3-1. VOC emissions during the transportation and storage of crude and residual oil**

| Activity | Emissions ($lb/10^3$ bbl throughput) Farmington Site | Clinch River Site |
|---|---|---|
| Crude Storage at Refineries[a] | 7.48 | 7.48 |
| Residual Oil Storage at Refineries[b] | 11.69 | 27.70 |
| Residual Oil Transportation | | |
| (1) Loading | 0.0084[c] | 0.0014[d] |
| (2) Transit | NA[e] | 0.0011[f] |
| Residual Oil Storage at Power Plants[g] | 4.09 | 11.69 |
| Total[h] | 23.268 | 46.873 |

[a] DeLuchi et al. (1992) have estimated a 149.6 lb/1,000 bbl crude throughput for fixed-roof tanks. We assume that the storage tanks in the two refinery sites are floating-roof tanks with a 95% control effectiveness for evaporative emissions. In 1990, there were 13.406 million barrels of crude fed to U.S. refineries; the total crude storage capacity of U.S. refineries was 171.366 million barrels (EIA, 1991a). Roughly speaking, the crude storage period in refineries is about 12.8 days. The longer the storage time, the more evaporative emissions from storage. The emission rates presented here are for crude stored in refineries for about 12.8 days.

[b] We assume that the evaporative emissions from residual oil storage in lb/bbl-day are the same as those from crude storage. In reality, the evaporative emissions of residual oil may be lower than those of crude, primarily due to the lower volatility of residual oil. However, we do not have any data on residual oil evaporative emissions. In 1990, 1.0247 million barrels of residual oil was produced; the residual oil storage capacity of U.S. refineries was 48.533 million barrels. The residual oil storage period in refineries is about 47.4 days. For the Clinch River site, we use this average storage period for residual oil and the average storage period for crude (12.8 days, see footnote a of this table) to adjust crude storage emissions to residual oil storage emissions for the Houston refinery. For the Farmington site, since tank trucks are used to transport residual oil from the Navajo refinery to the Farmington plant, and since trucks can operate on a more flexible schedule and can travel to and from locations frequently, the residual oil storage capacity of the Navajo can be smaller. We assume a 20-day equivalent storage capacity for the Navajo refinery.

[c] From EPA (1985). We use the emission rate for tank truck loading.

[d] From EPA (1985). We use the emission rate for barge loading.

[e] Not available. The amount is probably minimal due to the short distance (about 450 miles) from the Navajo refinery site to the Farmington site.

[f] EPA (1985) gives a transit emission rate for fuel oil of 0.003 mg/week-liter. It takes about a week for a barge to travel from Houston to Knoxville.

[g] We assume a 7-day equivalent storage capacity for the Farmington plant and a 20-day equivalent storage capacity for the Clinch River plant. We assume that the VOC emissions in lb/bbl-day from residual oil storage in power plants are the same as those for residual oil storage in refineries. See footnote b of this table for detailed discussion.

[h] We multiply crude storage emissions by 1.12, since 1.12 barrels of crude produce one barrel of residual oil, and add the calculated result together with the emissions of remaining categories.

minimal field observations. They apply to small, short-duration, hazardous substances in coastal and marine environments. Type B assessment procedures include alternative methodologies for conducting assessments in individual cases. They apply to all other releases in coastal and marine environments and releases in those environments not addressed by Type A procedures.

The 1990 Oil Pollution Act requires the Department of Commerce (DOC) to develop regulations for assessing natural resource damages resulting from oil spills. The National Oceanic and Atmospheric Administration (NOAA) of DOC has been assigned the task of developing these damage regulations.

DOI has developed a computer model for Type A assessment. The model assesses damage in three steps: assessment of the physical distribution of a spill in a water body, assessment of biological injury, and assessment of economic damage. The simulation of the physical distribution of spills in water bodies was conducted by Applied Science Associates in Rhode Island. The biological injury and economic damage assessments were conducted by HBRS company of Madison, Wisconsin. To conduct damage assessments, the Type A computer model requires input data specifying the date and location of a spill, the type of material spilled, the amount of material spilled, the duration of the spill, wind profiles, and cleanup activities.

Various existing regulations require that oil spills be reported to the appropriate authorities. At the federal level, various agencies within the Department of Transportation have maintained the majority of the reporting systems required by various regulations. These systems include the Hazardous Materials Information Reporting System (HMIRS) operated and maintained by the Materials Transportation Bureau (MTB); the Polluting Incident reporting System (PIRS) and the National Response Center (NRC), both maintained by the U.S. Coast Guard; and other specialized systems maintained by the Federal Aviation Administration and the Federal Railroad Administration.

Oil and toxic substance spills in and around U.S. waters must be reported to the U.S. Coast Guard (USCG). Spilled oil substances reported to USCG include crude oil, fuel oil, diesel fuel, gasoline, liquid petroleum gas, waste oils, petroleum distillate, and other petroleum products. USCG maintains a database containing all reported spills categorized by substance, by region, by transportation mode, and by year.

Although oil spills occur during both transportation and storage of oil, we do not consider oil spilled during oil storage since these spills are often small in scale and because little data is available. We consider only transportation-related oil spills.

Crude and crude products are transported by marine vessels, pipelines, railroad, and tank trucks. For our study of oil cycle externalities, we have assumed that the crude would be produced onshore near the two refineries or produced offshore in the Gulf of Mexico. We present oil spills for offshore oil production and transportation. We have assumed that the crude produced onshore near the two refineries would be transported to the refineries by small pipelines or trucks. The scale and probability of oil spills during this crude transportation would be minimal. Therefore, we do not consider onshore crude spills in this study. Oil spills from marine vessels during long-distance crude transportation is a major concern but is not applicable to this study. We present oil spills during long-distance transportation by marine vessels here for reference purposes only.

We have assumed that No. 6 residual oil would be transported from the refinery near Houston to the Clinch River plant in East Tennessee by barges through the Gulf Intracoastal waterway, the Tennessee-Tombigbee waterway, and the Tennessee River. We have assumed that No. 6 residual oil would be transported from the Navajo refinery site to the Farmington power plant by tank trucks. Therefore, we present data on residual oil spills occurring during both river and highway transportation.

### 5.4.1 Oil Spills During Water Transportation

We have obtained the data on oil spills during crude and residual oil transportation through waterways from USCG (Hantzes, 1992). Based on the USCG data, we have estimated oil spill probability and average amounts of oil spills for four regions: the Gulf Coast region, the East Coast region, the West Coast region, and the inland river region. The inland river region mostly includes the Mississippi and Ohio River areas. The Table 5.4-1 presents our calculated results.

Table 5.4-1 presents average spill probability and spill size by region. It indicates that the average spill size is small. This implies that many small oil spills are occurring. The environmental impacts of an oil spill are usually not a linear function of the amount of oil spilled. For example, one hundred barrels of oil spilled into the ocean may not create noticeable impacts, but the 240,000 barrels of the Exxon Valdez oil spill may create tremendous environmental impacts. A better way to estimate the damage of oil spills is to estimate the probabilities of different oil spill sizes and assess the damages of oil spills by spill size. We do not have data to estimate the probabilities of oil spills by spill size.

### 5.4.2 Oil Spills from Offshore Production and Transportation

The Minerals Management Service (MMS) of DOI conducts oil and gas leasing on the U.S. Outer Continental Shelf (OCS). The MMS normally prepares an environmental impact statement for each proposed offshore lease sale. The potential risks of oil spills occurring and contacting environmentally sensitive resources are assessed in the environmental impact statement. For this purpose, the MMS has estimated the probability of oil spills associated with the production and transportation of offshore oil on the U.S. Outer Continental Self (OCS).

Anderson and LaBelle (1990) have presented the MMS's estimated likelihood of oil spills from transportation and production of oil in the U.S. OCS. They give spill rates in number of spills per $10^9$ barrels of oil handled. They include two types of oil spills: platform oil spills associated with oil production and pipeline oil spills associated with oil transportation from offshore platforms to onshore storage facilities. Roughly 97% of the oil transported onshore from offshore production sites is transported through underwater pipelines.

Although spills smaller than 1,000 barrels account for 99% of all spill events, these small spills do not cause much environmental damage. Anderson and LaBelle include spills greater than or equal to 1,000 barrels in their study. This is because only these large-scale oil spills create noticeable environmental damage in the open ocean and because these spills are large enough to travel long distances to the coast where they may impact wetlands and wildlife.

Based on historical oil spill data, Anderson and LaBelle calculate spill rates of 0.60 and 0.67 spills per $10^9$ barrels of oil handled for U.S. OCS platforms and pipelines, respectively. For the oil spills greater than or equal to 1,000 barrels, their historical data show an average spill size of 18,046 barrels for platform spills and 26,450 barrels for pipeline spills.

Note that Anderson and LaBelle's estimated oil spills are for the outer continental shelf (OCS). Offshore oil production occurs in state waters (about three miles from shorelines) and in federal waters, or the outer continental shelf (i.e., between state water boundaries and U.S. water boundaries). Their estimate of oil spills does not include oil production in state waters. The oil spills due to offshore oil production in state waters should be less severe than the oil spills due to offshore OCS oil production. This is because oil production in state waters near the shoreline encounter less severe ocean conditions and because the oil produced

**Table 5.4-1. Oil spills in U.S. waters during transportation (ship movements): probability and scale[a]**

| Region | | Crude | Residual Oil |
|---|---|---|---|
| Gulf Coast | Probability[b] (%) | 5.20 | 2.33 |
| | Scale[c] (bbl) | 44.1 | 14.9 |
| East Coast | Probability[b] (%) | 1.89 | 0.21 |
| | Scale[c] (bbl) | 171.1 | 24.4 |
| West Coast | Probability[b] (%) | 0.87 | 0.05 |
| | Scale[c] (bbl) | 812.5 | 79.1 |
| Inland River | Probability[b] (%) | 0.10 | 0.16 |
| | Scale[c] (bbl) | 67.0 | 259.2 |
| Nationwide | Probability[b] (%) | 0.56 | 0.21 |
| | Scale[c] (bbl) | 223.5 | 85.2 |

[a] We have obtained oil spill data from Hantzes (1992) of USCG. We use the data on oil spilled between 1983 and 1989 maintained by USCG.

[b] The probability of oil spills is calculated by using two sets of information: the total number of ship movements of crude or residual oil and the total number of movements in which crude or residual oils are spilled. The probability is estimated by dividing the total number of spills by the total number of ship movements.

[c] The scale is calculated by dividing the total amount of crude or residual oils spilled by the total number of spills.

in state waters needs to be transported over shorter distances since they are close to shore. Consequently, applying the OCS oil spill rates to the oil production in state waters will certainly overestimate oil spills from state water oil production. We do not have information on oil spills from oil production in state waters.

Pollution discharges into U. S. navigable waters has been compiled by the U. S. Coast Guard (1989) for the 1986 - 1989 period. The Coast Guard information categorizes spills into three groups: oil, hazardous substances, and other. The data is presented in tables by general area, type of oil spilled, source of the spill (type of vessel, land vehicle, or land facility) occurred on, type of incident causing the spill, and a frequency distribution of oil spill sizes. The data is not summarized by frequency distribution, vessel, and location, which would be useful for this analysis. Consequently, it is impossible to assign the oil spill frequency distribution data to oil tankers and barges.

### 5.4.3 Oil Spills from Tank Trucks

The USCG has estimated oil spills during oil transportation along highways. Currently, refinery products such as gasoline and diesel are transported by tank trucks to service stations for short distances. The estimated amount of oil spilled per year for four years is presented in Table 5.4-2. This spilled oil is probably in the form of gasoline and diesel since these two fuels account for most of the petroleum products transported through tank trucks.

The oil spill rate of tank trucks is expressed in terms of total quantity of oil spilled per barrel-mile. Walter et al. (1985) estimated a spill rate of 0.14 million gallons of oil spilled per billion ton-miles, based on tank truck spill data for 1972 to 1979. This spill rate translates into an oil spill rate of $4.505 \times 10^{-4}$ bbl/$10^3$ bbl-mile (using an average mass density of 270 lb/bbl for gasoline and distillate fuels since most fuels transported by tank trucks are gasoline and distillate fuels). We will use this spill rate to calculate the amount of oil spilled transporting residual oil from the Navajo refinery site to the Farmington power plant by tank trucks.

## 5.5 AIR EMISSIONS FROM CRUDE REFINING

The Clean Air Act regulates criteria air emissions from refineries through state implementation plans. Under the Air Toxic Title of the 1990 Clean Air Act Amendments, any industrial facility that annually emits at least ten tons of any of 189 hazardous air pollutants will be required to control them to a minimum level. Petroleum refineries emit many of the 189 toxic air pollutants.

All criteria pollutants (e.g., $SO_X$, CO, $NO_X$, HC, and PM) are emitted from refineries. Hazardous air pollutants such as polycyclic aromatic hydrocarbons (PAHs), sulfur compounds (e.g., $H_2S$), nitrogen compounds (e.g., $NH_3$), and trace elements (e.g., vanadium, nickel, zinc, lead, copper, etc.) are also emitted from refineries.

### 5.5.1 Sources of Air Emissions in Refineries

EPA (1985) has categorized the following sources of air emissions for refineries.

a) Claus Units. These units include axillary facilities such as sulfur recovery plants and hydrogen production facilities.

b) Catalyst Regeneration. Catalytic regeneration processes employed during catalytic cracking and catalytic reforming processes produce air emissions. Air emissions from catalyst regeneration processes include large amounts of PM, $SO_X$, CO, HC, $NO_X$, aldehydes, $NH_3$, and $CO_2$ and small amounts of chlorides and aerosols.

**Table 5.4-2. The annual amount of highway oil spills (UCSG, 1982, 1984)**

| Year | Barrels of Oil Spilled |
|---|---|
| 1981 | 4,662 |
| 1982 | 4,813 |
| 1983 | 3,786 |
| 1984 | 3,422 |

c) Boilers and Process Heaters. Boilers and process heaters are used extensively to generate steam and heat for refining processes. Various types of fuels such as refinery gases, natural gas, and residual oil are used to fire boilers and process heaters. The combustion of these fuels produces small amounts of VOC and CO emissions but large amounts of $NO_X$, $SO_X$, PM, and $CO_2$. The emissions of $NO_X$, $SO_X$, and PM are subject to federal and state regulations, and are controlled in various degrees.

d) Other Point Sources. Burning waste gases for disposal purposes causes the emission of HC, $SO_X$, CO, $NO_X$ and $CO_2$. Wastewater treatment plants emit HC, $SO_X$, $H_2S$, $NH_3$, $NO_X$, PM, and $CO_2$.

e) Fugitive Emission Sources. Fugitive emission sources are generally defined as VOC emission sources that are not associated with a specific process but are scattered throughout a refinery. These sources include valves (e.g., pipeline, open-ended, and vessel-relief valves), flanges, pump and compressor seals, process drains, cooling towers, and oil/water separators (wastewater treatment). In fact, the majority of the VOC emissions produced from crude refineries might be from these so-called fugitive emissions.

Most fugitive emission sources are now regulated under the NSPS. The amount of fugitive emissions can be reduced by minimizing leaks and spills through equipment changes, procedure changes, improved monitoring, and housekeeping and maintenance practices. Fugitive emissions can be collected and flared to $CO_2$.

Fugitive VOC emissions are available from EPA (EPA 1993) giving the amounts in pounds per day for a 330,000 Bbl/day refinery. These estimates are converted for a refinery producing 8,940 Bbls/day of residual fuel oil - the amount of residual oil needed at each of the two reference power plant sites daily. Table 5.5-1 gives estimates of VOC emissions for this size refinery at the two reference sites (column 3). The second column of this table is the number of source units in a typical refinery. Column 4 gives the pounds of VOC emissions produced per day allocated to the amount of residual oil produced at the refinery.

To control the air emissions from refining processes, refineries are equipped with various emission control systems. PM emissions are usually controlled by cyclones, electrostatic precipitators, or wet scrubbers. $SO_X$ emissions from boilers are controlled by flue-gas desulfurization devices such as wet scrubbers. $NO_X$ emissions from boilers are controlled through water injection and other methods. VOC evaporative emissions from storage tanks and loading facilities are controlled by using floating-roof tanks.

Table 5.5-1. Fugitive VOC emissions from an oil refinery

| | | VOC emissions | |
|---|---|---|---|
| Source | Number | lb/day refinery | lb/day due to residual oil produced |
| Valves | 11,500 | 2,632 | 184.2 |
| Flanges | 46,500 | 232 | 16.3 |
| Pump seals | 350 | 503 | 35.2 |
| Compressors | 70 | 426 | 29.8 |
| Relief Valves | 100 | 194 | 13.5 |
| Drains | 650 | 387 | 27.1 |
| Cooling towers | | 619 | 43.3 |
| Oil/Water Separators (uncovered) | | 12,423 | 869.6 |
| Total | | 17,416 | 1,219.1 |

Pollution discharges into U. S. navigable waters has been compiled by the U. S. Coast Guard (1989) for the 1986 - 1989 period. The Coast Guard information categorizes spills into three groups: oil, hazardous substances, and other. The data is presented in tables by general area, type of oil spilled, source of the spill (type of vessel, land vehicle, or land facility) occurred on, type of incident causing the spill, and a frequency distribution of oil spill sizes. The data is not summarized by frequency distribution, vessel, and location, which would be useful for this analysis. Consequently, it is impossible to assign the oil spill frequency distribution data to oil tankers and barges.

### 5.5.2 The Amount of Criteria Pollutants

In its AP-42 document, EPA (1985) quantifies the emission factors of some major refining units. The EPA's emission factors for refining units are presented in Table 5.5-2. Table 5.5-2 does not list all units that produce air emissions in a refinery. Units not listed above include sulfur recovery plants, pipeline valves, open-ended valves, compressor seals, etc. We do not include units such as valves and seals because emissions per unit are difficult to quantify, and because the total number of these units in a refinery is unknown.

We do not include the emissions from sulfur recovery plants because we do not account for these emissions in estimating the emissions due to residual oil production. This is because the sulfur content of residual oil is equal to or greater than the sulfur content of crude, implying that the sulfur is removed from crude and further recovered in the sulfur recovery plant for the purpose of reducing the sulfur content of other products (such as gasoline and diesel) rather than residual oil. Therefore, emissions from sulfur recovery plants should be allocated to other products.

Next, we allocate emissions from each of the above units to several categories of refining processes. The refining categories relevant to residual oil production are distillation (atmospheric and vacuum), cracking, and finishing (including various treating processes and blending). Other processes, such as alkylation, reforming, and coking, are related to high-quality fuel production. Emissions from processes that are related to residual oil production are estimated in Table 5.5-3.

**Table 5.5-2. Air emissions of refining units**[a]

| Unit | PM | $SO_2$ | CO | HC | $NO_x$ | Aldehyde | $NH_3$ |
|---|---|---|---|---|---|---|---|
| **Boiler and Process Heater Emissions (lb/MMBtu fuel burned)** | | | | | | | |
| (1) Fuel Oil[b] | 0.024[c] | 0.1573[d] | 0.0334[e] | 0.009[f] | 0.147[g] | 0 | 0 |
| (2) NG[h] | 0.0029 | 0.0006 | 0.0339 | 0.0056 | 0.0543[i] | 0 | 0 |
| **Cracking--FCC**[j] | 45 | 493 | Neg. | Neg. | 71.0 | Neg. | Neg. |
| **Cracking--MCC**[k] | 17 | 60 | Neg. | 87 | 5 | 12 | 6 |
| **Fluid Coking**[l] | 6.85 | NA | Neg. | Neg. | NA | Neg. | Neg. |
| **Blowdown System**[m] | Neg. | 26.9 | 4.3 | 0.8 | 18.9 | Neg. | Neg. |
| **Fugitive Emissions** | | | | | | | |
| (1) Cooling Tower[n] | 0 | 0 | 0 | 1.2 | 0 | NA | NA |
| (2) Oil/Water Separator[o] | 0 | 0 | 0 | 10 | 0 | NA | NA |

[a] Except where otherwise noted, all data is taken from EPA (1985) and is given in lb/$10^3$ bbl feed input.

[b] We use *emission factors of industrial boilers fired with residual oil. EPA's emission factors are given in lbs/$10^3$ gal of fuel input.* We converted this unit to lbs/MMBtu fuel input by using an energy content of 6.287 MMBtu/bbl for residual oil (EIA, 1991d).

[c] AP-42 shows that PM emissions of industrial boilers fired by No. 6 residual oil can be calculated as 10*S + 3 (lb/$10^3$ gal oil input). In 1990, the sulfur content of residual oil used in power plants was 0.99% by weight (EIA, 1991c). However, the residual oil used in refineries has a higher sulfur content. We use a sulfur content of 1.5% in our estimate. We use an energy content of 6.287 MMBtu/bbl for residual oil to convert emissions from lbs/$10^3$ gal to lbs/MMBtu. The PM emissions calculated from this formula are uncontrolled emission rates. Since PM emissions of industrial boilers are subject to regulations, we assume that refinery boilers are installed with electrostatic precipitators to control PM emissions. We assume an 80% control effectiveness for the control system.

[d] The uncontrolled $SO_2$ emission factor is calculated as 157 * S (lb/$10^3$ gal oil input), where S is the sulfur content of No. 6 residual oil, which we assume as 1.5%. We assume that $SO_2$ emissions are controlled by 90% through using wet scrubbers in refinery boilers because $SO_2$ emissions from refinery boilers are subject to regulations. For other assumptions, see footnote c of this table.

[e] The uncontrolled CO emission factor is 5 lbs/$10^3$ gal fuel input. We use the uncontrolled emission factor for CO because CO emissions from refinery boilers are not subject to regulations. For other assumptions, see footnote c of this table.

[f] The uncontrolled HC emission factor is 2.28 lbs/$10^3$ gal of fuel input. We use the uncontrolled emission factor for HC because HC emissions from refinery boilers are not subject to regulations. For other assumptions, see footnote c of this table.

[g] The uncontrolled $NO_x$ emission factor is 55 lbs/$10^3$ gal oil input. Since $NO_x$ emissions from refinery boilers are subject to regulations, we assume a control effectiveness of 60% for $NO_x$ emissions through flue-gas recirculation, staged combustion, and other technologies to calculate the controlled $NO_x$ emission factor. For other assumptions, see footnote c of this table.

[h] We use an energy content of 1,031 Btu/$ft^3$ for natural gas to convert emissions from lb/$ft^3$ to lb/MMBtu. We use uncontrolled emission factors for PM, $SO_2$, HC, and CO because these emissions from refinery boilers fired by natural gas are small.

[i] We assume that uncontrolled $NO_x$ emissions are reduced by 60% because $NO_x$ emissions are subject to regulations. For $NO_x$ emission reduction assumptions, see footnote g of this table.

[j] These are emission factors for fluid catalytic cracking units equipped with an electrostatic precipitator to control PM and a CO boiler to control CO.

[k] These are emission factors for moving-bed catalytic cracking units equipped with a CO boiler to control CO emissions.

[l] These are emission factors for fluid coking units equipped with an electrostatic precipitator for PM control and a CO boiler for CO control.

[m] These are emission factors for blowdown systems equipped with an HC vapor recovery system and a CO flaring system.

[n] These are controlled emission factors for cooling towers.

[o] These are controlled emission factors for oil/water separators in wastewater treatment plants.

The above table presents emission rates in lb/$10^3$ bbl of feedstock input. As discussed in a previous section, about 1.12 barrel of crude is needed to produce one barrel of residual oil. Therefore, in order to calculate emission rates in lb/$10^3$ bbl of residual oil produced, the emission rates in the above table need to be multiplied by 1.12.

Finally, we allocate the emissions of each of the processes presented in Table 5.5-3 to residual oil production, based on the percentage of residual oil produced, relevant to other products, from a specific process. DeLuchi (1992) estimates that residual oil accounts for 7% of the products from the distillation process, 8.5% of the products from the catalytic cracking process, and 0% of the products from the coking process. In calculating the emissions from residual oil production, we assume that 5% of the emissions from distillation and 6% of the emissions from cracking result from the production of residual oil. We use a percentage number smaller than the residual oil production percentage number for the two processes because we believe that the production of residual oil requires less intensive refining activities than the production of other products such as gasoline or distillate fuels. In calculating residual oil emissions, we assume that the emissions from oil/water separators accountable to residual oil production are proportional to the residual oil production of a refinery. Table 5.5-4 presents emissions per $10^3$ barrels of residual oil produced.

### 5.5.3 The Amount of Toxic Chemicals Released from Refineries

There are various types of chemicals released from petroleum refining processes. Many of them are listed as toxic by EPA. Refiners are required to report the amount of toxic chemicals released from their facilities every year. The reported amount of toxic chemicals is maintained for each of the major refineries by EPA in its Toxic Release Inventory (TRI) database. We have obtained the TRI data for some refineries in Texas and Louisiana from EPA. Table 5.5-5 below presents the amount of toxic chemicals released to air, land, and water from the refinery near Houston in 1989. This information may be used to assess health and ecological impacts of toxic refinery chemicals.

## 5.6 AIR EMISSIONS FROM OIL-FIRED POWER PLANTS

### 5.6.1 Regulations of the Air Emissions from Power Plants

Oil-fired power plants produce emissions of HC, CO, $NO_X$, $SO_X$, PM, and $CO_2$. The amount of $SO_X$ and PM emissions depends mainly on the

**Table 5.5-3. Air emissions of refining process (lb/$10^3$ bbl feed input)**

| Process | PM | $SO_2$ | CO | HC | $NO_2$ |
|---|---|---|---|---|---|
| Distillation[a] | 0.7717 | 11.9992 | 6.9983 | 1.6686 | 16.8525 |
| Cracking[b] | 45.3044 | 497.7330 | 2.7604 | 0.6582 | 77.6474 |
| Coking[c] | 0.0687 | 1.0679 | 0.6228 | 0.1485 | 1.4999 |
| Others[d] | 0 | 0 | 0 | 10.0 | 0 |

[a] We allocate a portion of the emissions from boilers and process heaters, cooling towers, and blowdown systems to the distillation process. We calculate the average emission factors of oil-fired and natural-gas-fired boilers by using the ratio of energy consumed for oil and gas in refineries. DeLuchi (1992) estimated that 6.77% of the energy consumed in refineries came from residual oil and that 70.5% came from natural gas and refinery gas. We use these numbers to calculate the average emission factors for boilers and process heaters. To convert emissions from lbs/MMBtu to lbs/$10^3$ bbl feedstock input, we assume that the energy consumption of refining processes account for 10% of the energy contained in the feedstock (Gaines et al., 1981; DeLuchi, 1992). That is, to process 1,000 barrels of crude which contain about 5,800 MMBtu, 580 MMBtu of energy is consumed for refinery processes. We assume that 77% of the energy consumed is used to fire boilers and process heaters. Therefore, to process 1,000 barrels of crude, about 446.6 MMBtu of energy is needed to fire boilers and process heaters. We have calculated emissions (in lbs/$10^3$ bbl feedstock) as follows: 2.1473 for PM, 6.4310 for $SO_2$, 15.1397 for CO, 2.6349 for HC, and 27.9125 for $NO_2$.

Emissions from boilers, blowdown systems, and cooling towers contribute to emissions from the distillation process. However, these sources contribute to the emissions from other processes as well. We allocate emissions from each of the units in Table 5.5-1 to each of the processes in this table based on the energy consumption of each process. DeLuchi (1992) states that distillation processes account for 36% of the total process energy, cracking processes account for 14.2%, coking processes account for 3.2%, and finishing processes account for 5.5%. We use these percentage numbers to allocate emissions from boilers and process heaters to each of the refining processes.

[b] We attribute 100% of all cracking emissions to the cracking process and 14.2% of emissions from boilers, blowdown systems, and cooling towers to the cracking process. (14.2% is the amount of process energy used in cracking out of the total process energy.) Most cracking units are currently FCC units. We use FCC unit emissions to estimate cracking emissions.

[c] We allocate 3.2 % of emissions from boilers, blowdown systems, and cooling towers to the coking process since 3.2% of the total process energy is consumed in the coking process.

[d] Emissions of oil/water separators.

**Table 5.5-4. Air emissions of residual oil production lbs/$10^3$ bbl residual oil produced)**

| PM | $SO_2$ | CO | HC | $NO_2$ |
|---|---|---|---|---|
| 17.7861 | 196.5414 | 3.3261 | 49.6130 | 35.4933 |

**Table 5.5-5. The amount of toxic chemicals released from the Southeast Texas refinery during 1989[a] (lb/year)**

| Substance Name | Releases | | | Transfers[b] |
|---|---|---|---|---|
| | Air | Land | Water | |
| 1,1,1-Trichloroethane | 0 | 0 | 0 | 0 |
| 1,2,4-Trimethylbenzene | 9,040 | 0 | 0 | 0 |
| 1,3-Butadiene | 104,000 | 0 | 0 | 0 |
| 2-Ethoxyethanol | 23 | 0 | 0 | 0 |
| 4,4'-Isopropylidenediphenol | 82,160 | 1,200 | 0 | 0 |
| Acetone | 686,340 | 4,200 | 0 | 0 |
| Acetonitrile | 63,310 | 0 | 0 | 0 |
| Allyl Chloride | 680 | 0 | 0 | 68,600 |
| Ammonia | 11,980 | 0 | 15,200 | 0 |
| Barium Compounds | 0 | 0 | 1,990 | 0 |
| Benzene | 572,880 | 40 | 100 | 1,580 |
| Butyraldehyde | 114,040 | 60 | 0 | 0 |
| Chloride | 0 | 0 | 0 | 0 |
| Chromium Compounds | 62,140 | 300 | 2,800 | 7,420 |
| Cobalt Compounds | 0 | 0 | 0 | 0 |
| Cumene | 272,490 | 60 | 0 | 0 |
| Cumene Hydroperoxide | 25,360 | 0 | 0 | 0 |
| Cyclohexane | 18,280 | 0 | 0 | 0 |
| Diethanolamine | 6,822 | 0 | 0 | 0 |
| Epichlorohydrin | 147,420 | 2 | 0 | 700,700 |
| Ethyl Acrylate | 160 | 0 | 0 | 0 |

**Table 5.5-5. The amount of toxic chemicals released from the Southeast Texas refinery during 1989[a] (lb/year)**

| Substance Name | Releases | | | Transfers[b] |
|---|---|---|---|---|
| | Air | Land | Water | |
| Ethylbenzene | 31,660 | 0 | 0 | 0 |
| Ethylene | 398,660 | 0 | 0 | 0 |
| Ethylene Glycol | 20 | 0 | 0 | 0 |
| Glycol Ethers | 36,290 | 0 | 0 | 0 |
| Hydrazine | 170 | 0 | 0 | 0 |
| Hydrochloric Acid | 5,370 | 0 | 0 | 0 |
| Methanol | 109,340 | 1,700 | 0 | 0 |
| Methyl Ethyl Ketone | 886,900 | 30 | 0 | 0 |
| Methyl Isobutyl Ketone | 157,080 | 80 | 0 | 0 |
| Methyl Tert-Butyl Ether | 49,820 | 0 | 0 | 0 |
| Molybdenum Trioxide | 0 | 0 | 0 | 0 |
| N-Butyl Alcohol | 125,280 | 260 | 0 | 0 |
| Nickel Compounds | 0 | 350 | 4,660 | 1,020 |
| O-Xylene | 29,790 | 0 | 0 | 0 |
| Phenol | 196,100 | 680 | 760 | 1,081 |
| Phosphoric Acid | 0 | 0 | 0 | 0 |
| Propylene | 456,120 | 0 | 0 | 0 |
| Sec-Butyl Alcohol | 590 | 4 | 0 | 0 |
| Sulfuric Acid | 440 | 0 | 0 | 0 |
| Toluene | 738,900 | 130 | 100 | 1,580 |
| Xylene (mixed isomers) | 130,530 | 40 | 0 | 1,580 |
| Zinc Compounds | 8,960 | 0 | 1,850 | 2,776 |

[a] From L. Capozzoli (1992) of EPA.

[b] This is the amount of toxic waste transferred from on-site to off-site facilities (such as publicly owned treatment works, landfills, etc.

sulfur content of the residual oil burned in power plants. $NO_x$ emissions come from the oxidation of fuel-bound nitrogen and the thermal fixation of the nitrogen in combustion air. Fuel $NO_x$ is primarily a function of the nitrogen content of the fuel and the available oxygen. Thermal $NO_x$ is largely a function of the peak flame temperature and the available oxygen. Generally, oil boilers produce more fuel $NO_x$ than thermal $NO_x$.

Small amounts of HC and CO are emitted from burning residual fuel oil in steam boilers. Organic compounds presented in the flue-gas streams include aliphatic and aromatic hydrocarbons, esters, ethers, alcohols, carbonyls, carboxylic acid, and polycyclic aromatic hydrocarbons. Heavy metals such as arsenic, cadmium, lead, mercury, nickel, manganese, chromium, copper, and vanadium are present in flue gases.

The quantity of trace metals emitted depends on combustion temperature, fuel feed mechanism, and the composition of the fuel. The temperature determines the degree of volatilization of specific compounds contained in the fuel. The fuel feed mechanism affects the separation of emission into bottom ash and fly ash. The quantity of any given metal emitted, in general, depends on:

1) the physical and chemical properties of the element itself;
2) its concentration in the fuel;
3) the combustion conditions; and
4) the type of particulate control device used, and its collection efficiency as a function of particle size.

Table 5.6-1 gives the trace elements and estimates of emissions for the oil-fired power plants used at the Southeast and Southwest sites. The values were compiled by EPA (1993) and present the range of estimates presented in the literature. If only one data point was found, it is reported in this table.

**Table 5.6-1. Range of trace elements from oil-fired boilers (EPA, 1993)**

| Constituent | Emission factor (lb/$10^{12}$ Btu) |
|---|---|
| Antimony | 24 - 46 |
| Arsenic | 19 - 114 |
| Beryllium | 4.2 |
| Cadmium | 16 - 211 |
| Chromium | 21 - 128 |
| Cobalt | 77 - 121 |
| Lead | 28 - 194 |
| Manganese | 23 - 74 |
| Mercury | 1.4 - 32 |
| Nickel | 837 - 2330 |
| Selenium | 38 |

Utility power plants are required to comply with federal and state emission standards. Current federal air emission regulations include the New Source Performance Standards (NSPS), the Revised New Source Performance Standards (RNSPS), the Prevention of Significant Deterioration (PSD) rules, and the new $SO_X$ and $NO_X$ standards established in the 1990 CAA Amendments. State air emission regulations include both requirements for obtaining permits for construction and operation of major pollution-generating facilities and pollution control statutes that enforce State Implementation Plans (SIPs).

Power plants built at different periods of time are subject to different standards. Pre-NSPS units whose construction began before August 18, 1971 are subject to SIPs, which are generally less stringent than NSPS. Those units whose construction began between August 18, 1971 and September 18, 1978 are subject to NSPS. Those units whose construction began after September 19, 1978 are subject to RNSPS. The 1990 CAA amendments require the utility sector to reduce $SO_X$ emissions by 10 million tons per year below the 1980 baseline emissions by the year 2000 and to reduce $NO_X$ emissions by 2 million tons. In the 1990 CAA, $SO_X$ and $NO_X$ emission standards were established for power plants operating after 1995.

### 5.6.2 Air Emission Control

#### 5.6.2.1 Control of $NO_x$

When residual oil burns, it first transforms into a vapor. During this transformation, "fuel-bound" nitrogen transforms into $NO_x$. The rate of the $NO_x$ formation may be controlled by reducing the amount of air near the burner since this limits the number of oxygen molecules available to oxidize nitrogen to $NO_x$.

Thermal $NO_x$ forms when any fuel burns at a temperature above 1,630° C. At this high temperature, the nitrogen contained in combustion air is oxidized into $NO_x$. The amount of thermal $NO_x$ formed in this way increases dramatically with an increase in flame temperature. Two approaches may be employed to control $NO_x$ emissions: combustion control and flue-gas control.

5.6.

(a) Combustion Control. Combustion control of $NO_x$ emissions is accomplished by retarding the oxidation of nitrogen with several techniques. Low $NO_x$ burners use a proper fuel-to-air ratio to limit both fuel-bound $_x$NO and thermal $NO_x$. The design of low $NO_x$ burners ensures that the area immediately adjacent to the burner is fuel rich. A fuel-lean zone is created immediately beyond this fuel-rich zone. By limiting the amount of oxygen available near the burner, thermal $NO_x$ emissions can be reduced. $NO_x$ emissions can be reduced as much as 50% by this method.

Other burner designs, such as ceramic fiber burners, help reduce $NO_x$. Ceramic fiber burners are made from porous ceramic materials which diffuse gaseous fuel and air to the surface of burners. When fired, the surface of the burner is an incandescent, hot, flameless area which radiates heat uniformly and efficiently to its surrounding areas. Due to the characteristics of flameless combustion, $NO_x$ emissions are reduced. Ceramic fiber burners operate at a higher thermal efficiency and can achieve emission reductions as high as 90%.

Furnace modifications ranging from fairly modest approaches (e.g., operation at low excess air conditions, staged combustion, biased burner firing, burners out of service, and flue-gas recirculation) to more dramatic modifications (e.g., overfiring) can achieve a combined 50-90% $NO_x$ reduction.

Steam or liquid urea can be injected into a burner to reduce the flame temperature and, thus, reduce $NO_x$. The control efficiency is sensitive to flue-gas temperature.

(b) Flue-gas Control. Flue-gas control reduces certain pollutants contained in flue gases before the gases exit the exhaust stack of a power plant.

Selective Catalytic Reduction (SCR). SCR is a chemical process that converts $NO_X$ into $N_2$ and $CO_2$ with the help of catalysts. With the system, ammonia is injected into the flue-gas stream. The flue gas then passes over a catalyst bed at a temperature of 300-400 °C where $NO_X$ is converted into $N_2$ and $CO_2$. Vanadium and titanium can be used as catalysts. SCR systems can achieve a 90% $NO_X$ reduction.

Ammonia must be stored for the SCR system. Ammonia storage tanks can burst and release a potentially lethal ammonia flume. Ammonia can also pass through the boiler without reacting with $NO_X$. This "ammonia slip" is emitted into the atmosphere as a pollutant. $SO_X$ formed during combustion can react with ammonia to form ammonium hydrogen sulphate which can accumulate on catalysts and affect their ability.

Selective Non-catalytic Reduction (Thermal-de$NO_X$). Selective non-catalytic reduction is similar to selective catalytic reduction, except that metal catalyst beds are not used, and ammonia must be injected into the flue gas when the flue temperature is 870-1,200 °C. The system can have a $NO_X$ reduction rate as high as 90%; actual tests show a 50-60% reduction rate (CEC, 1991). However, the selective non-catalyst reduction system increases the emissions of ammonia and CO. The $SO_2$ that is generated with the combustion of high-sulfur-content residual oils reacts with ammonia to produce salts which can foul boilers.

### 5.6.2.2 $SO_X$ Control

$SO_X$ emissions from residual oil combustion are mainly in the form of $SO_2$. Other components of $SO_X$ emissions include $SO_3$. $SO_2$ emissions result from the oxidation of the sulfur contained in residual oil. The amount of $SO_2$ emissions from residual oil combustion is almost entirely dependent on the sulfur content of the fuel. There are two approaches to controlling $SO_X$ emissions: substituting low-sulfur oils for high-sulfur oils and controlling flue gas.

(a) Fuel Substitution. Residual oil produced from refineries can have a sulfur content ranging from less than 1% to over 4%. To decrease the sulfur content of residual oil, additional refining processes such as finishing and blending are needed. Usually, the sulfur content of the residual oil produced in refineries corresponds with user demands. Currently, high-sulfur residual oils are sold to ships or barges, or used in refineries, while low-sulfur residual oil is used in power plants.

High-sulfur residual oils generate high emissions of $SO_X$ and PM. Substituting low-sulfur oils for high-sulfur oils helps reduce $SO_X$ and PM. Electric power plants currently demand low-sulfur residual oils for two primary reasons:

low-sulfur fuels help power plants meet stringent $SO_x$ emission standards, and they limit $SO_x$ corrosion damage to generating units. In 1990, U.S. electric power plants used residual oil with an average sulfur content of about 0.99% (EIA, 1991c). Virtually all new oil-fired plants are designed to burn low-sulfur oil. Although some grandfather oil-fired plants can burn high-sulfur residual oil, they may not do so, because stringent $SO_x$ emission standards adopted in the 1900 CAA will go into effect after 1995.

Currently, the refinery near Houston produces residual oil with a sulfur content of above 3% (personal communication with W. Brown, 1992). This residual oil is sold mainly to ship or barge operators. The Southwest refinery produces residual oil with a sulfur content of 3.5% (personal communication with D. Blair, 1992). The high sulfur content of the residual oil produced at the two refineries is due to the type of crude used in the refineries as well as the lack of adequate de-sulfurization processes. We assume that the two refineries would either modify their processes or purchase lower sulfur crude oil in order to supply the two power plants with residual oil with a 1% sulfur content. Consequently, the two plants would have to pay higher prices in the future for the low-sulfur residual oil. For example, the current price of residual oil with a 1% sulfur content is approximately $1.75 higher per barrel than the price of residual oil with a 3% sulfur content.[2]

(b) Flue-Gas Control. $SO_x$ emissions in flue gases can be controlled by different control systems. The following three control systems are commonly used.

Wet Scrubbers. Wet scrubbers employ lime or limestone suspended in water to remove $SO_2$ from flue-gas streams. Lime or limestone can react with $SO_2$ to generate a liquid waste which can be readily removed from flue gases. The emission reduction rate of scrubbers can be as high as 95%.

Spray Dryer Systems. In a typical spray dryer, flue gas enters the top of a reactor where it comes in contact with a finely atomized liquid alkali slurry. The water is evaporated by humidifying the flue gas. During this process, $SO_2$ in the flue gas reacts with the alkali material and forms solid materials. The solid materials contain less than 1% free moisture. The solid materials are removed from the flue gas by a downstream particulate removal device, typically an electrostatic precipitator or baghouse. The system's control efficiency can be as high as 90%.

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[2] Refinery air emissions of $SO_2$ and PM due to input of high sulfur crude can be estimated by using the emissions algorithms in footnotes c and d in Table 5.5-2.

Dry Sorbent Injection. This system is similar to spray dryers, except that sorbent material is injected into the flue gas in a dry powder form. High temperatures of 250-600°C are required for the process. Sodium-based materials, ammonia, or alkalized alumina can be used as sorbent material. The system is capable of removing 90% of the $SO_2$.

### 5.6.2.3 PM Control

PM emissions from residual oil combustion are a function of the sulfur content of the oil. PM emission can be reduced considerably by using low-sulfur oil. This is because low-sulfur oils usually exhibit lower viscosity and reduced asphaltene, ash, and sulfur, all of which result in better atomization and cleaner combustion. Therefore, substituting low-sulfur oil for high-sulfur oil helps reduce PM and $SO_2$ emissions. Two major flue-gas control technologies are commonly used to control PM emissions.

Fabric Filtration. A fabric filter (baghouse) consists of a number of filtering elements (bags) along a bag cleaning system contained in a main shell structure with dust hoppers. Particulate-laden flue gases are passed through the bags so that the particles are retained on the upstream side of the fabric, thus cleaning the flue gas. The removal efficiency of fabric filtration can be as great as 99.9%.

Electrostatic Precipitation. This system collects PM by an electrostatic precipitator. Particulate collection in an electrostatic precipitator (ESP) occurs in three steps: suspended particles are given an electrical charge; the charged particles migrate to a diverging electric field; and the collected PM is removed from the collecting electrodes. This study assumes the collection efficiency of precipitators for oil-fired boilers vary from 45% to 90% (EPA, 1993), although the efficiency can be higher.

### 5.6.3 The Amount of Air Emissions

We use EPA's AP-42 emission factors to calculate both uncontrolled and controlled emissions per $10^3$ barrels of residual oil input to oil-fired power plants with steam boiler technology. The controlled emissions have been estimated for 1990 and 2010. Table 5.6-2 presents the calculated emission rates for the five pollutants.

In this section, we have presented and estimated the air emissions of power plants fired with steam boiler technology. No electric utilities in the U. S. have had residual oil-fired boilers installed in the 1990 time period. All of the residual oil-fired systems have been put in place before 1980.

The emissions control technologies for pollutants produced by residual oil-fired boilers represented here describe systems that would realistically be configured in 1990 and 2010. The control effectiveness levels for the emissions generated by the oil-fired boilers are well within a feasible range given in AP-42.
Particulates:
1990 - Baghouse with 90% removal efficiency, and a wet scrubbing system with 50% control effectiveness.
2010 - Baghouse with 95% removal efficiency, and a wet scrubbing system with 60% control effectiveness.
$SO_2$:
1990 - Wet scrubbing system with 90% control effectiveness.
2010 - Wet scrubbing system with 95% control effectiveness.
$NO_X$:
1990 - Low $NO_X$ burners with 40% control effectiveness and ammonia injection with 50% control effectiveness.
2010 - Low $NO_X$ burners with 40% control effectiveness, ammonia injection with 50% control effectiveness, and selective catalytic reduction with 90% control effectiveness.

Oil-fired gas turbines typically use distillate oil and produce air emissions of PM, $SO_X$, $NO_X$, CO, and HC. Since solids and heavy metals are removed with distillate oil pretreatment systems, PM emissions from gas turbines are expected to be smaller than those from steam boilers. Direct-firing gas turbines may produce an amount of $SO_X$ emissions similar to that of steam boiler technology, if oil with the same sulfur content is used for the both systems.

Gas turbines with residual oil gasification produce much less $SO_2$ emissions than steam boilers because $SO_2$ can be readily converted into elemental sulfur through $H_2S$. During residual oil gasification, $H_2S$ appearing in syngases can be converted into elemental sulfur with some sulfur recovery methods. The amount of $SO_X$ emissions in flue gas is therefore reduced.

The flue-gas control technologies discussed above for steam boilers are usually not applied to gas turbine technology to control emissions of PM, $SO_X$, and $NO_X$. Gas turbines manufactured currently utilize improved combustor designs and water or steam injection which eliminates the need for emission control technology used for oil-fired boilers.

There is no data on air emissions from gas turbines fired with residual oils. Consequently, we do not include the air emissions of gas turbine technology.

**Table 5.6-2. Air Emission Rates of Oil-fired Power Plants ($lb/10^3$ bbl of oil input)**

| | PM | $SO_2$ | CO | $NO_2$ | VOC |
|---|---|---|---|---|---|
| Uncontrolled Emissions[a] | 546[b] | 6594[c] | 210 | 2814 | 43.68 |
| Controlled Emissions: 1990 | 27.3 | 659.4 | 210 | 844.2 | 43.68 |
| Controlled Emissions: 2010 | 10.92 | 329.7 | 210 | 84.42 | 43.68 |

[a] From EPA's AP-42 (EPA, 1986). We use emission rates for utility boilers fired with No. 6 residual oil.

[b] The PM emission rate is calculated as (10*S + 3)*42 ($lb/10^3$ bbl). S is the weight percentage of sulfur in the oil. We assume a 1% sulfur content of No. 6 residual oil.

[c] The $SO_2$ emission rate is calculated as (157*S)*42. S is the weight percentage of sulfur in the oil. We assume a 1% sulfur content of No. 6 residual oil.

## 5.7 AIR EMISSIONS FROM OIL EXTRACTION AND OIL TREATMENT IN OIL FIELDS

VOCs (volatile organic compounds) emitted during oil extraction and treatment are mainly caused by leakage of crude during production and treatment, evaporative emissions from wastewater pits and storage tanks, and combustion of diesel fuels used to provide power for oil production and treatment operation. Recently, EPA found that the amount of VOC emissions from oil 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 $C_2O$ are primarily caused by the combustion of diesel fuels used for oil production operations. PM emissions are mainly caused from dust. These emissions are minimal on a per-barrel-of-crude-produced basis.

Data for fugitive emissions from pumps, compressors, and well heads associated with an active well were reported for the state of California (EPA, 1992) and are reported in Table 5.7-1. Emission factors for fluids emitted from well heads were also reported by EPA and are shown in Table 5.7-2.

EPA also reports on emission factors due to flaring at oil production sites. These factors were compiled by the Ventura County, California, Resource Management Agency/Air Pollution Control District for oil field flares, regardless of size. The emission factors for flares are reported in Table 5.7-3.

### 5.7.2 Offshore Oil Platform Air Emissions

A typical offshore oil platform consists of gas turbines, emergency generators, crane engines, and other equipment. Due to the requirements of EPA air quality rules, control technologies and control strategies which would reduce the level of air pollutant emissions from the equipment are assumed to be installed on offshore platforms (E. H. Pechan & Assoc. 1992). A model platform developed by E. H. Pechan & Associates consists of 25 wells with 12,000 barrels of oil per day piped to onshore processing facilities.

The emission controls for the power generation units, the gas turbines, include dry low-$NO_X$ combustors, or lean premixed combustion configuration. The use of low sulfur diesel fuel is used for generators. A model platform is assumed to be serviced by support vessels: two crew boats per week, two supply boats per week, and five helicopters per week. All boats have engines rated at 2,500 horsepower, and emissions from all boats are expected to be 17.7 tons $NO_X$. Table 5.7-4 gives the model platform annual emissions produced from the platform projected power demands.

**Table 5.7-1. VOC Emission factors for pumps and compressors**

| Equipment | Emission factor/component (lb/day/unit) |
|---|---|
| Pump | 0.141 |
| Compressor | 25.00 |

**Table 5.7-2. VOC Emission factors for well heads (lb/day/well)**

| Fluids | Onshore | Offshore |
|---|---|---|
| Gas | 4.24 | 0.412 |
| Heavy Crude | No prediction | No prediction |
| Light Crude | 1.73 | 0.155 |
| Condensate | 0.181 | 0.0130 |
| Mixtures | 0.00293 | 0.000215 |

**Table 5.7-3. Emission factors for oil field flares (lb/MMcf)**

| | |
|---|---|
| Nitrogen Oxides (NOx) | 72 |
| Sulfur Oxides (SOx) | 0.6 |
| Carbon Monoxide (CO) | 40 |
| Reactive Organic Carbon (ROC) | 114 |
| Total Organic Carbon (TOC) | 1196 |
| Particulate Matter<br>(assume 99% destruction efficiency) | 3 |

**Table 5.7-4. Annual emissions for offshore platform producing 12,000 barrels of oil per day. (lbs emissions per $10^3$ bbls oil)**

| Source | HC | $NO_X$ |
|---|---|---|
| Gas-turbine generator | 13.69 | 28.12 |
| Oil processing equipment | 7.4 | - |
| Cranes | 0.28 | 2.47 |
| Emergency generator | 0.11 | 0.05 |
| Firewater pumps | 0.08 | - |
| Backup generators | 1.15 | 0.46 |
| Cement units | 1.35 | 0.19 |
| Total | 24.07 | 31.29 |

## 5.8 SUMMARY OF EMISSIONS FROM OIL CYCLE

Tables 5.8-1 and 5.8-2 are presented in order to compare the magnitudes of air pollutant emissions from the stages of the oil cycle. Emissions in lbs/$10^3$ bbl residual oil produced are given in Table 5.8-1 and those values converted to lbs/$10^3$ kWh electricity produced are given in Table 5.8-2. Air pollutants from onshore wells consist of emission factors for oil field flares (Table 5.7-3) and are not reported in Tables 5.8-1 and 5.8-2 since the data are not in consistent units (the flare releases are given in units of lb/MMcf of gas released; we require units to be lbs/$10^3$ bbl oil produced).

## 5.9 WATER POLLUTION FROM CRUDE REFINING

A large amount of wastewater is produced during crude refining. The discharge of wastewater from refineries is regulated through the permit programs of the National Pollutants Discharge Elimination System (NPDES) and state permit programs.

In petroleum refining, water is consumed in the following processes: evaporative cooling (about 71% of total water consumption), boiler feed water (about 26%), and sanitary and other in-plant uses (the remaining 3%) (Gloyna and Ford, 1975). Approximately, 0.17 to 0.71 barrels of water is consumed

**Table 5.8-1. Emissions from oil cycle stages.**
**(lbs/$10^3$ bbl residual oil produced)**

| Emissions | Residual Oil Production | Oil-fired Power Plants | Trans. and storage | Offshore Platforms[a] |
|---|---|---|---|---|
| PM | 17.79 | 27.3 | | |
| $SO_2$ | 196.54 | 659.4 | | |
| CO | 3.3 | 210 | | |
| HC | 49.61 | 24.07 | | 24.07 |
| $NO_2$ | 35.49 | 844.2 | | |
| $NO_x$ | | | | 31.29 |
| VOC | | 43.68 | 23.3[b]<br>46.9 | |

[a] Emissions for offshore platforms are given in terms of lbs per $10^3$ barrels of crude oil produced.

[b] The two emission values pertain to the SW and SE reference sites, respectively.

**Table 5.8-2. Emissions from oil cycle stages.**
**(lbs/$10^3$ bbl residual oil produced)**

| Emissions | Residual Oil Production | Oil-fired Power Plants | Trans. and storage | Offshore Platforms[a] |
|---|---|---|---|---|
| PM | 0.028 | 0.042 | | |
| $SO_2$ | 0.305 | 1.024 | | |
| CO | 0.005 | 0.326 | | |
| HC | 0.077 | | | 0.037 |
| $NO_2$ | 0.055 | 1.311 | | |
| NOx | | | | 0.049 |
| VOC | | 0.068 | 0.036[b]<br>0.073 | |

[a] Emissions for offshore platforms are given in terms of lbs per $10^3$ kWh of electricity converted from crude oil produced.

[b] The two emission values pertain to the SW and SE reference sites, respectively.

per barrel of crude processed (Gloyna and Ford, 1975). Consequently, large amounts of wastewaters are produced from refining processes.

The major constituents in refining wastewaters are $BOD_5$, COD, TOC, TSS, oil and grease, phenolic compounds, ammonia, sulfides, and chromium. The constituent concentrations of wastewater depend on the sources of refinery wastewaters.

### 5.9.1 Sources of Wastewaters in Refineries

a) Process Wastewater. Process wastewater is from non-segregated cooling water, cooling tower blowdown, boiler blowdown, oily process water, desalting water, tank emulsion water, water treatment system blowdown, and air pollution control equipment blowdown.

Raw process wastewater contains large amounts of oil and grease, as well as significant amounts of sulfur compounds, $NH_3$, dissolved inorganic particulates (resulting in TSS), and toxic chemicals. To oxidize these pollutants, wastewater exerts a chemical oxygen demand (COD). Bio-degradable compounds exert a biochemical oxygen demand (BOD).

Toxic pollutants contained in wastewater include benzene, PAHs (such as benzopyrene, chrysene, and pyrene), ethylbenzene, toluene, 2,4-dimethyphenol, acenaphthene, fluranthene, chrysene, chromium, phenanthrene, arsenic, cyanide, copper, lead, nickel, and zinc.

The amount of process wastewater can be reduced by several techniques: housekeeping to insure effective wastewater volume and pollutant loading; segregation to insure effective wastewater management (separation of clean water sewer, oily water sewer, and high contamination sewer); process modifications to reduce water use; and recycling and reuse schemes to reduce the amount of effluents. Process wastewater accounts for most of the wastewaters generated from a refinery. We estimate the amount of process wastewater in this report.

b) Storm Wastewater. This wastewater is the runoff from precipitation at the site of a refinery. Storm wastewater in refineries is usually contaminated by raw materials and products from refining processes. To minimize the load of storm wastewater, separate storm water storage and sewer systems can be established.

c) Ballast Water of Marine Vessels. Marine vessels that transport residual oil from refineries to power plants discharge ballast water at the site of a refinery.

Ballast water is contaminated by the previous contents of the cargo compartments. The discharge of ballast water into surface water causes water pollution. Before being discharged into surface water, ballast water is required to be treated. Treatment methods such as heating, settling, or filtration may be applied to recover the oil contained in ballast water. The recovered oil, which may be considerable, is generally sent to the slop oil system.

d) Sanitary Wastewater. Sanitary wastewater from refineries has pollutant characteristics similar to those of domestic sewage and is usually treated by biological oxidation.

### 5.9.2 Wastewater Treatment

The discharge of refining wastewaters is regulated through NDPES and state programs. To meet discharge requirements, refiners usually incorporate wastewater treatment systems in their refineries. Wastewater treatment systems at refineries generally consist of the following elements: (1) a drainage and collection system to collect and carry wastewaters to treatment units; (2) a primary treatment system to separate oils, water, and solids, and (3) a secondary biological treatment system to remove soluble biodegradable wastewater pollutants.

a) Primary Treatment. The primary treatment involves the physical and/or chemical separation of oils, water, and solids in the wastewater stream. The treatment is conducted in two stages: primary (gravitational) oil/water/solids separation and secondary (emulsified) oil/water/solids separation.

Gravity separators remove a majority of the free oil found in refinery wastewaters. The effectiveness of gravity-separators depends on the temperature of the water, the density and size of the oil globules, and the amounts and the characteristics of suspended solids present in the wastewater. Among the gravity-separators, the API separator is widely used. The basic design of an API separator includes a long rectangular basin in which enough detention time is allowed for most of the oil to float to the surface and be removed.

Other methods such as the dissolved air flotation method are also used to separate oils, water, and solids. In a dissolved air flotation system, a portion of the wastewater is saturated in a flotation unit at high pressures. The waste stream is suddenly released to a chamber under atmospheric pressure. The sudden reduction in pressure results in the release of microscopic air bubbles which attach themselves to the oil and suspended particles contained in the wastewater. Subsequently, the oil and particles rise to the surface with air bubbles to form a layer which can be easily removed.

b) Secondary Treatment Methods. These treatment methods mainly employ biological treatment of wastewaters. Micro-organisms digest the degradable dissolved oil and soluble biodegradable wastewater pollutants. Biological methods include oxidation ponds, aerated lagoons, trickling filters, rotating biological contactors, and activated sludge.

Oxidation Ponds. An oxidation pond has a large surface area and a shallow depth. The algae in the pond produce oxygen through photosynthesis. The created oxygen is then used by bacteria to oxidize the wastes.

Aerated Lagoon. An aerated lagoon is a smaller, deeper oxidation pond equipped with mechanical aerators or diffused air units which add oxygen to the oxidation pond. The addition of oxygen enables the aerated lagoon to have a higher concentration of microbes than a regular oxidation pond.

Trickling Filter. A trickling filter is an aerobic biological process. Filtration media are spread on a filtration bed. Biomass is attached to the bed media. The filter works by the adsorption of organics by the biological slime, diffusion of air into the biomass, and oxidation of the dissolved organics.

Activated Sludge Tank. This is an aerobic biological treatment process in which high concentrations of newly-grown and recycled micro-organisms are suspended uniformly throughout a holding tank to which raw wastewater is added. Oxygen is introduced by mechanical aerators, diffused air systems, or other means. The organic materials in the waste are removed from the aqueous phase by the microbiological growths and stabilized by the biochemical synthesis and oxidation reactions.

### 5.9.3 The Amount of Process Wastewater

The amount of wastewater and the concentration of pollutants in wastewater depend on the type of refining process, quality of crude feedstock, and treatment methods employed. It is probably rare to find refineries that generate the same pollutants in similar amounts per barrel of crude processed. A U.S. DOE study has estimated the average amount of water pollutants generated from petroleum refining. Table 5.9-1 presents the amount of water pollutants produced from each of the major refining processes.

### 5.9.4 The Amount of Wastewaters Attributable to Residual Oil Production

Not all of the four refining processes in Table 5.9-1 are relevant to residual oil productions. For example, petrochemical and lube processes are primarily designed to produce petrochemical feedstocks and lubricant oils. It would not be proper to assign wastewater from these two processes to residual oil production. Therefore, we do not assign any wastewater from these two processes to residual oil production in this study.

For the topping and cracking processes, we need to decide how to convert lb/$10^3$ bbl of feedstock throughput to lbs/$10^3$ bbl of residual oil produced. Two factors need to be considered to conduct the conversion. First, the effluent discharge rate needs to be adjusted by the density difference between crude and residual oil. Although one ton of crude may produce one ton of residual oil (due to the law of mass conservation), one barrel of crude does not necessarily produce one barrel of residual oil (because of the density difference). While the density of crude is about 295 lb/bbl, the density of residual oil is about 331 lb/bbl (API, 1991b). Assuming an equal mass of residual oil and crude, 1.12 bbl of crude is needed to produce one barrel of residual oil. Therefore, the discharge rate in lb/$10^3$ bbl of crude needs to be multiplied by 1.12 to convert the discharge rate to lb/$10^3$ bbl of residual oil produced.

Second, different refining products produced from a refining process require different levels of refining intensity. Because less refining intensity is required to produce residual oil, it is proper to assign a smaller portion of the generated wastewater to residual oil than to other products such as gasoline. We have considered these two factors when estimating the discharge rate of residual oil production.

In this study, the refining category "topping" includes crude distillation and catalytic reforming. While crude distillation is relevant to residual oil production, catalytic reforming is not. We need to allocate the shares of wastewater generated from the topping category between crude distillation and catalytic reforming. We will then use the wastewater generated from crude distillation to estimate the wastewater generated from residual oil production. We allocate the wastewater shares between these two processes based on the amount of water required by each of them to process one barrel of feedstock. Generally speaking, catalytic reforming requires more water than crude distillation. On the average, crude distillation requires 20 gallons of cooling water per barrel of crude feed, while catalytic reforming requires 40 gallons of cooling water per barrel of feedstock input (Hydrocarbon Processing, 1990). Therefore, we allocate 1/3 of the wastewater from the topping category to the process of crude distillation.

DeLuchi (1992) estimates that 7% of the output product from crude distillation and 8.5% of the output product from catalytic cracking is residual oil. To allocate the wastewater generated from these two processes to residual oil production, we use a percentage number smaller than the residual oil production percentage. This is because the production of residual oil requires less intensive refining activities than the production of high-quality fuels such as gasoline and distillate fuels. Therefore, to estimate the wastewater due to residual oil production, we assume that 5% of the wastewater produced during crude distillation (compared with a 7% residual oil production share) and 6% of the wastewater produced during catalytic cracking (compared with a 8.5% residual oil production share) are due to the production of residual oil. Table 5.9-2 presents the amount of wastewater and water pollutants per $10^3$ barrels of residual oil produced.

## 5.10 HAZARDOUS WASTES FROM CRUDE REFINING

### 5.10.1 Sources and Types of Hazardous Wastes

Various types of solid wastes are produced during crude refining. They include DAF (dissolved air flotation) float, slop-oil emulsion solids, sludge from heat-exchanger bundles, API separator sludge, leaded gasoline tank bottoms, spent catalysts, vessel sludges and sediments, coking and wax wastes, and wastes generated in wastewater treatment plants. The constituents of concern in these wastes are usually benzene, benzo(a)pyrene, chrysene, chromium, lead, selenium, arsenic, mercury, beryllium, nickel, silver, cadmium, etc. (EPA, 1988).

Based on their generating patterns, refinery solid wastes may be categorized into intermittent wastes and continuous wastes. Intermittent wastes include sludges from crude oil storage tanks, solids settling in API separators, alkylation sludges, sludges from primary settling tanks, sludges from cooling water systems, sediments from heat-exchanger bundles, spent catalysts in fixed-bed catalyst systems, and silt from stormwater settling basins. Continuous wastes include fixed-bed clays used to remove color bodies, chemical treatment residues, traces of moisture from various products, and resides from wastewater treatment facilities.

Hazardous wastes are regulated through the Resource Conservation and Recovery Act (RCRA) of 1976 and other legislation. The RCRA is designed to reduce hazardous wastes and to minimize their adverse effects during treatment, storage, and disposal. The RCRA gives the EPA the authority to determine whether or not a solid waste is a hazardous waste. If a solid waste is categorized as hazardous, a manifest must accompany the waste from its point of generation

**Table 5.9-1. Wastewater loadings by refining processes[a] (lb/$10^3$ bbl throughput)**

| | Topping[b] | Cracking | Petrochemical | Lube |
|---|---|---|---|---|
| Flow[c] | 55.464 | 21.948 | 13.1987 | 6.6735 |
| $BOD_5$ | 1.2 | 24.8 | 34 | 17 |
| COD | 13 | 64 | 84 | 28 |
| TOC | 2.8 | 12.2 | 38 | 0 |
| TSS | 4.2 | 2.1 | 10.7 | 8 |
| $NH_3$-nitrogen | 0.42 | 9.38 | 2.2 | 0 |
| Phenols | 0.01 | 1.39 | 1.3 | 0.2 |
| Oil and grease | 2.9 | 8.1 | 8 | 23 |
| Sulfides | 0.02 | 0.31 | 0 | 0 |
| Total chromium | 0.002 | 0.088 | 0 | 0 |

[a] From DOE (1988). DOE's estimated amount of water pollutants is the amount remaining after treatment by API separators.

[b] We define refining processes differently from DOE's refining categories. A DOE category may include more than one process that we define here. For example, DOE's cracking category includes distillation and cracking processes. Our cracking category includes the cracking process only. The topping process here includes distillation and catalytic reforming.

[c] The flow rate of wastewater is given in $10^3$ bbl of wastewater per $10^3$ bbl of feedstock throughput.

to its point of disposal in a permitted facility. (For an overview of hazardous waste regulations in the U.S., see Appendix A).

The RCRA categorizes hazardous wastes according to their generating sources and waste characteristics. Currently, hundreds of waste types are regulated by the RCRA. Of them, seven types are produced by the petroleum refining industry. These include five K-type hazardous wastes and two F-type hazardous wastes. The five K hazardous wastes include K048 (DAF float), K049 (slop oil emulsion solids), K050 (heat-exchanger bundle cleaning sludges), K051 (API separator sludge), and K052 (leaded tank bottoms). The two F hazardous wastes are F037 (petroleum refinery primary oil/water/solids separation sludge) and F038 (petroleum refinery secondary [emulsified] oil/water/solids separation sludge) (EPA, 1990). The two F hazardous wastes are produced by wastewater treatment facilities in refineries. The secondary biological sludges from biological treatment plants in refineries are not currently regulated by the RCRA.

### 5.10.2 The Amount of Wastes Generated Due to Residual Oil Production

In the past, the American Petroleum Institute (API) conducted surveys to estimate the quantity and dispositions of the wastes generated by the petroleum refining industry. The API has started to conduct an annual waste generation and management survey. The most recent published survey results are the wastes generated and managed between 1987 and 1988 by the refining industry. Based on API survey results, we have estimated the amount of wastes generated per $10^3$ barrels of crude processed for 28 waste types, which we present in Table 5.10-1.

**Table 5.9-2. The amount of wastewater and water pollutants[a] (lb/$10^3$ bbl residual oil produced)**

| Pollutant | Amount |
|---|---|
| Flow ($10^3$ bbl/$10^3$ bbl of residual oil) | 16.20 |
| $BOD_5$ | 10.896 |
| COD | 29.313 |
| TOC | 5.627 |
| TSS | 1.417 |
| $NH_3$ (nitrogen) | 4.120 |
| Phenols | 0.604 |
| Oil and grease | 3.861 |
| Sulfides | 0.137 |
| Total chromium | 0.038 |

[a] Calculated as [(amount of waste generated during topping)/3 x 0.05+(amount of waste generated during cracking) x 0.06)/(0.07+0.085)] x 1.12. See text for detailed discussion.

### Table 5.10-1. Refinery waste generation[a]

| Waste Type | Wet ton/10$^3$ bbl of Crude Input | Wet ton/10$^3$ Residual Oil Output[c] |
|---|---|---|
| Other Aqueous Wastes (NOS[b]) | 2.3484 | 1.6768 |
| Biomass | 0.1620 | 0.1157 |
| Spent caustics | 0.1396 | 0 |
| Dissolved air flotation float | 0.1373 | 0.0980 |
| API separator sludge | 0.0793 | 0.0566 |
| Pond sediments | 0.0634 | 0.0453 |
| Other inorganic wastes (NOS[b]) | 0.0566 | 0.0404 |
| Nonleaded tank bottoms | 0.0362 | 0.0258 |
| Slop oil emulsion solids | 0.0454 | 0.0324 |
| Other wastes (NOS[b]) | 0.0646 | 0.0461 |
| Contaminated soil/solids | 0.0425 | 0.0303 |
| Fluid cracking catalyst or equivalent | 0.0385 | 0.0275 |
| High pH/low pH waters | 0.0296 | 0.0211 |
| Spent acids | 0.0288 | 0 |
| Other contaminated soils (NOS[b]) | 0.0157 | 0.0112 |
| Other separator sludges | 0.0191 | 0.0136 |
| Waste coke/carbon/charcoal | 0.0115 | 0 |
| Spent sulfite solution | 0.0087 | 0 |
| Other oily sludges and inorganic waste | 0.0105 | 0.0075 |
| Hydroprocessing catalysts | 0.0080 | 0 |
| Other spent catalysts (NOS[b]) | 0.0074 | 0 |
| Spent stretford solution | 0.0087 | 0 |
| Oil contaminated water (other than wastewater) | 0.0067 | 0.0048 |
| Waste sulfur | 0.0040 | 0 |
| Waste amines | 0.0028 | 0 |
| Leaded tank bottoms | 0.0018 | 0.0013 |
| Waste oils/spent solvents | 0.0012 | 0 |
| Heat exchanger cleaning bundle sludge | 0.0008 | 0.0006 |

[a] We use the total amount of wastes generated by the refinery industry estimated by the API (1991a) and the total amount of crude processed in 1987 and 1988 estimated by EIA (a total of 9.52 billion barrels of crude: 4.69 billion barrels produced in 1987 and 4.83 billion barrels produced in 1988)(EIA, 1991a).

[b] Not otherwise specified.

[c] We *do not* allocate wastes to residual oil proportional to the percentage of residual oil produced at a refinery. On the average, residual oil accounts for 7% of the products produced by refineries. Since the production of residual oil does not require as intensive refining activities as do high-quality products, we allocate 5% of the total wastes to the 7% residual oil production.

Some of the wastes listed above are from refining processes that are irrelevant to residual oil production. In calculating wastes due to residual oil production, we assign a zero value to those wastes not generated due to residual oil production.

### 5.10.3 Management of Hazardous Wastes

The waste management practices in refineries include recycling, treatment (land and other treatment methods), and disposal. Recycling practices are used to recapture hydrocarbons in the form of waste oils, off-specification products, and used oils. Such recovered oils can be fed into refining processes for producing refining products. Recycling practices are also used for recovering catalysts, caustics, and acids applied in various refining processes. Table 5.10-2 shows the percentage of wastes managed by different methods.

Treatment methods include separation techniques such as decanting, centrifugation, and filtration; chemical, physical, heat, and stabilization/fixation methods; incineration; and land treatment.

The principal incineration method is fluid-bed incineration through which a bed of sand is preheated with hot air. Torch oil is then used to raise the bed temperature. Sludges are then introduced, and the torch oil is stopped. The solid products of combustion remaining in the bed are gradually withdrawn to maintain a constant bed height.

Land treatment, also known as land farming, employs the biodegradation of organic compounds by organisms naturally existing in soil. Through this method, organic wastes are spread on the soil surface, tilled (to provide oxygen), fertilized (to provide nutrients), and watered (to provide moisture), if needed. The residue from the biodegradation process remains on the ground and must be properly managed upon closure of the landfarm. This process is subject to RCRA land ban restrictions for hazardous wastes.

The wastes remaining after treatment are disposed of by various methods such as well injection, landfills, impoundments, or landspreading. A landfill operation requires a large amount of land. The wastes are disposed of in an excavation site. When the site is filled to capacity, it is covered with a thick layer of earth. The major problem with landfills is the potential adverse effects of leached toxic constituents to ground and surface waters. The API (1991a) found that the greatest quantity of wastes from the refinery industry is disposed of by deep well injection; the next largest quantity is disposed of in landfills.

**Table 5.10-2. Percentage of wastes managed through different methods[a]**

| | Recycling[b] | Treatment[c] | Land Treatment[d] | Disposal[e] |
|---|---|---|---|---|
| Other aqueous wastes (NOS) | 0.00 | 0.08 | 0.00 | 99.92 |
| Biomass | 3.59 | 43.75 | 33.89 | 18.78 |
| Spent caustics | 74.94 | 20.21 | 0.18 | 4.67 |
| Dissolved air flotation float | 16.70 | 46.13 | 28.02 | 9.15 |
| API separator sludge | 13.82 | 34.48 | 27.58 | 24.12 |
| Pond sediments | 0.94 | 16.22 | 23.15 | 59.69 |
| Other inorganic waste (NOS) | 6.15 | 27.28 | 10.21 | 56.35 |
| Nonleaded tank bottoms | 11.92 | 25.24 | 28.72 | 34.11 |
| Slop oil emulsion solids | 27.61 | 38.34 | 21.50 | 12.55 |
| Other wastes (NOS) | 2.90 | 2.59 | 0.31 | 94.20 |
| Contaminated soil/solids | 7.20 | 0.00 | 11.68 | 81.12 |
| FCC catalysts or equivalent | 13.72 | 1.63 | 9.03 | 75.62 |
| High pH/low pH waters | 49.12 | 36.69 | 0.02 | 14.17 |
| Spent acids | 41.95 | 56.20 | 0.00 | 1.85 |
| Other contaminated soils (NOS) | 0.90 | 0.05 | 6.31 | 92.74 |
| Other separator sludges | 23.19 | 43.36 | 16.95 | 16.51 |
| Waste coke/carbon/charcoal | 73.97 | 0.00 | 0.51 | 25.51 |
| Spent sulfite solution | 31.59 | 58.58 | 0.00 | 9.83 |
| Other oily sludges & inorganic wastes | 49.70 | 1.99 | 18.01 | 30.30 |
| Hydroprocessing catalysts | 64.01 | 0.22 | 0.65 | 35.12 |
| Other spent catalysts (NOS) | 30.22 | 21.77 | 3.34 | 44.67 |
| Spent stretford solution | 0.00 | 69.03 | 0.00 | 30.97 |
| Oil contaminated water (not wastewater) | 0.48 | 95.39 | 0.03 | 4.10 |
| Waste sulfur | 4.65 | 0.00 | 0.09 | 95.26 |
| Waste amines | 40.30 | 19.31 | 2.39 | 38.00 |
| Leaded tank bottoms | 1.69 | 50.92 | 18.10 | 29.29 |
| Waste oils/spent solvents | 60.95 | 7.44 | 4.44 | 27.17 |
| Heat exchanger cleaning bundle sludge | 7.16 | 38.08 | 21.49 | 33.28 |

[a] Based on 1987-88 data. Calculated using data presented by API (API, 1991a).

[b] Major recycling methods include the reclamation and regeneration of spent catalysts, chemicals, and inorganic wastes. Recycling is conducted on-site or off-site, depending on the type of waste involved.

[c] Wastewater treatment is the major treatment method for most wastes. Virtually all wastes are treated on-site.

[d] Most wastes are land-treated on-site.

[e] Wastes are disposed of in impoundments, landfills, or injection wells or by landspreading. Wastes can be disposed of on-site or off-site.

### 5.10.4. Constituent Concentration of Wastes

Constituent concentrations of wastes vary among different wastes, refining processes, types of crude feedstock, and management methods. A U.S. DOE study has assessed the constituent concentrations of wastes from petroleum refining (DOE, 1988). Table 5.10-3 presents DOE's constituent concentration results.

Ideally, we would prefer to calculate the amount of pollutant by type of constituents from all wastes listed in Table 5.10-1. However, most of the waste types in Table 5.10-1 do not match with the waste types in Table 5.10-3. Because we do not have constituent concentration information for many types of wastes, and because the constituent concentration of one waste type could be very different from that for another, we are unable to calculate the total amount of pollutants by constituent type.

**Table 5.10-3. Constituent concentrations of petroleum refining wastes (unit: ppm in a mass basis of wet weight)**

| Solid Waste | Total Cr | Pb | Se | As | Hg | Be | Ni | Ag | Cd | Phenols | Cyanide |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DAF float | 140 | 7.5 | 2.02 | 2.0 | 0.27 | 0.0013 | 0.035 | 0.25 | 0.005 | 6.5 | 0.28 |
| Slop-oil emulsion solids | 525 | 28.1 | 1.0 | 7.4 | 0.59 | 0.0025 | 50.0 | 0.4 | 0.19 | 15 | 0.001 |
| Heat-exchanger bundle sludge | 311 | 78.0 | 27.1 | 10.6 | 1.9 | 0.20 | 116.0 | 0.005 | 1.3 | 13.3 | 1.7 |
| API separator sludge | 253 | 26 | 0.001 | 6.2 | 0.4 | 0.0025 | 0.9 | 0.45 | 0.42 | 13.6 | 0.001 |
| Leaded tank bottoms | 11.4 | 790 | 6.95 | 294 | 0.57 | 0.0025 | 314 | 0.88 | 6.3 | 12.6 | 0.0009 |
| Waste bio-sludge | 4.0 | 1.0 | 0.1 | 3.8 | 0.18 | 0.0013 | 0.025 | 0.3 | 0.3 | 4.5 | 0.001 |
| FCC catalyst fines | 48 | 72.5 | 0.01 | 1.0 | 0.0004 | 0.5 | 241 | 1.8 | 0.003 | 2.1 | 0.12 |
| Unloaded tank bottoms | 2.0 | 4.0 | 12.0 | 0.007 | 0.43 | 0.26 | 26.7 | 0.6 | 0.33 | 1.8 | 7.4 |
| Primary separator sludge | 235 | 23.5 | | | | | | | | | |
| Stretford solution | 71 | 79 | | | | | | | | | |
| HF alkylation sludge | 28.5 | 33 | 7.1 | 2.3 | 0.07 | 0.07 | 52.2 | 0.19 | 0.07 | 8.9 | 23.1 |
| Other spent catalysts | 13 | 70.5 | | | | | | | | | |
| Cooling tower sludge | 13 | 9 | 0.015 | 8.2 | 0.9 | 0.0013 | 6.8 | 0.28 | 0.3 | 3.5 | 0.1 |
| Treating clays | | 40,000 | | | | | | | | | |
| Secondary separator sludge | 1,085 | 875 | | | | | | | | | |
| Crude tank bottoms | 1.0 | 3.0 | 0.03 | 21.1 | 0.48 | 0.0026 | 16.2 | 0.19 | 0.31 | 15.8 | 0.0012 |

Note: A blank cell means that no data were available; it does not indicate a zero amount.

# 6. PRIORITY PATHWAYS

This chapter provides an overview of the impact-pathways for the oil fuel cycle. From this overview the priority impact-pathways are identified. The priority impact pathways are the basis for impact estimation and economic valuation in subsequent sections of this report.

## 6.1 OVERVIEW OF FUEL CYCLES STAGES AND IMPACTS

The drilling and production of crude oil, the transport of the crude oil to refineries, the conversion of crude oil to residual oil, the transport of residual oil to an oil-fired electric power plant, and the production of electricity are five major stages of the oil-to-electricity fuel cycle. Offshore, the primary factor inputs that give rise to ecological impacts in the first stage of the fuel cycle are crude oil spills and discharge of drilling fluids, 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 leaching to groundwater.

During the second stage of the fuel cycle the transport of crude oil by tanker truck leads to air emissions from combustion of diesel fuel. The tanker trucks also contribute to road deterioration, noise, traffic, and diminished aesthetic quality of the rural environment. Offshore, leaks of crude oil from pipelines in the vicinity of production platforms would have a similar impact to marine resources as oil spills from platforms.

The refining process, which is the third stage of the oil fuel cycle, produces sludge, air emissions from the combustion of gas and oil, and wastewater containing toxic compounds and oil. The major land and water impacts from the refining process can also lead to leaching of waste components to groundwater.

The fourth stage, the transport of residual oil to the electric utility by barges, railroad tank cars, and tanker trucks will produce air emissions from fuel combustion by the transport mode, and from cleaning of storage tanks. In addition, oil spills can occur during the transportation of residual fuel. The spills in water can have effects on marine or freshwater organisms, and drinking water, if spilled.

The final stage of the fuel cycle is electricity generation. This stage produces air emissions from the combustion of residual oil. The impacts from the emissions from the oil fuel cycle are primarily on health, with some potential ecological effects on crop yield and wildlife.

For each stage of the fuel cycle, there are potential health and safety impacts. There are potential safety impacts due to accidents from the drilling and transport stages. As with other fuel cycles, there are potential employment impacts, and these should be compared across fuel cycles.

## 6.2 OIL FUEL CYCLE IMPACT-PATHWAYS

Table 6.2-1 lists the emissions, environmental pathways, and ecological impacts that were discussed in detail in Chapters 4 and 5, and in Appendix D, and gives the reasons why these were evaluated. Impacts which are assessed in further 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. Further discussion of this screening procedure is in ORNL/RFF (1994, Chapter 4). Many impacts are minor and are not addressed further.

## 6.3 PRIORITY IMPACT PATHWAYS

This section lists the priority impact-pathways from an oil-to-electricity fuel cycle. 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 the most significant in terms of their potential for externalities.

Impacts from crude oil production:

- contamination of surface and ground water from onshore drilling
- effects on marine organisms due to wastewaters from offshore drilling
- effects on aquatic or marine organisms due to crude oil spills from offshore drilling platforms
- injuries from offshore production activities

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

| Emissions | Environmental Pathway | Impact | Impact Evaluation |
|---|---|---|---|
| | ***Air Emissions:*** | | |
| Carbon dioxide<br>Carbon monoxide | Atmospheric dispersion | Global warming | Nonquantifiable increment |
| Nitrogen oxides<br>Sulfur dioxide | Deposition on plant surfaces and soil; inhalation by wildlife. | Effects on plant growth, wildlife | No impact demonstrated |
| Acid aerosols from $NO_x$ and $SO_2$ | Long range transport, acid deposition | Effects on plants, wildlife | No impact demonstrated |
| Ozone | Secondary formation in the atmosphere; long range transport | *Effects on crop yield*;<br>Effects on wildlife | Quantified;<br>No direct effects on wildlife due to low concentrations |
| | ***Water Emissions:*** | | |
| Oil | Spills from drilling platforms, pipelines, or barges | *Effects on aquatic or marine organisms*; drinking water | Quantified |
| Produced water | Drilling byproduct disposed of at sea | *Effects on marine organisms* | Qualitative evaluation |
| Drilling fluids | Drilling waste disposed of at sea | *Effects on marine organisms* | Qualitative evaluation |
| Drill cuttings | Drilling waste disposed of at sea | *Effects on marine organisms* | Qualitative evaluation |
| Suspended sediments | Dredging for pipelines or channels | Effects on aquatic or marine organisms; drinking water | Qualitative evaluation |
| | ***Other Factors:*** | | |
| Erosion | Coastal activities | Effects on marine organisms | Qualitative evaluation |
| Solid wastes | Leaching to groundwater | Effects on drinking water, irrigation water, crops, livestock | Qualitative evaluation |

## Table 6.2-2 Emissions, pathways, and impacts of oil fuel cycle not examined in detail

| Emissions | Environmental Pathways | Impacts | Impact Evaluation |
|---|---|---|---|
| | ***Air Emissions:*** | | |
| Particulates,<br>Acid aerosols,<br>Hydrocarbons<br>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. |
| Inorganic compounds (metals) | Combustion emissions | Effects on plants and animals | Insufficient data |
| Organic compounds | Combustion emissions | Effects on plants and animals | Insufficient data |
| | ***Water Emissions:*** | | |
| Cooling water | Releases from power plant cooling system | Effects on aquatic organisms | Minimal impacts due to closed cycle and high dilution |
| Wastewater<br>BOD<br>COD<br>Metals | 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 an oil-to-electricity fuel cycle.

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

| Emissions/Burden | Environmental Pathway | Impact | Impact Evaluation |
|---|---|---|---|
| | | *Air Emissions:* | |
| Carbon monoxide | Atmospheric dispersion | Human health | Minimal impacts due to below threshold concentrations |
| $NO_x$<br>$SO_x$ | Atmospheric dispersion | *Human health* | Quantified |
| Particulates | Atmospheric dispersion | *Human health* | Quantified |
| Ozone | Ozone Model + dispersion | *Human health* | Quantified |
| Metals | Atmospheric dispersion | *Human health* | Difficult to quantify; likely small impact [refer to ORNL/RFF (1994b)] |
| | | *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* | Quantified |
| Refining | 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 oil 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 | Human health | Lack of knowledge on specific effluents |
| Waterborne effluents of refining | Drinking water/ food chain | Human health | Pathways studies lacking |
| | ***Other Factors:*** | | |
| Noise | Tractors/truck | Human health | Expected to be small |

Impacts from refining crude oil:

- ecological and health effects of emissions and other wastes from refineries

Impacts from crude and residual oil transportation:

- effects on aquatic or marine organisms due to crude and residual oil spills from barges, or tanker trucks
- fatalities and injuries from truck accidents
- road deterioration from oil tanker truck traffic

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 crude oil contamination of surface waters and 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.

# 7. IMPACTS AND DAMAGES FROM OIL

## 7.1 EFFECT OF ONSHORE WASTEWATERS ON AQUATIC RESOURCES

### 7.1.1 Activities and Emissions

The crude oil supplied to the Texas refinery would be produced onshore in southeast Texas in 1990 and offshore in the Texas Gulf in 2010. Crude oil for the northwestern New Mexico refinery would be produced onshore in southeast New Mexico in both 1990 and 2010.

The amounts of drilling wastes and produced water, concentrations of constituents in produced water, concentrations of constituents in drilling fluids, the total amounts of contaminants in produced water (per bbl), and the total amounts of contaminants in drilling fluid (kg/well) from onshore wells in New Mexico and Texas are described in Chapter 5 (Tables 5.1-4, 5.1-6, 5.1-7, 5.1-10, and 5.1-11, respectively).

### 7.1.2 Impact on Aquatic Resources

Oily and other wastewaters (produced water, drilling fluids, and drill cuttings) can impact surface water and stream biota and migrate to groundwater. Disposal practices for these wastes vary from state-to-state and site-to-site. Wastewaters from oil wells in southeastern Texas would most likely impact estuarine waters. In southeastern New Mexico, a limited number of surface streams makes groundwater a likely fate of wastewater discharges and concerns for human health and crop damage from contaminants are more likely than impacts to aquatic organisms in surface waters. While it is difficult to make generalizations concerning contamination of the environment, a limited number of descriptive case studies document environmental impacts in Texas and New Mexico.

Texas allows the discharge of produced water into tidally affected streams and estuaries and bays of the Gulf Coast from nearby onshore development of oil fields (U.S. EPA 1987). Along with the produced water, residual production chemicals and organic constituents including lead, zinc, chromium, barium, and water-soluble polycyclic aromatic hydrocarbons (PAH) may be discharged. Tabb's Bay, Texas, which receives produced water as well as discharges from upstream industry, has become severely degraded by PAH contamination. Another site, Petronilla Creek, which empties into Baffin Bay, contains high levels of chromium, barium, oil, grease, naphthalene, and benzene; no species of freshwater fish or vegetation are present. Discharges to Petronilla Creek are now prohibited. Other discharges to tidally-affected areas are permitted by the Texas Railroad Commission, but the U.S. EPA has not issued NPDES permits. Two cases of illegal disposal of drilling muds were also reported: in both cases reserve pits were breached allowing drainage into surface streams.

The reference site of Lea County in southeastern New Mexico has been a major petroleum producing area since the early 1900s. The depth to the water table in this area ranges from 30 to 250 feet, with a maximum saturated thickness of 200 feet. Contamination of groundwater with crude oil, natural gas, and produced water became evident in the 1950s. Groundwater contamination is of particular concern in New Mexico because approximately 88% of the population relies upon groundwater for their water supply (New Mexico Water Quality Control Commission 1990). New Mexico still allows the disposal of produced water into unlined pits (U.S. EPA 1987). However, because of groundwater contamination, the amount of produced water discharged into unlined pits is limited to five barrels per day (typically, each well is served by a single reserve pit). Also in southeastern New Mexico, inadequate maintenance of a saltwater injection well associated with oil production resulted in contamination of ground water with salt (injection occurs at 10,000 feet). When the groundwater was used as a source of irrigation water for crops, crop damage resulted (U.S. EPA 1987).

### 7.1.3 Economic Valuation

While impacts have been identified based on past studies, methods of damage recovery involve site-specific collection of data. There are no exposure data associated with oil wells that could be considered representative of our reference case scenarios.

## 7.2 EFFECT OF WASTEWATERS ON FISHERIES AND BENTHIC FAUNA

### 7.2.1 Activities and Emissions

Wastewater is caused by drilling activity, as described in Sections 4.1 and 5.1. Effluent concentrations were estimated by EPA (1991) and are cited in Table 5.1-5.

The 2010 scenario for the Southeast Reference site assumes *offshore* oil drilling in the Gulf of Mexico. 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 undertaken in the Gulf of Mexico (Neff 1987, U.S. Department of Interior 1991).

### 7.2.2 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 have 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 to 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.

> ***... chronic impacts on Gulf resources have been difficult to detect and quantify but remain***

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. These decreases have been attributed to overfishing. 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.

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. According to the U.S. Department of Interior (1991), no permanent degradation of water quality is expected in the offshore coastal environment. Dispersion models for drilling fluids and drill cuttings adequately describe short-term dispersion, but models have not been successful in adequately predicting the long-term dispersion of discharges from platforms (Payne et al. 1987). As noted above, 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. In some cases, effects on water quality have been observed within 1,000-1,500 meters of platforms.

Water quality criteria for saltwater organisms have been set for some of the priority pollutants of produced water and drilling fluid components (Table 7.2-1) (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.

The greatest measured 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 development.

***Drilling platforms attract fish and sport fishing has increased***

On the other hand, the Gulf of Mexico is a year-round habitat for many sport fishes. Drilling platforms attract fish and sport fishing has increased around platforms.

### 7.2.3 Economic Valuation

While impacts have been identified based on past studies, there are no exposure data associated with offshore drilling that could be considered representative of our reference case scenarios.

### Table 7.2-1 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.

## 7.3 EFFECT OF OIL SPILLS ON MARINE AND COASTAL RESOURCES

### 7.3.1. Accident Rates and Amounts Spilled

Under the 2010 scenario for the Southeast Reference site, drilling and production of crude oil takes place offshore. Oil spills of $\leq$10 barrels in size account for 99% of spills from oil activities on the Outer Continental Shelf of theGulf of Mexico (Anderson and LaBelle 1990). These small spills do not travel great distances or persist long enough to have measurable environmental impact. The spill rate for spills of 1,000 barrels and greater from platforms is 0.60 spills per billion barrels handled. The average size of these larger spills is 18,046 barrels.

Because oil spills are episodic rather than continuous events, ecological impacts should not be annualized. Rather, the probability of such an event occurring given the site and time for crude oil supplied to a 300-MW power plant should be considered. Using the spill rate of 0.60 spills per billion barrels handled, the probability of a major spill occurring during the handling of the yearly 3.26 million barrels needed for a 300-MW power plant is 0.00196 (spills/3.26 million barrels).

### 7.3.2 Impact on Marine and Coastal Resources

Oil spills in marine and coastal areas due to spills of crude oil from platforms would cause a direct and measurable ecological impact. Although effects would be site-specific and costs would depend on the economic value of the land and presence or absence of finfish and shellfish fisheries and wildlife, in general, these areas are considered valuable natural resources.

Injuries to marine and coastal resources from an oil spill can be estimated using the Natural Resource Damages Assessment Model for Coastal and Marine Environments (NRDAM/CME) (EA and ASA 1987). The NRDAM/CME provides a "Type A" natural resource damage assessment under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). A "Type A" assessment is a standard and simplified procedure in contrast to a "Type B" procedure which is used in individual cases. CERCLA provides that damages are compensated for injuries to natural resources. Injuries can be estimated for commercially and recreationally harvested fish, lower trophic biota (the food source for other animals), birds, fur seals, and public beaches. Damages are measured in terms of "willingness to pay," using established market prices where possible.

The impact of coastal spills on natural resources depends on the (1) characteristics of the environment in which the spill occurs, such as location and season of the incident, water depth, currents, temperature and (2) the natural resources at risk, which depends principally on the location of the spill. The model provides for selection among ten coastal or marine ecoregions or provinces (Cowardin et al. 1979) in which spills may occur. In addition, shoreline types are provided for the eastern, central, and western Gulf of Mexico. Within each region, resources are distributed according to bottom type, water depth, and many other factors.

The model is composed of a coupled system of numerical submodels for physical fates, biological effects, and economic damages. The physical fates submodel simulates the spreading on the sea surface, mixing, and degradation of oil in the environment (equations for these processes can be found in EA and ASA 1987). The physical fates submodel also has a chemical data base containing physical, chemical, and toxicological information on 469 oil and chemical substances. Evaporation into the atmosphere as well as distribution and concentrations of the oil on the water surface and concentrations in the upper and lower water columns and sediments are calculated. The user supplies site specific information on water depth, mean and tidal currents, wind speed and direction, and air temperature. The output of the model includes the concentration of the oil over time in the upper and lower water column and in bottom sediments and the surface area covered by the slick. For spills in intertidal areas, the area and length of shoreline affected is computed. The submodel provides for cleanup of spills. This information is fed to the biological effects submodel which calculates the effects of these concentrations on subtidal and tidal biota.

The biological effects submodel receives input from the physical fates submodel, the toxicological section of the chemical data base, a biological data base, and user input. The biological data base contains information on biological abundance of various categories of finfish, shellfish, fur seals, and birds in the ten provinces. The submodel calculates injury to biota and public facilities in the appropriate province, in this case the Louisianian Province, by season. The biological and physical injuries considered are:

(1) "direct, lethal effects on larvae, juveniles, and adult fish and shellfish, waterfowl, seabirds, shorebirds, fur seals, and lower trophic biota;

(2) indirect and long-term effects involving the eventual loss of fish and shellfish as a result of kills of larvae and juveniles, and birds, as a result of kills of lost broods;

(3) indirect effects resulting from kills of lower trophic level, non-commercial organisms (phytoplankton, zooplankton, and benthic biota); and

(4) direct effects resulting from oil or hazardous substances causing a closure of public recreational beaches, or a hunting or fishing area."

Threatened and endangered species in the Galveston area of the Gulf of Mexico include piping plover, bald eagle, Arctic peregrine falcon, brown pelican, and Kemp's ridley, green loggerhead, and hawksbill sea turtles (Department of Interior 1991). The biological data base contains the following information on biological abundance of various categories of finfish, shellfish, fur seals, and birds in the Louisianian Province by season (Tables 7.3-1 to 7.3-4):

**Table 7.3-1 Adult biomass (g wet wt per square meter)**

| Species Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| **Anadromous Fish** | | | | |
| Subtidal | 0.0010 | 0.0010 | 0.0010 | 0.0010 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Planktivorous Fish** | | | | |
| Subtidal | 11.4205 | 11.4232 | 11.4205 | 10.3178 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Piscivorous Fish** | | | | |
| Subtidal | 0.0209 | 0.0303 | 0.0209 | 0.0116 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Top Carnivores** | | | | |
| Subtidal | 0.0134 | 0.0134 | 0.0134 | 0.0134 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Demersal Fish** | | | | |
| Subtidal | 0.0098 | 0.0098 | 0.0098 | 0.0098 |
| Intertidal | 0.0380 | 0.2500 | 0.2100 | 0.2300 |
| **Semi-Demersal Fish** | | | | |
| Subtidal | 0.6367 | 0.6367 | 0.6367 | 0.6367 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Mollusks** | | | | |
| Subtidal | 0.0009 | 0.0009 | 0.0009 | 0.0009 |
| Intertidal | 5.2000 | 5.2000 | 5.2000 | 5.2000 |
| **Decapods** | | | | |
| Subtidal | 0.4315 | 0.4315 | 0.4315 | 0.4315 |
| Intertidal | 4.4000 | 4.4000 | 4.4000 | 4.4000 |
| **Squid** | | | | |
| Subtidal | 0.0086 | 0.0086 | 0.0086 | 0.0086 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

## Table 7.3-2 Larvae (numbers per square meter)

| Species Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| **Anadromous Fish** | | | | |
| Subtidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Planktivorous Fish** | | | | |
| Subtidal | 21.0000 | 10.0000 | 1.0000 | 21.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Piscivorous Fish** | | | | |
| Subtidal | 2.1000 | 2.0000 | 0.1000 | 0.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Top Carnivores** | | | | |
| Subtidal | 2.1000 | 0.0000 | 0.0000 | 0.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Demersal Fish** | | | | |
| Subtidal | 0.5000 | 1.0000 | 0.1000 | 1.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Semi-Demersal Fish** | | | | |
| Subtidal | 2.0000 | 3.0000 | 1.0000 | 2.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Mollusks** | | | | |
| Subtidal | 2.0000 | 20.0000 | 2.0000 | 0.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Decapods** | | | | |
| Subtidal | 0.0016 | 0.0042 | 0.0000 | 0.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Squid** | | | | |
| Subtidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

## Table 7.3-3 Mammals and birds (numbers per square kilometer)

| Species Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| **Fur Seals** | | | | |
| Subtidal | 0.00 | 0.00 | 0.00 | 0.00 |
| Intertidal | 0.00 | 0.00 | 0.00 | 0.00 |
| **Seabirds** | | | | |
| Subtidal | 2.30 | 2.30 | 2.30 | 2.30 |
| Intertidal | 0.00 | 0.00 | 0.00 | 0.00 |
| **Waterfowl/shorebirds** | | | | |
| Subtidal | 0.00 | 0.00 | 0.00 | 0.00 |
| Intertidal | 5450.00 | 2190.00 | 2520.00 | 23,900.00 |

**Table 7.3-4 Productivity (g carbon/square meter/day)**

| Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| **Primary Producers** | | | | |
| Subtidal | 0.6800 | 0.6800 | 0.6800 | 0.6800 |
| Intertidal | 0.0380 | 0.0380 | 0.0380 | 0.0380 |
| **Zooplankton** | | | | |
| Subtidal | 0.0879 | 0.0879 | 0.0879 | 0.0879 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Benthos** | | | | |
| Subtidal | 0.0481 | 0.0841 | 0.0841 | 0.0841 |
| Intertidal | 0.0080 | 0.0080 | 0.0080 | 0.0080 |

The chemical data base of the model contains the following chemical and toxicity values for medium crude oil (Tables 7.3-5 and 7.3-6):

**Table 7.3-5 Chemical parameter values for medium crude oil**

| Parameter | Value |
|---|---|
| Molecular weight (g/mole) | 160 |
| Density (g/cm$^3$) | 0.780 |
| Solubility (mg/L at 25°C) | 32.3 |
| Vapor pressure (atm at 25°C) | 0.0035 |
| Degradation rate in seawater (per day) | 0.001 |
| Degradation rate in sediments (per day) | 0.001 |
| Absorbed/dissolved partition coefficient, $K_{oc}$ | 902 |
| Viscosity at 25°C (cp) | 12.6 |

**Table 7.3-6 Toxicity parameter values for medium crude oil**

| Parameter | Value (ppb) |
|---|---|
| Threshold concentration for acute effects | 0.081 |
| Phytoplankton: 96-hr $EC_{50}$ | 417 |
| Zooplankton: 96-hr $EC_{50}$ | 340 |
| Fish: 96-hr $EC_{50}$ | 130 |
| Benthic invertebrates: 96-hr $EC_{50}$ | 276 |
| Larvae, fish and benthic invertebrates: 96-hr $EC_{50}$ | 14.3 |

The NRDAM/CME was applied to a hypothetical spill of 18,046 barrels (2,553 metric tons) of medium crude oil from a platform located 50 km off the coast of Texas on June 1, 1990. For maximum damages, it was assumed that the spill would come ashore, thus impacting intertidal as well as subtidal biota. It was assumed that 20% of the oil was cleaned up from the water surface on the day following the spill. The model calculated that 1,297 metric tons would come ashore following the spill. The user designated that no fishing or shellfishing areas were closed as a result of the spill.

The user must supply several environmental parameters to the model. Physical environmental parameters present in this area in spring are listed in Table 7.3-7 (Reed et al. 1989; NOAA 1985). In addition, the bottom type in this province is mud and the shoreline is salt marsh. Using a line drawn parallel to shore as the x-axis, the distance to shore (defined as the +y direction) was 50 km. Since we assumed that the spill would come ashore, the model had to be run twice, once for subtidal effects (offshore injuries) and once for intertidal effects. It is not immediately obvious to us whether or not a crude oil spill of this size and spilled at a distance of 50 km from shore would come ashore. Therefore, intertidal injuries may be overestimated.

**Table 7.3-7 Physical environmental parameters for crude oil spills**

| Parameter | Value |
|---|---|
| Mean ocean surface current | 0.1 m/sec |
| Tidal velocity parallel to the ocean surface current | 0.5 m/sec |
| Tidal velocity perpendicular to mean ocean current | 0.1 m/sec |
| Mean wind speed at spill event | 0.56 m/sec |
| Wind direction[a] | 315° |
| Depth of upper water column to pycnocline | 10 m |
| Depth of lower water column to bottom | 20 m |
| Air temperature | 20°C |

[a] Counter-clockwise from ocean current

The output of the biological model is in terms of injuries, i.e., lost catch and harvest of commercially and recreationally important species and nonconsumptive losses. Based on direct kills of adults and young, reduced weights of adults and young, and loss of primary and zooplankton productivity, the model calculated a total catch losses in grams (Table 7.3-8). This results in catch losses of 3,978,452 pounds of finfish (such as menhaden, tuna, groupers and scamp, snapper, swordfish, drum, shark, and seatrout) and 33,779 pounds of mollusks (clams, oysters, scallops, snails) and decapods (shrimp, prawns, crabs) over the next 20 years (Table 7.3-9). In addition, approximately 140 adult seabirds (cormorants, shearwaters, puffins, pelicans) and 3000 adult shorebirds (sandpipers, plovers, turnstones, herons) would be directly killed. No ducks or geese were lost. Because population numbers of shorebirds are higher than numbers of seabirds, more shorebirds are lost due to oiling. However, bird losses in general are low because of the distance of the spill from shore. Subtidal losses of fish were high compared to intertidal losses because most fish are subtidal and much of the crude oil sinks or dissipates in the subtidal area before transport to the shore. As noted in Table 7.3-1, decapods and mollusks (invertebrates) are confined primarily to the intertidal area. No fur seals are present in the Louisianian Province.

### 7.3.3 Economic Valuation of Loss of Fisheries

#### 7.3.3.1 Valuing Oil Spill Impacts

The value to society of avoiding impacts from oil spills into marine and coastal waters has been estimated for (i) commercial fisheries using market assessment techniques; (ii) recreational resources using either contingent valuation techniques or indirect methods, such as travel cost approaches or hedonic property value studies; and (iii) existence values using contingent valuation methods. By and large these efforts have been driven by legal proceedings associated with specific large spills, rather than concern for valuing more routine and smaller spills that would more likely be associated with our scenarios.

> ***Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM). ... is designed for use in estimating the impacts and damages associated with routine spills under the CERCLA "Type***

An exception is the modeling work embodied in the Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM). As noted in the previous section, this model is designed for use in estimating the impacts and damages associated with routine spills under the CERCLA "Type A" assessment rules. These rules effectively restrict the scope of concern to use values associated with marginal changes in resource stocks, i.e., those associated with "small" spills damaging non-unique resources. Existence

**Table 7.3-8 Lost catch of fish and invertebrates (g)**

| Species Category | Lost catch |
|---|---|
| Anadromous Fish | |
| Subtidal | 3,650 |
| Intertidal | 0.00 |
| Planktivorous Fish | |
| Subtidal | 112,000,000 |
| Intertidal | 0.00 |
| Piscivorous Fish | |
| Subtidal | 23,100,000 |
| Intertidal | 0.00 |
| Top Carnivores | |
| Subtidal | 1,630,000,000 |
| Intertidal | 0.00 |
| Demersal Fish | |
| Subtidal | 3,640,000 |
| Intertidal | 35,900 |
| Semi-Demersal Fish | |
| Subtidal | 41,800,000 |
| Intertidal | 0.00 |
| Mollusks | |
| Subtidal | 21,300 |
| Intertidal | 6,700,000 |
| Decapods | |
| Subtidal | 65,200 |
| Intertidal | 8,540,000 |
| Squid | |
| Subtidal | 8,470 |
| Intertidal | 0.00 |

**Table 7.3-9 Lost catch of fish and invertebrates (lb)**

| Species Category | Lost catch |
|---|---|
| Total finfish | |
| Subtidal | 3,978,373 |
| Intertidal | 79 |
| Mollusks/decapods | |
| Subtidal | 210 |
| Intertidal | 33,569 |

value concerns are effectively ruled out, since the regulations state that non-use values may be estimated only when use values cannot be determined (43 CFR Part 11, August 1, 1986, 51 FR at 27719). We feel a model like this is appropriate for use in a social costing exercise such as ours (or one that individual electric utilities might perform) because the model is portable, easy to use, and applies to any coastal or marine area within the jurisdiction of the U.S. We want to stress, however, that such a model is not a substitute for a detailed case study impact and valuation assessment that would estimate damage from any particular spill. And the model ignores existence values, which may be important in selected cases. In general, the model makes many simplifying assumptions that one might question were a more definitive and credible calculation be required.

Below we describe and critique the economics underlying this model. Then the results from using the NRDAM are presented for our reference environments. The reader should note that the NRDAM is being revised by HBRS, Associates and parameterized for application to the Great Lakes. When it becomes available, its improvements will be reviewed. However, this new model will not be available for our use because parameterization and application to other areas is not expected for at least a year.

### 7.3.3.2 Economics in the NRDAM Model

This model is an exercise in benefit transfer model building. It relies on published literature, and is designed to be applied to a wide range of areas and in a wide variety of situations. It provides damage estimates for five impact categories: commercial activities (fisheries and fur seal pelts), recreational fishing for finfish only (shellfishing is valued as if it were a commercial activity), hunting for ducks and geese, waterfowl viewing, and beach use. It indirectly values damages to lower trophic species than fish through tracing food web effects on commercially and recreationally valuable species. Value is defined as the WTP to avoid damage (or to obtain benefits), because the model relies on a literature that uses these measures. Values are only assigned to fish or birds that would have been caught or seen in the absence of a spill. Impacts to other birds or fish (except shorebirds) are not counted. Effects are tracked and valued over the time period in which they occur and discounted at a 10% rate to be consistent with OMB rules. As we are not limited by these rules and have agreed to use 3% and 5% discount rates where possible, the latter rates are used.

**Commercial Fishing.** Commercial and recreational fishing are addressed together in the model, on the reasonable theory that fish mortality from a spill affects both activities simultaneously. Proportionality of effects across these activities, based on data on recreation and commercial landings, is assumed. The appropriate measure of value is the loss to the fishery net of expenses involved in the catch. In a commercial activity, this is termed the change in economic rent, and is analogous to the measure used to estimate crop damage from air pollution. Fishing effort is assumed unchanged when a spill occurs, but the catch is reduced. Thus costs remain constant. With market prices assumed unchanged (as in our crop model), profits (or economic rent) fall. Prices are estimated as the four year average for commercial species in 10 coastal areas, called "provinces."

**Recreational Fishing.** Recreational fishing losses are estimated in a similar fashion, with unit values of such activities (denominated in the unusual units of $ per pound of catch) substituted for market price. These values are estimated from two recreational fishing studies (Norton et al 1983; Rowe 1985). The former estimated values for changes in striped bass catch rates off the east coast using the travel cost method. The latter study used a more sophisticated multinomial logit travel cost model to estimate west coast recreational fishery losses. Both studies provide conceptually correct measures of the value of a unit change in catch. The number of fish caught was transformed to weight using data on average weight of recreational fish caught. Four species were valued in this way (striped bass, flatfish, rockfish, and salmon) with their average value per pound ($1.84 in 1986 $'s) used in estimating damage.

**Viewing and Hunting Waterfowl, Shorebirds, and Seabirds.** Viewing values are estimated for birds that would have been viewed if not for the spill, not for all birds that might be injured or killed as a result of the spill. Brown and Hammack (1977) found a relationship between visits to a wildlife refuge and bird population at the refuge. This equation (which shows visits falling by one for every 5 bird decrease in population) is used along with a unit value of $9.39 (1986$'s) per viewing visit day, itself taken from another study, to estimate damage at any of the 10 provinces per month, for an assumed four month long viewing season.

Hunting losses to ducks and geese are estimated assuming that participation days are unchanged but bag rates fall as a result of the increased natural rate of bird mortality caused by the spill. Hay and Charboneau (1979) used a CVM survey to determine WTP for duck and geese hunting in major U.S. flyways. These results distinguish between values for ducks and geese (the latter are more highly valued) and by flyway (birds hunted in the Atlantic flyway are more highly valued).

**Marine Mammals.** Because of a lack of studies, the only aspect of mammal damage from an oil spill that is valued is a loss in economic value of fur seal pelts. These are valued at $15 per pelt with all losses counted, based on the assumption that commercial catch limits would be commensurately reduced with reductions in fur seal populations.

**Public Beach Damage.** Use values at national and state and local public beaches are estimated in theory as the net loss in consumer surplus from reduced trips to the beach and reduced enjoyment for trips that are made. In practice, the model estimates losses only when a beach is declared closed. Estimates of trips per foot of beach frontage by month and region times the number of days a beach is closed times the frontage of the beach closed times an estimate of consumer surplus per day at the beach provide the damage estimate. The consumer surplus estimate of $6.16 (1986 $'s) per individual per day is taken from the average of nine studies (ranging from $0.62 to $12 per trip), which consider to various degrees the availability of substitute sites, the preferences of both residents and tourists, and other factors affecting value. The average estimate, being based on studies of peak visit periods, applies to the peak visit month only with the amount reduced for other months proportional to the ratio of visits in the given month to visits in the peak month.

### 7.3.3.3 Critique

This model is currently being updated and extensively modified, particularly its biological science component, by HBRS, Inc. for application to the Great Lakes. Hence, some of the criticisms made here may no longer be appropriate. However, the model we use is the current version reviewed here.

The overall approach to valuation has strengths and weaknesses. Its primary strength is that an economic welfare perspective on valuation is taken throughout, in that (i) a distinction is made between impacts that have value (e.g., fish that would actually be caught in the absence of the spill) and gross impacts and (ii) the model uses valuation studies that measure damages correctly, i.e., as consumer surplus losses.

It can be criticized, however. First, and most obvious, the model only addresses a portion of the possible damages from a spill. It ignores nonuse values (which may be trivial for a small spill that does not harm unique coastal resources), most damage to mammals, and damages to private beaches, to name a few. Second, the model uses a unit value approach to transferring benefit estimates from settings addressed by the original studies to the particular spill sites being examined with the model. This approach is crude, because it does not permit the adjustment of unit values for differences in the attributes of the setting addressed by the original studies versus those addressed by the model. For instance, the oceanographic, biological, and economic activities in the area examined by the original study may be quite different than those in the area of the spill that we are concerned about. A better approach would be to embed the entire function estimating consumer surplus change into the model. This would permit adjustments in values for attribute differences.

Another pervasive assumption of the model is that the output of economic activity is assumed to be affected by the changes in the environment induced by the spill, but not the amount of economic inputs. For instance, after a spill, fishing effort is assumed unchanged even as the yield from this effort falls because of lower fish populations. One may characterize this assumption as being a short-run response to the environmental change. In the long-run, effort would change, substitute activities might be undertaken, etc. Thus, while this assumption greatly simplifies the calculations and information requirements of the model, it probably overestimates damage to the extent that long-run responses act to mitigate economic losses but are not admitted in the model.

Another general, if less basic, criticism is that the model uses a single estimate of consumer surplus or unit values that is drawn from a set of estimates, instead of applying specific unit values in the appropriate cases. Usually, this single estimate is an average of the estimates reviewed. This approach is justified by the authors as a reasonable simplification because the difference in estimates is small in absolute terms. While this is true, the range is generally large in percentage terms, which can lead to equally large percentage differences in estimated damages. For instance, the recreational values per pound of fish vary over fish type from \$1.18 to \$2.90 per pound, with an average of \$1.84. While small in dollar terms, these differences matter. Using the average value when the lowest value is appropriate results in a 56% overestimate of damage while using the average when the highest estimate is appropriate results in a 37% underestimate of damage. Thus, the model could be improved by applying species-specific unit values to fish mortality rather than the average value.

### 7.3.3.4 Model Results

The damages computed by the economic submodel were discounted to 3% and 5% rates and are expressed in constant 1989 dollars (Table 7.3-10). Total damages under the scenario used were $2,026,572 (3% discount rate) and $1,825,000 (5% discount rate). This amounts to a cost of approximately $100/bbl of oil spilled. The expected annual rate of such a spill is 0.00196 (Sect. 7.3.1). With annual generation of 2.1 x $10^9$ kWh, the expected damage (using a 5% discount rate) is 0.0017 mills/kWh. This is the expected damage from only the larger, (low-probability) spills.

The authors of the economic submodel (Opaluch and Grigalunas, 1989) ran the model for spills of 100 metric tons (750 bbl) of crude oil under "average" seasonal conditions in nine of the coastal provinces. Estimated natural resource costs ranged from $4.40 to $250/bbl spilled and $300,000 to almost $20 million per billion barrels of oil developed. For the Louisianian Province, costs ranged from $11/bbl spilled in the Western Gulf of Mexico to $37/bbl spilled in the Eastern and Central Gulf of Mexico. Costs per billion barrels of oil developed in the Louisianian Province ranged from $600,000 in the Western Gulf of Mexico to $3 million in the Eastern Gulf of Mexico. The results of our model run using a larger spill size and summer conditions for the Western Gulf of Mexico are higher than the average costs estimated by the authors for the Louisianian Province but are within the range for all oil spills in coastal areas. In addition, we adjusted our values to 3% and 5% discount rates rather than the 10% rate used by the model.

> ***Total damages ...***
> ***... amounts to a cost of approximately $100/bbl of oil spilled.***

## 7.4 ACCIDENT RATES FOR OFFSHORE DRILLING

This section gives estimates of days lost form injuries and the expected deaths from offshore drilling. These injuries and deaths occur prior to electricity production.

### 7.4.1 Non-Fatal Injuries

Offshore wells average about 10,000 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 600 bbl/day for each well (Chapter 5) and a 7% conversion of crude to residual, it will require about 240 wells to supply 10,000 bbl/day to the generating facility. If 240 wells are required to supply the 10,000 bbl/day requirement of a single plant, and if these wells do not require replacement, then the total labor amounts to 6.9 million hours.

Table 7.3-10 Damages due to loss of fish, invertebrates, and birds

| | 3% Discount rate | 5% Discount rate |
|---|---|---|
| Commercial and Recreational finfish | | |
| Subtidal | $1,920,000 | $1,722,000 |
| Intertidal | 142 | 138 |
| Commercial invertibrates | | |
| Subtidal | 345 | 343 |
| Intertidal | 31,800 | 30,940 |
| Seals and birds | | |
| Subtidal | 5,150 | 4,825 |
| Intertidal | 69,900 | 67,570 |
| Total | $2,026,572 | $1,825,000 |

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

***The proportion (7%) of expected annual deaths from drilling activity that is attributable to residual oil is 0.1 deaths.***

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 6,400 days lost for the drilling of 240 wells. The projection attributable to the residual oil (7%) is 448 days lost. 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 1.4 deaths. The proportion (7%) of expected annual death from drilling activity that is attributable to residual oil is 0.1 deaths.

# 8. IMPACTS AND DAMAGES FROM CRUDE OIL REFINING

## 8.1 EFFECTS OF WATER AND AIR EMISSIONS

### 8.1.1 Emissions

Chapters 4 and 5 provide data on wastes from refining processes. Residuals from this stage of the oil fuel cycle include water and air emissions. Constituent concentrations of wastes vary, depending on the specific refining processes, types of crude feedstock and waste management methods.

Final process water from the refinery for the Southeast plant is monitored for water temperature, pH, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Organic Compounds (TOC), Total Suspended Solids (TSS), oil and grease, total copper, total nitrogen, total sulfide, hexavalent and total chromium, and total phenolics (EPA 1992a). The process water meets National Pollutants Discharge Elimination System (NPDES) limits.

### 8.1.2 Effects of Air and Water Emissions on Wildlife and Crops

Petroleum refineries require land for tank farms to store crude oil and refinery products, and for process facilities including settling ponds, water treatment plants, and disposal sites for oily wastes. Data on emission rates were available for airborne primary pollutants - CO, $NO_x$, $SO_2$, and particulates - and for toxic chemicals from the refinery sites.[1] However, pollutant transport was not modelled due to the lack of data on local meteorological conditions. 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. Collection of these data was beyond the scope of this study. Therefore, impacts from air emissions could not be quantified.

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[1] Hydrogen fluoride (HF) is released during the alkylation stage of oil refining. Its contribution to overall health costs in the oil fuel cycle was considered to be minor compared to other health risks, especially since HF-related occupational damages would likely be internalized. Releases of HF also usually have an effect on vegetation within 0.5 km of a refinery, but in general the effects are difficult to quantify (EPA 1992).

Treated wastewaters from the Texas refinery enter the Houston Ship Channel and Galveston Bay, both of which have been heavily impacted by industrialization. The Southwest refinery is situated in an area with a deep, and therefore relatively protected, groundwater table. However, the Pecos River is located only two miles from the refinery and may receive wastewater emissions. Lack of data on concentrations of contaminants in wastewater and water quality of the receiving water bodies preclude descriptions of impacts on aquatic biota.

### 8.1.3 Economic Valuation

No economic valuation was done due to the lack of data on the impacts at our two refinery sites. Estimating the damages from oil refining operations requires an analysis comparable to that for the generation stage of the fuel cycle. These data include:

- meteorological conditions (e.g., wind speed and direction)
- background concentrations of pollutants, to 1,600 km (1,000 mi) from the sites in Texas and New Mexico
- other sources of $NO_x$ and non-methane organic compounds (NMOC) that will affect ozone formation
- population distribution, as far as 1,600 km from the refinery.

Collecting these data at the refinery sites was beyond the scope of this study.

Table 5.8-1 listed estimates of emissions from different stages of the oil fuel cycle. Emissions of hydrocarbons or volatile organic compounds are comparable for oil refining and power generation, on a per barrel of residual oil or per kWh basis. Otherwise, emissions from generation far exceed those from refining operations on a per kWh basis. Other things being equal, we expect that the damages from generation would greatly exceed those from oil refining activities. Of course, all else is not equal. In our Southeast Reference case, the population in the vicinity of the Houston refinery is greater than that in the area of the Southeast power plant. Thus, the damages from emissions of particulate matter (PM) from the refinery are likely to be the same order of magnitude as (and quite possibly greater than) the PM-related damages from the power plant.

> ***... emissions from generation far exceed those from refining operations on a per kWh basis.***

# 9. IMPACTS AND DAMAGES FROM TRANSPORTATION AND STORAGE OF RESIDUAL FUEL OIL

## 9.1 BARGE TRANSPORTATION OIL SPILLS IN COASTAL AREAS

### 9.1.1 Barge Accidents

A barge oil spill scenario was analyzed to study the possible impacts of such a spill in a coastal area. This scenario would only pertain to oil production for the Southeast Reference site.

According to the U.S. Coast Guard (1989, p. 47-49), the total quantity of oil spilled from tank barges in the U.S. during the 1984-1986 period was 192,000 barrels. There were 1,523 events -- both coastal and river channels. However no data are provided on the relative frequency of different size events, particularly the larger events such as the hypothetical 35,000 barrel spill analyzed below.

### 9.1.2 Impacts on Marine and Coastal Resources

*Injuries to marine and coastal resources from a barge transportation spill of No. 6 residual oil are estimated using the NRDAM/CME ...*

Injuries to marine and coastal resources from a barge transportation spill of No. 6 residual oil are estimated using the NRDAM/CME (See Section 7.3.2). A site off the coast of Biloxi, Mississippi was chosen for the spill site because at this point barges traversing the coast from Texas to Mobile leave the Intracoastal Waterway and are in open water (the model is not applicable to river-type waterways). The distance to shore was estimated at 15 km. It was assumed that approximately half of the volume of a barge carrying 70,000 barrels (35,000 bbl or 5023 metric tons) would spill.

Because this spill is in the same Louisianian Province as the previously described crude oil spill and the bottom type was assumed to be mud, adult biomass of adult and larval fish and invertebrates, abundance of mammals and birds, and productivity are the same as the previous scenario (see Tables 7.3-1 to 7.3-4). The chemical and toxicity parameters for No. 6 refined oil, as provided in the chemical data base, are listed in Tables 7.3-5 and 7.3-6. Although chemical parameters differ, the model uses the same toxicity values for medium crude and No. 6 fuel oil. Data on accident probabilities are insufficient to calculate expected annual damages.

The model was run using different seasonal and weather conditions and for both subtidal and intertidal effects. Using simulated winter conditions, the following parameters were supplied by the user (Table 9.1-1). For storm conditions, the wind speed was increased to 11 m/sec and the air temperature was changed to 10°C. The distance to shore was 15 km in the +y direction and 60 km in the -x direction. The model calculated that 4,910 metric tons of oil entered the intertidal area. No areas were closed to fishing or shellfishing and no cleanup was assumed.

**Table 9.1-1. Physical environmental parameters for a No. 6 fuel oil spill**

| Parameter | Value |
|---|---|
| Mean ocean surface current | 0.07 m/sec |
| Tidal velocity parallel to the ocean surface current | 0.5 m/sec |
| Tidal velocity perpendicular to mean ocean current | 0.1 m/sec |
| Mean wind speed at spill event | 5 m/sec (winter)<br>3 m/sec (fall) |
| Wind direction[a] | 90° |
| Depth of water column | 20 m |
| Depth of lower water column to bottom | 0.00 m |
| Air temperature | 10°C (winter)<br>26°C (fall) |

[a] Counter-clockwise from ocean current

This hypothetical spill off the coast of Biloxi in winter would result in a total catch loss of 5,303 pounds of finfish and 100,126 pounds of invertebrates

(Table 9.1-2). In addition, approximately 39,500 shorebirds in the intertidal area would be directly killed. This rather high number is due to the presence of overwintering birds in the Gulf area (23,900/km$^2$ compared to 2,200 to 5,500 in other seasons). Addition of parameters for storm conditions at the time of the spill did not greatly increase injuries. Injuries were reduced, primarily due to reduced numbers of shorebirds in the intertidal area, when the season of the spill was changed to fall (data not provided).

### 9.1.3 Economic Valuation of Fishery Losses

As in Section 7.2.3, output from NRDAM/CME model runs are used to compute total losses for the scenario for both 3 and 5 percent discount rates. For the 3% discount rate case, subtidal losses amount to $3,850. Intertidal losses amount to $1,010,700 and the total amounts to $1,014,550. Equivalent losses for the 5% discount rate case are $3,534 for subtidal losses and $977,600 for intertidal losses. The total losses for the 5% discount rate case amount to $981,134 or $28.03 per barrel spilled. An annualized estimate would be computed from an estimate of the probabilities of different size barge accidents, and from the estimated amount of residual fuel oil needed per year. The expected annual damages would be small.

**Table 9.1-2. Lost catch of fish and invertebrates (lb)**

| Species Category | Lost catch | Lost catch per bbl spilled |
|---|---|---|
| Total finfish | | |
| Subtidal | 3,878 | 0.11 |
| Intertidal | 1,425 | 0.041 |
| Invertebrates | | |
| Subtidal | 1 | 0.000029 |
| Intertidal | 100,125 | 2.86 |

## 9.2 BARGE TRANSPORTATION OIL SPILLS IN RIVER SYSTEMS

### 9.2.1 Barge Accident Rates

After being produced at the Southeast refinery site in Texas, the residual fuel oil is sent by barge to the Southeast Reference power plant site through the

Tennessee-Tombigbee waterway and the Tennessee and Clinch Rivers. These waterways serve several functions: navigation, recreational fishing (bass, catfish, and crappie), other recreational activities, and municipal and industrial water sources.

Barges carrying 70,000 barrels of residual oil every 7.8 days would traverse this system to provide fuel for the Southeast Reference site power plant. Information on accident rates of oil-carrying barges are summarized in Section 9.1.1. These data do not distinguish between coastal and river channel accidents. Most events occur in river channels (U.S. Coast Guard 1989, p. 17).

### 9.2.2 Impacts on Freshwater Environments

At the present time no model similar to the NRDAM/CME model exists for assessment of biological injury and economic damages from oil spills in freshwater streams and rivers. In the future, a simple dilution model can be applied on a site-specific basis. However, additional data on presence and abundance of aquatic biota such as that from creel censuses, water use, and land use would be necessary in order to calculate biological and physical injuries and assess damages.

*Many states recover damages in the form of civil penalties through their clean water statutes.*

The American Petroleum Institute (API 1992a, 1992b) summarized available NRDA oil spill case histories in freshwater systems. Most of the assessments, performed by the respective states, are simplistic, based mainly on the number of organisms, generally fish, killed and a dollar cost for replacing these organisms. Monetary values for fish are given by the American Fisheries Society. This method of assessment does not always reflect the extent of damages to natural resources and reflects only short-term effects. Nevertheless, these case histories represent a first approach for estimating injuries and collecting damages. Spills of No. 6 residual oil or Bunker C crude oil (similar in toxicity to No. 6 residual oil) and injuries are briefly summarized in Table 9.2-1.

### 9.2.3 Economic Valuation

Many states recover damages in the form of civil penalties through their clean water statutes. For example, a total of $1.2 million was assessed by the states of Georgia and South Carolina and the federal government for the spill in the Savannah River (API 1992a).

Table 9.2-1. Case histories of residual No. 6/Bunker C oil spills in river systems

| Amount spilled | Waterbody | Injuries |
|---|---|---|
| 2,100 gallons | river-estuary | not available |
| 7,000 gallons | river-estuary | ca. 300 birds |
| 84,000 gallons | creek | 40,000 fish<br>14 miles of stream |
| 500,000 gallons | Savannah River | unknown number of birds, vegetation<br>800,000 acres tidal marsh<br>5,500 acres wildlife refuge |

*Total* tanker barge traffic in the U.S. resulted in an annual average of 64,000 barrels in spills during 1984-1986 (refer to p. 9-1). The additional barge traffic that would result from the requirements of a power plant would be a very small percentage of the total existing traffic.

Assume that the damage from the annual average barge spills to be in proportion to the damage calculated for the 35,000 bbl spill:

$$(64{,}000/35{,}000) \times 98{,}134 = \$1{,}794{,}074.$$

The total increment in barge traffic due to a power plant is probably about 0.51% of the total barge traffic in the U.S. Thus, we expect an average of $9,104 in annual damages -- i.e. 0.00433 mills/kWh.[1]

## 9.3 ROAD PAVEMENT IMPACTS AND DAMAGES FROM TRUCK TRAFFIC

A refinery located in Eddy County in Southeast New Mexico is assumed to provide residual oil to power plants in the Southwest Reference environment. The

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[1] Assuming average daily barge traffic of 1.76 million barrels/day in inland waters (Temple, Barker & Shane, Inc. 1991, Table 3.3.2), based on a 7.3 bbl/ton conversion factor. The residual oil requirement of power plant is 3.26 million barrels/yr, producing $2.102 \times 10^9$ kWh/yr.

main impact from transporting residual oil from the refinery to the power plant in the Southwest Reference environment is that associated with the truck traffic, while the main impact in the Southeast Reference environment is associated with potential natural resource damages from oil spills on waterways.

This section presents an analysis of the damage to roadway surfaces that would occur due to the construction of an oil-fired power plant in the Southwest Reference environment if oil were transported on public highways. For an introduction to the theory that is presented in this section, see ORNL/RFF (1994a,b).

The power plant in Northwest New Mexico is located in San Juan County, thirty-five miles south of Farmington. Residual oil is too viscous to be transported through pipelines without extra handling activities, and there is no railroad passing through the Farmington area. **Consequently the residual oil would be transported by tank trucks to the Farmington power plant from the Navajo refinery over a distance of 413 miles on public highways. Transporting oil over such a great distance by truck would not be economically viable and would not be done. Thus, we *assume* a situation in which the residual oil is transported 30 miles, which we consider to be a more reasonable indication of the distances traveled.**

### 9.3.1 Burden

The oil-fired power plant in the Southwest Reference environment would require about 8,940 barrels of residual oil per day. In New Mexico, a typical tank truck has a capacity of 152 barrels, so the daily demand for oil at the power plant will require about 59 truck-trips per day or 21,581 trips per year from the refinery to the power plant.

The passage of heavy trucks on public highways accelerates the deterioration of roadway surfaces. This necessitates earlier resurfacing than would otherwise occur. In addition, there are maintenance expenses that are incurred on a regular basis due to the new traffic. Also, other drivers are exposed more often to impaired driving conditions and delays due to road construction. Finally, the presence of trucks directly contributes to congestion and worsened driving conditions and additional noise. The economic damage from increased road congestion and noise are difficult to quantify. The knowledge base is lacking and these impacts are not quantified in our study.

### 9.3.2 Impacts

To determine the impacts that result from this burden we estimate the injury to roadway surfaces that occur due to each passage of an oil truck. This impact is calculated in terms of the effect of each passage on the life of a road surface.

Road overlays define the endpoints of a pavement's life. The configurations and number of axles on a vehicle matter--as a rule, the more axles a vehicle has to distribute its weight the less damage it will cause.[2] The life of a road surface (i.e., the interval between road overlays) is affected by the number and type of the axles that pass over it.

The following equation yields the number of axle passages for each type of axle (j) on the truck that the road will withstand before requiring an overlay.[3]

$$N_j = (A_0 (D+1)^{A_1} (L_2)^{A_3})/((L_1+L_2)^{A_2})$$

where:

$L_1$ = thousands of pounds of load on axle j.

$L_2$ = the type of axle weight. $L_2 = 1$ for single axles, $L_2 = 2$ for tandem axles (two axles close together).

D = the road's durability. (For rigid pavements, D equals the pavement's thickness in inches. For flexible pavements, D is a linear combination of pavement, base and subbase thicknesses with coefficients 0.44, 0.14 and 0.11 [i.e., D = 0.44 (pavement) + 0.14 (base) + 0.11 (subbase)].

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[2] Many state laws, however, penalize trucks with a greater number of axles. Fuel taxes punish because they require larger engines and get lower fuel economy. Many state turnpikes charge more for a given weight if it is carried on a vehicle with many axles. From: Clifford Winston, "Efficient Transportation Infrastructure Policy," *J. Econ Perspectives*, Vol. 5, No. 1, Winter 1991, p. 116.

[3] Kenneth A. Small, Clifford Winston and Carol A. Evans, *Roadwork: A New Highway Pricing and Investment Policy*, The Brookings Institution, Washington D.C., 1989, p. 24.

$A_j$ = structural coefficients that describe the durability of rigid and flexible pavements, derived from an empirical study by the American Association of State Highway Officials.[4]

For rigid pavements,

$A_0$ = $e^{13.505}$ or 733.073;

$A_1$ = 5.041;

$A_2$ = 3.241;

$A_3$ = 2.270.

For flexible pavements,

$A_0$ = $e^{12.062}$ or 173.165;

$A_1$ = 7.761;

$A_2$ = 3.652;

$A_3$ = 3.238.4[5]

The surface type under consideration in the Southwest Reference environment is almost entirely flexible pavement, and in the future all resurfacings will be of this type because it is superior in the New Mexico environment. The majority of the surface along I-40 is engineered so that the durability index is D=5. Along the other highways the average surface has a pavement of 4 inches, base of 8 inches and subbase of 8 inches, producing a value of D = 3.76.

We assume that a tanker truck weighs 80,000 pounds fully loaded and 30,000 pounds empty. This weight is distributed unevenly among the axles. For

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[4] The study evaluated 264 rigid and 284 flexible experimental pavement sections, using previously estimated values of N as dependent variables. Cited in *Roadwork*, Small, Winston and Evans, p. 25, from Highway Research Board, *The AASHO Road Test: Report 5, Pavement Research*, Special Report 61E (Washington, D.C.: National Research Council, 1962) pp. 36-40.

[5] Small, Winston and Evans, *Roadwork*, p.27. The authors reanalyzed and revised figures from the AASHO report.

example, on a fully loaded truck about 12,000 pounds is borne by the single steering axle and 17,000 pounds is borne by each of the four tandem axles. For each roadway surface of varying durability we calculated a value $N_j$ representing the number of passages the roadway surface will withstand for each axle type j for a fully loaded truck. Appropriately transforming these numbers into comparable units and summing across all five axles yields an estimate of the number of passages for an oil truck that the roadway will withstand before resurfacing is needed.

### 9.3.3 Economic Valuation

Roadways have to be resurfaced regularly with or without the impacts of heavy trucks. The roadway in this example would regularly be resurfaced about once every ten years. The measure of damages per mile should be adjusted to reflect the change in the resurfacing schedule for the road. The present discounted value of damage is the difference between the present discounted value of resurfacing costs given oil truck traffic minus the present discounted value of resurfacing costs absent the oil trucks. Finally, this difference in present discounted value should be levelized over the assumed 40 year operation of the oil-fired power plant.

As indicated previously, high-volume, long-distance transportation of residual oil is consistent with the geographical context of this study but is extremely unlikely in reality — thus our reason for assuming a 30 mile distance. The calculated damages should be prorated to suit the particular situation under study. This discussion that follows is an illustration of the methodology. The numerical estimates should not be applied to actual siting of planning decisions.

To illustrate the methodology we employ, consider one of the types of roadway affected by the truck traffic, a flexible pavement surface along a stretch of two-lane highway on US285. This highway would withstand about 996,922 passages of a fully loaded oil truck until resurfacing is required if this were the only traffic on the road. In accordance with the present ten year resurfacing schedule, we calculate that present traffic conditions are equivalent to the passage of about 99,692 fully loaded oil trucks annually. The proposed facility would add 21,581 truck passages to that figure. Hence, with the addition of the oil truck traffic this stretch of roadway would need to be resurfaced according to a 8.22 year schedule in order to maintain comparable roadway conditions during the forty year operation of the facility.[6] After this time we assume the resurfacing schedule reverts to a ten year schedule.

All adjacent lanes of a multi-lane highway are resurfaced at the same time. If roadway damage is distributed evenly on both lanes of the two-lane highway prior to the addition of oil truck traffic, the lane bearing fully loaded trucks determines the resurfacing schedule after the addition of the oil truck traffic. The cost of resurfacing a typical two-lane highway with flexible pavement in New Mexico per road mile (both lanes) is $485,000.[7] For a divided four-lane highway, each side may be resurfaced at different times so we calculate different schedules for the roadway surfaces affected by passage of a fully loaded truck and an empty truck on the return haul.

In the example for highway US285, the present discounted value of future resurfacing needs per road mile prior to the addition of oil truck traffic is approximately $984,261. With the addition of oil truck traffic the present discounted value of future resurfacing needs per mile is estimated to be $1,170,444. The difference between these numbers is $186,183, which is the net present discounted cost per mile traveled along this stretch of roadway by the new oil truck traffic.

This estimate is not an abatement cost measure of damage, but a true damage measure analogous to medical costs associated with health effects. Analogous to pain and suffering are the effects associated with more rapid deterioration of the road surface, such as the congestion and safety problems associated with a marred road surface and the resurfacing operation itself. As this set of damages is ignored, the resurfacing costs are a lower bound to the damages that result from the transport of oil on public roads in the Southwest Reference site.

We estimated the damage for each different stretch of highway along the route from the refinery to the power plant in a manner similar to the example above, and summed these to obtain an estimate for the entire route. The total levelized cost for damage that results is $217,277 per year for a 30 mile route.

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[6] In practice it is possible that roadway engineers in New Mexico would respond to the additional traffic by increasing the durability of the road surface in order to maintain the ten year schedule. We do not have sufficient information to calculate the cost differential associated with the requisite improvement in durability, so we take current standards as a given and vary the resurfacing schedule instead. We expect that these two approaches are roughly equivalent.

[7] This figure is high relative to other parts of the country due to a lack of competition in the industry, the remoteness of many locations, and the harsh variations in temperature and moisture conditions which necessitate more durable road surfaces.

Expressed as a levelized cost per kilowatt-hour this estimate of road damage is equal to 0.101 mills/kWh. This is the midpoint estimate of maintenance costs, and other factors that have not been quantified.

Our estimate of a 95% confidence interval ranges from 0.0287 mills/kWh as a low estimate to 0.354 mills/kWh as a high estimate. These ranges are derived based on uncertainty bounds associated with the calculation of $N_j$, the number of passages the roadway surface will withstand for each type of axle. These uncertainty bounds are estimated and reported in Winston and Small (1989). We assume that the uncertainty bound for each axle type is perfectly correlated. That is, if the true estimate for one axle type is at its lower bound, then this is the case for each axle type, etc. We have not considered uncertainty in the other parameters in this problem.

As discussed in ORNL/RFF (1994a,b), some of these damages are internalized through an array of taxes. The transportation scenario for the Southwest Reference site is similar between the oil and coal fuel cycles. The trucks carrying the coal are identical in weight to those carrying the residual oil. Thus, we simply use the same ratio of externalities to damages as calculated in the coal fuel cycle (ORNL/RFF 1994b, pp. 9-21 to 9-22).[8] In that analysis, 61.3% of the damages are externalities if we attribute all taxes paid in oil transportation against the damage to roadways, and 91.2% of the damages are externalities if only the heavy-vehicle use tax and the weight-distance fee are credited against the damage to roadways. We use the first percentage as a low estimate and apply it to the estimate of damages to get a low-externality estimate of 0.0176 mills/kWh. We use the second percentage as both a mid- and high-percentage and apply it to the mid- and high-damage estimates to get mid- and high- externality estimates of 0.0921 and 0.323 mills/kWh, respectively. Expressed on a per (one-way) mile basis, the mid-estimate of road damage externalities amounts to 0.00307 (mills/kWh)/mi.

***Expressed on a per (one-way) mile basis, the mid-estimate of road damage externalities amounts to 0.00307 (mills/kWh)/mi.***

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[8] This approximation is reasonable in that the variable-taxes portion of tax revenues are about 95% of the total.

# 10. ESTIMATING THE EXTERNALITIES OF ELECTRIC POWER GENERATION

This chapter concerns the estimation of externalities associated with electric power generation using residual oil. A table of contents for Chapter 10 is given below as a reference. The effects of air and water emissions from oil-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 7. The estimates of externalities are for the Southeast and Southwest Reference sites, with the benchmark oil-fired boiler. In a State 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

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[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 300 MW and 2,102 million kWh per year production, then the estimates of the number of injuries per year are 5.1 and 3.36. As a "best" estimate, we use the average of the two estimates, 4.23 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 \$33,900-\$144,000 (mid-estimate of \$43,600) per year, or 0.016 to 0.0679 mill/kWh (mid-estimate of 0.0206 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$_2$ (N O), tropospheric ozone (O ), 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]

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[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

Many of these gases are associated with the emissions from coal fired 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. The power plants at the Southeast and Southwest Reference sites emit an estimated 844 tons of $CO_2$ per gigawatt hour (GWh). Of course, other oil-fired power plants could have different levels of emissions.

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 $CO_2$ 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 an 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).

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

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concentrations will reach a maximum around the year 2006. Additionally, one would expect CFC emission and atmospheric accumulation 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.

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 approximately 0.5° C over the last 100 years, although there is less consensus in attributing this to increased carbon dioxide emissions.

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 0.5° 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 0.3° C per decade, or 3° 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 Intergovernmental Panel on Climate Change, which is composed of scientists from many countries, estimates a warming of about 0.3° C per decade, or 3° C over the next one hundred years.

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.

As can be seen in this table, 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.

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 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. 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

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[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.

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]

**Table 10.2-2. 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 | | Estimated time for research that leads to consensus (years) |
|---|---|---|---|---|---|---|
| | | | | Global average | Regional | |
| Temperature[c] | +2 to +5C | -3 to +10 C | Yes | High | Medium | 0 to 10 |
| Sea Level | 0 to 80 cm[d] | (*d*) | Yes[d] | 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 $\geq 3°$ 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.

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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.

### 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. 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 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 (1991) 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 (1991) 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

***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).***

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.

### Managed Forest and Grasslands

> ***The agricultural sector is accomplished at adapting continuously to the risks associated with normal climate variability ...***

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

***... the current consensus is that sea level rise will be quite slow.***

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.

### 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

***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.***

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.

## 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 oil. 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 oil fuel cycles.

> *... one must be ... cautious in expressing estimates of the social costs of the global warming effect of oil 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

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

Here, $\phi$ summarizes the sinks and atmospheric chemistry that lead to declining $CO_2$ concentrations over time. The $\Upsilon$ 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, $\psi$ 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).

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

The most important point that can be 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 (1993) 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 degrees 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 $CO_2$, 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.

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

**Table 10.2-4. 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)**

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.

> ***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 ...***

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.

**Table 10.2-5. Illustration of the sensitivity of global warming damages from oil 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 (844 tons of $CO_2$ emissions /GWh) |
|---|---|
| 12.72[b,d] | 0.0107 |
| 10.9[c,d] | 0.0092 |
| 3.55[b,e] | 0.0030 |
| 5.27[c,e] | 0.0044 |
| 2.0[b,f] | 0.0021 |
| 3.45[c,f] | 0.0029 |

[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

A more meaningful measure of the global warming damages associated with a kilowatt-hour of electric generation from oil 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 $5.1 dollars per metric ton if the damage function was quadratic and $6.1 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.

***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.***

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 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]

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[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.

**Table 10.2-6. Marginal present value of $CO_2$ control (assumes 5% discount rate)**

| | Both Reference Sites (844 tons of $CO_2$ emissions /GWh) |
|---|---|
| Quadratic damage function | $0.00385 |
| Linear damage function | $0.00514 |

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 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

### 10.3.1 Emissions and Changes in Concentration of $SO_2$

Air pollutants resulting from the operation of an oil-fired plant may be classified as primary (emitted directly from the plant) or secondary (formed in the atmosphere from primary pollutants). Sulfur dioxide is one of the primary pollutants.

$SO_2$ emissions from the reference power plants were estimated to be 0.546 tons/GWh (1,075 tons/year or 30.94 grams/second).

The ground-level pollutant concentrations of $SO_2$ that could be expected to occur as the result of the operation of the 300 MW reference 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 taken in the vicinity of the stack are used to predict the dimensions (i.e., vertical and horizontal width) 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 EPA Industrial Source Complex Long-Term (ISCLT) model (EPA 1986) was used to predict the annual average and seasonal average ground-level concentrations of $SO_2$ expected to occur as the result of the operation of the power plant. A description of the computer modeling is presented in the Analytical Methods document [ORNL/RFF (1994a, Part I, Paper 1)]. A summary of the modeling input data and results specific to the oil fuel cycle are presented in Appendix C. In an effort to provide consistency and standardization of model applications for regulatory purposes, the U.S. EPA has published the "Guideline on Air Quality Models (Revised)". The ISCLT model is identified in the EPA guide as a preferred model for determining long-term concentrations in simple terrain.

***$SO_2$ emissions from the reference power plants were estimated to be 0.546 tons/GWh (1,075 tons/year or 30.94 grams/second).***

The highest predicted ambient annual concentration of $SO_2$ from the Southeast Reference plant site for the 1990 case is 0.347 micrograms per cubic meter ($\mu g/m^3$). The highest predicted ambient annual concentration of $SO_2$ from the Southwest Reference plant site is 0.316 $\mu g/m^3$. Because the focus of the health effects is on population effects, not the maximum exposed individual [ORNL/RFF

(1992)], an additional step in the analysis was performed. This step involved the computation of an average change in $SO_2$ concentrations, obtained by averaging estimated concentrations and population over the 16 wind rose sectors. That is, ambient air concentrations of $SO_2$ (Ci) were calculated at 384 receptor locations around the reference site [as discussed in ORNL/RFF (1994a, Part I)]. The population distribution (Pi) is also known for these locations. The population weighted air concentration is given by

$$C_{pop}(SO_2) = \sum_{i=1}^{384} Ci(SO_2)\,Pi/P_{total}$$

This $C_{pop}(SO_2)$ average concentration is then used in impact analyses. For example, the population weighted concentrations of $SO_2$ within a 50 mile radius of the power plant were 0.0681 and 0.0464 $\mu g/m^3$ in the Southeast and Southwest sites, respectively.

The ISCLT results are used up to a distance of 50 miles from the power plant. Beyond that, statistical extrapolations are used. Extrapolation of ISCLT results is described in ORNL/RFF (1994a, Part I, Paper 2). Estimates of concentrations from 0-1,000 miles were computed.

### 10.3.2 $SO_2$ and Morbidity

#### 10.3.2.1 Impacts of $SO_2$ on Morbidity

Effects of $SO_2$ on health have been observed for a variety of morbidity endpoints (related to pulmonary function and chronic respiratory disease) as well as for premature death. However, it has generally been difficult to separate the effects of $SO_2$ from those of particulates because of high correlations between these two types of pollutants and because $SO_2$ can be transformed into acid sulfates, which would be classified as a particulate.

Nevertheless, several studies have been identified that permit identification of an independent effect of $SO_2$ on health. Specifically, Schwartz and Dockery (1991a,b) and Schwartz et al. (1989) have published dose-response functions linking 24-hour average concentrations of $SO_2$ to the probability of a child experiencing a day of coughing (cough-day) and to the probability of an adult experiencing chest discomfort, respectively.

Table 10.3-1 shows these functions after having been linearized, expressed in annual terms, and reworked to calculate population effects instead of individual probabilities of experiencing effects. For these pathways, the annual number of effects observed in the population at large is a product of a coefficient, the applicable population, and the marginal change in the population-weighted average concentration of $SO_2$. 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.

Tables 10.3-2 (a) and (b) show the estimated total number of impacts for the Southeast reference environment, when confining the analysis to within 50 miles and out to 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 coefficient of the quantified pathway. The estimated mean number of impacts total 410 symptom-days within 50 miles (1,600 symptom-days within 1,000 miles) of the Southeast plant. Tables 10.3-3 (a) and (b) show the corresponding impacts for the Southwest reference environment, for which mean impacts total 12 symptom-days within 50 miles, or 53 symptom-days within 1,000 miles.

**Table 10.3-1. Linearized dose-response functions for effects of $SO_2$ on morbidity**

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Schwartz et al. (1991):

$\Delta$ cough-days per year = $C_{cough}$ Pop F $\Delta SO_2$

Schwartz et al. (1988):

$\Delta$ chest-discomfort-cases per year = $C_{chest}$ Pop $\Delta SO_2$

where

$\Delta SO_2$ = Population-weighted annual average $SO_2$ concentration

Pop = Total population over which population-weighted $SO_2$ concentration is determined

F = Fraction of Pop that are children

$C_{cough}$ = Normal (mean=0.0181, standard deviation=0.01)

$C_{chest}$ = Normal (mean=0.0102, standard deviation=0.0053)

Table 10.3-2a. $SO_2$ morbidity: number of impacts per year at the Southeast site [for 0-50 miles]

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et.al (1991) | 25 | 160 | 290 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 34 | 250 | 470 |

Table 10.3-2b. $SO_2$ morbidity: number of impacts per year at the Southeast site [for 0-1,000 miles]

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et.al (1991) | 99 | 630 | 1,100 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 240 | 1,000 | 1,800 |

Table 10.3-3a. $SO_2$ morbidity: number of impacts per year at the Southwest site [for 0-50 miles]

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et al. (1991) | 0.27 | 4.5 | 7.8 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 1.1 | 7.4 | 14 |

Table 10.3-3b. $SO_2$ morbidity: number of impacts per year at the Southwest site [for 0-1,000 miles]

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et al. (1991) | 3.8 | 20 | 33 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 3.7 | 33 | 60 |

### 10.3.2.2 Morbidity Damages from SO$_2$[12]

Marginal damages can be estimated using unit values for the willingness to pay (WTP) to avoid a symptom-day of cough and chest discomfort, in children and adults, respectively. Data were obtained from three contingent valuation surveys of adults [see ORNL/RFF (1994a, Paper 11)]. These data are applied to both children and adults. Cough-day values range from \$1.66 to \$13.13, with a midpoint estimate of \$4.77 (in 1989 dollars), while chest tightness days range from nearly \$3 to \$21.48, with a midpoint estimate of nearly \$6 (again in 1989 dollars).

In the Monte Carlo simulation [refer to Section 4.8.1 of ORNL/RFF (1994b)], the range of cough-day values is fit by a lognormal distribution with a median of \$4.67 and geometric standard deviation (GSD) of 1.69.[13] Similarly, the range of chest tightness days is fit by a lognormal distribution with median, \$6.00, and a GSD of 1.66.

> ***Cough-day values range from \$1.66 to \$13.13, with a midpoint estimate of \$4.77 (in 1989 dollars), while chest tightness days range from nearly \$3 to \$21.48, with a midpoint estimate of nearly \$6 (again in 1989 dollars).***

Tables 10.3-4 (a) and (b), in addition to the mean estimate, provide 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 Southeast plant, respectively. The range reflects only the uncertainty in the dose-response functions and unit damage values of the quantified pathways. The mean estimate of total damages within 50 miles is 1.2 x $10^{-3}$ mill/kWh, and 4.8 x $10^{-3}$ mill/kWh within 1,000 miles. Figures 10.3-1 (a) and (b) are plots of the cumulative density function (CDF) for total damages for the Southeast Reference environment for the two geographical scopes. From the CDF plots, any percentile can be quickly found, and confidence intervals of any desired degree can be drawn. Tables 10.3-5 (a) and (b) and Figs. 10.3-2 (a) and (b) show the corresponding information for the Southwest Reference environment, for which mean damages are 3.3 x $10^{-5}$ mill/kWh within 50 miles and 1.6 x $10^{-4}$ mill/kWh within 1,000 miles. There is

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[12] Further general discussion of economic valuation issues are given in ORNL/RFF (1994a) and ORNL/RFF (1994b, Chapter 4.)

[13] Where the uncertainty of phenomena is described by a lognormal distribution, there is a two-thirds chance that the true value lies between the median divided by the GSD and the median times the GSD, and there is a 95 percent chance that the true value lies between the median divided by the GSD squared and the median times the GSD squared. A GSD of 1 implies perfect certainty.

a difference of over one order of magnitude in the damages between the two sites. The difference is mainly dependent on population differences, as nine times more people are located within 50 miles of the Southeast plant than within 50 miles of the Southwest plant. Also, meteorological conditions play a significant role. Many of the people who live within 50 miles of the plant at the Southwest site live due north, away from the prevailing wind directions. This factor accounts for about an order of magnitude in the difference between the two sites.

> ***There is a difference of over one order of magnitude in the damages between the two sites.***

**Table 10.3-4a. $SO_2$ morbidity: damages per year (in thousands of 1989 dollars) at the Southeast site [for 0-50 miles]**

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et al. (1991) | 0.061 | 0.83 | 2.3 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 0.19 | 1.7 | 3.9 |
| Total pathway damages | 0.81 | 2.5 | 4.8 |
| Total pathway damages (mills/kWh) | $3.9 \times 10^{-4}$ | $1.2 \times 10^{-3}$ | $2.3 \times 10^{-3}$ |

**Table 10.3-4b. $SO_2$ morbidity: damages per year (in thousands of 1989 dollars) at the Southeast site [for 0-1,000 miles]**

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et al. (1991) | 0.39 | 3.3 | 8.3 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 1.1 | 6.8 | 15 |
| Total pathway damages | 3.4 | 10 | 20 |
| Total pathway damages (mills/kWh) | $1.6 \times 10^{-3}$ | $4.8 \times 10^{-3}$ | $9.5 \times 10^{-3}$ |

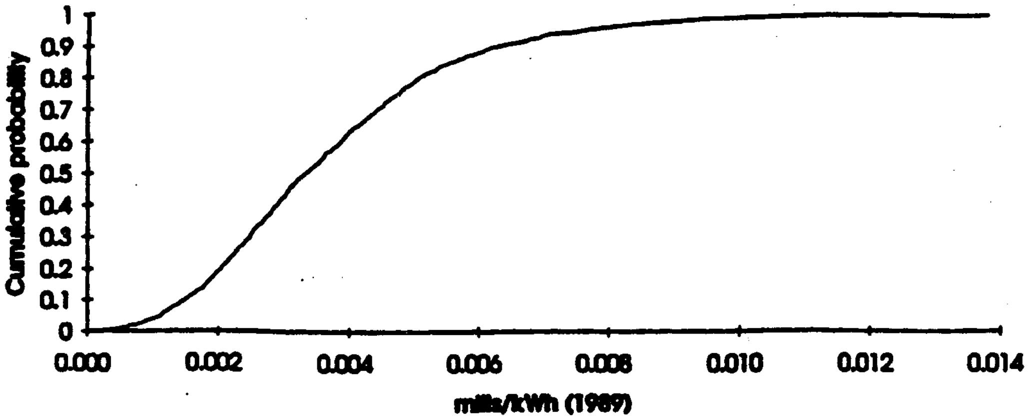

**Figure 10.3-1 (a). Sulfur dioxide--morbidity damages within 50 miles of the Southeast plant**

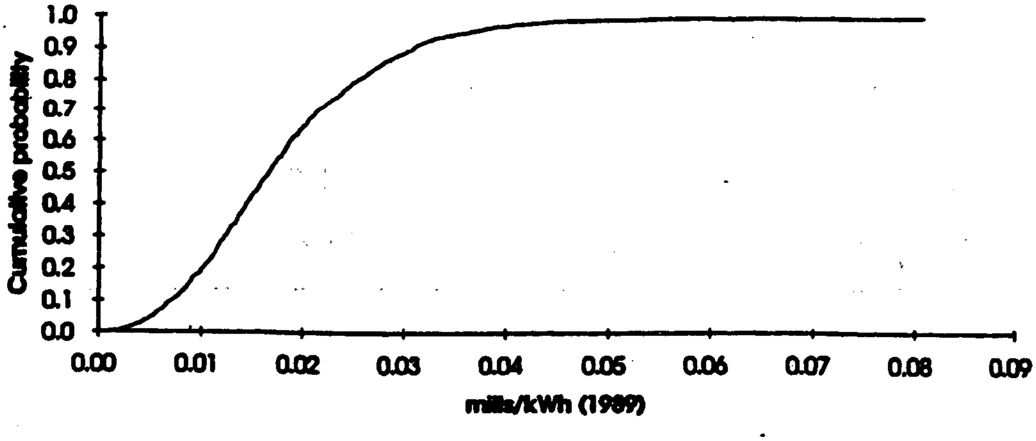

**Figure 10.3-1 (b). Sulfur dioxide -- morbidity damages within 1000 miles of the Southeast plant**

**Table 10.3-5a. $SO_2$ morbidity: damages per year (in thousands of 1989 dollars) at the Southwest site [for 0-50 miles]**

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et al. (1991) | 0.00042 | 0.023 | 0.06 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 0.0069 | 0.047 | 0.11 |
| Total pathway damages | 0.021 | 0.07 | 0.15 |
| Total pathway damages (mills/kWh) | $9.8 \times 10^{-8}$ | $3.3 \times 10^{-5}$ | $6.9 \times 10^{-5}$ |

**Table 10.3-5b. $SO_2$ morbidity: damages per year (in thousands of 1989 dollars) at the Southwest site [for 0-1,000 miles]**

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Children's cough-days: Schwartz et al. (1991) | 0.01 | 0.11 | 0.25 |
| Adults' chest discomfort-days: Schwartz et al. (1988) | 0.022 | 0.23 | 0.5 |
| Total pathway damages | 0.098 | 0.33 | 0.65 |
| Total pathway damages (mills/kWh) | $4.7 \times 10^{-5}$ | $1.6 \times 10^{-4}$ | $3.1 \times 10^{-4}$ |

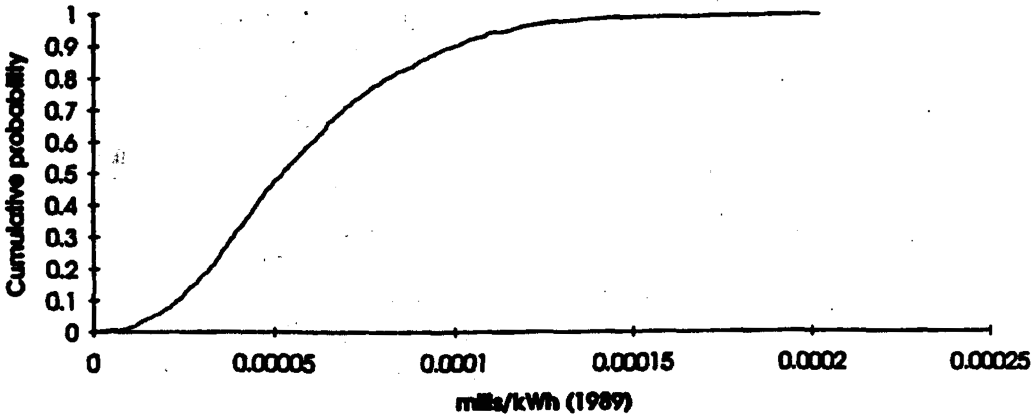

Figure 10.3-2 (a). Sulfur dioxide–morbidity damages within 50 miles of the Southwest plant

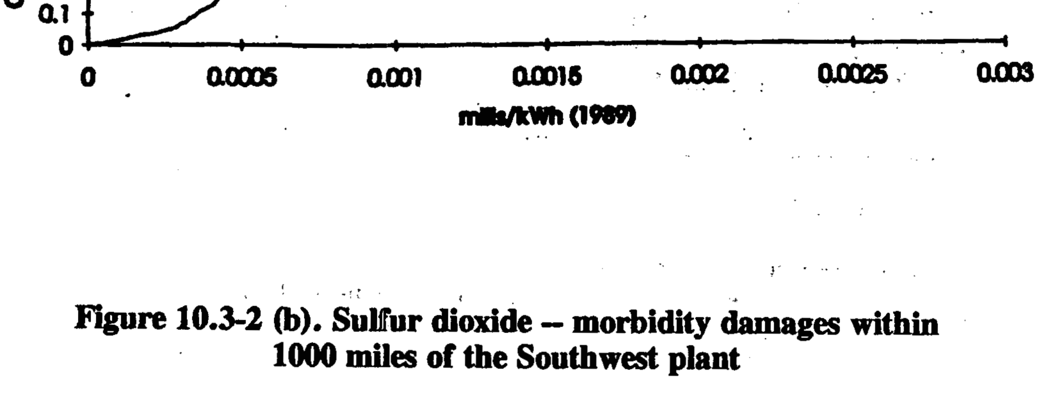

Figure 10.3-2 (b). Sulfur dioxide -- morbidity damages within 1000 miles of the Southwest plant

### 10.3.2.3 Externalities from $SO_2$ Morbidity Impacts

Beginning in 1995, sulfur dioxide emissions from power plants will be regulated under a national emission permit trading system established under Title IV of the 1990 Clean Air Act Amendments. This program will be implemented in two phases. The first phase will begin in 1995 and will directly affect the 111 most polluting facilities; the second phase will begin in 2000 and will affect all large electric power plants. If trading rules for a permit trading program properly reflect the relative damages that occur from emissions by sources in different geographic locations, then the net damage from emissions at a new facility would be zero because the damage from its emissions would be precisely offset by reductions in damages elsewhere.[14] The economics literature is in widespread support of the need to recognize offsets in a tradable permit program such as Title IV regulating $SO_2$ allowances.[15] Trading rules under Title IV do not, however, account for differences in damage that occur from spatial differentiation in the effects of emissions. Damages are site specific (as is plainly evident in the previous section). Consequently, the *net* marginal damage of $SO_2$ may not be zero due to the spatial differentiation of the impacts or damages from emission. In fact, it may be either positive or negative.

ORNL/RFF (1994b, pp. 10-40 to 10-42) describes some analysis that provides a first approximation of the extent to which the net damages are in fact positive or negative. It is essentially impossible, however, to estimate this magnitude with any acceptable degree of accuracy. Therefore, for our best estimate of externality, we adopt the "rebuttable presumption" that damages by a unit of emission at the reference environment are approximately offset by reductions in damages elsewhere, and hence the externality is zero. For an upper bound, we include an estimate of damages without consideration of offsets due to allowance trading, representing the possibility that the allowance market fails to materialize or that the trading program is terminated.

### 10.3.3 Effects of $SO_2$ on Mortality

Over the years there has been much debate in the U.S. over the role played by $SO_2$ and particulates in raising mortality risks. The current majority view in the U.S. [see ORNL/RFF (1994a, Part III)] is that particulates are the major culprit rather than $SO_2$ (see *Journal of the American Medical Association* (JAMA), June 23/30, 1993, Vol 269, No. 24 for a recent summary). This conclusion is reached

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[14] Freeman et al. (1992).

[15] Even in cases such as the State of Wisconsin, where potential suppliers of allowances have already been required under State law to reduce emissions below their allowance allocation under Title IV, their excess allowances will be available on the market enabling emissions at some other location. Hence, their use by the coal facility in one of our two reference environments will still offset their use elsewhere in the country.

on the basis of the weight of the statistical evidence. In studies where $SO_2$ concentrations and particulate concentrations are included, the former are rarely significant while the latter generally are significant, whether both variables are included in the regressions or each one separately (although collinearity between these two measures clouds inferences one can make about the attribution of effects). Given the need to choose, however, the weight of the evidence strongly supports $PM_{10}$-mortality as the primary relationship [refer to ORNL/RFF (1994a, Paper 5)]. Thus, we estimate that there are no mortality-related damages from $SO_2$ emissions.

At the same time, sulfates are frequently identified as an important cause of premature death, though the evidence is not conclusive [refer to Paper 5 in Part III of ORNL/RFF (1994a)]. These products are created from the oxidation of $SO_2$ and are counted as particulates. Therefore, finding a particulate effect without an $SO_2$ effect does not preclude the finding of an indirect effect through sulfates. A priority for future analysis is estimating the conversion of $SO_2$ to sulfates, and their impacts on health.

## 10.4 FERTILIZATION BENEFITS OF $SO_2$ AND $NO_X$ EMISSIONS

### 10.4.1 Deposition of Sulfur and Nitrogen

Sulfur and nitrogen oxides are emitted during the operation of an oil-fired power plant. These emissions are primarily sulfur dioxide ($SO_2$) and nitrogen oxide (NO) with lesser quantities of sulfur trioxide ($SO_3$) and nitrogen dioxide ($NO_2$). Emissions of $SO_2$ and $NO_x$ from the Southeast Reference power plant are each estimated to be 0.507 and 0.634 tons/GWh (30.7 and 38.4 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 strong acids, $H_2SO_4$ and $HNO_3$. These compounds may be deposited on the soil both directly by dry deposition and by removal in rainfall. This deposition results in additions of sulfur (S) and 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 determine 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 S and N were calculated.

### 10.4.2 Impacts of Sulfur Deposition on Crop Growth

Although extensive quantitative estimates of the relative importance of atmospherically derived sulfur in meeting plant nutritional requirements are not available, several studies provide some insight in this regard. Results of experiments with simulated acid rain exposures to a forage mix (timothy and red clover) suggested that these species might benefit from levels of sulfur and nitrogen increased above ambient levels in rain (Irving 1986). Atmospheric deposition of S can represent a significant fraction of the S requirement for some crops in some regions of the United States. Noggle (1980) estimated that soybeans growing at various distances from sources of atmospheric sulfur obtained between 10 and 50% of their sulfur requirement from the atmosphere. Jones and Suarez (1980) reported increased yield of corn grain and silage with 9 and 18 kg/ha of sulfur added in fertilizer trials. Atmospheric sulfur deposition at the sites was approximately 11 kg/ha per year. The authors concluded that the probability was low that plant health was being influenced by either too much or too little atmospheric or soil sulfur. In their South Carolina studies, only one crop (corn) out of eight studied and one soil (a loamy sand) out of five studied, showed positive responses to sulfur additions. At none of the 15 locations studied was there an indication of too much atmospheric sulfur for healthy plant growth.

In general, it is difficult to claim that the sulfur deposited as a result of a single power plant's $SO_2$ emissions contributes to crop growth. Thus, we take the effect to be negligible, even on a per kWh basis.

### 10.4.3 Benefits of Crop Growth Increases from $SO_2$ and $NO_x$ Emissions

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 and S crop fertilization in the eastern half of the United States. A 50% increase in passive sources of N increased total welfare by $241M annually for the 31 eastern state region. Furthermore, even assuming the full $241M 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.

### 10.4.4 Impacts: Increases in Forest Growth

Response functions do not exist upon which to base an evaluation of S and N fertilization of forests on a large scale. As a result, the discussion of increases in forest growth is primarily qualitative in nature.

> ***... little possibility for beneficial effects of S deposition except in the most pristine areas ... possibility that atmospheric N dispersion is at least partially benefitting large acreages of N-deficient forests throughout the United States ...***

Atmospheric deposition contains nitrogen and sulfur which, as essential plant nutrients, have the theoretical potential for beneficial as well as detrimental effects on forest nutrient status. Various analyses of forest S cycles indicate clearly that typical S deposition values in polluted regions (>10 kg/ha/yr) exceed forest S requirements for growth increments (1-2 kg/ha/yr) by a factor of 5-10, leaving little possibility for beneficial effects of S deposition except in the most pristine areas (Johnson 1984). 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 either S or 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).

### 10.4.5 Benefits of Increase in Forest Growth from $SO_2$ and $NO_x$ Emissions

No quantitative estimates are possible, but any increase in forest growth as a result of a power plant's $SO_2$ and $NO_x$ emissions appears to be small, and limited to sulfur and nitrogen deficient soils.

## 10.5 EFFECTS OF $SO_2$ ON MATERIALS

As noted in Section 10.10 of ORNL/RFF (1994b), NERA (1993) reports on a re-analysis of the Manuel et al. study linking $SO_2$ and particulates to consumer expenditures on "cleanliness" in 24 cities. This analysis reveals a small, but significant $SO_2$ damage coefficient. The LOW, MID, and HIGH estimates of damage (in \$1990) to materials per household for a 1 $\mu g/m^3$ change in $SO_2$ concentrations are \$0.18, \$0.83, and \$1.50, respectively.

*The LOW, MID, and HIGH estimates of damage (in \$1990) to materials per household for a 1 $\mu g/m^3$ change in $SO_2$ concentrations are \$0.18, \$0.83, and \$1.50, respectively.*

Applying these estimates to the number of households in the Southeast Reference environment, damages to materials from $SO_2$ amount to from \$3,500 to \$16,000 (with a mean of \$9,900) within 50 miles of the plant, or from \$15,000 to \$68,000 (a mean of \$41,000) within 1,000 miles of the plant. Corresponding damages for the Southwest Reference environment are considerably smaller, ranging from \$95 to \$470 (mean \$219) within 50 miles and from \$470 to \$2,300 (mean \$1,300) within 1,000 miles. Damages in terms of mills/kWh are given in Table 10.5-1.

**Table 10.5-1. Damages to materials from $SO_2$ (mills/kWh)**

| | SE Site | | SW Site | |
|---|---|---|---|---|
| | Within 50 mi | Within 1,000 mi | Within 50 mi | Within 1,000 mi |
| Low | 0.0017 | 0.0072 | 0.000045 | 0.00022 |
| Mid | 0.0047 | 0.019 | 0.00014 | 0.00064 |
| High | 0.0078 | 0.032 | 0.00023 | 0.0011 |

### 10.5.1 Externalities from $SO_2$ Materials Impacts

The calculation of externalities on the basis of damages presented above depends on the implementation of the $SO_2$ allowance trading program under Title IV of the 1990 Clean Air Act Amendments, as discussed previously with respect to externalities from $SO_2$ health impacts. Under the allowance trading program, an additional unit of emission by one of the reference facilities must be offset by a reduction at another facility somewhere in the U.S. This reduction will have an offsetting environmental benefit through reduced impacts on materials in the vicinity of the facility reducing its emissions.

For a midpoint estimate of materials damage we adopt a value of zero, reflecting the "rebuttable presumption" that damages from emissions at the reference sites just offset damages from reductions in emissions elsewhere. For an upper bound, one could use the full value of damages that would be observed from increases in emissions at the reference site, without accounting for decreases in emissions elsewhere. This reflects the possibility that the allowance market may not materialize, or that the trading program could be dismantled.

## 10.6 EFFECTS OF SO$_2$ (WITH NO$_x$ AND PARTICULATE MATTER) ON VISIBILITY

One of the most 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 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.

The Decision Focus study estimates the value of visibility improvements in the Grand Canyon region to be 0.47 mill/kWh, but this estimate is based on their value to 100 million U.S. households and a 50% $SO_2$ reduction. Such an estimate clearly overestimates the value of damages from either of our reference power plants.

While the studies are interesting, they are too imprecise to include in our final tabulation in Chapter 11. Since we do not model reduction in visual range, we do not use the unit values of NERA and others. Also, the non-use values for the Grand Canyon region are for a different site and are difficult to transfer to our context.

***... the non-use values for the Grand Canyon region are for a different site and are difficult to transfer to our context.***

## 10.7 EFFECTS OF $NO_x$ ON HEALTH

### 10.7.1 Emissions and Changes in Concentration of $NO_x$

When residual oil 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 oil and the thermal fixation of nitrogen in the combustion air. $NO_x$ emissions from the reference power plants were estimated to be 0.66 tons/GWh (1,378 tons/year or 39.62 grams/second).

The ground-level pollutant concentrations of $NO_x$ that could be expected to occur as a result of the operation of the 300 MW reference oil-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 oil fuel cycle analysis are presented in Appendix C. The highest predicted ambient annual concentration[16] of $NO_x$ from the Southeast Reference plant site was 0.444 micrograms per cubic meter ($\mu g/m^3$). The highest predicted ambient annual concentration of $NO_x$ from the Southwest plant site was 0.405 $\mu g/m^3$. As with $SO_2$, the maximum values alone are not used in the impacts analysis. Rather, a population weighted concentration of $NO_x$ was evaluated according to the process described in Section 10.3. These population weighted concentrations of $NO_x$ are 0.087 $\mu g/m^3$ and 0.059 $\mu g/m^3$ for the 0-50 mile and the 0-1,000 mile population for the Southeast and Southwest sites, respectively.

### 10.7.2 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

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[16] The ambient annual concentration is defined as the arithmetic mean (or average) concentration predicted to occur during a 365 day period at outdoor, ground level receptors. The highest ambient annual concentration is the highest concentration predicted among the 384 receptor locations used in the dispersion model.

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.[17]

Table 10.7-1 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.

**Table 10.7-1. Linearized dose-response function for effects of $NO_2$ on morbidity**

Schwartz and Zeger (1990):

$\Delta$ phlegm-days per year = $C_{phlegm}$ Pop $\Delta$ $NO_2$

where

$\Delta$ $NO_2$ = 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=0.0054, standard deviation=0.0032)

A 95% confidence interval of between 5.5 and 430 phlegm-days, with a mean of 220 phlegm-days, is estimated within 50 miles of the Southeast plant. Extending the analysis out to 1,000 miles, this interval is 22 to 1,700 with a mean of 880. The corresponding impacts for the Southwest reference environment range from 0.2 to 12 phlegm-days (mean 6.3) within 50 miles, or from 0.7 to 58 (mean 30) phlegm-days within 1,000 miles.

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[17] 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.

### 10.7.3 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.

## 10.8 EFFECTS OF PARTICULATES ON MORTALITY[18]

### 10.8.1 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 oil-fired boiler particulate matter composition and emission levels are a complex function of firing configuration and boiler operation (EPA 1988). Emission levels are also a function of the particulate control device employed. An electrostatic precipitator (ESP) 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 0.02 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.

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 300 MW reference oil-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.

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[18] Our air dispersion modeling does *not* account for the formation of acid aerosols from $SO_2$ and $NO_x$ emissions. Acid aerosols are part of $PM_{10}$. Thus, our estimates of $PM_{10}$ externalities underestimates them. Due to the $SO_2$ emissions cap required by the Clean Air Act Amendments, we take the rebuttable presumption that the net effects of sulfate aerosols is zero. A fraction of the $NO_x$ emissions, however, 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 may be the most important of those that can be quantified.

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). The highest predicted ambient annual concentration of $PM_{10}$ from the Southeast Reference plant site for 1990 was 0.012 micrograms per cubic meter ($\mu g/m^3$). The highest predicted ambient annual concentration of $PM_{10}$ from the Southwest Reference plant site is 0.011 $\mu g/m^3$. Calculations of impacts utilized the $PM_{10}$ concentrations predicted around the reference sites, weighted by the populations. For example, population-weighted concentrations of $PM_{10}$ are 0.00229 and 0.00156 $\mu g/m^3$ for the 0-50 mile populations in the Southeast and Southwest sites, respectively.

### 10.8.2 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.

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 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.[19] 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

***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.***

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[19] 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 of ORNL/RFF 1994b) for more discussion of the scientific evidence on the effects of particulate matter on human health, including a summary of the most contentious issues.

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 10.8-1 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 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 10.8-2 and 10.8-3.

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 10.8-1. Estimates of the mortality effects of a change in $PM_{10}$

| | | | | Estimated percent change in mortality due to 10 $\mu g/m^3$ change in $PM_{10}$ | | |
|---|---|---|---|---|---|---|
| City | Author | Original measure | Mean $PM_{10}$ equivalent | 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 10.8-2 (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 was 0.00063 deaths while the highest 95th percentile estimate was 0.02 deaths. In the absence of a threshold, damages are about 50% greater. Damages out to 1,000 miles are approximately four times larger than damages within 50 miles for both threshold assumptions. Tables 10.8-3 (a) and (b) provide the same information for the Southwest Reference environment.

**Table 10.8-2a. Particulates—mortality: deaths per year for the Southeast site [for 0-50 miles][1]**

| Study | Low | Mid | High |
|---|---|---|---|
| Schwartz and Marcus (1990) | 0.0058 | 0.0066 | 0.0074 |
| | **0.0040** | **0.0045** | **0.0051** |
| Plagiannakos and Parker (1988) | 0.0017 | 0.0095 | 0.018 |
| | **0.0012** | **0.0066** | **0.012** |
| Schwartz and Dockery (1991a)-$PM_{10}$ | 0.0030 | 0.0062 | 0.0094 |
| | **0.0021** | **0.0043** | **0.0065** |
| *Schwartz and Dockery (1991a)-TSP* | 0.0021 | 0.0042 | 0.0064 |
| | **0.0014** | **0.0029** | **0.0044** |
| Schwartz and Dockery (1991b)-$PM_{10}$ | 0.0079 | 0.012 | 0.016 |
| | **0.0054** | **0.0081** | **0.011** |
| Schwartz and Dockery (1991b)-TSP | 0.0054 | 0.0079 | 0.011 |
| | **0.0037** | **0.0055** | **0.0073** |
| Fairley (1991) | 0.0047 | 0.011 | 0.017 |
| | **0.0032** | **0.0075** | **0.012** |
| Schumway et al. (1988) | 0.016 | 0.024 | 0.029 |
| | **0.011** | **0.015** | **0.020** |
| Evans et al. (1984) | 0.00092 | 0.0070 | 0.013 |
| | **0.00063** | **0.0048** | **0.0090** |

**[1] Numbers in bold are with a threshold.**

**Table 10.8-2b. Particulates—mortality: deaths per year for the Southeast site [for 0-1,000 miles][1]**

| Study | Low | Mid | High |
|---|---|---|---|
| Schwartz and Marcus (1990) | 0.023 | 0.027 | 0.030 |
| | **0.011** | **0.013** | **0.014** |
| Plagiannakos and Parker (1988) | 0.0068 | 0.038 | 0.070 |
| | **0.0033** | **0.019** | **0.034** |
| Schwartz and Dockery (1991a)-$PM_{10}$ | 0.012 | 0.025 | 0.038 |
| | **0.0059** | **0.012** | **0.018** |
| *Schwartz and Dockery (1991a)-TSP* | 0.0083 | 0.017 | 0.026 |
| | **0.0040** | **0.0083** | **0.013** |
| Schwartz and Dockery (1991b)-$PM_{10}$ | 0.032 | 0.047 | 0.062 |
| | **0.015** | **0.023** | **0.030** |
| Schwartz and Dockery (1991b)-TSP | 0.022 | 0.032 | 0.042 |
| | **0.011** | **0.016** | **0.021** |
| Fairley (1991) | 0.019 | 0.044 | 0.067 |
| | **0.0091** | **0.021** | **0.034** |
| Schumway et al. (1988) | 0.064 | 0.090 | 0.12 |
| | **0.031** | **0.044** | **0.057** |
| Evans et al. (1984) | 0.0037 | 0.028 | 0.053 |
| | **0.0018** | **0.014** | **0.026** |

[1] **Numbers in bold are with a threshold.**

**Table 10.8-3a. Particulates—mortality: deaths per year for the Southwest site [for 0-50 miles][1]**

| Study | Low | Mid | High |
|---|---|---|---|
| Schwartz and Marcus (1990) | 0.00032<br>**0** | 0.00036<br>**0** | 0.00040<br>**0** |
| Plagiannakos and Parker (1988) | 0.00005<br>**0** | 0.00027<br>**0** | 0.00050<br>**0** |
| Schwartz and Dockery (1991a)-$PM_{10}$ | 0.00009<br>**0** | 0.00018<br>**0** | 0.00027<br>**0** |
| *Schwartz and Dockery (1991a)-TSP* | 0.00006<br>**0** | 0.00012<br>**0** | 0.00018<br>**0** |
| Schwartz and Dockery (1991b)-$PM_{10}$ | 0.00023<br>**0** | 0.00033<br>**0** | 0.00044<br>**0** |
| Schwartz and Dockery (1991b)-TSP | 0.00015<br>**0** | 0.00023<br>**0** | 0.00030<br>**0** |
| Fairley (1991) | 0.00013<br>**0** | 0.00031<br>**0** | 0.00049<br>**0** |
| Schumway et al. (1988) | 0.00046<br>**0** | 0.00064<br>**0** | 0.00083<br>**0** |
| Evans et al. (1984) | 0.00003<br>**0** | 0.00020<br>**0** | 0.00038<br>**0** |

[1] **Numbers in bold are with a threshold.**

**Table 10.8-3b. Particulates—mortality: deaths per year for the Southwest site [for 0-1,000 miles][1]**

| Study | Low | Mid | High |
|---|---|---|---|
| Schwartz and Marcus (1990) | 0.0015 | 0.0017 | 0.0019 |
| | **0.00075** | **0.00085** | **0.00095** |
| Plagiannakos and Parker (1988) | 0.00023 | 0.0013 | 0.0023 |
| | **0.00011** | **0.00064** | **0.0012** |
| Schwartz and Dockery (1991a)-$PM_{10}$ | 0.00041 | 0.00084 | 0.0013 |
| | **0.00020** | **0.00042** | **0.00063** |
| *Schwartz and Dockery (1991a)-TSP* | 0.00028 | 0.00057 | 0.00086 |
| | **0.00014** | **0.00028** | **0.00043** |
| Schwartz and Dockery (1991b)-$PM_{10}$ | 0.0011 | 0.0016 | 0.0021 |
| | **0.00053** | **0.00078** | **0.0010** |
| Schwartz and Dockery (1991b)-TSP | 0.00072 | 0.0011 | 0.0014 |
| | **0.00036** | **0.00053** | **0.00070** |
| Fairley (1991) | 0.00063 | 0.0015 | 0.0023 |
| | **0.00031** | **0.0073** | **0.0012** |
| Schumway et al. (1988) | 0.0021 | 0.0030 | 0.0039 |
| | **0.0011** | **0.0015** | **0.0019** |
| Evans et al. (1984) | 0.00012 | 0.00094 | 0.0018 |
| | **0.00006** | **0.00047** | **0.00088** |

**[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 $\mu/m^3$, a 95% confidence interval of between 0.0014 and 0.0044 premature deaths, with a mean of 0.0029 deaths, is estimated within 50 miles of the Southeast plant. Extending the analysis out to 1,000 miles, this interval is 0.004 to 0.013 with a mean of 0.0083. The corresponding impacts for the Southwest reference environment are zero within 50 miles, or from 0.00014 to 0.00043 (mean 0.00028) premature deaths within 1,000 miles.

### 10.8.3 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.[20] 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

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[20] 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.

premature deaths; and (ii) multiplying the value of a statistical life associated with 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.[21] 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 10.8-4 (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 0.0026 to 0.017 mill/kWh within 50 miles, or

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[21] 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.

from 0.011 to 0.068 mill/kWh within 1,000 miles of the plant. Tables 10.8-5 (a) and (b) present the same information for the Southwest Reference environment, for which the damages range from 0.000083 to 0.00047 mill/kWh within 50 miles, and from 0.00036 to 0.0023 mill/kWh within 1,000 miles of the plant. Figures 10.8-1 (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 0.0018 to 0.012 mills/kWh within 50 miles, or from 0.0052 to 0.033 mill/kWh within 1,000 miles of the plant. Tables 10.8-5 (a) and (b) present the same information for the Southwest Reference environment, for which there are no damages within 50 miles, and from 0.00018 to 0.0011 mill/kWh within 1,000 miles of the plant. Figures 10.8-1 (a) and (b) are plots of the cumulative density function (CDF) for total damages for the Southeast Reference environment.

**Table 10.8-4a. 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 | 5.5<br>**3.8** | 17<br>**12** | 35<br>**24** |
| Total pathway damages (mills/kWh) | 0.0026<br>**0.0018** | 0.0082<br>**0.0057** | 0.017<br>**0.012** |

[1] Numbers in bold are with threshold.

**Table 10.8-4b. 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 | 22<br>**11** | 69<br>**34** | 140<br>**70** |
| Total pathway damages (mills/kWh) | 0.011<br>**0.0052** | 0.033<br>**0.016** | 0.068<br>**0.033** |

[1] Numbers in bold are with threshold.

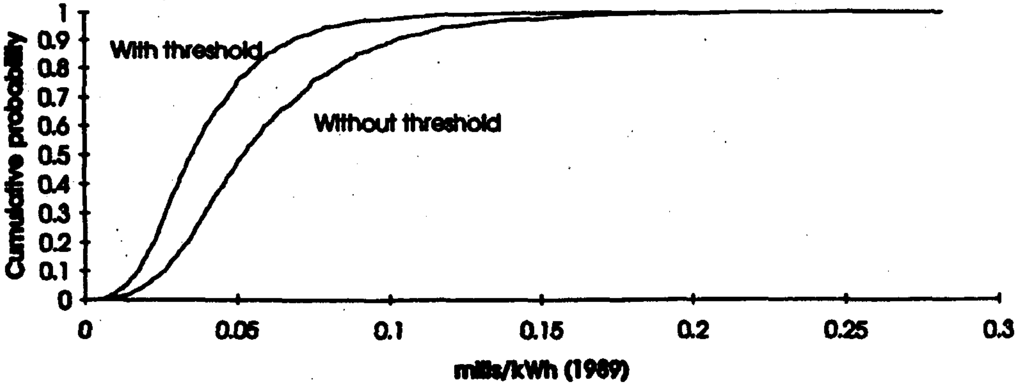

**Figure 10.8-1 (a). Particulate -- mortality damages within 50 miles of Southeast plant with and without 30 microgram/cubic meter threshold**

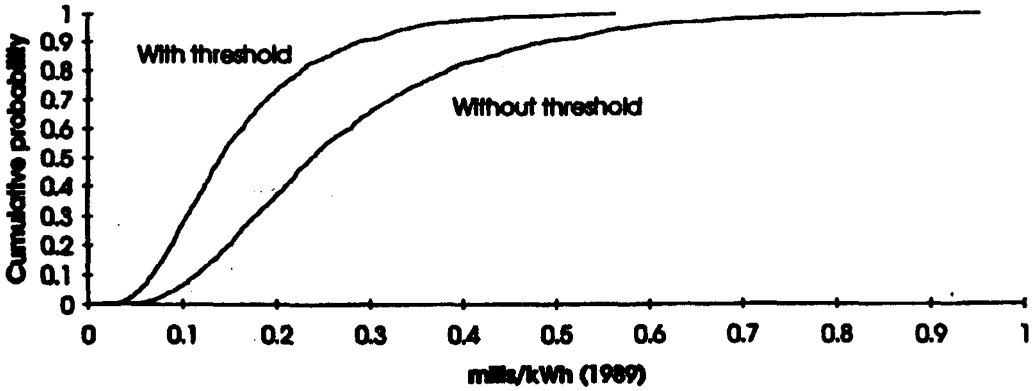

**Figure 10.8-1 (b). Particulate -- mortality damages within 1000 miles of Southeast plant with and without 30 microgram/cubic meter threshold**

**Table 10.8-5a. 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 | 0.17 | 0.49 | 1 |
| | **0** | **0** | **0** |
| Total pathway damages (mills/kWh) | 0.000083 | 0.00023 | 0.00047 |
| | **0** | **0** | **0** |

[1] Numbers in bold are with threshold.

**Table 10.8-5b. 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 | 0.76 | 2.3 | 4.8 |
| | **0.38** | **1.1** | **2.4** |
| Total pathway damages (mills/kWh) | 0.00036 | 0.0011 | 0.0023 |
| | **0.00018** | **0.00054** | **0.0011** |

[1] Numbers in bold are with threshold.

## 10.9 EFFECTS OF PARTICULATES ON MORBIDITY[22]

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. 10.9-1. 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

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[22] Refer to the footnote at the beginning of Section 10.8.

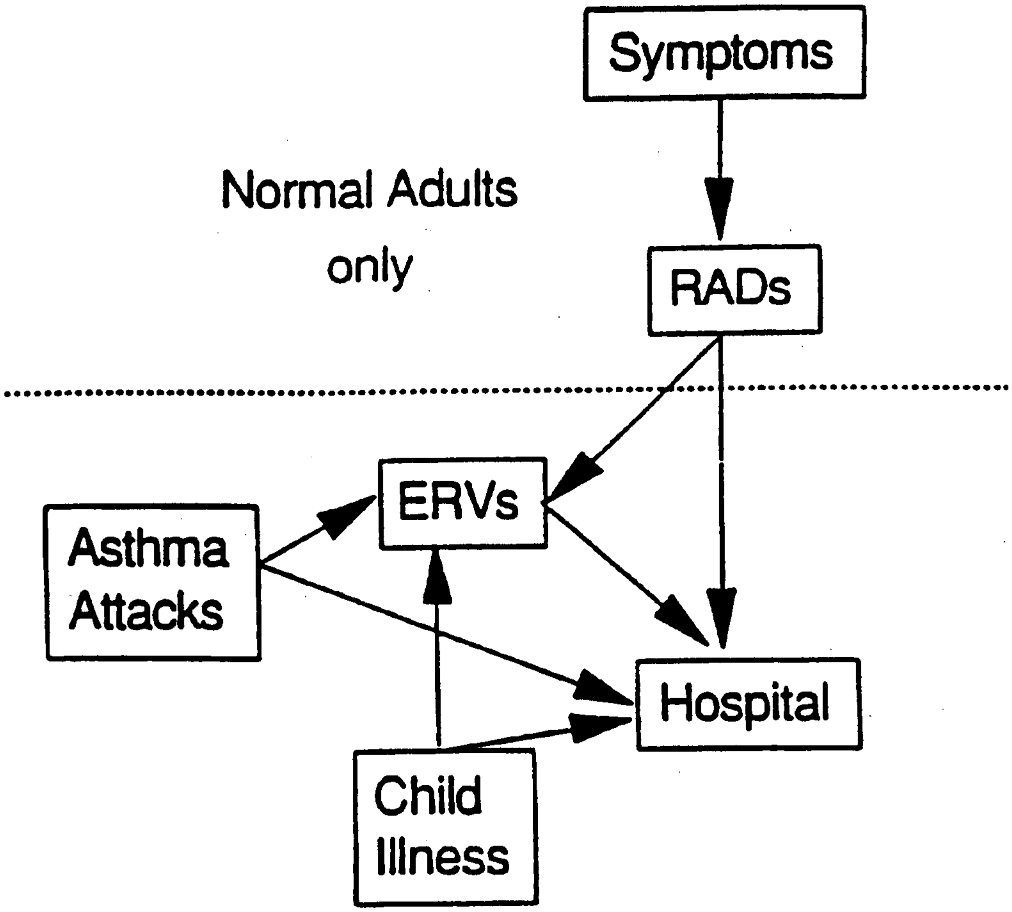

Figure 10.9-1. Flowchart of particulate-morbidity effects.

admitted to the 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.

### 10.9.1 Impacts of Particulates on Morbidity

The following shaded table (Table 10.9-1) 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 10.9-1 Linearized dose-response functions for effects of $PM_{10}$ on morbidity.**

**Respiratory hospital admissions** *(Plagiannakos & Parker 1988)*:
$\Delta$ RHA per year = $C_{RHA}$ Pop $\Delta PM_{10}$

**Emergency room visits** *(Samet et al. 1981)*:
$\Delta$ ERV per year = $C_{ERV}$ Pop $\Delta PM_{10}$

**Symptom-days** *(Krupnick et al. 1990)*:
$\Delta$ symptom-days per year = $C_{symptom\text{-}day}$ Pop $F_{adult}$ $\Delta PM_{10}$

**Restricted activity days** *(Ostro 1987)*:
$\Delta$ RAD per year = $C_{RAD}$ Pop $(1-F_{asthmatic})$ $F_{adult}$ $\Delta PM_{10}$

**Children bronchitis** *(Dockery et al. 1989)*:
$\Delta$ children bronchitis cases per year = $C_{children\ bronchitis}$ Pop $F_{children}$ $\Delta PM_{10}$

**Children chronic cough** *(Dockery et al. 1989)*:
$\Delta$ children chronic cough cases per year = $C_{children\ cough}$ Pop $F_{children}$ $\Delta PM_{10}$

**Asthma attacks** *(Ostro et al. 1991)*:
$\Delta$ asthma attacks per year = $C_{asthma\ attacks}$ Pop $F_{asthmatic}$ $\Delta PM_{10}$

**Chronic bronchitis in adults** *(Abbey et al. 1993)*:
$\Delta$ chronic bronchitis in adults = $C_{adult\ bronch}$ Pop $F_{adult}$ $\Delta PM_{10}$ T
where
$\Delta PM_{10}$ = 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 > 100 $\mu g/m^3$ > 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=$6.15 \times 10^{-5}$, standard deviation=$3.07 \times 10^{-5}$)

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 10.9-2 (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 (1,100), RADs (28), asthma attacks (12), children with chronic cough (0.33), children with chronic bronchitis (0.28), ERVs (0.16), RHAs (0.071), and, finally, adults with chronic bronchitis (0). Tables 10.9-3 (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-thirtieth 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 10.9-2a. Particulate—morbidity: number of impacts per year for the Southeast site [for 0-50 miles][1]**

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Restricted activity day | 8.1 | 41 | 74 |
| --Ostro (1987) | **6.1** | **28** | **51** |
| Emergency room visit | 0.025 | 0.24 | 0.45 |
| --Samet et al. (1981) | **0.017** | **0.16** | **0.31** |
| Asthma attack-day | 3.2 | 17 | 31 |
| --Ostro et al. (1991) | **2.2** | **12** | **21** |
| Child chronic bronchitis | 0.069 | 0.41 | 0.75 |
| --Dockery et al. (1989) | **0.048** | **0.28** | **0.52** |
| Child chronic cough | 0.082 | 0.47 | 0.86 |
| --Dockery et al. (1989) | **0.056** | **0.33** | **0.60** |
| Respiratory hospital admission | 0 | 0.10 | 0.21 |
| --Plagiannakos and Parker (1988) | **0** | **0.071** | **0.14** |
| Any symptom-day | 970 | 1,500 | 2,100 |
| --Krupnick et al. (1990) | **670** | **1,100** | **1,500** |
| Chronic bronchitis in adults | 0 | 0 | 0 |
| --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 10.9-2b. 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 | 35 | 170 | 300 |
| --Ostro (1987) | **17** | **81** | **140** |
| Emergency room visit | 0.1 | 0.96 | 1.8 |
| --Samet et al. (1981) | **0.048** | **0.47** | **0.89** |
| Asthma attack-day | 13 | 68 | 123 |
| --Ostro et al. (1991) | **6.2** | **33** | **60** |
| Child chronic bronchitis | 0.28 | 1.6 | 3 |
| --Dockery et al. (1989) | **0.14** | **0.80** | **1.5** |
| Child chronic cough | 0.33 | 1.9 | 3.5 |
| --Dockery et al. (1989) | **0.16** | **0.93** | **1.7** |
| Respiratory hospital admission | 0 | 0.41 | 0.83 |
| --Plagiannakos and Parker (1988) | **0** | **0.41** | **0.41** |
| Any symptom-day | 3,900 | 6,200 | 8,600 |
| --Krupnick et al. (1990) | **1,900** | **3,000** | **4,200** |
| Chronic bronchitis in adults | 0.029 | 0.16 | 0.29 |
| --Abbey et al. (1993) | **0.029** | **0.16** | **0.29** |

[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 10.9-3a. Particulate—morbidity: number of impacts per year for the Southwest site [for 0-50 miles][1]**

| Pathway endpoint | Low | Mid | High |
|---|---|---|---|
| Restricted activity day | 0.3 | 1.2 | 2.1 |
| --Ostro (1987) | **0** | **0** | **0** |
| Emergency room visit | 0.0007 | 0.0068 | 0.013 |
| --Samet et al. (1981) | **0** | **0** | **0** |
| Asthma attack-day | 0.091 | 0.48 | 0.87 |
| --Ostro et al. (1991) | **0** | **0** | **0** |
| Child chronic bronchitis | 0.002 | 0.012 | 0.022 |
| --Dockery et al. (1989) | **0** | **0** | **0** |
| Child chronic cough | 0.0023 | 0.014 | 0.025 |
| --Dockery et al. (1989) | **0** | **0** | **0** |
| Respiratory hospital admission | 0 | 0.0029 | 0.0059 |
| --Plagiannakos and Parker (1988) | **0** | **0** | **0** |
| Any symptom-day | 28 | 44 | 61 |
| --Krupnick et al. (1990) | **0** | **0** | **0** |
| Chronic bronchitis in adults | 0 | 0 | 0 |
| --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 10.9-3b. 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 | 1.2 | 5.6 | 9.9 |
| --Ostro (1987) | **0.6** | **2.8** | **4.9** |
| Emergency room visit | 0.0033 | 0.032 | 0.061 |
| --Samet et al. (1981) | **0.0017** | **0.016** | **0.03** |
| Asthma attack-day | 0.43 | 2.3 | 4.1 |
| --Ostro et al. (1991) | **0.21** | **1.1** | **2.0** |
| Child chronic bronchitis | 0.0093 | 0.055 | 0.1 |
| --Dockery et al. (1989) | **0.0046** | **0.027** | **0.05** |
| Child chronic cough | 0.011 | 0.064 | 0.12 |
| --Dockery et al. (1989) | **0.0055** | **0.032** | **0.056** |
| Respiratory hospital admission | 0 | 0.014 | 0.028 |
| --Plagiannakos and Parker (1988) | **0** | **0.0069** | **0.014** |
| Any symptom-day | 130 | 210 | 290 |
| --Krupnick et al. (1990) | **65** | **100** | **140** |
| Chronic bronchitis in adults | 0.001 | 0.0054 | 0.0098 |
| --Abbey et al. (1993) | **0.001** | **0.0054** | **0.0098** |

[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 $\mu g/m^3$.

## 10.9.2 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.

First, it is worth noting that these disparate estimates pass a reality check, in the sense that comparing the affects of a unit change in $PM_{10}$ in the various endpoints reveals that they are related to one another in a reasonable way. For instance, a comparison of the effect of a unit change in $PM_{10}$ on emergency room visits and hospital admissions shows that the former (23.54/100,000) are over twice the latter (10.15/100,000). In addition, the number of adult RADs (5,750/100,000) vastly exceeds the number of ERVs, and the number of adult symptom days (205,000/100,000) vastly exceeds the number of RADs.

Referring back to Fig. 10.9-1, 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 10.15). 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 10.9-4) 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[23]), 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

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[23] Since the average wage is so similar in the two reference environments, we use the Tennessee wage throughout.

$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.[24]

**Table 10.9-4. 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 1991) | 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).

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[24] 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.

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 (1991) 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 10.9-5 (a) and (b) and Tables 10.9-6 (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.[25] 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

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[25] 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.

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, 0.028, 0.0018, and 0.002 mill/kWh, respectively. If there is a threshold of 30 $\mu g/m^3$, then the corresponding damages are 0.0042 and 0.015 for the Southeast, and 0 and 0.0016 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 10.9-2 (a) and (b) and Figs. 10.9-3 (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.

**Table 10.9-5a. 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 | 0.43 | 2.1 | 3.8 |
| | **0.29** | **1.4** | **2.6** |
| Emergency room visit | 0.0025 | 0.041 | 0.078 |
| | **0.0017** | **0.029** | **0.053** |
| Asthma attack-day | 0.056 | 0.51 | 1.1 |
| | **0.038** | **0.35** | **0.74** |
| Child chronic bronchitis | 0.01 | 0.055 | 0.098 |
| | **0.007** | **0.038** | **0.067** |
| Child chronic cough | 0.00037 | 0.0026 | 0.0068 |
| | **0.00025** | **0.0018** | **0.0047** |
| Respiratory hospital admission | 0.021 | 0.68 | 1.4 |
| | **0.015** | **0.47** | **0.93** |
| Any symptom-day | 4.4 | 9.6 | 17 |
| | **3** | **6.6** | **12** |
| Adult chronic bronchitis | 0 | 0 | 0 |
| | **0** | **0** | **0** |
| Total pathway damages | 7.3 | 13 | 20 |
| | **5** | **8.8** | **14** |
| Total pathway damages (mills/kWh) | 0.0035 | 0.0061 | 0.0097 |
| | **0.0024** | **0.0042** | **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 10.9-5b. 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 | 1.9<br>**0.91** | 8.6<br>**4.2** | 15<br>**7.3** |
| Emergency room visit | 0.014<br>**0.0066** | 0.17<br>**0.084** | 0.32<br>**0.16** |
| Asthma attack-day | 0.31<br>**0.15** | 2<br>**0.99** | 4.2<br>**2** |
| Child chronic bronchitis | 0.036<br>**0.017** | 0.22<br>**0.11** | 0.41<br>**0.2** |
| Child chronic cough | 0.0015<br>**0.00072** | 0.01<br>**0.005** | 0.025<br>**0.012** |
| Respiratory hospital admission | 0.065<br>**0.032** | 2.7<br>**1.3** | 5.5<br>**2.7** |
| Any symptom-day | 17<br>**8.5** | 40<br>**19** | 73<br>**36** |
| Adult chronic bronchitis | 1.1<br>**1.1** | 5.8<br>**5.8** | 11<br>**11** |
| Total pathway damages | 35<br>**19** | 58<br>**31** | 92<br>**48** |
| Total pathway damages (mills/kWh) | 0.017<br>**0.009** | 0.028<br>**0.015** | 0.044<br>**0.023** |

[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 10.9-6a. 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 | 0.016<br>0 | 0.062<br>0 | 0.11<br>0 |
| Emergency room visit | 0.00086<br>**0** | 0.00012<br>**0** | 0.0022<br>**0** |
| Asthma attack-day | 0.0015<br>**0** | 0.014<br>**0** | 0.03<br>**0** |
| Child chronic bronchitis | 0.00031<br>**0** | 0.0015<br>**0** | 0.0028<br>**0** |
| Child chronic cough | 0.0000077<br>**0** | 0.000072<br>**0** | 0.00019<br>**0** |
| Respiratory hospital admission | 0<br>**0** | 0.019<br>**0** | 0.038<br>**0** |
| Any symptom-day | 0.13<br>**0** | 0.28<br>**0** | 0.5<br>**0** |
| Adult chronic bronchitis | 0<br>**0** | 0<br>**0** | 0<br>**0** |
| Total pathway damages | 0.21<br>**0** | 0.37<br>**0** | 0.59<br>**0** |
| Total pathway damages (mills/kWh) | 0.0001<br>**0** | 0.00018<br>**0** | 0.00028<br>**0** |

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[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 10.9-6b. 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 | 0.052 | 0.29 | 0.52 |
| | **0.026** | **0.14** | **0.26** |
| Emergency room visit | 0.00083 | 0.0061 | 0.011 |
| | **0.00041** | **0.003** | **0.0055** |
| Asthma attack-day | 0.0095 | 0.069 | 0.14 |
| | **0.0047** | **0.034** | **0.069** |
| Child chronic bronchitis | 0.0012 | 0.0072 | 0.013 |
| | **0.00059** | **0.0036** | **0.0066** |
| Child chronic cough | 0.000044 | 0.00033 | 0.00082 |
| | **0.000022** | **0.00017** | **0.00041** |
| Respiratory hospital admission | 0 | 0.087 | 0.18 |
| | **0** | **0.043** | **0.088** |
| Any symptom-day | 0.59 | 1.3 | 2.3 |
| | **0.29** | **0.66** | **1.1** |
| Adult chronic bronchitis | 0.51 | 2.5 | 4.7 |
| | **0.51** | **2.5** | **4.7** |
| Total pathway damages | 2.1 | 4.2 | 6.6 |
| | **1.3** | **3.4** | **5.6** |
| Total pathway damages (mills/kWh) | 0.00098 | 0.002 | 0.0031 |
| | **0.00062** | **0.0016** | **0.0027** |

[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 $\mu g/m^3$.**

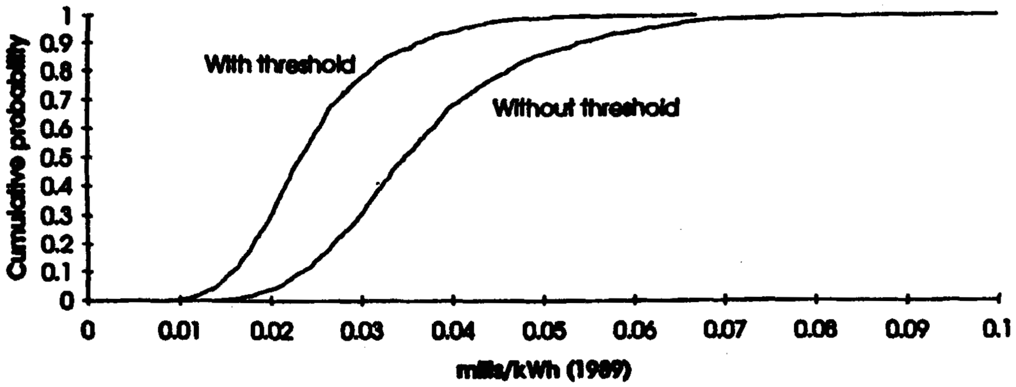

Figure 10.9-2 (a). Particulate–morbidity damages within 50 miles of Southeast plant with and without 30 microgram/cubic meter threshold

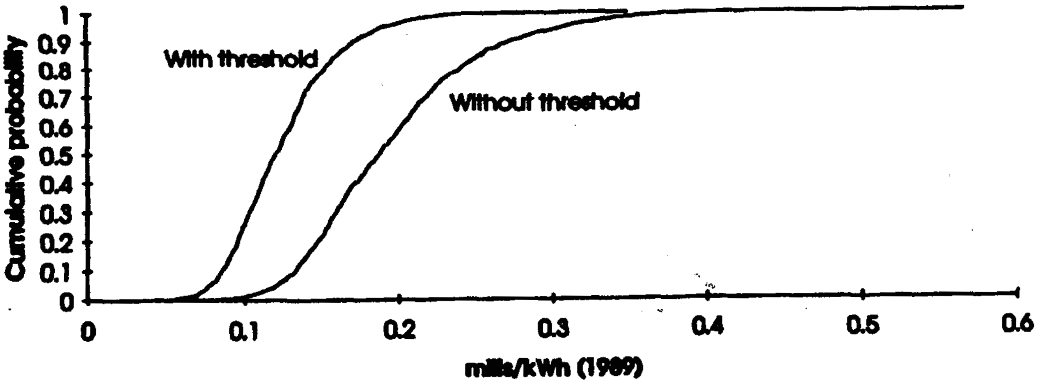

Figure 10.9-2 (b). Particulate--morbidity damages within 1000 miles of Southeast plant with and without 30 microgram/cubic meter threshold

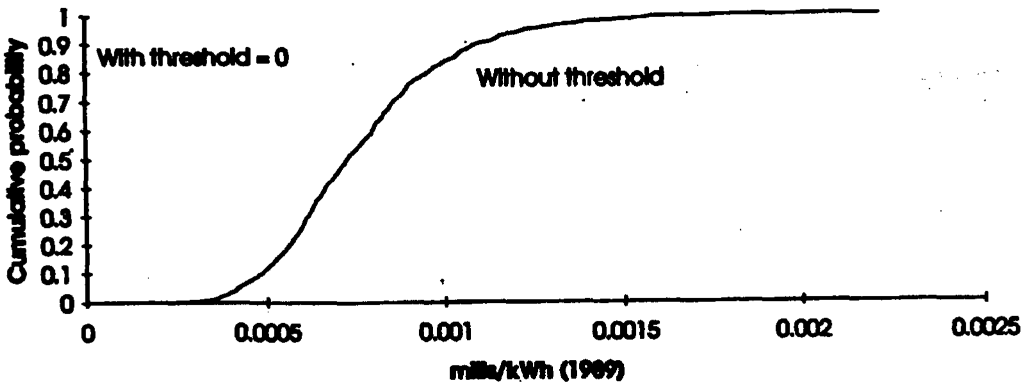

Figure 10.9-3 (a). Particulate--morbidity damages within 50 miles of Southwest plant with and without 30 microgram/cubic meter threshold

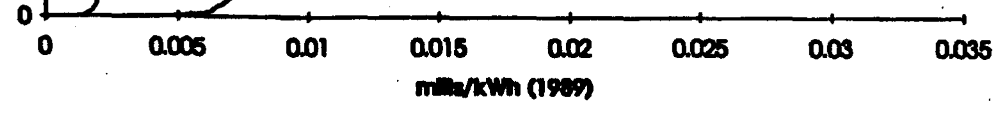

Figure 10.9-3 (b). Particulate--morbidity damages within 1000 miles of Southwest plant with and without 30 microgram/cubic meter threshold

## 10.10 EFFECTS OF PARTICULATES ON MATERIALS

### 10.10.1 Emissions of Particulates

***Total particulate emissions from the Reference power plants were estimated to be 0.02 tons/GWh.***

Total particulate emissions from the Reference power plants were estimated to be 0.02 tons/GWh. $PM_{10}$ emissions were estimated to be 67% of the total particulate emissions i.e., 0.014 tons/GWh (323 tons/year or 9.3 grams/second). This estimate was based on the particle size distribution of emissions from an electrostatic precipitation used to control particulate emissions (EPA 1988).

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 300 MW reference oil-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 0.012 micrograms per cubic meter ($\mu g/m^3$). The highest predicted ambient annual concentration of $PM_{10}$ from the Southwest Reference plant site is 0.011 $\mu g/m^3$.

### 10.10.2 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.

### 10.10.3 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.

## 10.11 EFFECTS OF ACIDIC DEPOSITION ON RECREATIONAL FISHERIES

### 10.11.1 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.

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.

The increment of sulfur deposition at each watershed that is attributable to the reference plant could be calculated as the National Acid Precipitation Assessment Program (NAPAP) did using the Regional Acid Deposition Model (RADM; Dennis et al. 1990, Clark et al. 1989). There is a great deal of uncertainty in estimating wet and dry deposition to watersheds, both for current deposition (Turner et al. 1990) and for future deposition (Dennis et al. 1990). Because the aquatic effects of sulfur deposition are not linear, the incremental effect of the reference plant could be quite different under higher versus under lower sulfur emissions/deposition rates. The incremental effects could also change over time. For example, they could be higher when the regional sulfur deposition loading (ie., from other power plants) was high, and lower or nonexistent below a certain threshold or critical load of sulfur deposition.

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 NAPAP, but source-specific results that could be used for this report are not available at this time.

### 10.11.2 Impacts of Acidic Deposition on Recreational Fisheries

The principal source of quantitative information on effects of acidic deposition on recreational fishing is the National Acid Precipitation Assessment Program Integrated Assessment (NAPAP 1991) 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.

## 10.12 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.

## 10.13 EFFECTS OF ACIDIC DEPOSITION AND OZONE ON FORESTS

### 10.13.1 Impacts of Acidic Deposition and Ozone on Forests

It is difficult to evaluate the damage costs of an oil 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.

### 10.13.2 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).

Commercial Effects

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.*

Recreation Effects

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.

## 10.14 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 10.10, 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).

## 10.15 HEALTH EFFECTS OF OZONE

### 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 300 MW oil-fired power plant are given in Table 6.1-2. 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 10.15-1 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 10.15-1 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. 10.15-1 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 ($\nu$). 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.

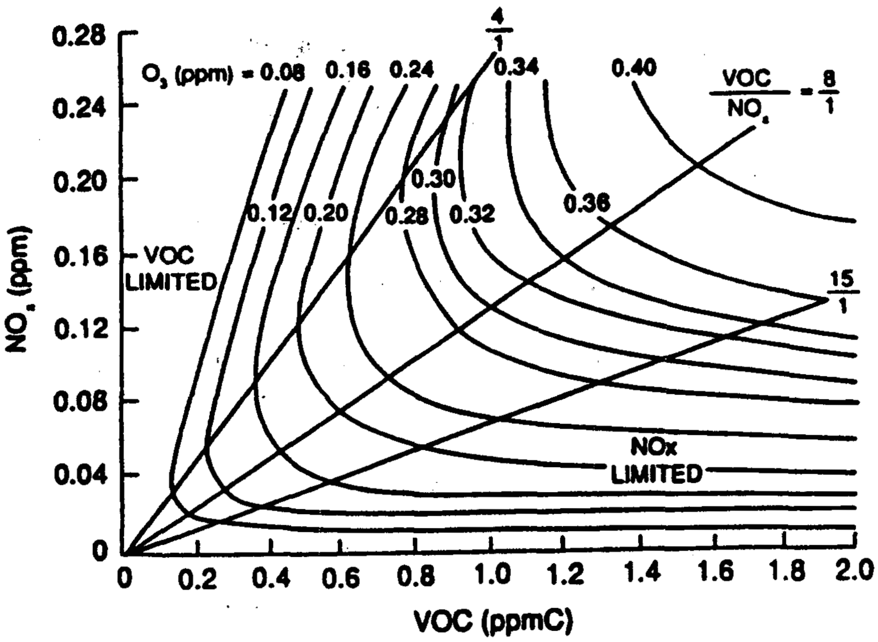

**Figure 10.15-1. Typical ozone isopleths generated with the EKMA option of EPA's OZIPM-4 model. The $NO_x$-limited region is typical of rural and suburban areas and the VOC-limited region is typical of highly polluted urban areas.**

**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 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).

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 10.15-2 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 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. 10.15-2 are the maximum daily peak ozone concentrations at each location in the receptor grid. As seen in Figure

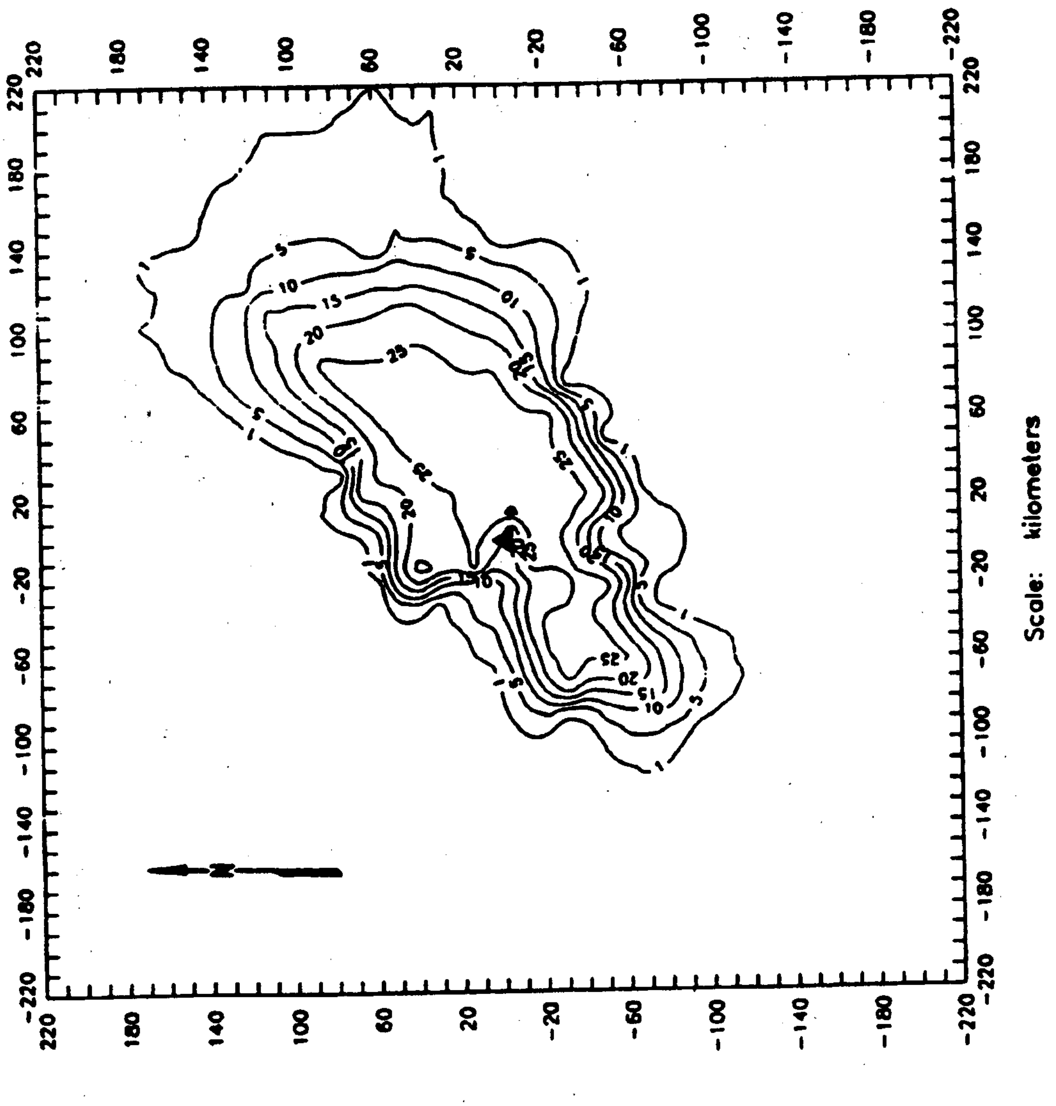

**Figure 10.15-2. Maximum daily peak incremental ozone concentrations (ppb) (one hour average) for May to September 1990 due to emissions from the oil-fired power plant at the Southeast Reference site**

10.15-2 the greatest increase in daily peak ozone concentration due to the power plant emissions during the ozone season, was 7 ppb, occurring within 15 kilometers of the plant. An increase in 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. An increase in daily peak ozone concentration of 1 ppb was seen as far away as 170 kilometers in the northeast (NE) direction and 100 kilometers in the southwest (SW) direction.

### 10.15.2 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.

#### 10.15.2.1 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. 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.[26]

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 found to be significantly associated with oxidant exposure to members of the total population.

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[26] Increased risk of subsequent mortality due to lower than expected pulmonary function is implicitly addressed in Section 10.15.2.2.

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 10.15-1a and 10.15-1b 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 10.15-1a gives estimated impacts within 50 miles (80 km) of the power plant. Table 10.15-1b gives the total impacts for the maximum extent of the ozone plume.

**Table 10.15-1a. Health effects estimated to occur from ozone exposure (in thousands) within 50 miles (80 km)**

| Southeast Reference site | Low | Mid | High |
|---|---|---|---|
| 1. Total restricted activity day | 0 | 2.4 | 4.8 |
| 2. Any-symptom day | 0.70 | 5.2 | 9.6 |
| 3. Asthma-attack day | 0.11 | 0.28 | 0.45 |
| 4. Eye-irritation day | 5.3 | 7.0 | 8.7 |
| 5. Cough day | 1.4 | 2.8 | 4.2 |
| 6. Cough incidence | 9.5 | 16 | 23 |
| 7. Shortness of breath | 5.6 | 9.3 | 13 |
| 8. Pain upon deep inspiration | 2.2 | 9.1 | 16 |

## 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

$\Delta c$ = 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

$\gamma$ = -1.98

$\beta$ = 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

$\Delta e$ = 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

$\gamma$ = -2.48

$\beta$ = 1.72, 2.02, 2.32

pop = entire population

## Dose-response functions: ozone (continued)

*Incidences of coughing*: Based on McDonnell et al. (1983),

$$\Delta C = \{[1/(1+\exp(-\gamma-\beta\omega X_1))] - [1/(1+\exp(-\gamma-\beta\omega X_0))]\}\ f\theta(\mathrm{mpop})$$

where

$\Delta C$ = 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

$\gamma$ = -1.742

$\beta$ = 10.961, 14.1, 17.239

mpop = entire population

$\theta$ = percent of a two-hour period the population is exercising

f = the incidence-day factor

$\omega$ = the scaling factor for two-hour period t

## Dose-response functions: ozone (continued)

*Incidences of shortness of breath*: Based on McDonnell et al. (1989)

$$\Delta C = \{[1/(1+\exp(-\gamma-\beta\omega X_1))] - [1/(1+\exp(-\gamma-\beta\omega X_0))]\}\ f\theta(mpop)$$

where

$\Delta C$ = 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

$\gamma$ = -0.076

$\beta$ = 4.938, 7.265, 9.562

mpop = entire population

$\theta$ = percent of a two-hour period the population is exercising

f = the incidence-day factor

$\omega$ = 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

$\Delta$ARD = change in the number of days of "any" symptoms/conditions

$\beta^{*}$ = 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 $\beta$ 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

$\Delta TRRAD$ = 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

$\beta$ = 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

$\Delta a$ = 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.)]

$\omega$ = scaling factors for half-day periods

$\beta$ = 3.58, 6.20, 8.82

**Table 10.15-1b. Health effects estimated to occur from ozone exposure (in thousands) for the maximum extent of the ozone plume**

| Southeast Reference site | Low | Mid | High |
|---|---|---|---|
| 1. Total restricted activity day | 0 | 2.6 | 5.3 |
| 2. Any-symptom day | 0.77 | 5.7 | 11 |
| 3 Asthma-attack day | 0.12 | 0.31 | 0.50 |
| 4. Eye-irritation day | 5.8 | 7.7 | 9.6 |
| 5. Cough day | 1.5 | 3.1 | 4.7 |
| 6. Cough | 10 | 18 | 25 |
| 7. Shortness of breath | 6.2 | 10 | 14 |
| 8. Pain upon deep inspiration | 2.5 | 10 | 18 |

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.

### 10.15.2.2 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.[27] The daily peak standard is 12 pphm. The population of Los Angeles County during this period averaged about 7.2 million, with daily mortality

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[27] We assume that the ozone concentration is approximately equal to oxidants, since the impacts are difficult to distinguish.

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:

$$\frac{\Delta\ Mortality}{\Delta\ Ozone} \cdot \frac{E\ [Ozone]}{E\ [Mortality]} = 0.3 \left( \frac{7.5}{152} \right) = 0.0148,$$

*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 0.021, 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),

$$\Delta D = \beta \bullet D_B \bullet \Delta O \bullet 365 \bullet \text{pop}$$

where

$\Delta D$ = the change in annual deaths
$\beta$ = 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)
$\Delta O$ = the change in average daily peak ozone concentration in pphm
pop = population

### 10.15.3 Damages and Externalities from Ozone

#### 10.15.3.1 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 (1989). 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 (1989), this approach was abandoned and "ballpark" estimates of values were used instead. Here, both sets of estimates (updated to 1989 dollars) are provided (Table 10.15-2) 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 10.15-2 are fit with lognormal distributions, with the exception of asthma attack values, which are fit with a normal distribution.

**Table 10.15-2. Unit values of ozone-morbidity end-points (in 1989 dollars)**

| Endpoint | Low | Medium | High |
|---|---|---|---|
| Any symptom day<br>(Krupnick and Kopp 1989) | 2.98 | 5.97 | 11.93 |
| MRRAD<br>(Krupnick and Kopp 1989) | 13.13 | 21.48 | 36.40 |
| Asthma attack<br>(Krupnick and Kopp 1989) | 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 10.15-3(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 0.068 mill/kWh for Aggregation I and 0.072 mill/kWh for Aggregation II. The confidence intervals reported are also similar, 0.04-0.1 mill/kWh for Aggregation I and 0.028-0.14 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 and sulfur dioxide. Figures 10.15-3(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 10.15-3a. 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 | 1.2 | 55 | 120 |
| | Any symptom-day | 6 | 33 | 74 |
| | Asthma attack-day | 2.3 | 8.4 | 16 |
| | Eye irritation-day | 22 | 46 | 83 |
| | Cough-day | 4.1 | 15 | 36 |
| | Total pathway damages I | 84 | 140 | 220 |
| | Total pathway damages I (mills/kWh) | 0.04 | 0.068 | 0.1 |
| II Clinical studies | Cough incidence | 6.2 | 35 | 100 |
| | Shortness of breath | 6.8 | 55 | 160 |
| | Pain upon deep inspiration | 10 | 61 | 140 |
| | Total pathway damages II | 58 | 150 | 290 |
| | Total pathway damages II (mills/kWh) | 0.028 | 0.072 | 0.14 |

## Table 10.15-3b. 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 | 61 | 130 |
| | 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 |
| | Total pathway damages I | 89 | 160 | 240 |
| | Total pathway damages I (mills/kWh) | 0.042 | 0.074 | 0.11 |
| II Clinical studies | Cough incidence | 6.7 | 37 | 100 |
| | Shortness of breath | 8.2 | 57 | 170 |
| | Pain upon deep inspiration | 13 | 65 | 140 |
| | Total pathway damages II | 65 | 160 | 300 |
| | Total pathway damages II (mills/kWh) | 0.031 | 0.076 | 0.14 |

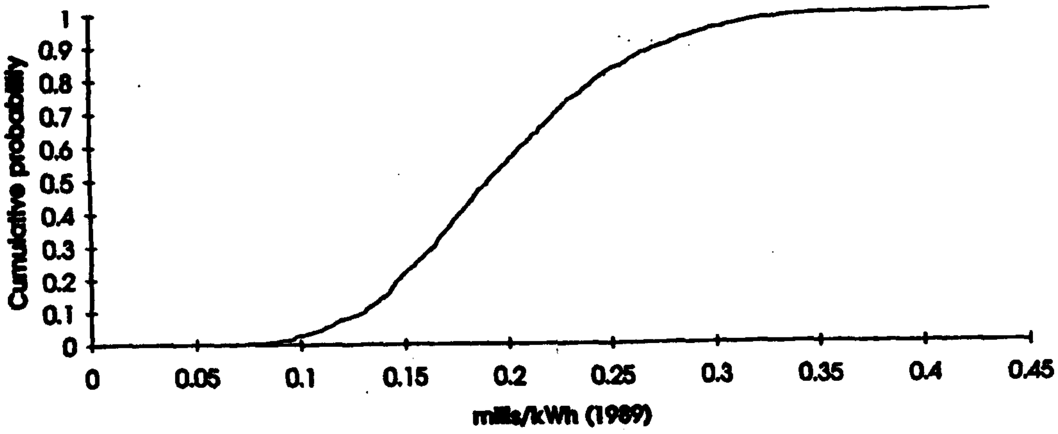

**Figure 10.15-3 (a). Ozone -- morbidity damages within 50 miles of the Southeast plant based on epidemiological studies.**

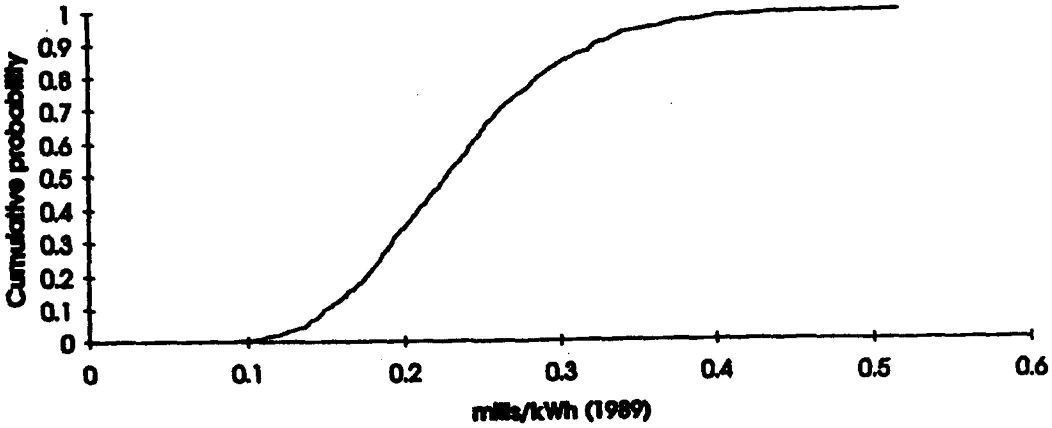

**Figure 10.15-3 (b). Ozone -- morbidity damages within 1000 miles of the Southeast plant based on epidemiological studies.**

### 10.15.3.2 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 0.042 mills/kWh, while the low (5th percentile) estimate is 0 and the high estimate (95th percentile) is 0.38 mills/kWh. Figures 10.15-4 (a) and (b) show 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.

## 10.16 EFFECTS OF OZONE ON CROPS[28]

### 10.16.1 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 300 MW oil-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.

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[28] Refer to Appendix D for discussion of $SO_2$ impacts on crops and forests.

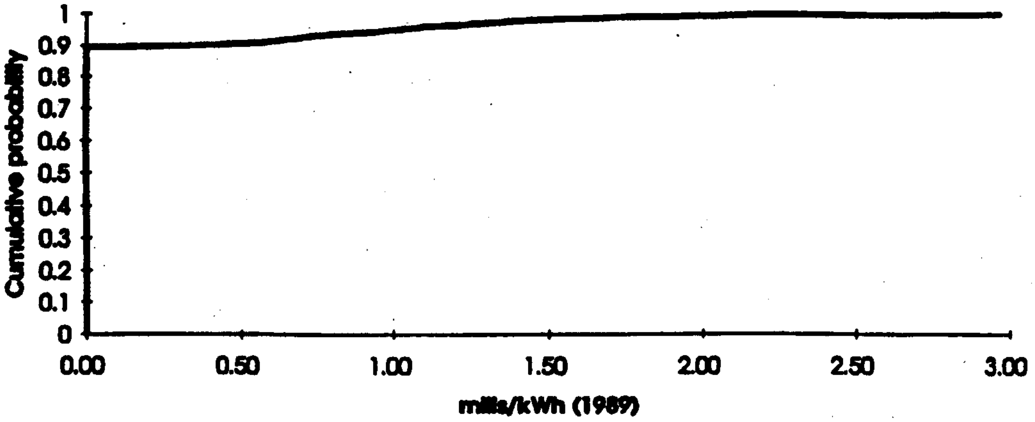

Figure 10.15-4 (a). Ozone--mortality damages within 50 miles of the Southeast plant

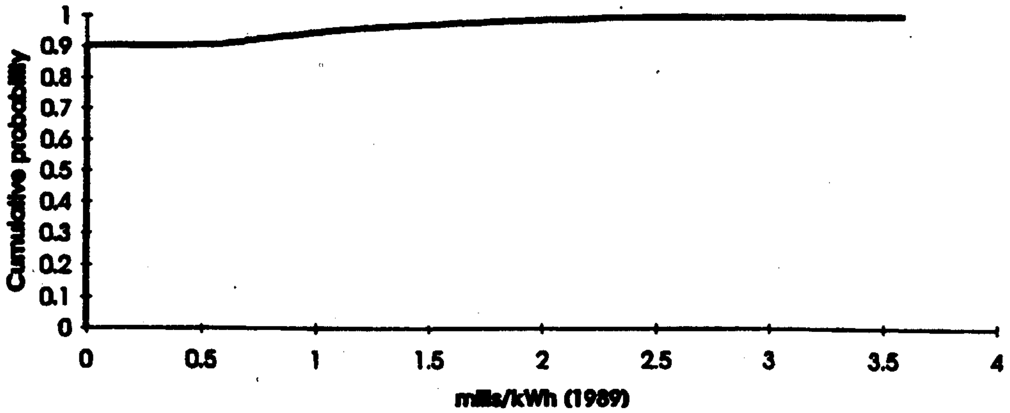

Figure 10.15-4 (b). Ozone--mortality damages within 1000 miles of the Southeast plant

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 oil fuel cycle analysis requires that an estimate be made of ozone concentrations that occur in the vicinity of a oil-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-$O_3$).[29] 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 oil fuel cycle analysis are shown on isopleth maps in Figures 10.16-1 and 10.16-2. (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

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[29] 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 10.16-1 shows the predicted impact of the oil-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 10.16-1, the highest 12-hour seasonal average ozone concentration (based on ozone bulges only) is 0.4 ppb (the smallest isopleth line) and occurred approximately 20 kilometers from the plant in the east northeast (ENE) direction. The lowest isopleth plotted in Figure 10.16-1 is 0.01 ppb. This increase in seasonal average ozone concentration occurred as far away as 220 kilometers from the plant in the northeast direction (NE) and 130 kilometers in the southwest (SW) direction.

Figure 10.16-2 shows the predicted impact of the oil-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 0.4 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. 10.16-2 is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 220 kilometers from the plant in the northeast direction (NE) and 130 kilometers in the southwest (SW) direction. The results shown in Figure 10.16-1 and 10.16-2 are essentially the same since $NO_x$ emissions from the oil-fired power plant do not cause significant ozone depletion on a seasonal average.

In addition to the results seen in Fig. 10.16-1 and 10.16-2, the seasonal 12-hour average measured background ozone concentration of 53 ppb was also used in the crop effects portion of the study.

### 10.16.2 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.).

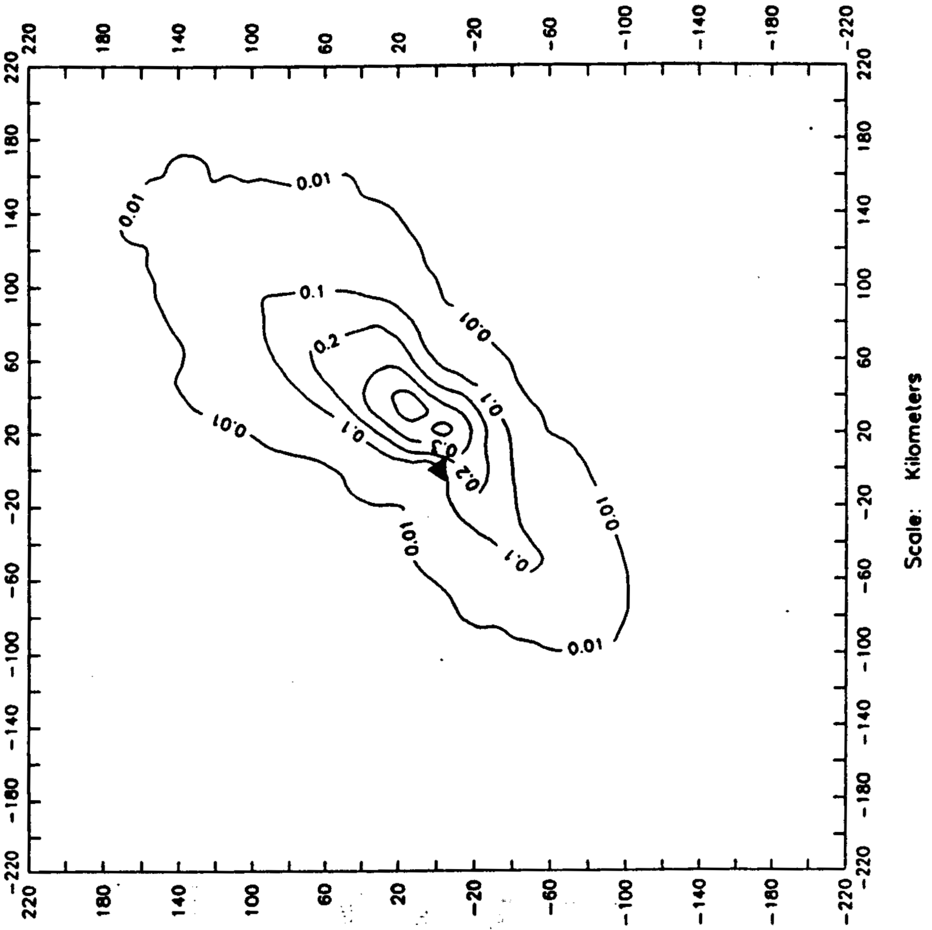

**Figure 10.16-1. Positive incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the oil-fired power plant at the Southeast Reference site, (positive concentrations are above ambient)**

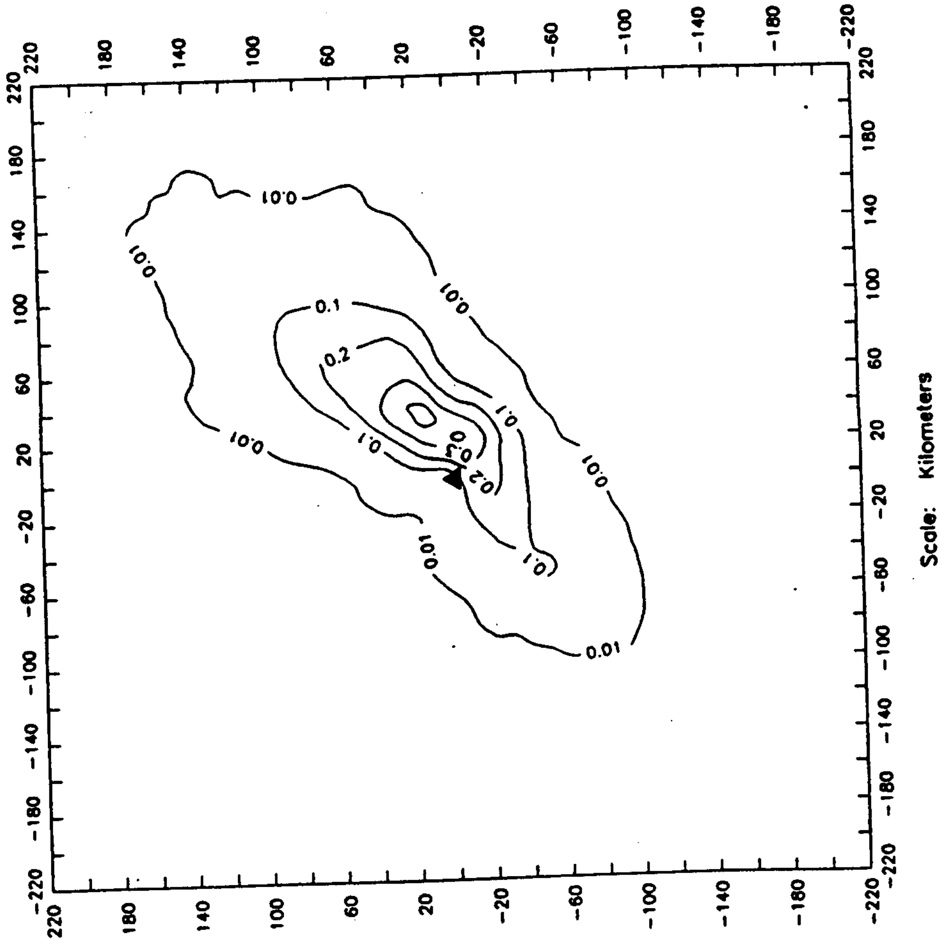

**Figure 10.16-2. Total incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the oil-fired power plant at the Southeast Reference site, (total concentrations include both positive and negative incremental concentrations)**

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 10.16-1 (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 10.16-2 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 10.16-1. Crop yield losses in (percent) estimated to result from various ozone concentrations

| | Mean ozone concentration during 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% |
| 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 10.16-2. 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 10.16-3. 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.

### 10.16.3 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.[30]

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 10.16-3 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.

## 10.17 EFFECTS OF PLANT CONSTRUCTION AND OPERATION ON EMPLOYMENT

### 10.17.1 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 oil-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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[30] For an explanation of these terms, see ORNL (1994a, Part IV).

Table 10.16-3. 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.[31] 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 some "frictional" unemployment is considered to be an efficient way for the labor

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[31] Sanghi (1991).

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.[32]

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.[33] 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.

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

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[32] Hamilton et al. (1991).

[33] 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.

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.[34] 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.[35]

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. 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 oil 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

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[34] 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).

[35] 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.

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.[36] 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.[37]

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 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

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[36] 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.

[37] See Haveman (1970), Gramlich (1981) or Sassone and Schaffer (1978) for additional exposition.

natural rate of unemployment range from 4.7 to 6.5 percent (although, in principle, they can vary by occupation and region).[38] 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 workers.[39] 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.

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[38] 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.

[39] 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).

### 10.17.2 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 0.735 mills/kWh for the Southeast Reference environment and 0.542 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 0.461 to 2.221 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 0.735 mills/kWh indicate our confidence that employment benefits are significant. Similarly, in the Southwest the 90% confidence interval between 0.271 and 2.192 mills/kWh, and the midpoint estimate of 0.542 mills/kWh, indicate that the true value is greater than zero.

### 10.17.3 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 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.

## 10.18 ENERGY SECURITY EXTERNALITIES AND OIL FUEL CYCLES[40]

The term "energy security" refers to the *economic security* of a country that is relatively dependent on oil imports from a supplier(s) with considerable market power [i.e., the Organization of Petroleum Exporting Countries (OPEC)]. Energy security *costs* may exist for an oil-importing country when its economic welfare is not as great as it could be if the oil market were efficient. The magnitude of these energy security costs depends on the degree of market power that OPEC possesses, on the concentration of oil supply within OPEC, and on the ability of the oil-importing country to respond to oil price shocks. The extent to which these factors exist is contentious.

Analysts who need to estimate the health and environmental impacts of electricity options will likely not be required to do original research on energy security, in part because its impacts do not depend on the locations of the oil-fired power plants within a country. This section provides analysts with basic information about energy security, and with a range of possible energy security costs associated with the use of oil.

Energy security costs, to the extent that they exist, have two major components. One component is the economic rent that OPEC extracts from the market, due to its power as a cartel. Theoretically, an oil importer with considerable market power, such as the United States, could recover this rent due to its monopsony power as a major consumer of oil. If the oil importer does not exercise its monopsony power, then the price of oil is "unnecessarily" high. The other component occurs when there are sudden changes in the price or availability of imported oil. These price shocks result in spillover effects on the total performance of the economy, that are not reflected in market prices, as the economy adjusts to the price shock. Oil-importing countries with limited economic, political, or military power generally cannot recover any economic rent. Thus, in theory, this rent is not an energy security cost. However, such countries may be extremely vulnerable to the second type of energy security cost.

Analysts differ greatly in their assessments of the magnitude of these costs. There are basically two positions. The first position is that these costs are *unlikely* to be very large *or* that they are not policy relevant because there are no practical options to ameliorate these costs. Bohi and Toman are the major proponents of this position (Bohi 1989, 1991a, 1991b, 1993; Bohi and Powers 1993; Bohi and Toman 1986, 1987, 1993, 1994; Lichtblau 1994; Stagliano 1995; Toman 1993). The second position is that they are sizeable and policy relevant. A number of analysts

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[40] More discussion is provided in the paper, "Energy Security Externalities and Fuel Cycle Comparisons," by D. R. Bohi and M. S. Toman, presented in the Analytical Methods and Issues document (ORNL/RFF 1994a), and in Leiby et al. (1995).

take the latter position (Adelman 1990, 1994; Huntington and Eschbach 1987; Mork 1994; Mork et al. 1994; Greene and Leiby 1993; Leiby 1993; and Greene et al. 1995). Each position is supported by a number of careful studies. However, the studies differ in their assumptions, data, and statistical methods. Each side in the debate is critical of data, methods, and analyses used in the studies that the other side uses to buttress its arguments. We do not attempt to resolve this issue in our report. The issue is one of ongoing analysis and debate in a study funded by the U.S. Department of Energy. Proponents of both positions agree, however, on the need for more detailed analysis on key points of contention.

Thus, we do not recommend any specific value as an estimate of the energy security costs of oil fuel cycles. Instead, we summarize the major arguments of both sides in this debate, and tabulate a range of possible values. The summary is organized so that the two energy-security components are discussed separately. Within each of these two sections, we provide the key arguments of each side of the debate.

### 10.18.1 Cartel Rents and the Long-Term Cost of Oil Imports

In a perfectly competitive market, the price of oil completely reflects its cost (at the margin). However, when sellers such as OPEC exercise some market power, the price may lie above the perfectly-competitive level. If an oil importer such as the United States can take advantage of its position as a major consumer of oil to offset this price premium, then the importer has some monopsony power. If a country can successfully use its monopsony power to reduce the price of oil, but does not do so, then this inaction is an opportunity cost.

These costs, to the extent they exist, occur over long periods of time, in contrast to the short-term effects related to oil price volatility that we discuss in Section 10.18.2.

#### The View that Cartel Rents are Significant[41]

The viewpoint that there *are significant and policy-relevant cartel rents* is based on the argument that oil supply is not provided in a competitive market, and that the importer's policies can countervail the exporters' market power. Analysts justify these claims with three reasons: (a) empirical evidence that suggests that OPEC behavior conforms more closely to an (imperfect) output-sharing cartel than to a confederation of competitive suppliers (Griffin 1985, Jones 1990, Dahl and Yucel 1991); (b) the fact that most estimates of the marginal cost of production are well below the prevailing price; and (c) the contention that any price premium associated with the depletability of oil is likely to be small given the large resource base and the ability to replenish reserves with improved technology and greater effort.

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[41] Based largely on Leiby et al. (1995).

Although oil prices have been stable and the influence of OPEC seemingly diminished in the past several years, many analysts argue that OPEC still functions as a cartel, even if not a completely effective one. For example, although Adelman (1994) sees increasing pressure on OPEC, he still describes Saudi Arabia as the leading firm of a cartel and warns that it would be imprudent to expect the cartel to disappear any time soon (Adelman 1994, p.11). In fact, according to Greene et al. (1995), OPEC's increasing market share will likely increase its monopoly market power in the future, as well as the risk of oil market disruptions.

Leiby et al. (1995) use the 1994 version of the U.S. Department of Energy's Oil Market Simulation Model (DOE's OMS94) to estimate the marginal benefit of a reduction in oil imports. They consider different assumptions about the response of OPEC supply to changes in U.S. import demand.[42] With an OPEC supply elasticity of five, the marginal cartel rent is $0.90/barrel (1993$). With an elasticity of one, it is $2.86/barrel. These rents, to the extent they exist, are part of the energy-security cost of the oil fuel cycle.

### The View that Cartel Rents are *Unlikely* to be Large or Policy Relevant

Other analysts have a viewpoint opposite to the one previously mentioned. They argue that *recoverable cartel rents are unlikely to be large.* These analysts are skeptical of OPEC's effectiveness as a cartel. For example, Bohi and Toman inspected petroleum production data and questioned whether OPEC supply behavior has been consistent with that of a cartel. They suggest that Dahl and Yucel's (1991) analysis has problems with the specification of the econometric framework (Bohi and Toman 1995, p.38) They further note the increasing rivalries among the countries within OPEC. Stagliano (1995) argues that the power of OPEC is more a "ghost" than a reality. His assessment is that the fears of OPEC's potential ability to curb oil supplies to the United States, or to unexpectedly raise prices to economy-damaging levels, are unfounded. He regards OPEC to be ineffective as a cartel operating in a global, generally free, oil-trading system (Stagliano 1995, p.8).

These analysts also question whether it would be wise for the United States to use its monopsony power to recover cartel rents, even if they do exist. These analysts contend that monopsony effects are usually thought to be only "pecuniary" externalities that redistribute rents but that do not bear on market efficiency. When the rent redistribution involves rent transfers out of the purchasing country, the size of these wealth transfers may be a concern for policy makers even if the market is efficient from a global perspective. However, these analysts say that it is not necessarily advantageous to exploit a potential monopsony position. In fact, the U.S., for example, eschews the exercise of monopsony power in a number of international markets. To argue for the exploitation of monopsony in the world oil market, it is necessary to conclude that the policy decision can affect world prices

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[42] The model summarizes OPEC price response to reductions in demand will an elasticity, although strictly speaking, the response function of a cartel does not correspond to a well-defined supply curve.

and that it will not provoke a retaliation by exporters which would leave the country in worse condition.

Should monopsony effects be included in fuel cycle evaluations? Bohi and Toman's (1994) position is that they are not relevant to individual local fuel cycle decisions because monopsony effects operate only at a national scale. These analysts contend that these effects cannot be addressed directly in the absence of some means for coordinating oil demands at a national level. They state that even at a national level, the capacity of a country, even the United States, to influence world oil prices by curbing demand or imports is likely to be limited. They suggest that the national government can take concerns over oil import costs into account by promoting domestic sources of oil, or in the design of R&D policies that favor research on energy technologies that use energy sources other than oil.

These analysts acknowledge that even without the presence of monopsony power or the exercise of market power by oil exporters, transfers of wealth for oil imports could have secondary effects on the economy that are not reflected in the price of oil and that constitute a potential externality in the oil fuel cycle. The payments for oil imports have an unfavorable effect on the U.S. merchandise trade balance, which could in turn have a negative effect on the international exchange value of the dollar and on the cost of all imported goods. It also has been argued that higher oil prices could aggravate "structural" inflation that leads to adverse macroeconomic consequences. But these analysts state that even if these effects constitute real externalities and are significant in magnitude, they are not amenable to policy responses. These analysts say that exchange rate and inflation issues are meaningful only at the national level, such as for guiding R&D.

### 10.18.2 The Costs of Oil Market Disruptions

Like any other commodity, the price of oil fluctuates. More importantly, its supply is geographically concentrated. Some analysts contend that this region is politically unstable, making it subject to disruptions that cause oil price shocks. When these shocks occur, payments for oil imports greatly increase. Demand for oil is relatively inelastic in the short run. Thus, oil price shocks may also have a ripple effect throughout the economy.

As in the case of the debate about cartel rents during normal (i.e., stable) markets, there are two divergent views about the costs of oil market disruptions. One view is that the increase in payments for imports is an external cost and that the macroeconomic adjustments during oil price shocks are large and attributable to the shocks themselves. The other view is that increased payments for oil imports are part of a competitive market and that there is little evidence to support the claim that the macroeconomic adjustment costs are large. We expand on the two points of view in the following sections.

### The View that Oil Market Disruptions Lead to Significant Externalities[43]

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[43] Taken from Leiby et al. (1995).

According to this view, oil market disruptions lead directly, or indirectly, to price shocks. When prices increase, the principal losses are increased payments for imports and macroeconomic adjustment losses. Estimates of these losses depend, of course, on the probabilities of disruptions of different sizes. The following estimates take these probabilities into account.

### Increased Payment for Imports

The price of oil, according to this view, increases greatly during disruptions, even though demand decreases. The net effect is that more is paid for imported oil. This increase in cost is likely not to have been taken into account by producers and consumers in any fuel-related investments that they made previously. According to this line of reasoning, to the extent that oil consumers and producers do not fully anticipate and insure against either the microeconomic or macroeconomic effects of oil price shocks, the increase in the oil import bill will not reflect a cost fully captured in the current price of oil.

Leiby et al. (1995) use DOE's OMS94 to estimate a range of values for the marginal external costs of the increase in import costs during disruptions. Their analysis accounts for a range of possible disruption probabilities, the existence of cartel rents, effects of imports on disruption probabilities, and the degree of anticipation and hedging. Their results generally range from zero (if there is complete anticipation and hedging) to $2.11/barrel (1993$).

### Macroeconomic Adjustment Costs

Analysts who suggest that energy security costs are significant, contend that oil disruptions lead to large costs to the macroeconomy. Whereas wealth transfers to pay for imports depend on the *level* of energy prices and the volume of energy *imports*, macroeconomic adjustment losses depend on the *change* in energy prices and the volume of *total* (not just imported) energy consumption.

The reasoning of these analysts is that when the oil price suddenly increases, real wages will not adjust to maintain employment, leading to unemployment. The use of energy-using capital equipment will also decline, reducing productivity throughout the economy. The losses are compounded by difficulties in reallocating factors of production in response to changes in the mix of final demand brought about by changes in product prices.

Over a dozen empirical studies have linked GNP losses to oil price increases. Among the more recent studies are Hamilton (1983, 1985) Mork (1989), Mork et al. (1994), and Tatom (1993). The GNP adjustment losses estimated in these studies depend on the size of the proportional price increase as well as on the vulnerability of the macroeconomy to adjustment losses for a price shock of a given size. Leiby et al. (1995) calculate a range of macroeconomic adjustment cost estimates. The range reflects different assumptions about disruption probabilities, effects of imports on disruption risk, and GNP elasticity. The range is from zero to $6.48/barrel ($1993), with a "narrowed range" of

$0.44/barrel to $1.60/barrel, reflecting a narrower range of values for these assumptions.

## The View that Disruptions Are *Unlikely* to Lead to Significant Externalities

An alternative viewpoint is that there may not be large spillover costs caused by oil price volatility. These doubts are based on the causes of rigid adjustment in the economy and the degree to which volatility of energy prices is accommodated ex ante.[44]

Empirical studies of the macroeconomic effects of energy price shocks do not try to distinguish between internalized and externalized costs. Therefore, the best that can be accomplished, is to try to assess the importance of the gross macroeconomic costs of energy price shocks and to draw inferences about the empirical significance of the externality component.

The evidence about the gross costs at the national level is mixed. The coincidence in the timing of the the two oil price increases and two recessions during the 1970s leads many observers to believe that the effects of energy price shocks on the economy are large. However, some analysts contend that equations of models used to reach these conclusions employ parameters estimated from limited experience with price shocks over the 1950 to 1980 period. During this period, real oil prices were stable or falling except for the two brief explosions during the 1970s. Thus, the conclusions of the models regarding the relationship between oil price increases and GNP will be determined by the experience with the two recessions that followed the 1970s price shocks (even though this experience may not be representative of the true energy-economy relationship). These analysts explain the recessions experienced in some countries by factors other than energy prices, such as differences in macroeconomic stabilization policies. In other words, according to this viewpoint, it is possible that the econometric models are confusing the effects of the deflationary macroeconomic policies with those of changes in oil prices.

The doubts of these analysts are based on their examination of disaggregated industry data for the U.S., Germany, Japan, and the U.K. for explanations of the experiences of these countries during the 1973–1974 and 1979–1980 shocks. These analysts explain that energy prices may have had little to do with the macroeconomic problems of the 1970s. These analysts find that, within each country, the industries hit hardest are quite dissimilar from one recession to the next and, for each recession, the industries hit hardest are dissimilar across the four countries. There are no significant negative correlations between energy intensity and changes in output, employment, or capital formation for any of the four countries. Nor does the evidence suggest that adjustment costs

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[44] Although the timing of oil price shocks is unknown, producers and consumers account for the possibility when they make decisions. One way of hedging against price shocks is through the oil futures market (some analysts state that the effectiveness of this hedging has not been empirically measured).

caused by changes in the composition of final demand are more severe in energy-intensive sectors. Finally, these analysts suggest that, in contrast with the rigid-wages argument, changes in real wages appear to vary negatively with energy intensity in the two shock periods. This relation would suggest that wages were more responsive in labor markets where unemployment has been more serious.

An alternative hypothesis suggested by these analysts is that the industrialized countries were already combatting inflation when the oil price shocks occurred and that these price shocks further reduced the ability of the countries' economies to mitigate inflation.[45] Given that Japan was the only industrial country to avoid a recession after the 1979 oil shock, it is plausible that the monetary authorities rather than energy prices are to blame for the recessions in other countries.

More study is required to understand better the nature of energy-economy interactions at the national and regional levels. If nothing definitive can be said about the gross economic costs of energy price shocks, it follows that even less can be said about the magnitude of any embedded externalities that are relevant for comparing fuel cycles at a local or national level.

### 10.18.3 Potential Externalities Related to R&D

Market signals alone do not generate a socially efficient level of investment in research for acquiring basic knowledge for the development of new technologies. The basic problem is that information has attributes of a public good, with benefits to many other agents beyond those who bear the costs of information acquisition. Since those who bear the costs of information acquisition generally cannot appropriate all the benefits, too little information acquisition is undertaken.

There are specific aspects of energy security that intersect with R&D externalities. Research and development of cost-effective alternative energy sources and less energy-intensive technologies may be the strongest tools (over the longer term) for countering any market power exerted by energy exporters. Enhanced energy conservation and flexibility in energy storage provide a means for mitigating any adjustment costs associated with energy price shocks. Thus the presence of both energy security externalities and R&D externalities provides strong support for a government role in supporting R&D activities. This includes R&D related to fuel cycles, even though the importance of the energy security spillovers remains unresolved. The government has already responded to the public good argument with considerable support for energy R&D. In view of this effort, together with the contribution of existing patent and copyright laws, it is conceivable that the R&D externality has already been adequately internalized. Indeed, we have little basis for saying whether the level of effort is deficient or excessive.

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[45] Except for Japan in 1979.

# 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 changes in the environment as estimated for the benchmark oil fuel cycles. Sections 11.3 through 11.5 summarize the range of marginal damages and benefits that were estimated for the oil 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 oil 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 a representative oil fuel cycle. The assumed technology was an oil-fired boiler 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. Although the specific numerical results are project- and site-specific the *analytical methods* are general and can be applied to other studies.

The third major objective was assess 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; and in the papers presented in the Appendices. 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 and aquatic dispersion 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) and site (including sites of the upstream activities which involve onshore oil extraction).

(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 crude oil 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 and modeling in atmospheric physics, chemistry and transport will lead to better atmospheric transport models. 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 oil-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 oil-to-electricity fuel cycle, and the perspective in which economic valuation is cast.

## 11.2. EMISSIONS FROM AN OIL 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 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, as well as to a distance 1,000 miles from the plant.

Tables 11.2-1 and 11.2-2 contain listings of the emissions or other discharges (in the first column of the tables) that were evaluated for each of the reference sites. The formats of the tables are different because the fuel cycle activities at the two sites differ. Within the tables, an assessment is made as to the quality of information about the emissions. As can be seen in the tables, there is a wide range of information quality, all the way from none to very good.

The two most important emission transport issues identified in this study are related to the need for regional-scale models. Many of the ecological effects can, at present, only be evaluated on a regional basis. The more important pollutants are secondary pollutants that are formed in chemical reactions involving some of the emissions from a power plant best characterized using a regional scale model. Secondary pollutants such as ozone and sulfates, are formed at some point beyond the plant. Formation depends on a wide range of factors, many of which depend on regional air quality. Clearly, *more work is called for in the development of long-range transport models that can be used for both site-specific and regional analyses.*

## 11.3. MARGINAL ECOLOGICAL IMPACTS OF THE OIL FUEL CYCLE

This evaluation of the ecological impacts of an oil fuel cycle is based on a very specific set of parameters, which affect the range of possible impacts and the magnitude of these impacts. The major factors in this assessment are the location of oil production and refining, the size, design, and location of the power plants, and the method of transport of both crude and refined oil. The size of the power plant determines the magnitude of point source emissions from the power plant, as well as the incremental amount of wastes and discharges from oil drilling, refining, and transportation. The locations of the power plant and refineries are important in determining whether the emissions from a single facility (which in themselves may be too small to have any significant impacts) would contribute, on an incremental basis, to cumulative impacts caused by other sources and defined by ambient conditions. Therefore, the conclusions discussed below must be considered in terms of the size (300 MW) and location of the oil-fired power plants.

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.

**Table 11.2-1. Pollutant emissions, concentrations, or other changed conditions for an oil fuel cycle at the Southeast reference site**

| Fuel cycle stage and emission | Inform. quality | Emissions or Changed Concentration | | |
|---|---|---|---|---|
| | | Quantity | Unit | Comments |
| | | | ***Oil Production*** | |
| ***Onshore:*** | | | | |
| Land use | - | c | acres | |
| Produced water | ● | 6.83 | bbl/bbl product | Texas |
| Arsenic | ● | 0.02 | mg/L | Concentration in produced water |
| Benzene | ● | 0.47 | mg/L | Concentration in produced water |
| Boron | ● | 9.9 | mg/L | Concentration in produced water |
| Sodium | ● | 9,400 | mg/L | Concentration in produced water |
| Chloride | ● | 7,300 | mg/L | Concentration in produced water |
| Mobile ions | ● | 23,000 | mg/L | Concentration in produced water |
| Drilling wastes | ● | 4,509 | bbl/well | Texas |
| ***Offshore:*** | | | | |
| Crude oil | ⊖ | spill size<br>0.62 | barrels<br>spills/$10^9$ barrels | Average spill size<br>Spill rate for average large spill of 18,000 bbl |
| Coastal erosion | - | c | tons/year | |
| Produced water | ● | 486 | bbl/day/well | Average for Gulf of Mexico |
| Oil and grease | ● | 79.16 | mg/L | Concentration in produced water |
| Benzene | ● | 0.931 | mg/L | Concentration in produced water |
| Bis(2-ethylhexyl-phthalate) | ● | 0.031 | mg/L | Concentration in produced water |
| Ethylbenzene | ● | 0.066 | mg/L | Concentration in produced water |
| Naphthalene | ● | 0.090 | mg/L | Concentration in produced water |
| Phenol | ● | 0.914 | mg/L | Concentration in produced water |
| Toluene | ● | 0.693 | mg/L | Concentration in produced water |
| Copper | ● | 0.107 | mg/L | Concentration in produced water |
| Nickel | ● | 0.150 | mg/L | Concentration in produced water |
| Silver | ● | 0.059 | mg/L | Concentration in produced water |
| Zinc | ● | 0.133 | mg/L | Concentration in produced water |
| Drilling muds | ● | 5,614 | bbl/well | Gulf of Mexico |
| Drill cuttings | ● | 1,192 | bbl/well | Gulf of Mexico |
| HC | ⊖ | 34.9 | lb/$10^3$ bbl | For model platform |

**Table 11.2-1. Pollutant emissions, concentrations, or other changed conditions for an oil fuel cycle at the Southeast reference site**

| | | Emissions or Changed Concentration | | |
|---|---|---|---|---|
| Fuel cycle stage and emission | Inform. quality | Quantity | Unit | Comments |
| $NO_x$ | Θ | 33.4 | lb/10$^3$ bbl | For model platform |
| | | | ***Refinery*** | |
| CO | Θ | 0.16 | g/sec | Emission rate |
| $NO_x$ | Θ | 1.67 | g/sec | Emission rate |
| $SO_2$ | Θ | 9.22 | g/sec | Emission rate |
| TSP | Θ | 0.83 | g/sec | Emission rate |
| PM-10 | Θ | 0.68 | g/sec | Emission rate |
| Hydrocarbons | - | c | | |
| | | | ***Generation*** | |
| $CO_2$ 1990 | ● | 844 | tons/GWh | Emission rate |
| CO - 1990<br>- 2010 | Θ | 9.85<br>9.85 | g/sec | Emission rate |
| $NO_x$ - 1990<br>- 2010 | Θ | 39.63<br>3.96 | g/sec | Emission rate |
| $SO_2$ - 1990<br>- 2010 | Θ | 30.96<br>15.48 | g/sec | Emission rate |
| Hydrocarbons | - | c | | |
| Ozone | ● | 1.0 | ppb | Increase in annual mean concentration |
| Acid deposition | Δ | | | |
| PM-10 - 1990<br>- 2010 | Θ | 0.96<br>0.38 | g/sec | Emission rate |
| Peroxyacetyl nitrate (PAN) | Δ | b,c | | Modeling needed to determine concentrations |
| Inorganics | Δ | c | | |
| Cooling system - blowdown | Δ | c | | Modeling required to determine concentrations |
| Wastewaters | Δ | c | | Modeling required to determine concentrations |
| Ash | - | c | tons/yr | Emissions |

**Table 11.2-1. Pollutant emissions, concentrations, or other changed conditions for an oil fuel cycle at the Southeast reference site**

| Fuel cycle stage and emission | Inform. quality | Emissions or Changed Concentration | | |
|---|---|---|---|---|
| | | Quantity | Unit | Comments |
| | | *Transportation* | | |
| Pipeline-crude oil | ● | spill size<br>spill rate | barrels<br>bbl/bbl handled | Frequency distribution unavailable for different sized spills. |
| Barge-residual oil | ϴ | c | | Spill size and accident rates needed |
| $CO_2$ | - | c | | |
| $NO_x$ | - | c | | |
| $SO_2$ | - | c | | |
| Particulates | - | c | | |
| Hydrocarbons | - | 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 needed.
c. Data limited by lack of site specific studies

**Table 11.2-2. Pollutant emissions, concentrations or other changed conditions for an oil fuel cycle at the Southwest reference site:**

| | | Emissions or Changed Concentration | | |
|---|---|---|---|---|
| Fuel cycle stage and residuals | Inform. quality | Quantity | Unit | Comments |
| | | | ***Oil Production*** | |
| Land use | - | c | acres | |
| Crude oil spill | - | c | | |
| Produced water | ● | 5.93 | bbl/bbl product | New Mexico |
| Arsenic | ● | 0.02 | mg/L | Concentration in produced water |
| Benzene | ● | 0.47 | mg/L | Concentration in produced water |
| Boron | ● | 9.9 | mg/L | Concentration in produced water |
| Sodium | ● | 9,400 | mg/L | Concentration in produced water |
| Chloride | ● | 7,300 | mg/L | Concentration in produced water |
| Mobile ions | ● | 23,000 | mg/L | Concentration in produced water |
| Drilling wastes | ● | 6,332 | bbl/well | New Mexico |
| | | | ***Refinery*** | |
| CO | Θ | 0.16 | g/sec | Emission rate |
| $NO_x$ | Θ | 1.67 | g/sec | Emission rate |
| $SO_2$ | Θ | 9.22 | g/sec | Emission rate |
| TSP | Θ | 0.83 | g/sec | Emission rate |
| PM-10 | Θ | 0.68 | g/sec | Emission rate |
| Hydrocarbons | - | - | - | Emission rate |
| | | | ***Generation*** | |
| $CO_2$ 1990 | ● | 844 | tons/GWh | Emission rate |
| CO - 1990 | Θ | 9.85 | g/sec | Emission rate |
| - 2010 | | 9.85 | g/sec | |
| $NO_x$ - 1990 | Θ | 39.63 | g/sec | Emission rate |
| - 2010 | | 3.96 | g/sec | |
| $SO_2$ - 1990 | Θ | 30.96 | g/sec | Emission rate |
| - 2010 | | 15.48 | | |
| Hydrocarbons | - | c | | |
| Ozone | - | a | | Modeling required to determine atmospheric concentrations |

**Table 11.2-2. Pollutant emissions, concentrations or other changed conditions for an oil fuel cycle at the Southwest reference site:**

| | | Emissions or Changed Concentration | | |
|---|---|---|---|---|
| Fuel cycle stage and residuals | Inform. quality | Quantity | Unit | Comments |
| Acid deposition | - | a | | |
| PM-10 - 1990<br>- 2010 | ϴ[a] | 0.96<br>0.38 | g/sec | Emission rate |
| 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 |
| | | | ***Transportation*** | |
| Road damage | ● | | miles affected | Tank truck traffic, New Mexico |
| Refined oil spills | Δ | c | | |
| $CO_2$ | - | b,c | | |
| $NO_x$ | - | b,c | | |
| $SO_2$ | - | b,c | | |
| Particulates | - | b,c | | |
| Hydrocarbons | - | b,c | | |

Legend:

-, no data;
Δ, qualitative data;
○, 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

Although quantitative information on many of the potential environmental impacts of an oil fuel cycle is limited, some general qualitative conclusions can be made based on the available data. In the scenarios that this study considered, impacts from an oil fuel cycle involve: (1) potential effects of wastewaters from onshore production on aquatic resources, (2) potential effects of wastewater and discharges from offshore drilling on local biota and regional fisheries, (3) effects of possible crude oil spills, either from a platform or from a pipeline, on marine and coastal resources, (4) the changes in crop yield from ozone formation from power plant emissions of hydrocarbons and $NO_x$, (5) damage to coastal wetlands and marine resources from potential spills of residual oil during barge transport along coastal areas, and (6) damage to freshwater aquatic resources from potential spills of residual oil during barge transport through a river system. A lack of data prevented estimates of impacts from wastewater and air emissions at refineries. Most of the quantitative ecological data that are available are on the potential impacts of oil spills on marine and coastal resources, and on the impacts of ozone on crop yields at the Southeast Reference site.

Under the scenario created for this study, the parts of the oil fuel cycle that are likely to have the greatest potential for ecological impacts are spills of crude oil in the marine system and a barge transportation accident with No. 6 residual oil either along the coast or in the Tennessee-Tombigbee-Clinch River system. Time constraints and lack of a specific model for freshwater systems preclude the modeling of aquatic impacts to the river system. A simple dilution model could be applied in the future as time and resources permit. Offshore spills can result from platform leaks or blowouts or from pipeline ruptures or chronic leaks. A spill of large amounts of crude or residual oil in coastal systems can result in significant impacts on resources. However, spills of a magnitude capable of significant damage are rare.

Injuries to marine and coastal resources of the Gulf of Mexico from hypothetical crude and residual oil spills were estimated using the U.S. Department of the Interior's Natural Resource Damages Assessment Model for Coastal and Marine Environments (NRDAM/CME). The model provides estimates of injuries to adult and larval fish, mollusks, decapods, and birds. An average large leak or spill of crude oil (18,046 barrels) from a platform or pipeline located 50 km off the coast of Texas in spring could result in a total catch loss of 3,978,452 pounds of finfish (commercial and recreational) and 33,779 pounds of mollusks and decapods over the next 20 years. Approximately 140 adult seabirds and 3,000 adult shorebirds would be directly killed. The probability of such an occurrence is 0.60 spills/$10^9$ barrels of oil handled.

## Table 11.3-1. Summary table for key ecological impacts in different resource categories

| | Crops | Forests | Commer. Fishing | Recre. fishing | Rec. parks[a] | Bio-diversity |
|---|---|---|---|---|---|---|
| ***Production onshore:*** | | | | | | |
| Wastewaters:<br>Produced water,<br>Drilling fluids,<br>Drill cuttings | n.e. | n.e. | n.e. | n.e. | n.e. | xx |
| ***Production offshore:*** | | | | | | |
| Crude oil spill | n.e. | n.e. | ■ | ■ | xx | xx |
| Wastewaters:<br>Produced water<br>Drilling fluids<br>Drill cuttings | n.e. | n.e. | □[b] | □[b] | n.e. | n.e. |
| ***Refinery:*** | | | | | | |
| Air emissions,<br>Water emissions | n.e. | n.e. | n.e. | n.e. | n.e. | n.e. |
| ***Transportation:*** | | | | | | |
| Crude oil spill | n.e. | n.e. | ■ | ■ | xx | xx |
| Refined oil spill | n.e. | n.e. | ■ | ■ | n.e. | n.e. |
| ***Power generation:*** | | | | | | |
| Ozone | ■ | xx | n.e. | n.e. | n.e. | n.e. |

■ = Impact quantified in this report
xx = Impact qualitatively described, but not quantifiable given current knowledge base
□ = Negligible impact
n.e. = Impact not examined

[a] Includes coastal and wetland areas and public beaches
[b] Impacts negligible with current data

A hypothetical spill of No. 6 residual oil off the coast of Biloxi, Mississippi, in winter could result, on average in a total catch loss of 5,303 pounds of finfish and 100,126 pounds of invertebrates. Approximately 12 adult seabirds and 4,000 adult shorebirds would be directly killed. Information on barge accident rates in coastal waters was not located.

The impact of chronic discharges of produced water and other wastes to the marine environment from offshore oil production are localized; pre-drilling surveys are not available for comparison purposes. According to several studies, 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. Under offshore conditions, suspended solids reach background levels 1,000 to 2,000 meters downcurrent of the discharge and within 2 to 3 hours of discharge. 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 the resulting concentrations, components of the discharged water would not be toxic to marine organisms. The greatest impact from platform discharges is to benthic fauna. Local benthic fauna abundance and diversity are reduced within 100-200 m of the platform. These localized and small increments of pollutants may be significant to an already stressed ecosystem. Increased recreational fishing activity at offshore platforms may be viewed as an economic benefit, but quantitative data on this activity were not located.

Air emissions from the oil-fired power plant, the impacts of which were evaluated only for the 1990 technology at the Southeast Reference site, were assumed to be small. Except for the impact of ozone on crops, no direct ecological impacts were identified. The concentration of sulfur in the oil is 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). Quantitative estimates of the impact of ozone on crop yield indicate that the incremental effect of the power plant would represent extremely small (much less than 0.1%) decreases in soybean, wheat, corn, and tobacco production.

Emissions of $NO_x$, $SO_2$, and hydrocarbons from the stack do not result in ambient atmospheric concentrations that exceed currently identified toxicity thresholds for biota. However, $NO_x$ and $SO_2$ can be dispersed over wide areas, and can contribute to regional impacts such as acid deposition. 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. For the oil fuel cycle impacts of acid deposition are expected to be relatively low because of the low concentration of sulfur in the fuel.

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 AN OIL-TO-ELECTRICITY FUEL CYCLE ON HEALTH

The emissions and impact-pathways which were evaluated in this study (see Table 11.4-1 and 11.4-2) probably represent many of the more of the adverse health effects related to oil fuel cycles. One of the potentially more important pathways that this study did not address are the health effects from sulfates and nitrates. These are secondary pollutants formed from $SO_2$ and $NO_x$ emissions. Regional models are needed to model the chemical transformations and long-range transport of these secondary pollutants.

Notwithstanding, the impact-pathways considered in this study 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 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.

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 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 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.

## 11.5. MARGINAL ECONOMIC DAMAGES AND BENEFITS

In this report, we estimate impacts for each priority pathway associated with the oil-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 present these aggregate estimates of the marginal damages and benefits.

However, it must be recognized that the economics methodology is conceptually limited. In reality, were a new plant to be built, an individual would be offered a package of both positive and negative impacts. Thus, many impacts would be experienced simultaneously. For our approach to be 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, say, two different but substitutable types of recreation sites are degraded, then 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

Table 11.4-1. Health and environmental impacts for an oil fuel cycle at the Southeast Reference site

| Fuel cycle stage and impact pathway | Inform. quality | Annual impact | | |
|---|---|---|---|---|
| | | Quantity | Unit | Comments |
| | | *Production* | | |
| Occupational health: | ⊖ | | | |
| Fatal accidents | ⊖ | 0.1 | Fatalities | During drilling (not annually) |
| Injuries | | 448 | Work days lost | During drilling (not annually) |
| Crude oil spills<br>commercial,<br>recreational<br>fisheries | ● | <br>$4 \times 10^6$<br>3,140 | Losses -<br>Lbs. of fish<br>No. of birds | Losses over 20 year period; most during first year. Probability of annual occurrence small |
| Produced water<br>biodiversity,<br>fisheries | Δ | b,c | | Modeling required for dilutions of specific compounds |
| Drilling fluids<br>biodiversity | Δ | b,c | | Modeling required for dilutions of specific compounds |
| Drill cuttings<br>biodiversity | Δ | b,c | | Modeling required for dilutions of specific compounds |
| | | *Transportation* | | |
| Accidents | | | | |
| Deaths | ○ | a,c | | |
| Injuries | ○ | a,c | | |
| Crude oil spills<br>land, biodiversity,<br>commercial and<br>recreational<br>fisheries | Δ | <br>$4 \times 10^6$<br>3,140 | Losses -<br>Lbs. of fish<br>No. of birds | Spills from offshore - 2010 (onshore - 1990, not evaluated) Reference scenarios do not involve the use of tankers. |
| Refined oil spills | | | | |
| marine:<br>land,<br>biodiversity,<br>fisheries | ● | <br>5,306<br>4,012 | Losses -<br>Lbs. of fish<br>No. of birds | Probability of annual occurrence small |
| freshwater:<br>land,<br>biodiversity,<br>recreational<br>fisheries | Δ | a | | Modeling required for damages due to ecological impacts |

## Table 11.4-1. Health and environmental impacts for an oil fuel cycle at the Southeast Reference site

| Fuel cycle stage and impact pathway | Inform. quality | Annual impact Quantity | Unit | Comments |
|---|---|---|---|---|
| | | ***Refinery*** | | |
| Occupational health | | | | |
| Deaths: | ○ | a,c | Deaths/GWe-y | Data unavailable |
| Injuries | ○ | a,c | Injuries/GWe-y | Data unavailable |
| Air, water emissions crops, biodiversity | Δ | b,c | | Insufficient data on specific compounds, concentrations and dose-response functions |
| | | ***Generation*** | | |
| Occupational health | | | | |
| Deaths | ○ | a,c | Deaths/GWe-y | Data not obtained |
| Injuries | ○ | a,c | Injuries/GWe-y | Data not obtained |
| $CO_2$ - 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 | | Resulting ambient concentrations below threshold levels for direct ecological impacts |
| $NO_2$ - morbidity: | | | | |
| Phlegm days | ⊖ | 880 | Symptom days | |
| $SO_2$ biodiversity | ● | 0 | | Resulting ambient concentrations below threshold levels for direct ecological impacts |
| $SO_2$ - morbidity | | | | |
| Children cough-days | ⊖ | 630 | Symptom days | |
| Adult chest discomfort | ⊖ | 1000 | Symptom days | |
| Hydrocarbons biodiversity | Δ | b,c | | Insufficient data on specific compounds, concentrations and dose-response functions |
| Ozone crops | ● | <0.026% | Percent | Lost productivity in major crops |

**Table 11.4-1. Health and environmental impacts for an oil fuel cycle at the Southeast Reference site**

| Fuel cycle stage and impact pathway | Inform. quality | Annual impact | | |
|---|---|---|---|---|
| | | Quantity | Unit | Comments |
| Ozone - morbidity: | | | | |
| Total respiratory restricted activity days | Θ | 2,600 | Symptom days | |
| Any-symptom day | Θ | 5,700 | Symptom days | |
| Asthma-attack day | Θ | 310 | Symptom days | |
| Eye-irritation day | Θ | 7,700 | Symptom days | |
| Cough days | Θ | 3,100 | Symptom days | |
| Acid deposition - crops | Δ | b | | No effect anticipated |
| Particulates - air quality | Δ | a,c | | Modeling required to determine effects on visibility |
| Particulates ($PM_{10}$) mortality | Θ | 0.017/0.008<br>3 | Deaths | Second number assumes threshold |
| Particulates ($PM_{10}$) morbidity: | | | | |
| Respiratory hospital admissions | Θ | 0.41/0.41 | Admissions | Second number assumes threshold |
| Emergency room visits | Θ | 0.96/0.47 | Visits | Second number assumes threshold |
| Restricted activity days | Θ | 170/81 | Days | Second number assumes threshold |
| Respiratory symptoms | Θ | 6,200/3,000 | Symptoms | Second number assumes threshold |
| Chronic bronchitis in children | Θ | 1.6/0.80 | Added children | Second number assumes threshold |
| Chronic cough in children | Θ | 1.9/0.93 | Symptoms | Second number assumes threshold |
| Asthma attack-days | Θ | 68/33 | Days | Second number assumes threshold |
| 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<br>- 1990<br>- 2010 | - | b,c | | |

Table 11.4-1. Health and environmental impacts for an oil fuel cycle at the Southeast Reference site

| | | Annual impact | | |
|---|---|---|---|---|
| Fuel cycle stage and impact pathway | Inform. quality | Quantity | Unit | Comments |

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 an oil fuel cycle at the Southwest Reference site

| Fuel cycle stage and impact pathway | Inform. quality | Annual impact | | |
|---|---|---|---|---|
| | | Quantity | Unit | Comments |
| | | *Production* | | |
| Occupational health: | | | | |
| Fatal accidents | ⊖ | 0.1 | Fatalities | During drilling (not annual) |
| Injuries | ⊖ | 448 | Work days lost | During drilling (not annual) |
| Crude oil spills<br>land,<br>water quality,<br>biodiversity | Δ | c | | |
| Drilling fluids<br>land,<br>water quality,<br>biodiversity | Δ | c | | |
| Drill cuttings | Δ | c | | |
| | | *Transportation* | | |
| Road damage | ● | 30 | Miles | Assumed length of road requiring periodic repair |
| Accidents | | | | |
| Deaths | ○ | a,c | | |
| Injuries | ○ | a,c | | |
| Crude oil spill - land, water | Δ | c | | Occurrence episodic |
| Refined oil spill land, water | Δ | c | | Occurrence episodic |
| | | *Refinery* | | |
| Occupational health | | | | |
| Deaths: | ○ | a,c | Deaths/G We-y | Awaiting specific data |
| Injuries | ○ | a,c | Injuries/G We-y | Awaiting specific data |
| Air emissions,<br>Water emissions<br>biodiversity | Δ | b,c | | Insufficient data on specific compounds, concentrations and dose-response functions |
| | | *Generation* | | |

### Table 11.4-2. Health and environmental impacts for an oil fuel cycle at the Southwest Reference site

| | | Annual impact | | |
|---|---|---|---|---|
| Fuel cycle stage and impact pathway | Inform. quality | Quantity | Unit | Comments |
| **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 | Θ | 30 | Symptom days | |
| $SO_2$ - air quality | Δ | a | | |
| $SO_2$ - morbidity: | | | | |
| Children cough-days | Θ | 20 | Symptom days | Awaiting specific data |
| Adult chest discomfort | Θ | 33 | Symptom days | Awaiting specific data |
| Hydrocarbons - air quality | Δ | b,c | | Insufficient data on specific compounds, concentrations and dose-response functions |
| Ozone crops | Δ | a | Percent | Lost productivity negligable due to sparse crop land |
| Acid deposition - crops | Δ | b | | No effect anticipated |
| Particulates - air quality | Δ | a,c | | Modeling required to determine effects on visibility |
| Particulates ($PM_{10}$) mortality | Θ | 0.00057/0.00028 | Deaths | Second number assumes threshold |
| Particulates ($PM_{10}$) - morbidity: | | | | Second number assumes threshold |
| Respiratory hospital admissions | Θ | 0.014/0.0069 | Admissions | Second number assumes threshold |
| Emergency room visits | Θ | 0.032/0.016 | Visits | Second number assumes threshold |

### Table 11.4-2. Health and environmental impacts for an oil fuel cycle at the Southwest Reference site

| | | Annual impact | | |
|---|---|---|---|---|
| Fuel cycle stage and impact pathway | Inform. quality | Quantity | Unit | Comments |
| Restricted activity days | Θ | 5.6/2.8 | Days | Second number assumes threshold |
| Respiratory symptom-days | Θ | 210/100 | Symptoms | Second number assumes threshold |
| Chronic bronchitis in children | Θ | 0.055/0.027 | Added children | Second number assumes threshold |
| Chronic cough in children | Θ | 0.064/0.032 | Symptoms | Second number assumes threshold |
| Asthma attack-days | Θ | 2.3/1.1 | Days | Second number assumes threshold |
| 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 | | No effluents; evaporation ponds used |
| Wastewaters - water quality | Δ | c | | No effluents; evaporation ponds used |
| Ash - 1990<br>- 2010<br>land, water quality | - | 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

study that addressed how much more a person would be willing to pay to avoid a new oil 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 oil 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 oil 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 the 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.

Table 11.5-1 and 11.5-2 summarize the annual damages and externalities (in mills/kWh, in 1989 dollars) associated with the operation of the specified oil plant at the two reference sites. The list of pathways 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 several cells no estimates are possible, either because of missing knowledge base or an effect too small to estimate or value.

## 11.6. CONCLUSIONS

### 11.6.1. Scope of the Study

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 an oil fuel cycle. Also, as more studies are done using this approach, it will be easier and less costly to implement. Insofar as many organizations are considering ways of internalizing the external damages of fuel cycles, it seems all the more important to invest in thorough assessments. Even in the United States, with its focus on restructuring the industry and the elimination of onerous regulations, there is still concern about retaining some of the so-called strandable benefits of those regulations such as environmental protection. 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 the limitations in this approach and the gaps in the base of scientific knowledge, results gained from studies using this approach add to the base of knowledge*** to support informed decisions about energy.

At this point, the method is rather complex in terms of the modeling procedures and data requirements. In the next phase of this project, (which is being carried forward by the European Commission' "ExternE" study) an information system is being developed. This system will greatly facilitate the application of the damage function approach.

### 11.6.3. Marginal Damages and Benefits

Of the impacts that were quantified, the major source of damage from the oil fuel cycle is damage to public roads, whenever residual oil is transported in tank trucks over some (e.g., 30 mile) distances, 0.101 mills/kWh of which 0.0921 mills/kWh is an externality. These damages pertain to only the Southwest Reference site under the specific assumptions used in the analysis.[1] To the extent that truck traffic is less than that assumed, road damage will be proportionally less. For comparison, the average total cost to generate electricity from coal-fired power plants in the United States in 1990 was about 3 cents/kWh (EIA 1991). Comparable data were unavailable for oil-fired plants, but the cost of producing electricity from oil is widely held to be greater than that from coal.

The greatest health impact is from ozone, at least in areas with high baseline concentrations. High ozone concentrations are associated with elevated rates of respiratory illnesses. Based on inspection of data on ambient ozone concentrations in the rural Southeast, high ozone concentrations are not uncommon. For the 1990 scenario, estimated damage to the population within 1,000 miles of the plant at the Southeast Reference site was 0.074 mills/kWh. Other health effects were at least an order of magnitude less than the damages from ozone.

If the oil plant were situated in a region with 10 million people nearby, rather than only one million, as in the Southeast Reference site, then the damages would be significantly greater -- assuming that meteorological conditions, topography, population density, demographic characteristics, and baseline ambient conditions 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 oil plant, in areas with high baseline concentrations.***

The estimated damage associated with oil spills at offshore platforms is only 0.0017 mills/kWh. Tankers were not used to transport oil in any of the scenarios

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[1] Damages associated with the barge transportation of residual oil to the Southeast Reference plant site were not quantified.

that were studied. Thus, no tanker spills, -- in particular, Valdez-scale spills -- were considered. These catastrophic spills are infrequent and are largely internalized through insurance coverage, but remain a major issue for the oil fuel cycle. Oil was assumed to be from domestic sources, but of course spills of foreign crude oil would still result in damages as well.

The energy security issue is relevant to the oil fuel cycle but, by itself, the addition of a single oil-fired plant probably does little to affect energy security. The cumulative effect of all plants in the country may.

Similarly, even if it could be quantified, the incremental impact of the $CO_2$ from a single power plant on climate change would be very difficult to measure. But the cumulative impact of many power plants may have an overwhelming effect on the total damages from using fossil fuels to generate electric power. The damage function approach is not well suited to this type of analysis.

Estimates of damages are highly uncertain, and are project- and site-specific. The estimates should not be summed and then directly 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 and coal). It is, however, informative to compare **individual** impact-pathways -- between sites, technologies, or fuel cycles.

### 11.6.4. 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 an oil-fired 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 limitation that 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 pay for certain environmental conditions, even though the individuals may never experience those conditions themselves. The issue is probably the most important point of contention about developing the Arctic National Wildlife Refuge. Neither of the reference scenarios in this study uses oil from Alaska. Thus, these types of non-use damage issues were not addressed.

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 residuals 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.

## Table 11.5-1. Selected impact-pathways, damages and externalities for the oil fuel cycle in the *Southeast* Reference environment

| | Damages (mills/kWh) | | | Externalities (mills/kWh) | | | |
|---|---|---|---|---|---|---|---|
| | Low | Mid | High | Low | Mid | High | Comments |
| *Production* | | | | | | | |
| Occupational health: | | | | | | | |
| Fatal accidents | a,c | a,c | a,c | a,c | a,c | a,c | $35,000 from potential drilling accidents, prior to power production |
| Injuries | a,c | a,c | a,c | a,c | a,c | a,c | 450 lost work days from drilling accidents, prior to power production |
| Crude oil spills commercial, recreational fisheries | c | 0.0017 | c | c | <0.0017 | c | some damages internalized in U.S. by Oil Pollution Act |
| Produced water biodiversity, fisheries | b,c | b,c | b,c | b,c | b,c | b,c | Refer to Sect. 5.1 and Chapter 7 |
| Drilling fluids biodiversity | b,c | b,c | b,c | b,c | b,c | b,c | Refer to Sect. 5.1 and Chapter 7 |
| Drill cuttings biodiversity | b,c | b,c | b,c | b,c | b,c | b,c | Refer to Sect. 5.1 and Chapter 7 |
| *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 | |
| Crude oil spills land, biodiversity, commercial and recreational facilities | c | c | c | c | c | c | Refer to Sect. 9.1 |
| Refined oil spills: | | | | | | | |
| marine land, biodiversity, fisheries | c | c | c | c | c | c | Refer to Sect. 9.2 |
| freshwater land, biodiversity, recreational fisheries | a,c | 0.0043 | a,c | a,c | <0.0043 | a,c | |

**Table 11.5-1. Selected impact-pathways, damages and externalities for the oil fuel cycle in the *Southeast* Reference environment**

| | Damages (mills/kWh) | | | Externalities (mills/kWh) | | | |
|---|---|---|---|---|---|---|---|
| | Low | Mid | High | Low | Mid | High | Comments |
| *Refinery* | | | | | | | |
| Occupational | | | | | | | |
| Deaths | a,c | a,c | a,c | a,c | a,c | a,c | Lack of data |
| Injuries | a,c | a,c | a,c | a,c | a,c | a,c | Lack of data |
| Hydrocarbons crops, biodiversity | a,c | a,c | a,c | a,c | a,c | a,c | Lack of data |
| *Generation* | | | | | | | |
| Occupational | | | | | | | |
| Deaths | a,c | a,c | a,c | a,c | a,c | a,c | Lack of data |
| Injuries | 0.016 | 0.021 | 0.068 | <0.16 | <0.021 | <0.068 | Difficult to ascertain fraction internalized |
| $CO_2$—global warming | b | b | b | b | b | b | Could be 4-5 mills/kWh (refer to Sect. 10.2.3) |
| $CO_2$—plant growth | b | b | b | b | b | b | Positive effect, subsumed under estimate above |
| $NO_x$ biodiversity | c | c | c | c | c | c | |
| $NO_2$ - morbidity: | | | | | | | |
| Phlegm days | b | b | b | b | b | b | No valuation function available |
| $SO_2$ biodiversity | c | c | c | c | c | c | |
| $SO_2$ — morbidity: | 0.0016 | 0.0048 | 0.0095 | b | b | b | Effect of $SO_2$ emission trading is unclear |
| Children cough-days | $1.9 \times 10^{-4}$ | 0.0016 | 0.0039 | b | b | b | Effect of $SO_2$ emission trading is unclear |
| Adult chest discomfort | $5.2 \times 10^{-4}$ | 0.0032 | 0.0071 | b | b | b | Effect of $SO_2$ emission trading is unclear |
| $SO_2$-Materials | 0.0072 | 0.019 | 0.032 | b | b | b | Effect of $SO_2$ emission trading is unclear |
| Hydrocarbons biodiversity | b,c | b,c | b,c | b,c | b,c | b,c | |
| Ozone crops | a | 0.060 | a | a | 0.60 | a | |
| Ozone - morbidity total | 0.042 | 0.074 | 0.11 | 0.042 | 0.074 | 0.11 | |
| Minor respiratory restricted activity days | 0.0 | 0.029 | 0.062 | 0.0 | 0.029 | 0.062 | |
| Any symptom-day | 0.0017 | 0.018 | 0.039 | 0.0017 | 0.018 | 0.039 | |
| Asthma attack-day | 0.0013 | 0.0044 | 0.0086 | 0.0013 | 0.0044 | 0.0086 | |
| Eye irritation-day | 0.011 | 0.024 | 0.045 | 0.011 | 0.024 | 0.045 | |
| Cough-day | 0.0021 | 0.0076 | 0.018 | 0.0021 | 0.0076 | 0.018 | |
| Acid deposition—crops | b | b | b | b | b | b | Probably negligible (based on Coal Report) |

**Table 11.5-1. Selected impact-pathways, damages and externalities for the oil fuel cycle in the *Southeast* Reference environment**

| | Damages (mills/kWh) | | | Externalities (mills/kWh) | | | |
|---|---|---|---|---|---|---|---|
| | Low | Mid | High | Low | Mid | High | Comments |
| Particulates (PM$_{10}$)—mortality | 0.011/<br>0.0052 | 0.033/<br>0.016 | 0.068/<br>0.033 | 0.011/<br>0.0052 | 0.033/<br>0.016 | 0.068/<br>0.033 | Second number with threshold |
| Particulates (PM$_{10}$)—morbidity total: | 0.017/<br>0.009 | 0.028/<br>0.015 | 0.044/<br>0.023 | 0.017/<br>0.009 | 0.028/<br>0.015 | 0.044/<br>0.023 | Second number with threshold |
| Respiratory hospital admissions | 1.5x10$^{-5}$ | 6.3x10$^{-4}$ | 1.3x10$^{-3}$ | 1.5x10$^{-5}$ | 6.3x10$^{-4}$ | 1.3x10$^{-3}$ | Number is with threshold |
| Emergency room visits | 3.1x10$^{-6}$ | 4.1x10$^{-5}$ | 7.7x10$^{-5}$ | 3.1x10$^{-6}$ | 4.1x10$^{-5}$ | 7.7x10$^{-5}$ | Number are with threshold |
| Restricted activity days | 4.3x10$^{-4}$ | 2.0x10$^{-3}$ | 3.5x10$^{-3}$ | 4.3x10$^{-4}$ | 2.0x10$^{-3}$ | 3.5x10$^{-3}$ | Number are with threshold |
| Respiratory symptoms | 4.0x10$^{-3}$ | 9.2x10$^{-3}$ | 1.7x10$^{-2}$ | 4.0x10$^{-3}$ | 9.2x10$^{-3}$ | 1.7x10$^{-2}$ | Number are with threshold |
| Chronic bronchitis in children | 8.1x10$^{-6}$ | 5.3x10$^{-5}$ | 9.6x10$^{-5}$ | 8.1x10$^{-6}$ | 5.3x10$^{-5}$ | 9.6x10$^{-5}$ | Number are with threshold |
| Chronic cough in children | 3.4x10$^{-7}$ | 2.4x10$^{-6}$ | 5.9x10$^{-6}$ | 3.4x10$^{-7}$ | 2.4x10$^{-6}$ | 5.8x10$^{-6}$ | Number are with threshold |
| Asthma attack-days | 7.1x10$^{-5}$ | 4.8x10$^{-5}$ | 9.6x10$^{-4}$ | 7.1x10$^{-5}$ | 4.8x10$^{-5}$ | 9.6x10$^{-3}$ | Number are with threshold |
| Chronic bronchitis in adults | 5.2x10$^{-4}$ | 2.8x10$^{-3}$ | 5.3x10$^{-3}$ | 5.2x10$^{-4}$ | 2.8x10$^{-3}$ | 5.3x10$^{-3}$ | Number are with threshold |
| Peroxyacetyl nitrate (PAN) - air | b,c | b,c | b,c | b,c | b,c | b,c | |
| Inorganics - biodiversity | c | c | c | c | c | c | |
| Cooling system blowdown - water quality | c | c | c | c | c | c | |
| Wastewaters - water quality | c | c | c | c | c | c | |
| Ash - land water quality | b,c | b,c | b,c | b,c | b,c | b,c | |

Legend:
- a. An estimate may be possible, with additional analysis.
- b. Possibility of estimate limited by state of the science; i.e., new models needed.
- c. Possibility of estimate limited by lack of site-specific studies.

**Table 11.5-2. Selected impact-pathways, damages and externalities for the oil fuel cycle in the *Southwest* Reference environment**

| | Damages (mills/kWh) | | | Externalities (mills/kWh) | | | |
|---|---|---|---|---|---|---|---|
| | Low | Mid | High | Low | Mid | High | Comments |
| *Production* | | | | | | | |
| Occupational | | | | | | | |
| Fatal accidents | a,c | a,c | a,c | a,c | a,c | a,c | Same as Table 11.5-1 |
| Injuries | a,c | a,c | a,c | a,c | a,c | a,c | Same as Table 11.5-1 |
| Drilling fluids land, water quality, diversity | b,c | b,c | b,c | b,c | b,c | b,c | Refer to Sect. 5.1 and Chapter 7 |
| Drill cuttings | b,c | b,c | b,c | b,c | b,c | b,c | Refer to Sect. 5.1 and Chapter 7 |
| *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 | |
| Crude oil spills land, water | c | c | c | c | c | c | |
| Refined oil spills land, water | c | c | c | c | c | c | |
| Highway damage | 0.0287 | 0.101 | 0.354 | 0.0176 | 0.0921 | 0.323 | Based on 30 mi. Distance from refinery to power plant. |
| *Refinery* | | | | | | | |
| Occupational | | | | | | | |
| Deaths | a,c | a,c | a,c | a,c | a,c | a,c | Lack of data |
| Injuries | a,c | a,c | a,c | a,c | a,c | a,c | Lack of data |
| Hydrocarbons biodiversity | a,c | a,c | a,c | a,c | a,c | a,c | Lack of data |
| *Generation* | | | | | | | |
| Occupational health: | | | | | | | |
| Deaths | a,c | a,c | a,c | a,c | a,c | a,c | Same as Table 11.5-1 |
| Injuries | | | | | | | |
| $CO_2$—global warming | b | b | b | b | b | b | Same as Table 11.5-1 |
| $CO_2$—plant growth | b | b | b | b | b | b | Same as Table 11.5-1 |

## Table 11.5-2. Selected impact-pathways, damages and externalities for the oil fuel cycle in the *Southwest* Reference environment

| | Damages (mills/kWh) | | | Externalities (mills/kWh) | | | |
|---|---|---|---|---|---|---|---|
| | Low | Mid | High | Low | Mid | High | Comments |
| $NO_x$ biodiversity | c | c | c | c | c | c | |
| $NO_2$ - morbidity: | | | | | | | |
| Phlegm days | b | b | b | b | b | b | No valuation function available |
| $SO_2$ - biodiversity | c | c | c | c | c | c | Effect of $SO_2$ emissions trading is unclear |
| $SO_2$ — morbidity: | 4.7x10$^{-5}$ | 0.00016 | 0.00031 | b | b | b | Effect of $SO_2$ emissions trading is unclear |
| Children cough-days | 4.8x10$^{-6}$ | 5.3x10$^{-5}$ | 1.2x10$^{-4}$ | b | b | b | Effect of $SO_2$ emissions trading is unclear |
| Adult chest discomfort | 1.1x10$^{-5}$ | 1.1x10$^{-4}$ | 2.4x10$^{-4}$ | b | b | b | Effect of $SO_2$ emissions trading is unclear |
| $SO_2$-Materials | 2.2x10$^{-4}$ | 6.4x10$^{-4}$ | 3.2x10$^{-2}$ | b | b | b | Effect of $SO_2$ emissions trading is unclear |
| Hydrocarbons - air quality | b,c | b,c | b,c | b,c | b,c | b,c | |
| Ozone | | | | | | | |
| crops | a | a | a | a | a | a | Very small impact |
| health | a | a | a | a | a | a | Very small impact |
| Acid deposition - crops | b | b | b | b | b | b | Probably negligible (based on Coal Report) |
| Particulates - air quality, crops | a,c | a,c | a,c | a,c | a,c | a,c | |
| Particulates ($PM_{10}$)— mortality | 0.00036/<br>0.00018 | 0.0011/<br>0.00054 | 0.0023/<br>0.0011 | 0.00036/<br>0.00018 | 0.0011/<br>0.00054 | 0.0023/<br>0.0011 | Second number is with threshold |
| Particulates ($PM_{10}$)— morbidity total: | 0.0098/<br>0.00062 | 0.002/<br>0.0016 | 0.0031/<br>0.0027 | 0.0098/<br>0.00062 | 0.002/<br>0.0016 | 0.0031/<br>0.0027 | Second number is with threshold |
| Respiratory hospital admissions | 0.0 | 2.0x10$^{-5}$ | 4.2x10$^{-5}$ | 0.0 | 2.0x10$^{-5}$ | 4.2x10$^{-5}$ | Numbers are with threshold |
| Emergency room visits | 2.0x10$^{-7}$ | 1.4x10$^{-6}$ | 2.7x10$^{-6}$ | 2.0x10$^{-7}$ | 1.4x10$^{-6}$ | 2.7x10$^{-6}$ | Numbers are with threshold |
| Restricted activity days | 1.2x10$^{-5}$ | 6.6x10$^{-5}$ | 1.3x10$^{-4}$ | 1.2x10$^{-5}$ | 6.6x10$^{-5}$ | 1.3x10$^{-4}$ | Numbers are with threshold |
| Respiratory symptoms-day | 1.4x10$^{-4}$ | 3.1x10$^{-4}$ | 5.3x10$^{-4}$ | 1.4x10$^{-4}$ | 3.1x10$^{-4}$ | 5.3x10$^{-4}$ | Numbers are with threshold |
| Chronic bronchitis in children | 2.8x10$^{-8}$ | 1.7x10$^{-6}$ | 3.2x10$^{-6}$ | 2.8x10$^{-8}$ | 1.7x10$^{-6}$ | 3.2x10$^{-6}$ | Numbers are with threshold |
| Chronic cough in children | 1.0x10$^{-8}$ | 8.0x10$^{-8}$ | 2.0x10$^{-7}$ | 1.0x10$^{-8}$ | 8.0x10$^{-8}$ | 2.0x10$^{-7}$ | Numbers are with threshold |
| Asthma attack-day | 2.2x10$^{-6}$ | 1.6x10$^{-5}$ | 3.3x10$^{-5}$ | 2.2x10$^{-6}$ | 1.6x10$^{-5}$ | 3.3x10$^{-5}$ | Numbers are with threshold |
| Adult chronic bronchitis | 2.4x10$^{-4}$ | 1.2x10$^{-3}$ | 2.3x10$^{-3}$ | 2.4x10$^{-4}$ | 1.2x10$^{-3}$ | 2.3x10$^{-3}$ | |

**Table 11.5-2. Selected impact-pathways, damages and externalities for the oil fuel cycle in the *Southwest* Reference environment**

| | Damages (mills/kWh) | | | Externalities (mills/kWh) | | | |
|---|---|---|---|---|---|---|---|
| | Low | Mid | High | Low | Mid | High | Comments |
| Peroxyacetyl nitrate (PAN) - crops, air quality | b,c | b,c | b,c | b,c | b,c | b,c | |
| Inorganics - biodiversity | c | c | c | c | c | c | |
| Cooling system blowdown - water quality | c | c | c | c | c | c | |
| Wastewaters - water quality | c | c | c | c | c | c | |
| Ash - land, water quality | b,c | b,c | b,c | b,c | b,c | b,c | |

Legend:

a. An estimate may be possible, with additional analysis.
b. Possibility of estimate limited by state of the science; i.e., new models needed.
c. Possibility of estimate limited by lack of site-specific studies.

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# APPENDIX A
# Supplemental Oil Refinery Operations and Oil Industry Regulations

## 1. Chemical Reaction Processes

These processes change the chemical compositions of oil fractions in order to upgrade certain refinery streams and to produce valuable products. For example, to meet the demands for high-octane gasoline, jet fuels, and diesel, components such as heavy ends (i.e., residual oils) and light ends (i.e., refinery gases and liquefied gases) are converted to gasoline and other light fractions through chemical reaction processes.

The residual fuel oils used in oil-fired power plants are the residues from physical distillation processes. Most chemical reaction processes are employed for producing gasoline and other high-quality fuels from residual oils. It may be proper to allocate emissions from these chemical reaction processes to gasoline, middle distillates, and other fuels, but not to residual fuel oils.

### 1.1 Cracking

Cracking reaction converts heavy fractions to lighter, more valuable products. There are three major cracking processes: catalytic cracking, hydrocracking, and thermal cracking. As of January 1991, U.S. refineries had a 9.3 million barrel per day cracking capacity. Of this capacity, 63% was catalytic cracking, 14% was hydro-cracking, and the remaining 23% was thermal cracking (Energy Information Administration, 1991a).

#### 1.1.1 Catalytic Cracking

Catalytic cracking processes convert heavy oils into lighter products such as gasoline and distillate blending components with the help of catalysts. Catalytic cracking processes can be classified into two categories: fluidized-bed and moving-bed catalytic cracking, both of which use a reactor for cracking reactions and a regenerator for catalyst regeneration.

Fluidized-Bed Catalytic Cracking (FCC). The FCC process uses catalysts which are in small particles. The feedstock is preheated in a process heater and introduced into the bottom of a vertical transfer line with the hot regenerated catalyst. Catalyst particles float in the fluid when the fluid moves upward with a certain speed and help cracking reactions. Hydrocarbon vapors are separated from the catalyst particles by cyclones in the reactor. The reaction products are sent to a fractionator for separation. The spent catalyst falls to the bottom of the reactor and is steam-stripped to remove absorbed hydrocarbons as it exits the reactor bottom. The catalyst is then conveyed to a regenerator where the coke deposited on the surface of the catalyst particles is burned off. The regenerated catalyst is then recycled and mixed with fresh hydrocarbon feedstock.

Moving-Bed Catalytic Cracking (MCC). The MCC process uses larger catalyst particles than those used in the FCC process. Gravity causes the catalyst particles to flow downward from the top of the reactor where they contact the hydrocarbon mixture. Cracking reactions take place as catalyst particles and hydrocarbons move concurrently downward through the reactor to a zone where the catalyst is separated from the hydrocarbon vapors. The reaction products flow from the reactor to a fractionator. The spent catalyst is steam-stripped to remove any absorbed hydrocarbons. It then flows into the regenerator where coke is burned off. Throughout the world, 82% of all refineries are equipped with catalytic cracking, 89% of which are FCC and the remainder of which are MCC (Neumann and Rahimian, 1984).

Air emissions from catalytic cracking processes are due to the combustion products of process heaters and the flue gas from catalyst regenerators. The emissions from process heaters include HC, CO, $NO_X$, $SO_X$, PM, and $CO_2$. The emissions from catalyst regenerators include HC, $SO_X$, $NH_3$, aldehydes, $NO_X$, cyanides, CO, and PM (Environmental Protection Agency, 1985). The PM emissions from the FCC process are much greater than those from the MCC process because of the higher catalyst circulation rate of the former (Environmental Protection Agency, 1985).

The PM emissions from the FCC process are controlled by cyclones and/or electrostatic precipitators. Waste-heat boilers can be used to reduce CO and HC emissions from the FCC process. The MCC process generates similar emissions, but in much smaller quantities. The PM emissions from MCC are usually controlled by cyclones. The HC and CO emissions from the MCC process are controlled by passing the flue gas through a process heater or smoke plume burner. $SO_X$ can be removed by passing the regenerator flue gas through a water or caustic scrubber.

Hazardous wastes are formed by the deactivated catalysts during the catalytic cracking processes. The deactivation of the catalyst is caused by coke deposited on the surface of the catalyst and by the poisoning effects of heavy metals such as vanadium, nickel, iron, and copper, and sulfur and nitrogen compounds, all of which are contained in crude. The deactivated catalysts are disposed of as sludges.

Catalytic cracking units are one of the largest sources of sour and phenolic wastewaters in a refinery. Pollutants from catalytic cracking processes generally come from the steam strippers and overhead accumulators on fractionators. The major water pollutants are oil, sulfides, phenols, cyanides, and ammonia. These pollutants produce an alkaline wastewater with a high $BOD_5$ and COD.

### 1.1.2 Hydrocracking

Hydrocracking is a cracking process coupled with catalytic hydrogeneration in a hydrogen atmosphere. This process can be used to produce a variety of products from a wide range of raw feedstocks. The large amount of hydrogen required in hydrocracking needs to be produced from light oil products or natural gas. Hydrocracking catalysts can be used over one or two years; thus, catalyst regenerators are not needed for hydrocracking processes.

Hydrocracking results in sour wastewater from steam stripping in the fractionator. Because of the tendency for hydrogen to strip sulfur from hydrocarbons, the wastewater is expected to be higher in sulfide content. Also, the wastewater may contain significant quantities of phenols and ammonia.

### 1.1.3 Thermal Cracking

By heating up feedstocks during thermal cracking processes, heavy oil components are broken into light oil components due to the thermal instability of hydrocarbon components. Thermal cracking includes visbreaking and coking.

During the visbreaking process, residues from distillation processes are heated and thermally cracked in the visbreaker furnace to reduce the viscosity of the feed. The cracked products are quenched with gas oil and fed into a fractionator. The vapors from the fractionator are separated into light distillate products. A heavy distillate recovered from the fractionator can be used as a heavy fuel oil. During the coking process, vacuum residues and thermal tars are cracked at a high temperature and low pressure. The reaction is endothermic.

Air emissions produced from thermal cracking processes include coke dust from de-coking operations, combustion gases from the visbreaking and coking process heaters, and fugitive HC emissions. Fugitive emissions from miscellaneous leaks are significant because of the high pressure involved. During de-coking, significant PM emissions are produced from removing the coke from the coke drum and from subsequent handling and storage operations. HC emissions are also produced from cooling and venting the coke drum prior to coke removal. PM emissions from the de-coking operation can be controlled by wetting down the coke. Generally, there is no method of controlling HC emissions from coking.

The major source of wastewater in thermal cracking processes is the overhead accumulator on the fractionator, where water is separated from the hydrocarbon vapor and sent to the sewer system. This water usually contains various oil and fractions. Therefore, it may be high in $BOD_5$, COD, ammonia, phenol, and sulfides and may have a high alkalinity.

## 1.2 Combining Hydrocarbon Molecules

### 1.2.1 Alkylation

With the help of catalysts, alkylation chemically combines petroleum fractions to produce high-octane gasoline components. The product of this operation is alkylate, one of the highest-quality components in motor gasoline. The reaction is exothermic. Heat is removed by adding liquid propane and/or butane to the reaction mixture. Sulfuric acid is the most widely used catalyst, although hydrofluoric acid is also used.

The major discharge from sulfuric acid alkylation is the spent caustic from the neutralization of hydrocarbon streams. These wastewaters contain dissolved and suspended solids, sulfides, oils, and other contaminants. The main waste stream from hydrofluoric acid alkylation units is the spent caustic and the caustic-contaminated wastewater which comes mainly from the overhead accumulator in the fractionator.

### 1.2.2 Polymerization

Polymerization combines light olefins from thermal and catalytic cracking units to form hydrocarbons of high molecular weight. The products from polymerization are blending stocks for gasoline. The process is helped by use of catalysts. The most commonly used catalyst is phosphoric acid.

Because of the small polymerization capacity of most refineries, the total waste production from this process is small. Even though the process uses acid catalysts, the waste stream is alkaline because the acid catalyst in most subprocesses is recycled and because any remaining acid is removed by caustic washing. Most of the waste materials come from the pretreatment of feedstock to the reactor. The wastewater is high in sulfides, mercaptans, and ammonia. These materials are removed from the feedstock in caustic acid.

## 1.3 Re-arranging Hydrocarbon Molecules

### 1.3.1 Reforming

The reforming process re-arranges the structure of hydrocarbon molecules to increase the octane rating of gasoline. Therefore, this process is primarily designed to produce better quality gasoline. Reforming is a relatively clean process. The volume of wastewater flow is small, and none of the wastewater streams has a high concentration of significant pollutants. Two types of reforming processes are used in refineries: catalytic reforming and thermal reforming.

Catalytic Reforming. There are three catalytic reforming methods: the non-regenerative method, the regenerative method, and the semi-regenerative method. In the non-regenerative method, the reaction conditions and feedstocks must be chosen carefully to keep the coke formation on the catalyst surface very low. Regeneration is accomplished by burning coke one time for 6-200 hours, depending on the type of feedstock. Semi-regeneration takes place after shutting down the whole plant. The regeneration of catalysts results in air emissions. The reforming process is endothermic, and heating by pipe stills is needed. Catalytic reforming is much more common than thermal reforming. In 1990, U.S. refineries had a 3.9 million barrel per day catalytic reforming capacity (Energy Information Administration, 1991a).

Thermal Reforming. A thermal reforming facility consists of a pipe still to heat feedstocks, where thermal reforming reaction takes place.

### 1.3.2 Isomerization

The isomerization process converts straight-chained hydrocarbon molecules into branch-chained molecules with the same chemical composition. The products are either used as alkylation feedstock or as gasoline blending components.

Isomerization wastewater presents no major pollutant discharge problems. Sulfides and ammonia are not likely to be present in the effluent. Isomerization wastewater should also be low in phenolics and oxygen demand.

## 1.4 Other Treating Processes

There are many other treating processes, besides the above three refining processes. They are briefly discussed below.

### 1.4.1 Asphalt Blowing

In the asphalt blowing process, asphaltic residual oils are polymerized by oxidation to increase their melting temperature and their hardness, thereby increasing their resistance to weathering. The oxidation is accomplished by blowing hot air through the liquid mixture. The reaction is exothermic, and quench steam is sometimes needed for temperature control.

Air emissions from asphalt blowing are primarily HC vapors vented with the blowing air. The emissions may contain hazardous polynuclear hydrocarbons. About sixty pounds of emissions is produced per one ton of asphalt produced (Environmental Protection Agency, 1985).

Petroleum treating processes remove impurities such as sulfur, nitrogen, and oxygen from products to improve their quality. For example, sulfur may be removed from fuel oils to reduce their damage to boilers and to limit $SO_x$ emissions from fuel oil combustion. There are several major treating processes: hydrotreating, solvent refining, sweetening, and adsorption.

### 1.4.2 Hydrotreating

Hydrotreating processes are used to saturate olefins and to remove sulfur and nitrogen compounds, odor, color, gum-forming materials, etc., by catalytic actions in the presence of hydrogen. Hydrotreating processes are used to reduce the sulfur content of product streams from sour crude and to reduce the nitrogen content of product streams.

The accumulation of coke and heavy metals on the surface of catalysts reduces catalytic activity. Regeneration of catalysts is needed, though not as often as in the catalytic cracking process. The reaction is exothermic, but the temperature increase during the reaction is minimal. In 1990, U.S. refineries had a 9.7 million barrel per day hydro-treating capacity.

The quantity of wastewater generated in hydrotreating processes depends on the subprocess and feedstocks used. Ammonia and sulfides are the primary contaminants, but phenols may also be present. $H_2S$ is generated during the removal of sulfur compounds, while $NH_3$ is generated during the removal of nitrogen compounds. Elemental sulfur can be recovered from $H_2S$.

### 1.4.3 Solvent Refining

Solvent refining is used to refine some products. Two processes, solvent de-asphalting and solvent de-waxing, are often used. The purpose of solvent de-asphalting is to recover catalytic cracking feedstocks from asphaltic residuals and to produce asphalt as a by-product. Solvent de-waxing removes wax from lubricating oil stocks by crystallizing the wax. The process yields de-oiled waxes, wax-free lubricating oils, aromatics, and recovered solvents.

The major potential pollutants from the various solvent refining processes are solvents that result from pump seal leaks, flange leaks, and other sources. Many of the solvents, such as phenol, glycol, and amines, can produce a high $BOD_5$.

### 1.4.4 Sweetening

Sweetening is applied to remove hydrogen sulfide, mercaptans, and thiophenes, which mainly cause a foul odor. The major sweetening operations are the oxidation of mercaptans or disulfides, the removal of mercaptans, and the destruction and removal of all sulfur compounds. HC emissions are produced during the conversion.

The most common wastewater produced from sweetening is spent caustics. The spent caustic is characterized as phenolic or sulfitic. Phenolic spent caustics contain phenol, cresols, xylenols, sulfur compounds, and some neutral oils. Sulfitic spent caustics are rich in sulfides but do not contain any phenols. These spent caustics have a very high $BOD_5$ and COD. Other waste streams result from water-washing the treated product and regenerating the treating solution. These waste streams contain small amounts of oil and treating materials.

### 1.4.5 Adsorption

Adsorption is performed on the vacuum distillates that have already been refined by acid treatment in order to remove gums, gum-forming components, and polymerized diolefins. Activated clay of bleaching earth is used for the purpose. This process also results in the removal of the coloring matter in the product.

### 1.4.6 Blending

Blending involves mixing blending stocks and additives to obtain a finished product. Most refinery products are ultimately produced by combining various blending stocks. In the past, batch or tank blending procedures were employed, but today in-line blending is practiced at most refineries. To begin the blending operation, a series of valves connecting the various component tanks with the blending lines are opened. Metering devices attached to the valves monitor the flows of the components to ensure that the proper mix is achieved. HC evaporative emissions and fugitive emissions are probably the major concern for the blending operation.

## 2. OIL INDUSTRY REGULATIONS

### 2.1 Regulations of Wastewaters from Oil Production

The wastes produced during oil well drilling and oil extraction are regulated by state and federal agencies. Most oil-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 oil 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 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 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 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 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.

## 2.2 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. A 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., ignitibility, 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 oil production sites for the oil fuel cycle study are located in New Mexico and Texas (both onshore and offshore). Some features of the regulations for oil production are unique to these states and are included for comparison with the national regulations.

# APPENDIX B
# Ozone Modeling

## 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 300 MW oil-fired power plant. The modeling methodology is described in detail in ORNL/RFF (1994) 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 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 NOx 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 oil fuel cycle. All other details of the ozone modeling are as described in ORNL/RFF (1994) and McIlvaine (1994).

## 2.0 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 (1994) and McIlvaine (1994) is given by:

$$F = \frac{8Q}{\pi u^2 t_t t_d}(0.2778)$$

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 time 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 oil-fired power plant at the Southeast reference site of 39.6 g/s was used to calculate the $NO_X$ emissions flux. The non-methane hydrocarbon emission rate of 1.5 g/s was used to calculate the NMOC emissions flux. 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 still 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 a.m. 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 ($F_{9\,a.m.} = F_{10\,a.m.} / 2$) 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.)

Wind speed data are used in to calculate the $NO_X$ and NMOC emissions flux for the oil-fired power plant under low, median and high ozone conditions. The 10-meter wind speeds are the 10-day average observations described in ORNL/RFF (1994) 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):

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^p$$

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 oil-fired power plant is 213 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 2.9, 3.8 and 4.5 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 11 p.m.

The calculated $NO_X$ and NMOC emissions flux for each hour are input to the OZIPM-4 model. This model predicts 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.

## *3.0 RESULTS*

### 3.1 CROP EFFECTS RESULTS

The crop effects analysis portion of the oil 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. [10.16.1] and [10.16.2]. 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 [10.16.1] shows the predicted impact of the oil-fired power plant emissions on the seasonal 12-hour 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 Fig. [10.16.1], the highest 12-hour seasonal average ozone concentration (based on bulges only) is 0.4 ppb (the smallest isopleth line) and occurred approximately 20 kilometers from the plant in the east northeast direction. The lowest isopleth plotted in Fig. [10.16.1] is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 220 kilometers from the plant in the northeast direction and 130 kilometers in the southwest direction.

Figure [10.16.2] shows the predicted impact of the oil-fired power plant emissions on the seasonal 12-hour average ozone concentrations due to both ozone bulges and depletions. These results represent the mid-case estimate of the impact of the power plant emissions on ozone concentrations. The highest 12-hour seasonal average ozone concentration is 0.40 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. 10.16.2] is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 220 kilometers from the plant in the northeast direction and 130 kilometers in the southwest direction. The results shown in Fig. [10.16.1] and [10.16.2] are essentially the same since emissions from the oil-fired power plant do not cause significant ozone depletion on a seasonal average.

In addition to the results seen in Fig. [10.16.1 ] and [10.16.2 ] 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 (Rutledge 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-O3 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 28 days during the 1990 ozone season. One of the 28 days was in the month of May, six of the days were in June, nine were in July, seven days were in August and five days were in September.

As stated above, results for the health effects analysis are in tabular form and correspond to 28 days of the ozone season. (If the actual results used in the health effects study were presented here graphically it would require 28 figures, one for each day). Alternatively, Fig. [10.16.1] 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. [10.16.1] are the maximum daily peak ozone concentrations at each location in the receptor grid. As seen in Fig. [10.16.2], the highest daily peak ozone concentration due to the power plant emission, during the ozone season, was 7 ppb, occurring from 20 to 80 kilometers in the northeast direction. A daily peak ozone concentration of 1 ppb was seen, as far away as 170 kilometers in the northeast direction and 100 kilometers in the southwest direction.

# APPENDIX C
# Air Dispersion Modeling of Primary Pollutants

## 1. INTRODUCTION

The ground-level pollutant concentrations that could be expected to occur as the result of the operation of a 300 megawatt (MW) oil-fired power plant were predicted using atmospheric dispersion modeling. An atmospheric dispersion model is a set 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 (NOx), 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 300 MW oil-fired power plant located at both the Southeast Reference site and the Southwest Reference site for 1990 and 2010. This appendix is intended to provide details of the primary pollutant modeling that are specific to the oil fuel cycle. All other details of the modeling study are described in (ORNL/RFF 1994a).

## 2.0 DATA USED IN THE COMPUTER MODELING

## 2.1 SOURCE CHARACTERISTICS

For the operation stage of energy production for an oil-fired power plant, there is one source of air emissions: the boiler 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 discussed in the next section.

It is assumed that in 1990, the hypothetical power plant is equipped with a baghouse, wet scrubber, low NOx burners and ammonia injection. In 2010, the power plant is equipped with all of the above and selective catalytic reduction (see Section 5.6.3).

The hypothetical oil-fired boiler was modeled with a stack height of 213 meters (700 feet) at the Southeast Reference site and 152 meters (500 ft) at the Southwest Reference site [WANG]. The boiler was modeled with an exit gas temperature of 325 Kelvin (126 degrees F) and an exit gas velocity of 15 meters per second (50 fps).

The exit gas flowrate was calculated using the F-factor from 40 CFR Part 60, Appendix A (7-1-90 edition). The F-factor is the ratio of the gas volume of the products of combustion to the heat content of the fuel. The wet F-factor for oil is 10,320 wscf/MMBtu (wet standard cubic feet per million Btu). Assuming an efficiency of 35%, design availability of 80%, and excess air of 15% (Babcock and Wilcox, 1972), the actual flowrate for a 300 MW oil-fired boiler was calculated to be 590,000 acfm (actual cubic feet per minute) or 280 cubic meters per second. This flowrate was input to the model as an exit gas velocity of 15 meters per second and an inside stack diameter of 4.9 meters.

## 2.2 EMISSIONS

The boiler was modeled using emissions estimates base on a capacity factor of 80%, with an efficiency rating of 35%. A detailed description of the emissions estimates is given in Section 5.6.3 of this report. The calculation of PM-10 emissions are discussed here.

The primary interest in particulate matter centers around the respirable fraction known as PM-10, i.e., the fraction of particulate matter with an aerodynamic diameter less than 10 micrometers. PM-10 emissions were estimated from total particulate emissions according to the method described in the EPA document AP-42 (EPA, 1988). AP-42 provides a cumulative particle size distribution of particulate matter for utility boilers burning residual oil. This distribution was used together with the estimated fractional control efficiencies of a baghouse to derive the controlled cumulative mass fraction. It is estimated that eighty-one percent of the total particulate matter emissions at the outlet of the baghouse have an aerodynamic diameter less than 10 micrometers.

Controlled emissions of total particulate, PM-10, $SO_2$, CO and NOx for 1990 and 2010 are shown in Table 1 in units of lbs per 1000 barrels of residual oil and grams per second (g/s). The g/s emission estimates are based on 8,940 barrels per day of residual oil (Section 4.2.15.1 of this report).

Controlled emission rates of 1.28 grams per second (g/s) total particulate matter, 1.04 g/s PM-10, 30.9 g/s $SO_2$, 9.85 g/s CO and 39.6 g/s NOx were used in this analysis for 1990.

## 3.0 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 0.011 micrograms per cubic meter ($\mu$g/m3) occurring 1 kilometers from the plant. The highest of these concentrations for the Southwest site is 0.010 ($\mu$g/m3) occurring 3 kilometers from the plant.

The highest 24-hour and highest 1-hour average unit concentrations for 24 downwind distances are presented in the second and third columns of Table 2. The highest 24-hour average concentration at the Southeast site is 0.65 $\mu$g/m3 and the highest 1-hour average concentration is 1.6 $\mu$g/m3 both occurring 1 kilometer from the plant. For the Southwest site, the highest 24-hour average concentration is 0.76 $\mu$g/m3 and the highest 1-hour average concentration is 1.9 $\mu$g/m3 both occurring 1 kilometer from the plant.

Differences in annual average concentrations (ISCLT) between the two sites are due to different stack heights and different meteorological conditions at each site. Differences in short-term concentration between the sites are due to stack height differences only.

## 3.2 POLLUTANT CONCENTRATIONS

The maximum pollutant concentrations of total particulate, PM-10, NOx and $SO_2$ predicted to occur at 24 downwind distances from the power plant at the Southeast site for 1990 and 2010 are presented in Tables 3 and 4. The corresponding results for the Southwest site are presented in Tables 5 and 6. These concentrations were determined by multiplying the unit concentrations in Table 2 by the controlled emission rate (grams per second) in Table 1 for each of the pollutants of interest.

The highest annual average incremental concentration of PM-10 at the Southeast and Southwest sites, for 1990, is 0.012 $\mu$g/m3 and 0.011 $\mu$g/m3 respectively. The highest annual average incremental concentration of NOx for the Southeast and Southwest sites is 0.44 $\mu$g/m3 and 0.41 $\mu$g/m3. The corresponding values for $SO_2$ are 0.35 $\mu$g/m3 and 0.32 $\mu$g/m3. Lower concentrations occur during 2010, at each site, since greater pollution control device efficiencies are assumed for 2010 (Wang, 1992).

## 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 7, 8, 9 and 10 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, NO2 and $SO_2$ at both sites for 1990 and 2010. As shown in Tables 7 through 10, 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).

**Table C-1. Summary of Emissions of Primary Pollutants for the Oil Technology Power Plant**

| | Pollutant | | | | |
|---|---|---|---|---|---|
| | TSP | PM-10 | $SO_2$ | CO | Nox |
| YEAR | (lb/1000 bbts residual) | | | | |
| 1990 | 27.3 | 22.1 | 659.4 | 210 | 844.2 |
| 2010 | 10.92 | 8.8 | 329.7 | 210 | 84.4 |
| | (grams per second) | | | | |
| 1990 | 1.28 | 1.04 | 30.9 | 9.86 | 39.6 |
| 2010 | 0.51 | 0.42 | 15.5 | 9.86 | 3.96 |

PM-10 is 81% of TSP (AP-42 Baghouse)

**Table C-2. Maximum Unit Concentrations at Downwind Distances from the Oil-Fired Power Plant Stack at the Southeast Reference Site (micrograms/cubit meter).**

| Downwind Distance From Stack (km) | Maximum Unit Concentration | | |
|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT |
| 1 | 0.648 | 1.621 | 0.0112 |
| 2 | 0.475 | 1.188 | 0.0058 |
| 3 | 0.343 | 0.857 | 0.0066 |
| 4 | 0.317 | 0.792 | 0.0066 |
| 5 | 0.289 | 0.722 | 0.0062 |
| 6 | 0.252 | 0.629 | 0.0056 |
| 7 | 0.221 | 0.553 | 0.0051 |
| 8 | 0.217 | 0.542 | 0.0047 |
| 9 | 0.216 | 0.540 | 0.0044 |
| 10 | 0.209 | 0.523 | 0.0042 |
| 15 | 0.158 | 0.394 | 0.0035 |
| 20 | 0.123 | 0.307 | 0.0031 |
| 25 | 0.101 | 0.253 | 0.0028 |
| 30 | 0.086 | 0.216 | 0.0025 |
| 35 | 0.075 | 0.189 | 0.0023 |
| 40 | 0.067 | 0.168 | 0.0021 |
| 45 | 0.061 | 0.152 | 0.0019 |
| 50 | 0.055 | 0.138 | 0.0018 |
| 55 | 0.027 | 0.067 | 0.0016 |
| 60 | 0.026 | 0.064 | 0.0015 |
| 65 | 0.025 | 0.061 | 0.0014 |
| 70 | 0.023 | 0.059 | 0.0013 |
| 75 | 0.022 | 0.056 | 0.0012 |
| 80 | 0.021 | 0.054 | 0.0012 |

## Table C-2 (cont). Maximum Unit Concentrations at Downwind Distances from the Oil-Fired Power Plant Stack at the Southeast Reference Site (micrograms/cubit meter).

| Downwind Distance From Stack (km) | Maximum Unit Concentration | | |
|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg ISCLT |
| 1 | 0.7636 | 1.9090 | 0.005962 |
| 2 | 0.5244 | 1.3110 | 0.009059 |
| 3 | 0.3788 | 0.9469 | 0.010227 |
| 4 | 0.3667 | 0.9168 | 0.009011 |
| 5 | 0.3224 | 0.8060 | 0.007533 |
| 6 | 0.2786 | 0.6964 | 0.006314 |
| 7 | 0.2611 | 0.6527 | 0.005381 |
| 8 | 0.2624 | 0.6561 | 0.004672 |
| 9 | 0.2542 | 0.6354 | 0.004123 |
| 10 | 0.2412 | 0.6031 | 0.003691 |
| 15 | 0.1764 | 0.4411 | 0.002689 |
| 20 | 0.1373 | 0.3432 | 0.002368 |
| 25 | 0.1130 | 0.2824 | 0.002075 |
| 30 | 0.0964 | 0.2409 | 0.001842 |
| 35 | 0.0842 | 0.2106 | 0.001649 |
| 40 | 0.0750 | 0.1875 | 0.00149[illegible] |
| 45 | 0.0687 | 0.1718 | 0.001354 |
| 50 | 0.0674 | 0.1685 | 0.001241 |
| 55 | 0.0323 | 0.0808 | 0.001145 |
| 60 | 0.0302 | 0.0756 | 0.001064 |
| 65 | 0.0284 | 0.0710 | 0.000991 |
| 70 | 0.0268 | 0.0670 | 0.000927 |
| 75 | 0.0254 | 0.0634 | 0.000871 |
| 80 | 0.0241 | 0.0602 | 0.000822 |

1-hr • .4 = 24-hr (Simple Terrain)

### Table C-3. Maximum Pollutant Concentration (micrograms/cubit meter) at Downwind Distances from the Oil-Fire Power Plant Stack at the Clinch River Site for 1990.

| Downwind Distance From Stack (km) | Maximum Particulate Concentration | | | Maximum PM-10 Concentration | | |
|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT |
| 1 | 0.830 | 2.075 | 0.014 | 0.674 | 1.686 | 0.012 |
| 2 | 0.608 | 1.521 | 0.007 | 0.494 | 1.236 | 0.006 |
| 3 | 0.439 | 1.097 | 0.008 | 0.356 | 0.891 | 0.007 |
| 4 | 0.406 | 1.014 | 0.008 | 0.330 | 0.824 | 0.007 |
| 5 | 0.369 | 0.924 | 0.008 | 0.300 | 0.750 | 0.006 |
| 6 | 0.322 | 0.805 | 0.007 | 0.262 | 0.654 | 0.006 |
| 7 | 0.283 | 0.707 | 0.007 | 0.230 | 0.575 | 0.005 |
| 8 | 0.277 | 0.694 | 0.006 | 0.225 | 0.564 | 0.005 |
| 9 | 0.276 | 0.691 | 0.006 | 0.225 | 0.561 | 0.005 |
| 10 | 0.268 | 0.669 | 0.005 | 0.217 | 0.543 | 0.004 |
| 15 | 0.202 | 0.505 | 0.005 | 0.164 | 0.410 | 0.004 |
| 20 | 0.157 | 0.393 | 0.004 | 0.128 | 0.320 | 0.003 |
| 25 | 0.129 | 0.324 | 0.004 | 0.105 | 0.263 | 0.003 |
| 30 | 0.110 | 0.276 | 0.003 | 0.090 | 0.224 | 0.003 |
| 35 | 0.097 | 0.241 | 0.003 | 0.078 | 0.196 | 0.002 |
| 40 | 0.086 | 0.215 | 0.003 | 0.070 | 0.175 | 0.002 |
| 45 | 0.078 | 0.194 | 0.002 | 0.063 | 0.158 | 0.002 |
| 50 | 0.071 | 0.177 | 0.002 | 0.058 | 0.144 | 0.002 |
| 55 | 0.035 | 0.086 | 0.002 | 0.028 | 0.070 | 0.002 |
| 60 | 0.033 | 0.082 | 0.002 | 0.027 | 0.067 | 0.002 |
| 65 | 0.031 | 0.078 | 0.002 | 0.025 | 0.064 | 0.001 |
| 70 | 0.030 | 0.075 | 0.002 | 0.024 | 0.061 | 0.001 |
| 75 | 0.029 | 0.072 | 0.002 | 0.023 | 0.058 | 0.001 |
| 80 | 0.027 | 0.069 | 0.001 | 0.022 | 0.056 | 0.001 |

**Table C-3 (cont). Maximum Pollutant Concentration (micrograms/cubit meter) and $SO_2$ Dry Deposition (micrograms/ m2-s) at Downwind Distances from the Oil-Fire Power Plant Stack at the Clinch River Site for 1990.**

| Downwind Distance From Stack (km) | Maximum SO2 Concentration | | | | Maximum NOx Concentration | | |
|---|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | Annual SO2 Dry Deposition (microgm/m2-s) | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg ISCLT |
| 1 | 20.1 | 50.2 | 0.347 | 0.007 | 25.7 | 64.2 | 0.444 |
| 2 | 14.7 | 36.8 | 0.180 | 0.004 | 18.8 | 47.1 | 0.230 |
| 3 | 10.6 | 26.5 | 0.203 | 0.004 | 13.6 | 33.9 | 0.260 |
| 4 | 9.81 | 24.5 | 0.204 | 0.004 | 12.6 | 31.4 | 0.261 |
| 5 | 8.93 | 22.3 | 0.191 | 0.004 | 11.4 | 28.6 | 0.245 |
| 6 | 7.78 | 19.5 | 0.174 | 0.003 | 9.97 | 24.9 | 0.223 |
| 7 | 6.84 | 17.1 | 0.159 | 0.003 | 8.76 | 21.9 | 0.204 |
| 8 | 6.71 | 16.8 | 0.147 | 0.003 | 8.59 | 21.5 | 0.188 |
| 9 | 6.68 | 16.7 | 0.138 | 0.003 | 8.55 | 21.4 | 0.176 |
| 10 | 6.47 | 16.2 | 0.131 | 0.003 | 8.28 | 20.7 | 0.167 |
| 15 | 4.88 | 12.2 | 0.109 | 0.002 | 6.25 | 15.6 | 0.140 |
| 20 | 3.80 | 9.51 | 0.097 | 0.002 | 4.87 | 12.2 | 0.124 |
| 25 | 3.13 | 7.82 | 0.087 | 0.002 | 4.01 | 10.0 | 0.111 |
| 30 | 2.67 | 6.67 | 0.079 | 0.002 | 3.42 | 8.54 | 0.101 |
| 35 | 2.33 | 5.83 | 0.071 | 0.001 | 2.99 | 7.47 | 0.091 |
| 40 | 2.08 | 5.19 | 0.065 | 0.001 | 2.66 | 6.65 | 0.083 |
| 45 | 1.87 | 4.69 | 0.059 | 0.001 | 2.40 | 6.00 | 0.076 |
| 50 | 1.71 | 4.28 | 0.054 | 0.001 | 2.19 | 5.48 | 0.070 |
| 55 | 0.835 | 2.09 | 0.050 | 0.001 | 1.07 | 2.67 | 0.064 |
| 60 | 0.795 | 1.99 | 0.047 | 0.001 | 1.02 | 2.55 | 0.060 |
| 65 | 0.758 | 1.90 | 0.043 | 0.001 | 0.971 | 2.43 | 0.055 |
| 70 | 0.724 | 1.81 | 0.040 | 0.001 | 0.927 | 2.32 | 0.052 |
| 75 | 0.693 | 1.73 | 0.038 | 0.001 | 0.888 | 2.22 | 0.049 |
| 80 | 0.664 | 1.66 | 0.036 | 0.001 | 0.851 | 2.13 | 0.046 |

**Table C-4. Maximum Pollutant Concentration (micrograms/cubic Meter) at Downwind Distances from the Oil-Fired Plant Stack at the Clinch River Site for 2010.**

| Downwind Distance From Stack (km) | Maximum Particulate Concentration | | | Maximum PM-10 Concentration | | |
|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT |
| 1 | 0.331 | 0.827 | 0.006 | 0.272 | 0.681 | 0.005 |
| 2 | 0.242 | 0.606 | 0.003 | 0.200 | 0.499 | 0.002 |
| 3 | 0.175 | 0.437 | 0.003 | 0.144 | 0.360 | 0.003 |
| 4 | 0.162 | 0.404 | 0.003 | 0.133 | 0.333 | 0.003 |
| 5 | 0.147 | 0.368 | 0.003 | 0.121 | 0.303 | 0.003 |
| 6 | 0.128 | 0.321 | 0.003 | 0.106 | 0.264 | 0.002 |
| 7 | 0.113 | 0.282 | 0.003 | 0.093 | 0.232 | 0.002 |
| 8 | 0.111 | 0.276 | 0.002 | 0.091 | 0.228 | 0.002 |
| 9 | 0.110 | 0.275 | 0.002 | 0.091 | 0.227 | 0.002 |
| 10 | 0.107 | 0.266 | 0.002 | 0.088 | 0.219 | 0.002 |
| 15 | 0.080 | 0.201 | 0.002 | 0.066 | 0.166 | 0.001 |
| 20 | 0.063 | 0.157 | 0.002 | 0.052 | 0.129 | 0.001 |
| 25 | 0.052 | 0.129 | 0.001 | 0.042 | 0.106 | 0.001 |
| 30 | 0.044 | 0.110 | 0.001 | 0.036 | 0.091 | 0.001 |
| 35 | 0.038 | 0.096 | 0.001 | 0.032 | 0.079 | 0.001 |
| 40 | 0.034 | 0.086 | 0.001 | 0.028 | 0.070 | 0.001 |
| 45 | 0.031 | 0.077 | 0.001 | 0.025 | 0.064 | 0.001 |
| 50 | 0.028 | 0.071 | 0.001 | 0.023 | 0.058 | 0.001 |
| 55 | 0.014 | 0.034 | 0.001 | 0.011 | 0.028 | 0.001 |
| 60 | 0.013 | 0.033 | 0.001 | 0.011 | 0.027 | 0.001 |
| 65 | 0.012 | 0.031 | 0.001 | 0.010 | 0.026 | 0.001 |
| 70 | 0.012 | 0.030 | 0.001 | 0.010 | 0.025 | 0.001 |
| 75 | 0.011 | 0.029 | 0.001 | 0.009 | 0.024 | 0.001 |
| 80 | 0.011 | 0.027 | 0.001 | 0.009 | 0.023 | 0.000 |

**Table C-4 (cont). Maximum Pollutant Concentration (micrograms/cubit meter) and $SO_2$ Dry Deposition (micrograms/ m2-s) at Downwind Distances from the Oil-Fire Power Plant Stack at the Clinch River Site for 2010.**

| Downwind Distance From Stack (km) | Maximum SO2 Concentration | | | | Maximum NOx Concentration | | |
|---|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | Annual SO2 Dry Deposition (microgm/m2-s) | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg ISCLT |
| 1 | 10.0 | 25.1 | 0.174 | 0.003 | 2.57 | 6.42 | 0.044 |
| 2 | 7.35 | 18.4 | 0.090 | 0.002 | 1.88 | 4.70 | 0.023 |
| 3 | 5.30 | 13.3 | 0.101 | 0.002 | 1.36 | 3.39 | 0.026 |
| 4 | 4.90 | 12.3 | 0.102 | 0.002 | 1.26 | 3.14 | 0.026 |
| 5 | 4.46 | 11.2 | 0.095 | 0.002 | 1.14 | 2.86 | 0.024 |
| 6 | 3.89 | 9.73 | 0.087 | 0.002 | 1.00 | 2.49 | 0.022 |
| 7 | 3.42 | 8.55 | 0.080 | 0.002 | 0.875 | 2.19 | 0.020 |
| 8 | 3.35 | 8.38 | 0.073 | 0.001 | 0.858 | 2.15 | 0.019 |
| 9 | 3.34 | 8.35 | 0.069 | 0.001 | 0.855 | 2.14 | 0.018 |
| 10 | 3.23 | 8.08 | 0.065 | 0.001 | 0.828 | 2.07 | 0.017 |
| 15 | 2.44 | 6.10 | 0.055 | 0.001 | 0.625 | 1.56 | 0.014 |
| 20 | 1.90 | 4.76 | 0.048 | 0.001 | 0.487 | 1.22 | 0.012 |
| 25 | 1.56 | 3.91 | 0.044 | 0.001 | 0.400 | 1.00 | 0.011 |
| 30 | 1.33 | 3.34 | 0.039 | 0.001 | 0.342 | 0.854 | 0.010 |
| 35 | 1.17 | 2.92 | 0.036 | 0.001 | 0.299 | 0.746 | 0.009 |
| 40 | 1.04 | 2.60 | 0.032 | 0.001 | 0.266 | 0.664 | 0.008 |
| 45 | 0.937 | 2.34 | 0.030 | 0.001 | 0.240 | 0.600 | 0.008 |
| 50 | 0.856 | 2.14 | 0.027 | 0.001 | 0.219 | 0.548 | 0.007 |
| 55 | 0.418 | 1.04 | 0.025 | 0.001 | 0.107 | 0.267 | 0.006 |
| 60 | 0.398 | 0.99 | 0.023 | 0.000 | 0.102 | 0.254 | 0.006 |
| 65 | 0.379 | 0.95 | 0.022 | 0.000 | 0.097 | 0.243 | 0.006 |
| 70 | 0.362 | 0.91 | 0.020 | 0.000 | 0.093 | 0.232 | 0.005 |
| 75 | 0.347 | 0.87 | 0.019 | 0.000 | 0.089 | 0.222 | 0.005 |
| 80 | 0.332 | 0.83 | 0.018 | 0.000 | 0.085 | 0.213 | 0.005 |

### Table C-5. Maximum Pollutant Concentration (micrograms/cubic Meter) at Downwind Distances from the Oil-Fired Plant Stack at the Farmington Site for 1990.

| Downwind Distance From Stack (km) | Maximum Particulate Concentration | | | Maximum PM-10 Concentration | | |
|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT |
| 1 | 0.977 | 2.444 | 0.008 | 0.794 | 1.985 | 0.006 |
| 2 | 0.671 | 1.678 | 0.012 | 0.545 | 1.363 | 0.009 |
| 3 | 0.485 | 1.212 | 0.013 | 0.394 | 0.985 | 0.011 |
| 4 | 0.469 | 1.174 | 0.012 | 0.381 | 0.953 | 0.009 |
| 5 | 0.413 | 1.032 | 0.010 | 0.335 | 0.838 | 0.008 |
| 6 | 0.357 | 0.891 | 0.008 | 0.290 | 0.724 | 0.007 |
| 7 | 0.334 | 0.835 | 0.007 | 0.272 | 0.679 | 0.006 |
| 8 | 0.336 | 0.840 | 0.006 | 0.273 | 0.682 | 0.005 |
| 9 | 0.325 | 0.813 | 0.005 | 0.264 | 0.661 | 0.004 |
| 10 | 0.309 | 0.772 | 0.005 | 0.251 | 0.627 | 0.004 |
| 15 | 0.226 | 0.565 | 0.003 | 0.183 | 0.459 | 0.003 |
| 20 | 0.176 | 0.439 | 0.003 | 0.143 | 0.357 | 0.002 |
| 25 | 0.145 | 0.361 | 0.003 | 0.117 | 0.294 | 0.002 |
| 30 | 0.123 | 0.308 | 0.002 | 0.100 | 0.251 | 0.002 |
| 35 | 0.108 | 0.270 | 0.002 | 0.088 | 0.219 | 0.002 |
| 40 | 0.096 | 0.240 | 0.002 | 0.078 | 0.195 | 0.002 |
| 45 | 0.088 | 0.220 | 0.002 | 0.071 | 0.179 | 0.001 |
| 50 | 0.086 | 0.216 | 0.002 | 0.070 | 0.175 | 0.001 |
| 55 | 0.041 | 0.103 | 0.001 | 0.034 | 0.084 | 0.001 |
| 60 | 0.039 | 0.097 | 0.001 | 0.031 | 0.079 | 0.001 |
| 65 | 0.036 | 0.091 | 0.001 | 0.030 | 0.074 | 0.001 |
| 70 | 0.034 | 0.086 | 0.001 | 0.028 | 0.070 | 0.001 |
| 75 | 0.032 | 0.081 | 0.001 | 0.026 | 0.066 | 0.001 |
| 80 | 0.031 | 0.077 | 0.001 | 0.025 | 0.063 | 0.001 |

## Table C-5 (cont). Maximum Pollutant Concentration (micrograms/cubit meter) and $SO_2$ Dry Deposition (micrograms/ m2-s) at Downwind Distances from the Oil-Fire Power Plant Stack at the Farmington Site for 1990.

| Downwind Distance From Stack (km) | Maximum SO2 Concentration | | | Annual SO2 Dry Deposition (microgm/m2-s) | Maximum NOx Concentration | | |
|---|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Av ISCLT |
| 1 | 23.6 | 59.1 | 0.184 | 0.004 | 30.3 | 75.6 | 0.236 |
| 2 | 16.2 | 40.6 | 0.280 | 0.006 | 20.8 | 51.9 | 0.359 |
| 3 | 11.7 | 29.3 | 0.316 | 0.006 | 15.0 | 37.5 | 0.405 |
| 4 | 11.3 | 28.4 | 0.279 | 0.006 | 14.5 | 36.3 | 0.357 |
| 5 | 9.98 | 24.9 | 0.233 | 0.005 | 12.8 | 31.9 | 0.298 |
| 6 | 8.62 | 21.5 | 0.195 | 0.004 | 11.0 | 27.6 | 0.250 |
| 7 | 8.08 | 20.2 | 0.166 | 0.003 | 10.3 | 25.9 | 0.213 |
| 8 | 8.12 | 20.3 | 0.145 | 0.003 | 10.4 | 26.0 | 0.185 |
| 9 | 7.86 | 19.7 | 0.128 | 0.003 | 10.1 | 25.2 | 0.163 |
| 10 | 7.46 | 18.7 | 0.114 | 0.002 | 9.56 | 23.9 | 0.146 |
| 15 | 5.46 | 13.6 | 0.083 | 0.002 | 6.99 | 17.5 | 0.107 |
| 20 | 4.25 | 10.6 | 0.073 | 0.001 | 5.44 | 13.6 | 0.094 |
| 25 | 3.49 | 8.74 | 0.064 | 0.001 | 4.48 | 11.2 | 0.082 |
| 30 | 2.98 | 7.45 | 0.057 | 0.001 | 3.82 | 9.54 | 0.073 |
| 35 | 2.61 | 6.52 | 0.051 | 0.001 | 3.34 | 8.34 | 0.065 |
| 40 | 2.32 | 5.80 | 0.046 | 0.001 | 2.97 | 7.43 | 0.059 |
| 45 | 2.13 | 5.32 | 0.042 | 0.001 | 2.72 | 6.81 | 0.054 |
| 50 | 2.09 | 5.21 | 0.038 | 0.001 | 2.67 | 6.68 | 0.049 |
| 55 | 1.00 | 2.50 | 0.035 | 0.001 | 1.28 | 3.20 | 0.045 |
| 60 | 0.936 | 2.34 | 0.033 | 0.001 | 1.20 | 2.99 | 0.042 |
| 65 | 0.879 | 2.20 | 0.031 | 0.001 | 1.125 | 2.81 | 0.039 |
| 70 | 0.829 | 2.07 | 0.029 | 0.001 | 1.061 | 2.65 | 0.037 |
| 75 | 0.785 | 1.96 | 0.027 | 0.001 | 1.005 | 2.51 | 0.035 |
| 80 | 0.745 | 1.86 | 0.025 | 0.001 | 0.954 | 2.38 | 0.033 |

Annual Dry Deposition = Annual Concentration * .02 meters/second

**Table C-6. Maximum Pollutant Concentration (micrograms/cubic Meter) at Downwind Distances from the Oil-Fired Plant Stack at the Farmington Site for 2010.**

| Downwind Distance From Stack (km) | Maximum Particulate Concentration | | | Maximum PM-10 Concentration | | |
|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Av ISCLT |
| 1 | 0.389 | 0.974 | 0.003 | 0.321 | 0.802 | 0.003 |
| 2 | 0.267 | 0.669 | 0.005 | 0.220 | 0.551 | 0.004 |
| 3 | 0.193 | 0.483 | 0.005 | 0.159 | 0.398 | 0.004 |
| 4 | 0.187 | 0.468 | 0.005 | 0.154 | 0.385 | 0.004 |
| 5 | 0.164 | 0.411 | 0.004 | 0.135 | 0.339 | 0.003 |
| 6 | 0.142 | 0.355 | 0.003 | 0.117 | 0.292 | 0.003 |
| 7 | 0.133 | 0.333 | 0.003 | 0.110 | 0.274 | 0.002 |
| 8 | 0.134 | 0.335 | 0.002 | 0.110 | 0.276 | 0.002 |
| 9 | 0.130 | 0.324 | 0.002 | 0.107 | 0.267 | 0.002 |
| 10 | 0.123 | 0.308 | 0.002 | 0.101 | 0.253 | 0.002 |
| 15 | 0.090 | 0.225 | 0.001 | 0.074 | 0.185 | 0.001 |
| 20 | 0.070 | 0.175 | 0.001 | 0.058 | 0.144 | 0.001 |
| 25 | 0.058 | 0.144 | 0.001 | 0.047 | 0.119 | 0.001 |
| 30 | 0.049 | 0.123 | 0.001 | 0.040 | 0.101 | 0.001 |
| 35 | 0.043 | 0.107 | 0.001 | 0.035 | 0.088 | 0.001 |
| 40 | 0.038 | 0.096 | 0.001 | 0.032 | 0.079 | 0.001 |
| 45 | 0.035 | 0.088 | 0.001 | 0.029 | 0.072 | 0.001 |
| 50 | 0.034 | 0.086 | 0.001 | 0.028 | 0.071 | 0.001 |
| 55 | 0.016 | 0.041 | 0.001 | 0.014 | 0.034 | 0.000 |
| 60 | 0.015 | 0.039 | 0.001 | 0.013 | 0.032 | 0.000 |
| 65 | 0.014 | 0.036 | 0.001 | 0.012 | 0.030 | 0.000 |
| 70 | 0.014 | 0.034 | 0.000 | 0.011 | 0.028 | 0.000 |
| 75 | 0.013 | 0.032 | 0.000 | 0.011 | 0.027 | 0.000 |
| 80 | 0.012 | 0.031 | 0.000 | 0.010 | 0.025 | 0.000 |

**Table C-6 (cont). Maximum Pollutant Concentration (micrograms/cubit meter) and $SO_2$ Dry Deposition (micrograms/ m2-s) at Downwind Distances from the Oil-Fire Power Plant Stack at the Farmington Site for 2010.**

| Downwind Distance From Stack (km) | Maximum SO2 Concentration | | | Annual SO2 Dry Deposition (microgm/m2-s) | Maximum NOx Concentration | | |
|---|---|---|---|---|---|---|---|
| | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT | | 24-hr Avg. SCREEN | 1-hr Avg. SCREEN | Annual Avg. ISCLT |
| 1 | 11.8 | 29.5 | 0.092 | 0.004 | 3.02 | 7.56 | 0.024 |
| 2 | 8.11 | 20.3 | 0.140 | 0.006 | 2.08 | 5.19 | 0.036 |
| 3 | 5.86 | 14.6 | 0.158 | 0.006 | 1.50 | 3.75 | 0.040 |
| 4 | 5.67 | 14.2 | 0.139 | 0.006 | 1.45 | 3.63 | 0.036 |
| 5 | 4.99 | 12.5 | 0.117 | 0.005 | 1.28 | 3.19 | 0.030 |
| 6 | 4.31 | 10.8 | 0.098 | 0.004 | 1.10 | 2.76 | 0.025 |
| 7 | 4.04 | 10.1 | 0.083 | 0.003 | 1.03 | 2.58 | 0.021 |
| 8 | 4.06 | 10.1 | 0.072 | 0.003 | 1.04 | 2.60 | 0.019 |
| 9 | 3.93 | 9.83 | 0.064 | 0.003 | 1.01 | 2.52 | 0.016 |
| 10 | 3.73 | 9.33 | 0.057 | 0.002 | 0.955 | 2.39 | 0.015 |
| 15 | 2.73 | 6.82 | 0.042 | 0.002 | 0.699 | 1.75 | 0.011 |
| 20 | 2.12 | 5.31 | 0.037 | 0.001 | 0.544 | 1.36 | 0.009 |
| 25 | 1.75 | 4.37 | 0.032 | 0.001 | 0.447 | 1.12 | 0.008 |
| 30 | 1.49 | 3.73 | 0.028 | 0.001 | 0.382 | 0.954 | 0.007 |
| 35 | 1.30 | 3.26 | 0.026 | 0.001 | 0.334 | 0.834 | 0.007 |
| 40 | 1.16 | 2.90 | 0.023 | 0.001 | 0.297 | 0.743 | 0.006 |
| 45 | 1.06 | 2.66 | 0.021 | 0.001 | 0.272 | 0.680 | 0.005 |
| 50 | 1.04 | 2.61 | 0.019 | 0.001 | 0.267 | 0.667 | 0.005 |
| 55 | 0.500 | 1.25 | 0.018 | 0.001 | 0.128 | 0.320 | 0.005 |
| 60 | 0.468 | 1.17 | 0.016 | 0.001 | 0.120 | 0.299 | 0.004 |
| 65 | 0.439 | 1.10 | 0.015 | 0.001 | 0.112 | 0.281 | 0.004 |
| 70 | 0.414 | 1.04 | 0.014 | 0.001 | 0.106 | 0.265 | 0.004 |
| 75 | 0.392 | 0.981 | 0.013 | 0.001 | 0.100 | 0.251 | 0.003 |
| 80 | 0.372 | 0.931 | 0.013 | 0.001 | 0.095 | 0.238 | 0.003 |

Annual Dry Deposition = Annual Concentration * .02 meters/second

**Table C-7. Summary of 1990 Modeling Results and Monitoring Data for an Oil-Fired Boiler Located at the Southeast Reference Site (micrograms per cubin meter).**

| | Particulate | | PM-10 | | $NO_x$ | $SO_2$ | |
|---|---|---|---|---|---|---|---|
| | 24-hour | Annual | 24-hour | Annual | Annual | 24-hour | Annual |
| Maximum Incremental Impact of the Facility | 0.83 | 0.014 | 0.67 | 0.012 | 0.44 | 20 | 0.35 |
| Background Concentration* | 108 | 47 | 71 | 37 | 23 | 78 | 25 |
| Total Concentration | 109 | 47 | 72 | 37 | 23 | 96 | 25 |
| Primary NAAQS** | None | None | 150 | 50 | 100 | 365 | 80 |

* From 1990 EPA AIRS database McMinn Co. TN monitoring station (Site ID 47-107-0101 ); 2nd highest24-hour average and annual mean

** For regulatory purposes the hightes second receptor concentration is added to the gaseline concentration and compared to the National Ambient Air Quality Standard (NAAQS).

**Table C-8. Summary of 1990 Modeling Results and Monitoring Data for an Oil-Fired Boiler Located at the Southeast Reference Site (micrograms per cubin meter).**

| | Particulate | | PM-10 | | $NO_x$ | $SO_2$ | |
|---|---|---|---|---|---|---|---|
| | 24-hour | Annual | 24-hour | Annual | Annual | 24-hour | Annual |
| Maximum Incremental Impact of the Facility | 0.33 | 0.006 | 0.27 | 0.005 | 0.04 | 10 | 0.17 |
| Background Concentration* | 108 | 47 | 71 | 37 | 23 | 78 | 25 |
| Total Concentration | 108 | 47 | 71 | 37 | 23 | 86 | 25 |
| Primary NAAQS** | None | None | 150 | 50 | 100 | 365 | 80 |

* From 1990 EPA AIRS database McMinn Co. TN monitoring station (Site ID 47-107-0101 ); 2nd highest24-hour average and annual mean

** For regulatory purposes the hightes second receptor concentration is added to the gaseline concentration and compared to the National Ambient Air Quality Standard (NAAQS).

**Table C-9. Summary of 2010 Modeling Results and Monitoring Data for an Oil-Fired Boiler Located at the Southeast Reference Site (micrograms per cubin meter).**

| | Particulate | | PM-10 | | $NO_x$ | $SO_2$ | |
|---|---|---|---|---|---|---|---|
| | 24-hour | Annual | 24-hour | Annual | Annual | 24-hour | Annual |
| Maximum Incremental Impact of the Facility | 0.98 | 0.013 | 0.79 | 0.011 | 0.41 | 24 | 0.32 |
| Background Concentration* | 66 | 427 | 64 | 24 | 15 | 93 | 14 |
| Total Concentration | 67 | 42 | 65 | 24 | 15 | 117 | 14 |
| Primary NAAQS** | None | None | 150 | 50 | 100 | 365 | 80 |

* From 1990 EPA AIRS database McMinn Co. TN monitoring station (Site ID 47-107-0101 ); 2nd highest24-hour average and annual mean

** For regulatory purposes the hightes second receptor concentration is added to the gaseline concentration and compared to the National Ambient Air Quality Standard (NAAQS).

? Indicates that the mean does not satisfy AIRS summary criteria.

**Table C-10. Summary of 2010 Modeling Results and Monitoring Data for an Oil-Fired Boiler Located at the Southwest Reference Site (micrograms per cubin meter).**

| | Particulate | | PM-10 | | $NO_x$ | $SO_2$ | |
|---|---|---|---|---|---|---|---|
| | 24-hour | Annual | 24-hour | Annual | Annual | 24-hour | Annual |
| Maximum Incremental Impact of the Facility | 0.39 | 0.005 | 0.32 | 0.004 | 0.04 | 11.6 | 0.16 |
| Background Concentration* | 108 | 47 | 71 | 37 | 23 | 76 | 25 |
| Total Concentration | 108 | 47 | 71 | 37 | 23 | 86 | 25 |
| Primary NAAQS** | None | None | 150 | 50 | 100 | 365 | 80 |

* From 1990 EPA AIRS database McMinn Co. TN monitoring station (Site ID 47-107-0101 ); 2nd highest24-hour average and annual mean

** For regulatory purposes the hightes second receptor concentration is added to the gaseline concentration and compared to the National Ambient Air Quality Standard (NAAQS).

? Indicates that the mean does not satisfy AIRS summary criteria.

# APPENDIX D
# Ecological Impacts

## 1. INTRODUCTION

The purpose of this appendix is to summarize the approach used to characterize the ecological effects of the oil 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 types of impacts for all phases of the oil fuel cycle, and identifies which of those are considered priority impacts.

## 2. DEFINITIONS OF IMPACT CATEGORIES

This section defines, for fuel technologies in general, 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). Resource categories affected by the procurement, processing, transport, and use of fuels for electric power generation can be characterized, for convenience, according to whether they relate to (1) natural biological systems, (2) managed biological systems, and (3) nonbiological environmental conditions.

The following is a general discussion of some of the resource categories that should be considered in evaluating the potential impacts of any fuel cycle used in electric power generation (i.e., coal, nuclear, biomass, etc.). Not all of these categories apply to the oil fuel cycle. Specific information on the oil fuel cycle is discussed in Sections 3-7.

### 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 Resource Categories and Potential Impacts for Fuel Cycle Technologies**[a]

| Resource Categories | Impact Pathways | Definition |
|---|---|---|
| | ***Natural Biological Systems:*** | |
| Biodiversity | Changes in air, water, soil quality; habitat alteration | Impacts on plants and animals; changes in species composition and community structure |
| Commercial fishing | Changes in water quality; habitat modification | Changes in production or quality of fishery products |
| Recreational fishing | Changes in water quality and flow; habitat alteration | Changes in opportunities to fish or rates of catch |
| Hunting | Habitat/landscape alteration | Changes in opportunities to hunt or rates of harvest |
| Timber harvesting | Altered land use; changes in soil quality; direct effects of emissions on trees | Changes in forest yield |
| Recreational land and water use | Habitat/landscape alteration; changes in air/water quality; changes in visibility | Changes in opportunities for touring, hiking, swimming, etc. |
| | ***Managed Biological Systems:*** | |
| Crops and suburban landscape | Altered land use or quality; deposition of emissions on or uptake by plants; changes in quality of soil and irrigation water | Changes in crop yield, land values |
| Livestock | Altered land use; emission deposition on plants; soil contamination or enrichment | Changes in productivity, or quality of products |
| | ***Nonbiological Environmental Conditions:*** | |
| Buildings and materials | Wet and dry deposition of emissions | Weathering of exposed metal or stone |
| Land | Altered land use due to development, impoundment, or emission releases | Changes in land values; asthetics; threats to archeological and historic sites |
| Water | Runoff; spills; atmospheric deposition | Changes in availablity, clarity, taste, potability, and aesthetics |
| Air | Dust or haze; odors; noise | Changes in visibility and aesthetics |

[a] For impacts specific to the oil fuel cycle see Sections 3-7.

### 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 oil-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, for example, 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. Oil spills or runoff in marine or freshwater systems may temporarily degrade habitat area and displace threatened and endangered aquatic species.

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. 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 substances which may 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 oil drilling activities and associated navigation activities needed to support offshore development have impacted coastal wetlands.

Assessment Issues - At the present time the quantification of impacts to natural systems is difficult because of a lack of exposure/response functions. However, our approach has been to carry an analysis through to its current limit to demonstrate the extent of the problem, and to show what can currently be achieved.

From a biological perspective there are two important issues to understand concerning assessment and valuation of impacts to biodiversity and natural biological systems.

- The first is long-term biological sustainability. This issue goes beyond the concept that nature conservation should protect life on the planet as it is, to address the protection of life in the future. It embraces protection of habitat and inter/intra-species genetic diversity. These factors are likely to be extremely important in the near future as ecosystems will need to be able to adapt in response to the anticipated effects of global climate change.

- The second issue is the generally accepted paradigm that ecosystems have a damage threshold. Under what may be considered the normal range of conditions, ecosystems are resilient and can cope with stress. However, should that stress exceed a threshold they are liable to crash or not be able to maintain a desired/acceptable condition. The threshold may be reached by the cumulative stress of several activities of the same or different kinds.

Marginal assessment of many impacts such as the effects of ozone on crop yield involves the application of a smooth dose-response function similar to those shown in Figures D-1 (a) and D-1 (b). For such situations estimation of incremental damages is reasonably straightforward and data are usually available at a suitable level of accuracy. In cases where a damage threshold exists analysis

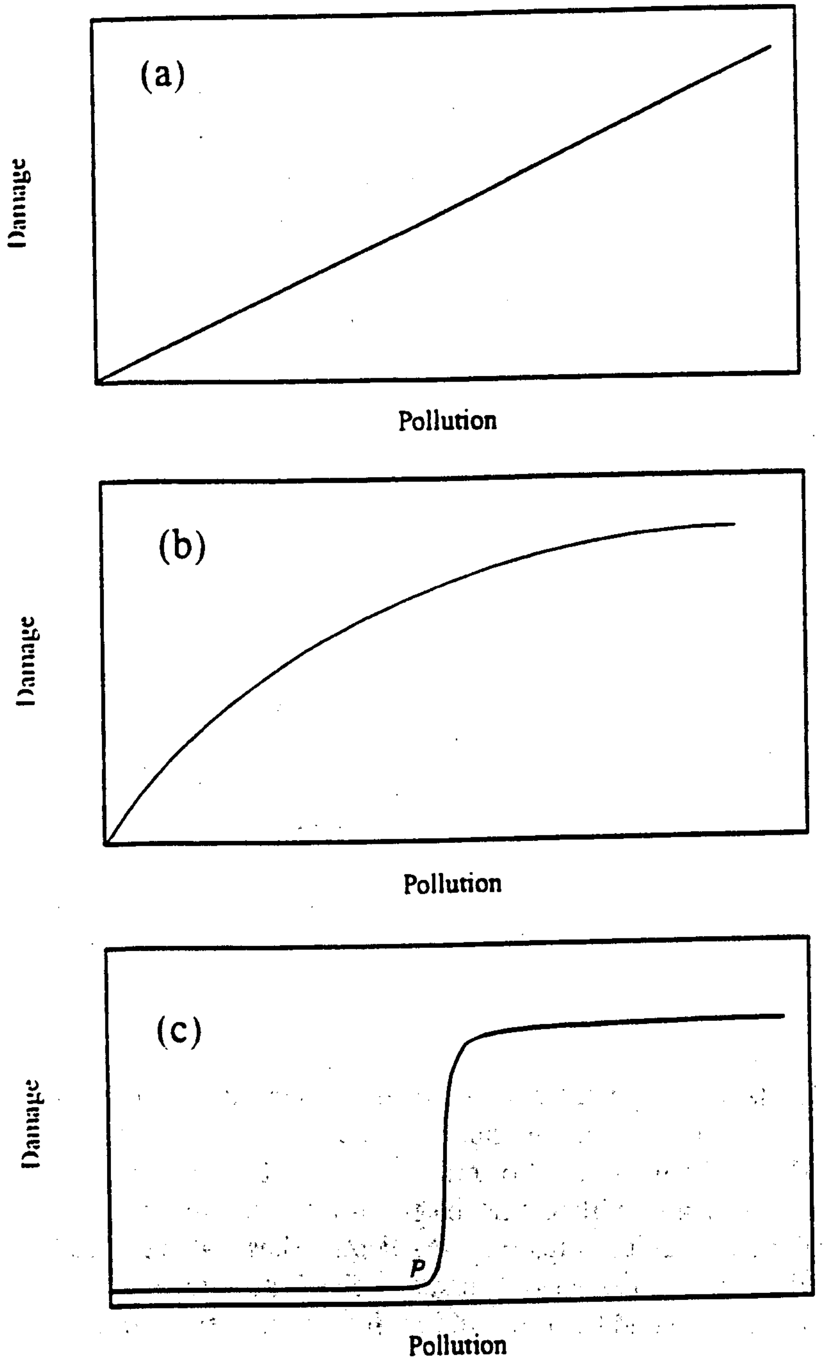

Figure D-1. Relationship between damage and pollution. Marginal assessment of cases (a) and (b) is reasonably straightforward. However, the discontinuity in case (c) complicates analysis. A large increase in damage is associated with the small increment in pollution at point P that raises deposition above a critical load. Note that these figures have been idealized for illustrative purposes.

is more difficult, particularly when attempting to assess the impacts of an incremental power station. At the threshold a slight increase in pollution will cause a large increase in damage [Figure D-1 (c)]. At background levels higher or lower than the threshold a small increase in deposition such as that from a single power station, is likely to have a negligible impact. Precise identification of sites pushed beyond the threshold is not possible at this time because baseline environmental data and models are not available at the required level of accuracy. Estimation of the number of sites concerned would be possible provided that some assumption was made about the distribution of numbers of habitats relative to the critical load or threshold condition.

Another factor involved in the analysis of impacts to biodiversity using a critical loads/condition approach is the fact that estimated impacts are heavily dependent on the future emissions or condition scenario chosen. Figure D-2 (which has been idealized for the purposes of illustration) shows the effect of introducing an incremental power station on ecosystems that differ in existing atmospheric deposition relative to their critical load. Under a constant emissions scenario the marginal impacts approach would only be of interest for the second case (b), in which the incremental deposition to the target ecosystem is sufficient to increase total deposition beyond the critical load. Under the constant emissions scenario there are no marginal damages associated with case (c); incremental deposition may increase the rate of degration at such sites but will have little or no additional effect on long-term ecosystem sustainability.

The constant future emissions scenario is known to be unrealistic. Governments of most industralized nations are now committed to reducing many of the emissions that affect biodiversity and other types of receptors. Accordingly, deposition levels at many sites will fall below critical loads in the future. The marginal effect of incremental emissions will be that some sites remain in excess of critical loads and the recovery of others that have not been degraded beyond the limit of their sustainability will be delayed (Figure D-3). Accordingly, within the framework of this project it is appropriate to identify sites that are already in excess of critical loads or in an unacceptable condition in addition to consideration of any that may be pushed beyond the threshold by incremental emissions or change.

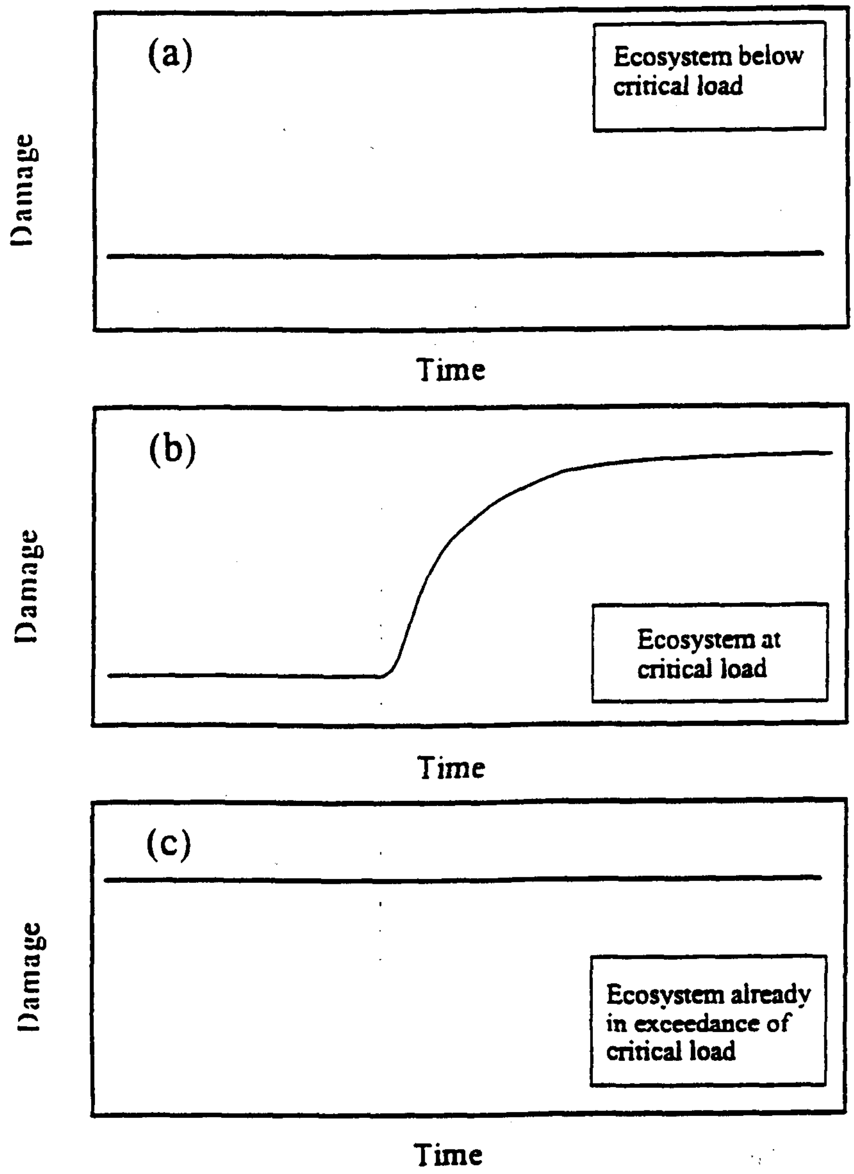

Figure D-2. Theoretical effect of the introduction of an incremental power plant (shown by the vertical dashed line) on ecosystems which differ in existing deposition relative to their critical load. This example is based on a scenario under which future emissions do not otherwise change. The ecosytem represented by case (a) is well below critical load, and the small increment from the reference power plant has no effect on sustainability. In case (b) the baseline for the ecosystem is at the critical load, and damage increases greatly in response to the small increase in deposition caused by the incremental power plant. In case (c) critical loads are already exceeded. The ecosystem is already experiencing damage and will continue to do so until it is completely degraded. Provided that future emissions do not change, marginal damages will only be associated with case (b). It should be noted that these diagrams have been simplfied for illustrative purposes.

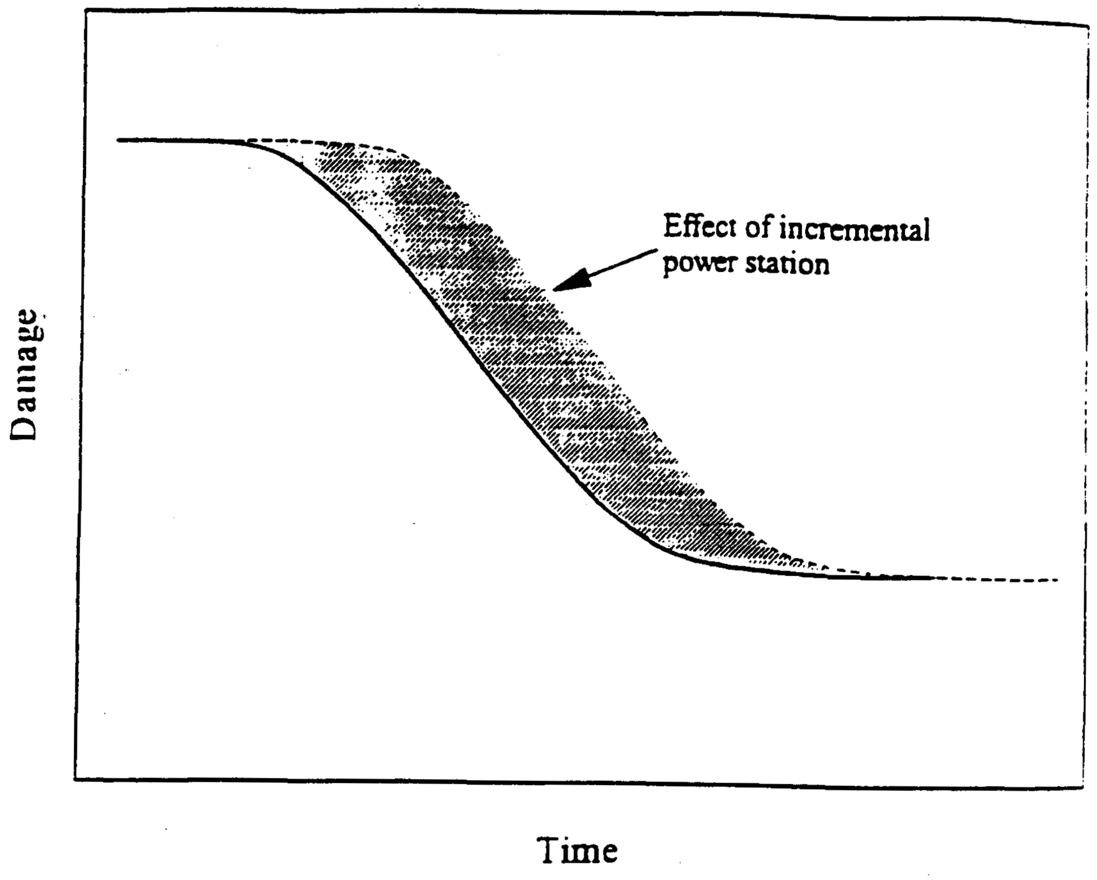

**Figure D-3.** Recovery of ecosystems following reduction of pollutant deposition to below critical loads/levels. Recovery is shown both with (solid line) and without (dashed line) the incremental power station. The marginal damage is that associated with the delay in recovery, shown by the shaded area between the two curves. In theory this could simply relate to temporary effects and at time *t* the ecosystem would recover to its original state. It is, however, likely that there would be some residual damage, the level of which could also be affected by emissions from the reference power station. Note that some ecosystems will have lost the ability to recover, at least within the forseeable future.

### 2.1.2 Commercially Valuable Natural Resources

Commercially valuable natural resources such as fisheries and natural stands of timber can be affected in varying degrees depending on the particular fuel cycle and energy technology utilized. Fisheries resources can be affected by habitat alteration or changes in water quality. For example, dredging and channelization of estuaries and construction of oil rigs may affect nursery areas for marine fish and shellfish. Water quality can be affected by spills, surface runoff, and atmospheric deposition. Water quality parameters of importance in fisheries are temperature, pH, dissolved oxygen, suspended sediments, plant nutrients (phosphates and nitrates), and toxic substances. Emissions of contaminants may 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 tissue accumulation of chemicals at levels above regulatory standards. Conversely, emissions of limited amounts of nutrients may increase levels of primary productivity which may be beneficial in some instances. Alterations in habitat may also have benefical consequences, as in the case of offshore oil platforms which provide hard substrate for benthic organisms and function as fish attractors.

Commercial fishing in the Gulf of Mexico is an important economic component of the United States. Economically-important species are menhaden, shrimp, oysters, blue crabs, 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. Conversely, under some conditions, certain emissions may represent sources of nutrients which could increase tree productivity.

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), Perchidae (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 MANAGED BIOLOGICAL SYSTEMS

### 2.2.1 Agricultural, Silvicultural and Horticultural Industries

Different fuel cycles and energy technologies may affect agricultural, silvicultural, and horticultural industries depending on changes in land use patterns and on the release of atmospheric emissions which may affect plant growth and crop yield. Some air emissions may function as plant nutrients, while others (or secondarily derived atmospheric products such as ozone) may adversely affect plant growth.

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 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

Livestock includes animals and poultry raised for meat or dairy products as well as animals raised for other commercial purposes such as show horses. Fuel cycle technologies may impact these industries through changes in land use patterns (i.e., decrease in land for pasture), through deposition of air emissions on plant surfaces followed by grazing, or through water emissions that may affect the quality of the animal's drinking water. Ambient air pollution levels in rural areas are usually far below levels that could cause direct effects on animals, and no data demonstrating such 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 site is used as pasture and about 19,480 acres for hay production. Vegetation at the southwestern site is used for grazing and browsing by domestic livestock and wildlife.

## 2.3 NONBIOLOGICAL ENVIRONMENTAL CONDITIONS

Included in this category are potential impacts on man-made structures, valued historic and archeological sites, and general changes in environmental aesthetics.

### 2.3.1 Buildings, Roads, and Materials

Air emissions (primarily $NO_x$ and $SO_2$) generated at different points in a fuel cycle, and the resulting formation of acidic compounds in the atmosphere, can have potential impacts in terms of enhanced weathering of exposed metal and stone. Acid deposition is generally identified as a regional impact caused by multiple sources, both mobile and stationary. The impacts of a specific point source such as a power plant are difficult to delineate.

Vehicles transporting crude oil to the refinery sites or residual oil to the power plants may increase rates of deterioration of road surfaces. Impacts on roads would be dependent on the size of the trucks utilized, the number of trips made, and on the mileage driven.

### 2.3.2 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 archaeological and historic 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.

### 2.3.3 Asthetics

Of concern in the development of any fuel cycle technology is the possibility of actual or perceived alterations in environmental asthetics through changes in the form, line, color, and texture of the landscape or seascape. Changes in air clarity (due to moisture content, hydrocarbons, or particulate matter) will affect perceptions of landscape elements and distances involved. The sensing of noxious odors from stacks, motor vehicles or transport vessels, changes in water clarity, taste and potability, the addition of process or wastewater effluents to local waters, and changes in noise due to machinery and vehicles, are some of the elements which can alter asthetic perceptions. Water availability can also be affected by various stages in a fuel cycle, and can be a major issue in areas where water resources are limited.

# 3. OVERVIEW OF ENVIRONMENTAL IMPACTS OF THE OIL FUEL CYCLE

Oil drilling, crude oil refining, energy generation from oil, and transportation and storage of crude and refined oil can have a variety of impacts on aquatic and terrestrial resources. Principal concerns have historically included landscape changes from drilling rigs and the impacts of oil spills on aquatic and terrestrial habitats. Large amounts of wastes and wastewaters associated with oil extraction and refining must be disposed of in an ecologically acceptable manner. More recently, regional and global effects of atmospheric pollutants: acid deposition, $CO_2$ release, and heavy metals have become major ecological concerns.

## 3.1 OIL DRILLING

The crude oil supplied to the Texas refinery would be produced onshore in southeast Texas in 1990 and offshore in the Gulf of Mexico in 2010; crude oil for the northwest New Mexico refinery would be produced onshore in southeast New Mexico in both 1990 and 2010.

### 3.1.1 Land-Based Drilling

The three major wastes from oil drilling and extraction are "produced" water (water associated with the oil or gas reservoir), drilling fluids or muds, and drill cuttings. The constituents of these three wastes vary from well to well, geographically, and over time. The primary pollution problem from onshore oil production is the disposal of produced water. Produced water and drilling wastes can enter surface waters or leach into groundwater which 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). The construction of roads and canal dredging can also affect water quality. Spills and leaks of oil or wastes can enter the surface and groundwater systems. Noise associated with drilling and production operations is generally a local problem.

Onsite treatment of drilling wastes includes evaporation in surface pits or ponds, underground injection, or treatment and discharge to surface waters. Following evaporation, solid wastes are disposed of in landfills or by landspread, roadspread, or pit burial (See sections 4 and 5 of this document for further details on on-site drilling waste disposal. See Appendix A for U. S. and state regulations on drilling waste disposal). Reserve pits (one per well) are used to accumulate, store (prior to recycling), and dispose of spent drilling fluids (referred to as muds), 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).

### 3.1.1.1 Produced Water

Produced water is treated by gravity separators, gas flotation cells, and/or stored in retention ponds to separate the oil and water. Following treatment, onshore produced water is disposed of by release to surface waters (in coastal areas), underground injection, or evaporation in surface ponds or pits. Injection of produced water into underground pits is extensively practiced by the petroleum industry. In some states such as Texas, oil producers operating near the Gulf Coast are allowed to discharge produced water as well as other drilling-associated wastes into tidally affected surface streams. Produced waters contain elevated concentrations of certain petroleum hydrocarbons, particularly the lighter aromatics, e.g., benzene through naphthalene, which are more acutely toxic than the heavier hydrocarbons. In addition, produced water may contain additives such as biocides and detergents and have a very high biological oxygen demand (BOD) level.

Concentrations of constituents of produced water effluents for 30 oil and gas platforms in the Gulf of Mexico were analyzed (U.S. EPA 1991). Limits for constituents of offshore produced water were set based on the average values (Table 5.1-5, Section 5). The U.S. EPA (1987) has also set limits for effluent concentrations of onshore produced water (Table 5.1-6, Section 5). Only arsenic, benzene, boron, sodium, chloride, and mobile ions are regulated.

Several states, such as Wyoming, allow the direct discharge of untreated produced water that is low in chlorides into dry bed streams or surface streams. Chronic discharge of low-levels of pollutants may be harmful to the receiving stream biota. At the Dallas oil field in central Wyoming, water produced with oil is separated and discharged at the rate of about 20,000 barrels per day into Little Popo Agie River, a recreational trout-fishing stream (Woodward and Riley 1983). The river flow ranges from 20 to 70 cu ft per second. The concentration of total hydrocarbons in the discharge was measured at 5.6 mg/L and resulted in concentrations of 46 to 85 $\mu$g/L within 1.4 km downstream. Concentrations in the sediments ranged from 979 to 2,515 mg/kg and were primarily from saturated hydrocarbons ($C_{12}$ to $C_{28}$). Naphthalenes were found in the stream water but not in sediments, and zinc was elevated in the sediments. Species diversity of macrobenthos, as measured by the Shannon-Weaver diversity index, was reduced below the discharge. Plecoptera and Trichoptera were almost completely eliminated while Diptera increased. Changes in the macrobenthos communities could threaten the fishery resource.

In laboratory studies, soluble oil components at concentrations less than 100 μg/L were detrimental to cutthroat trout (*Oncorhynchus clarki*) (Woodward et al. 1981, Woodward and Riley 1983). Maximum acceptable concentrations of oil-in-water were between 24 and 39 μg/L. Water samples collected from Salt Creek, Wyoming, which receives produced water effluents form the Salt Creek oil field were tested for toxicity to *Ceriodaphnia dubia* and the fathead minnow, *Pimephales promelas* (Boelter et al. 1992). Seven-day survival and growth tests resulted in reduced survival and reproduction of *C. dubia* compared to the upstream control, but fathead minnows were not affected. Major inorganic ions ($Na^+$, $K^+$, $Cl^-$, $HCO_3^-$, and $CO_3^{2-}$ appeared to account for the observed toxicity.

Produced water from offshore drilling has been successfully treated onshore in Alaska (Lysyj 1982). In this case, produced water was subjected to heat, gravity separators, gas flotation cells, and retention ponds to separate the oil from the water. Effluent from the retention ponds was returned to the coastal waters. In excess of 90% of the oil was removed; however, high concentrations of dissolved nonvolatile organic matter (300-400 mg C[1]/L) were present. Benzene, toluene, and xylenes averaged 3.7, 1.8, and 0.7 mg/L, respectively. These concentrations are not acutely toxic to freshwater organisms as indicated by U.S. EPA (1992b) Water Quality Criteria (benzene, 5.3 mg/L; toluene, 17.5 mg/L; and xylenes, no criteria). Criteria for chronic exposure to these three constituents have not been developed.

### 3.1.1.2 Drilling Fluids

Drilling fluids are slurries composed primarily of barite (barium sulfate), clays, lignosulfonates, and lignites. They are usually reused during drilling activities; spent fluids, referred to as muds, are discharged intermittently during well drilling. Several Gulf states allow discharge of onshore drilling muds into nearby estuaries.

### 3.1.1.3 Drill Cuttings

Drilled formation solids and silt are separated from fluids by a shale shaker screen and hydrocyclone and disposed of in landfills, by landspread, by

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[1] mg carbon/L; 1 mg C/L corresponds to approximately 1.16 mg/L of oil

roadspread, or by pit burial. No ecological impacts are expected from the disposal of drill cuttings.

### 3.1.1.4 Combined Wastes

Because the three types of wastes are not treated individually, the following discussion refers to combined wastes. The U.S. EPA (1987) has documented the following cases of environmental impacts. Incidences in which 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 inadequate or illegal disposal of oily water. Barium, sodium, iron, chlorides, and other ions have migrated into groundwater. Improperly plugged abandoned wells discharge oil which has contaminated land and entered surface water. These practices have led to contaminated domestic wells, degradation of wetlands, endangerment of estuarine fisheries such as oyster beds and crayfish, 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. In addition, commercially harvested foods such as crabs and clams in coastal areas could accumulate heavy metals and PAHs.

Tabb's Bay, Texas, which receives produced water as well as discharges from upstream industry, has become severely degraded by PAH contamination. Another site, Petronilla Creek, which empties into Baffin Bay, contains high levels of chromium, barium, oil, grease, naphthalene, and benzene; no species of freshwater fish or vegetation are present. Discharges to Petronilla Creek are now prohibited. Other discharges to tidally-affected areas are permitted by the Texas Railroad Commission (TRC), but the U.S. EPA has not issued NPDES permits. Two cases of illegal disposal of drilling muds were also reported: in both cases reserve pits were breached allowing drainage into surface streams. New Mexico allows the disposal of produced water into unlined pits. Because of groundwater contamination in the northwestern part of the state, the amount of produced water discharged into unlined pits is limited to five barrels per day. In southeastern New Mexico, inadequate maintenance of a saltwater injection well resulted in contamination of ground water with salt (injection occurs at 10,000 feet). When used as an irrigation source for crops, crop damage resulted.

### 3.1.2 Offshore Drilling

Approximately 17 wells on four platforms (four wells per platform) are needed to produce the 10,000 barrels of crude oil per day for the 300-MW oil-fired power plant (Wang 1992B).

Impacts to coastal areas and marine environmental resources such as fisheries and endangered species at offshore drilling sites can result from oil spills, discharge of produced water and drilling fluids and cuttings, and chronic loss of oil. Pre-construction seismic surveys and the construction and operation of platforms and pipelines can interfere with commercial, recreational, and subsistence fishing activities. Long-term chronic effects during operation of the platform are also a source of concern. The construction of pipelines and navigation channels through intertidal zones and wetlands can permanently destroy aquatic habitat. In addition, onshore construction of support facilities can have potential adverse economic effects on tourism, recreation, and fishing. If oil spills reach shore, coastal areas, including wetlands, could be destroyed (Neff et al. 1987). Major activities that may impact coastal and marine areas during development and operation of an offshore oil facility are listed in Table D-2.

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).

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 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.

Large oil spills from platforms and well blowouts are rare occurrences but may have a significant short-term impact. Stock recruitment results in recover of local fisheries within one to two years. More important than the short-term effects of these spills or well blowouts is the chronic low-level discharge of inert materials, hydrocarbons, and metals discharged with treated wastewater (Theodore and Buonicore 1980, Neff 1987). Chronic pollution may lead to subtle ecological changes and impairment of fishery resources. These studies have shown that early embryonic and larval stages are more sensitive to petroleum hydrocarbons than later larval and adult stages. Sublethal effects include developmental and behavioral changes, which increase susceptibility to disease and other stresses.

**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 | 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 | Chronic discharges of petroleum and other pollutants |
| Fabrication of storage facilities and pipelines | Coastal use conflicts |
| Offshore emplacement of storage 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.

These effects occur at concentrations of petroleum much lower than those that result in acute toxicity. For example, abnormalities in egg development of fish and changes in behavior of invertebrates occur at concentrations as low as 1 ppb (Vandermeulen and Capuzzo 1983).

The amounts and constituents of discharges associated with oil operations vary with the stage of oil production as well as the geologic formation. The most significant discharges associated with offshore oil operations are drilling fluids, drill cuttings, and produced waters (Menzie 1982, U.S. Department of the Interior 1991a). The amounts and concentrations of constituents of drilling fluids and produced waters are dependent on the method of recovery and nature of the geologic formation. Leakage and spillage of crude oil also occur. The fate and toxicity of such discharges have been studied separately, but in reality, the discharges occur concurrently and effects must be considered together.

Fisheries may be adversely affected by chronic petroleum discharges from offshore operations; 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, this represents a potentially significant impact from oil drilling (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 oil 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.

### 3.1.2.1 Produced Water

Produced waters contain oil and grease which are removed before disposal, water soluble hydrocarbons, other organic chemicals, and trace metals. Radioactivity in the form of radium-226 and radium-228 has been associated with some produced waters. Treated produced water is discharged directly from offshore platforms into the surrounding water; in some cases, the produced water is piped ashore, treated, and then discharged into nearshore or estuarine 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 in excess of 90%. The U.S. EPA Best Practicable Treatment (BPT) and Best Available Technology (BAT) limits for oil and grease in produced waters are 79.16 and 3.96 mg/L, respectively (Table 8, Appendix B). The BPT guidelines are currently in effect. Produced water discharged to the ocean is rapidly diluted.

Several studies listed concentrations of constituents of produced water effluents. The average free oil concentration in produced water from seven offshore platforms in the Gulf of Mexico off the Louisiana coast was 30 mg/L of water. Total aromatic hydrocarbons averaged 2 mg/L and dissolved organic carbon averaged 436 mg/L. The organic composition was complex; components originate from the crude oil as well as demulsifiers, defoamers, and flocculation reagents used to facilitate treatment. Four organic priority pollutants (benzene [1.1 mg/L], toluene [0.8 mg/L], xylenes/ethylbenzene [0.3 mg/L], and phenol [0.5 mg/L]) and two metal priority pollutants (chromium [0.3 mg/L] and lead [0.6 mg/L]) were found in all treated effluents; naphthalene, zinc, beryllium, cadmium, copper, silver, and nickel were found intermittently (Lysyj 1982). These concentrations of pollutants in treated produced water are below BPT guidelines. In another study (Neff et al. 1987) concentrations of benzene, toluene, xylenes, and ethylbenzene in a limited number of samples from the Gulf of Mexico were 6.1, 7.4, 3.5, 1.2 mg/L, respectively. Concentrations of metals varied greatly from sample to sample.

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.

Water Quality Criteria have been set for acute and chronic exposures of marine organisms to many of the organic and trace metal constituents of produced water (U.S. EPA 1992b) (Table D-3). These limits are much lower than BPT and BAT limits for offshore produced water discharges. However, a comparison of the BPT and BAT concentrations with the Water Quality Criteria after 10,000-fold dilution (100 meters downcurrent of the discharge) shows that all constituent concentrations would be below the acute and chronic criteria levels.

**Table D-3. Water quality criteria of produced water constituents for saltwater organisms (mg/L)**

| Constituent | Acute | Chronic |
|---|---|---|
| Benzene | 5.1[a] | 0.7[a] |
| Toluene | 6.3[a] | 5.0[a] |
| Ethylbenzene | 0.4[a] | - |
| Phenol | 5.8[a] | - |
| Chromium (III) | 10.3[a] | - |
| Chromium (VI) | 1.1 | 0.05 |
| Lead | 0.220 | 0.0085 |
| Naphthalene | 2.35[a] | - |
| Zinc | 0.095 | 0.086 |
| Beryllium | - | - |
| Cadmium | 0.043 | 0.0093 |
| Copper | 0.0029 | - |
| Silver | 0.0023 | 0.00092[b] |
| Nickel | 0.075 | 0.0083 |

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

### 3.1.2.2 Drilling Fluids

EPA (1991) estimates that, on the average, 6,926 barrels per well of water-based drilling fluid may be discharged during the first 100 days of well drilling in the Gulf of Mexico. Since approximately 17 wells on four platforms (four wells per platform, each producing 600 barrels per day) are necessary to produce the needed 10,000 barrels of crude per day, 117,742 barrels of drilling fluid would be discharged. Of this, 81.06% or 95,441 barrels would be attributed to gas production and the remainder to oil production (see Section 5.1.2.1).

Discharges of water-based drilling fluids are regulated by the Environmental Protection Agency; discharges of oil-based drilling fluids into marine waters is prohibited. 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).

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 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 heavy 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 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-4). 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 saltwater organisms chronically exposed.

### 3.1.2.3 Drill Cuttings

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). 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).

### 3.1.2.4 Oil Spills from Well Operations

Although oil discharged from offshore oil and gas operations contributes approximately 1% of oil inputs in the oceans worldwide from all sources, nonetheless accidents at the platform are a major source of both public concern and potential environmental damage (National Research Council 1990). Large spills from OCS platforms are rare; from 1976-1985, 99% of all spills in the Gulf of Mexico were less than 100 barrels (Anderson and LaBelle 1990). Spill rates for platform spills greater than 1000 barrels were calculated since these spills are large enough to travel long distances in the oceans. According to Anderson and LaBelle

(1990), the spill rate per $10^9$ barrels of oil handled was 0.60. No spills over 1,000 barrels occurred between 1981 and 1987. The average spill size was 18,046 barrels. (Underwater pipeline spills are discussed in Section 3.4.)

**Table D-4. 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.

The fate of oil released into the marine environment involves a number of factors: spreading, evaporation, dissolution, dispersion, emulsification, sedimentation, oxidation, and biodegradation. Oil spills in the ocean result in surface slicks that drift, spread, and weather in response to environmental conditions. Petroleum undergoes relatively rapid weathering; evaporative losses, dispersion, and dissolution into the water column occur within a few days to a week after a spill (National Research Council 1985).

Oil spills that come in contact with sensitive coastal and marine resources would probably cause the most direct and measurable effects on the environment. Crude oil spills at a distance of > 60 miles from the Gulf shore do not normally pose an immediate threat to the coastline because of prevailing winds and currents and natural dispersion (U.S. Department of the Interior 1991).

Characterization of the local fishery resources and distribution of other ecosystem components in the vicinity of platforms are needed to assess impacts. Fish, particularly eggs and larvae which concentrate near the surface, may be significantly impacted by oil. Many fish feed on benthic organisms which may be contaminated by oil in sediments or by accumulation of toxic oil components. The number of marine mammals - sea otters, whales, sea lions - and turtles affected by a spill would be small. A reported oil spill of 90,000 to 119,000 barrels seven miles from Timbalier Bay, Louisiana, stressed both benthic populations and fish near the platform. Within a mile of the platform, density of both populations decreased by more than half compared with the density outside a two mile radius. Burrowing mantis shrimp were absent from the sediment within a few miles of the platform. Except for a few ducks near the coast where the oil had drifted, no dead organisms were found (Gates 1985).

Injuries to marine and coastal resources from an oil spill can be estimated using the Natural Resource Damages Assessment Model for Coastal and Marine Environments (NRDAM/CME) (EA and ASA 1987). The NRDAM/CME provides a "Type A" natural resource damage assessment under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). CERCLA provides that damages are compensation for injuries to natural resources. Damages are measured in terms of "willingness to pay" using established market prices.

The impact of coastal spills on natural resources depends on the (1) characteristics of the environment in which the spill occurs, such as location and season of the incident, water depth, currents, temperature and (2) the natural resources at risk, which depends principally on the location of the spill. The model provides for selection among ten coastal or marine ecoregions or provinces (Cowardin et al. 1979) in which spills may occur. In addition, shoreline types within the Louisianan province are provided for the eastern, central, and western Gulf of Mexico. Within each region, resources are distributed according to bottom type, water depth, and many other factors.

The model is composed of a coupled system of numerical submodels for physical fates, biological effects, and economic damages. The physical fates submodel simulates the spreading on the sea surface, mixing, and degradation of oil in the environment (equations for these processes can be found in EA and ASA 1987). The physical fates submodel also has a chemical data base containing physical, chemical, and toxicological information on 469 oil and chemical substances. Evaporation into the atmosphere as well as distribution and concentrations of the oil on the water surface and concentrations in the upper and lower water columns and sediments are calculated. The user supplies site specific information on water depth, mean and tidal currents, wind speed and direction, and air temperature. The output of the model includes the concentration of the oil over time in the upper and lower water column and in bottom sediments and the surface area covered by the slick. For spills in intertidal areas, the area and length of shoreline affected is computed. The submodel provides for cleanup of spills. This information is fed to the biological effects submodel which calculates the effects of these concentrations on subtidal and tidal biota.

The biological effects submodel receives input from the physical fates submodel, the toxicological section of the chemical data base, a biological data base, and user input. The biological data base contains information on biological abundance of various categories of finfish, shellfish, fur seals, and birds in the ten provinces. The submodel calculates injury to biota and public facilities in the appropriate province by season. The biological and physical injuries considered are:

(1) "direct, lethal effects on larvae, juveniles, and adult fish and shellfish, waterfowl, seabirds, shorebirds, fur seals, and lower trophic biota;
(2) indirect and long-term effects involving the eventual loss of fish and shellfish as a result of kills of larvae and juveniles, and birds, as a result of kills of lost broods;
(3) indirect effects resulting from kills of lower trophic level, non-commercial organisms (phytoplankton, zooplankton, and benthic biota); and
(4) direct effects resulting from oil or hazardous substances causing a closure of public recreational beaches, or a hunting or fishing area."

The economic damages submodel uses information supplied by the user and results of the biological effects submodel to measure short-term and long-term losses to commercial and recreational fisheries, consumptive (hunting) and nonconsumptive (birdwatching) losses. Reduced productivity of the food chain, causing future losses of commercial and recreational fisheries and birds, are included. The output from the economic damages submodel are included in Section 7.

The NRDAM/CME was applied to a hypothetical spill of medium crude oil from a platform located 50 km off the coast of Texas (Louisianian Province) on

June 1, 1990. We assumed 18,046 barrels were spilled. This is the average size of large oil spills which are defined as spills >1,000 barrels (Anderson and LaBelle 1990). The spill rate for this size spill from platforms is 0.60 per $10^9$ barrels of oil handled. The spill rate for spills of 10,000 barrels or greater is 0.24 spills per $10^9$ barrels of oil handled. Some appropriate physical environmental parameters for the hypothetical spill are shown in Table D-5 (Reed et al. 1989; NOAA 1985). In addition, the bottom type in this province is mud and the shoreline is salt marsh. For maximum damages, we assumed that the spill would come ashore. Therefore, the model had to run twice, once for subtidal effects and once for intertidal effects. We also assumed that 20% of the oil was cleaned up from the water surface before reaching shore.

**Table D-5. Physical environmental parameters for crude oil spills**

| Parameter | Value |
|---|---|
| Mean ocean surface current | 0.1 m/sec |
| Tidal velocity parallel to the ocean surface current | 0.5 m/sec |
| Tidal velocity perpendicular to mean ocean current | 0.1 m/sec |
| Mean wind speed at spill event | 0.56 m/sec |
| Wind direction[a] | 315° |
| Depth of upper water column to pycnocline | 10 m |
| Depth of lower water column to bottom | 20 m |
| Air temperature | 20°C |

[a] Counter-clockwise from ocean current

The biological data base contains information on biological abundance of various categories of finfish, shellfish, fur seals, and birds in the ten provinces. Threatened and endangered species in the Galveston area of the Gulf of Mexico include piping plover, bald eagle, Arctic peregrine falcon, brown pelican, and Kemp's ridley, green loggerhead, and hawksbill sea turtles (Department of Interior 1991). The output of the biological model is in terms of injuries, i.e., lost catch and harvest of commercially and recreationally important species and nonconsumptive losses. The economic damages submodel places a dollar value on these losses.

### 3.1.2.5 Air Emissions

Air emissions from offshore drilling are not expected to cause any national or state air quality standards to be exceeded. Accidental oil spills could cause short-term increases in volatile organic carbon concentrations near the spill, but these would be of short duration (U.S. Department of the Interior 1991).

### 3.1.2.6 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. Wetland loss and saltwater intrusion may result from dredging of navigation channels and oil and gas transportation lines, filling or draining of wetlands for land use, and possibly, enhanced subsidence resulting from produced water withdrawals. A small amount of Louisiana or Texas 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 oil platforms. Offshore platforms may detract from coastal aesthetics (U.S. Department of the Interior 1991).

## 3.2 CRUDE REFINING

Petroleum refineries require land for tank farms to store crude oil and refinery products, and for process facilities including settling ponds, water treatment plants, and disposal sites for oily wastes.

The Texas refinery site is in a heavily industrialized metropolitan area. Water to the site is provided by the city of Houston through a channel system from the San Jacinto River (Bland 1992). Treated wastewaters enter the Houston ship channel and Galveston Bay, both of which have been heavily impacted by the oil industry and other industrialization. Final process water from a typical refinery is monitored for water temperature, pH, COD, BOD, TOC, TSS, flow, oil and grease, total copper, total nitrogen, total sulfide, hexavalent and total chromium, and total phenolics (EPA 1992a).

The Navajo, New Mexico, refinery is located on the east edge of Artesia, two miles from the Pecos River. The surrounding area is called "high desert;" the two main industries are agriculture and oil. Some of the water for the refinery is bought from the city of Artesia and some is obtained from groundwater via artesian wells (Gray 1992). The presence of artesian wells indicates a deep, and therefore relatively protected, groundwater table.

### 3.2.1 Wastes and Wastewaters

A large amount of waste and wastewater is produced during crude refining. (See Section 5.9 for the amounts and types of wastes generated at refineries.) The discharge of wastewaters from refineries is regulated by the National Pollutants Discharge Elimination System (NPDES) and state programs. Liquid effluents from refineries contain water pollutants including BOD, COD, oil, phenols, and suspended and dissolved solids (Theodore and Buonicore 1980). Hazardous wastes are disposed of by land treatment, landfills, impoundments, or landspreading. All of these treatments have the potential for leaching of toxic constituents to ground and surface waters. At the Deer Park refinery, discharge or runoff to surface waters would incrementally increase the load of contaminants in the water and sediments of the already impacted Houston Ship Channel and Galveston Bay. In at least one case, groundwater in New Mexico was contaminated from leaching of aromatic volatile organic carbons and ethylene dichloride from a refinery lagoon (U.S. EPA 1987); however, the groundwater at the Navajo refinery may be well protected due to its depth.

### 3.2.2 Air Emissions

Air emissions from refineries include particulate matter, sulfur dioxide, carbon dioxide, hydrocarbons, nitrogen dioxide, polycyclic aromatic hydrocarbons, hydrogen sulfide, ammonia and trace elements (Section 5.5.1). Incremental increases in atmospheric concentrations of primary pollutants for the two refinery sites were not available at this time. Effects on crops, forests, and wildlife would not be relevant at the Texas refinery because of the urban nature of the site.

## 3.3 POWER GENERATION

The generation of power by oil-fired power plants will impact the environment through the replacement of existing land resources by the generating facilities and associated support facilities, such as oil storage tanks, 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 resources, and wilderness and recreational resources are located near the southwestern site (U.S. Department of Interior 1982).

### 3.3.1 Air Emissions

The burning of oil produces particulate matter, carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide, and hydrocarbons. Heavy metals are also present in the flue gases. The emissions are a function of the combustion technology used, the composition of the oil, and the control devices in place. No data were available on air emissions of the 2010 gas turbine technology (Section 5.6.3). Information on emission rates and incremental increases in atmospheric concentrations of primary pollutants for the 1990 steam-boiler technology is given in Appendix C.

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 site.

#### 3.3.1.1 Carbon Dioxide

Carbon dioxide is the most important greenhouse gas implicated in global warming. Ecological impacts of global warming are discussed in ORNL/RFF (1992). As noted in that report, greenhouse gases such as $CO_2$ do not have local site-specific effects, but rather regional impacts, such as changes in precipitation patterns. However, these changes are difficult to predict and may be beneficial or detrimental depending on prior conditions. This uncertainty in predicting regional climatic changes precludes any attempt at identifying and quantifying the impacts of a single $CO_2$ source such as an oil-fired power plant.

Increases in atmospheric $CO_2$ may 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, at the present time adequate dose response functions are not available to quantify this impact, 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).

### 3.3.1.2 Hydrocarbons

Hydrocarbons are emitted from the power plant stack during the combustion process. Relative to the amount of energy produced, oil releases 0.001 lb hydrocarbons (as $CH_4$) per $10^6$ Btu (Sittig 1977, as reported in Watson and Etnier 1981). In general, ambient levels of hydrocarbons are not directly toxic to plants or animals (Amdur 1986).

Hydrocarbons released in the stack emissions also have the potential for reacting with $NO_x$ in the presence of sunlight to generate ozone and peroxyacetyl nitrate (PAN). Ozone formation is discussed in Section 3.3.1.4 and PAN in Section 3.3.1.3.

### 3.3.1.3 $NO_x$ and Other Nitrogen Compounds

For the 1990 technology, the maximum annual increase in $NO_x$ concentration due to the power plant was calculated to be 0.44 $\mu g/m^3$ (0.296 ppb) (Appendix C). In comparison, the average annual ambient concentration of $NO_x$ at the southeastern site was reported to be 23 $\mu g/m^3$ (about 15 ppb). $NO_x$ emissions from the hypothetical 300-MW oil-fired power plant in 1990 represent about a 2% increase in the annual average. Emissions of $NO_x$ about 175 times greater than 0.44 $\mu g/m^3$ would have to occur before the current primary NAAQS of 100 $\mu g/m^3$ is reached. For the 2010 technology, the maximum annual increase in $NO_x$ concentration was calculated to be much lower, 0.04 $\mu g/m^3$ (0.027 ppb) (Appendix C).

Information on the effects of $NO_2$ on animals is limited to laboratory studies (Table D-6). Nitrogen dioxide is a deep lung irritant capable of producing pulmonary edema if inhaled in sufficient concentrations (Amdur 1986). It can also cause significant alterations in pulmonary function, and 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. Therefore, no significant direct ecological impacts would be expected to occur to terrestrial animals from air pollution from the operation of a 300-MW oil-fired power plant.

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

**Table D-6. Effects of nitrogen dioxide on laboratory animals**[a]

| Species | Exposure | Effects |
|---|---|---|
| Rat | 1 ppm for 4 hours | Lipid peroxidation in lung |
| Rat | 166 ppm for 1 hour | $LC_{50}$ |
| Rat | 88 ppm for 4 hours | $LC_{50}$ |
| Rat | 0.5 ppm for 4 hours or 1 ppm for 1 hour | Damage to mast cells (repaired within 24 hours) |
| Rat | 10 or 25 ppm for 16 weeks | Emphysema-like lung damage |
| 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 |
| 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* |
| 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* |
| Guinea pig | 5-13 ppm for 2-4 hours | Changes in pulmonary function |
| Rabbit | 0.25 ppm, 4 hours/day for 6 days | Alterations in lung collagen |
| Dog | 25 ppm for 6 months | Emphysema-like lesions |
| 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 |
| Squirrel monkey | 5 or 10 ppm for 1-2 months; 50 ppm for 2 hours | Increased mortality following exposure to *K. pneumoniae* |

[a] Compiled from Amdur 1986

growth in some species (ORNL/RFF 1992, Appendix D), and levels of 500 ppb and above may cause foliar injury (Taylor and Eaton 1966).

$NO_x$ emissions from an oil-fired plant can also contribute to the formation of 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). 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, 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.

Based on these findings, ecological impacts of $NO_x$ at the southeastern site would be minimal and impacts of PAN are unquantifiable at this time.

### 3.3.1.4 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 et al. 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 a 50-km radius of the hypothetical oil-fired power plant at the 1990 southeastern reference site was calculated to be 15.5 ppb, and the monthly 12-hr average was estimated to be 1 ppb (Appendix B). Background concentrations of ozone at the reference site were reported to be 55 ppb. The presence of the power plant would result in a 1.8% annual average increase in atmospheric ozone.

Ozone can adversely affect animals (Table D-7). Chronic bronchitis, bronchiolitis, fibrosis, and emphysematous changes have been observed in several species of laboratory animals exposed to ozone concentrations slightly above 1000 ppb, 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). Insufficient information is available on the potential chronic effects following long-term exposures.

Ozone also 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,

## Table D-7. Effects of ozone on laboratory animals[a]

| Species | Exposure | Effects |
|---|---|---|
| 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 |
| 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. |
| 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 |
| 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. |
| 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 |
| Mouse | 20 ppm for 3 hours | $LC_{50}$ |
| 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. |
| Mouse | 0.08 ppm for 3 hours | Enhanced mortality from subsequent exposure to a bacterial aerosol of streptococcus (Group C) |
| Guinea pig | 50 ppm for 3 hours | $LC_{50}$ |
| Guinea pig | 0.34-1.8 ppm for 2 hours | Decreased tidal volume, increased flow resistance (both reversible); concentration-related reductions in compliance |
| 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 |
| 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 caliber of the small airways) |
| 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. |

[a] Compiled from Amdur 1986

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) as well as this appendix.

Reduction in crop yields due to incremental increases in atmospheric ozone concentrations is considered a potential impact of an oil-fired power plant. Dose-response functions are available to quantify this impact (Section 5.3). However, data are generally not available for estimating the response of whole trees or tree stands to air pollutant stresses such as ozone. Consequently, empirical models and conclusive quantitative estimates of such responses do not exist. Existing process models relate to responses of tree seedlings and branches to air pollutants. 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.

The ozone concentrations causing acute toxic efffects on plants and animals are generally greater than the ambient levels predicted for the hypothetical 300-MW oil-fired power plant (56 ppb); however, subtle effects such as reduced crop yields are possible.

### 3.3.1.5 Sulfur Dioxide

On the basis of the amount of energy produced, oil combustion releases 1.0 lb $SO_2/10^6$ Btu (Sittig 1977, as reported in Watson and Etnier 1981). The S$_2$O emission factor used in this study is 30.94 grams per second for the 1990 technology and 15.47 grams per second for the 2010 technology (Section 5.6.3). For the 1990 technology, the maximum 24-hr average increase in $SO_2$ was calculated to be 20.1 μg/m$^3$, and the maximum annual average increase 0.347 μg/m$^3$ (0.133 ppb) (Appendix C). The reported annual average ambient concentration of $SO_2$ near the southeastern reference site is 25 μg/m$^3$ (9.54 ppb) (Appendix C). The addition of $SO_2$ from a single 300-MW oil-fired power plant would represent about a 1.4% increase in the annual average. Emissions of $SO_2$ about 160 times greater than 0.347 μg/m$^3$ would have to occur before the current primary NAAQS of 80 μg/m$^3$ is reached.

Information on the toxicity of $SO_2$ to laboratory animals is shown in Table D-8. The reported toxicity thresholds are all above the predicted maximum ambient concentrations resulting from the operation of the 300-MW oil-fired power plant.

The lowest concentration of $SO_2$ reported to be deleterious to plants (lichens) is >50 μg/m$^3$ (Gilbert 1965, 1970; Barkman 1969; both as reported in Bradshaw 1973). For most other species, thresholds occur at much higher concentrations. Bell and Clough (1973) reported a 50% reduction in growth of rye grass at about 200 μg/m$^3$ (76 ppb). Gupta et al. (1991) reported that soybeans were stressed by 50 ppb (130 μg/m$^3$). A concentration of 100 ppb (261 μg/m$^3$, 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). Concomitant exposure to 450 ppm $CO_2$ compensated for the negative effect of the $SO_2$. $SO_2$ may act synergistically with ozone to damage plants at low concentrations. In laboratory studies, 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). Dochinger et al. (1970) reported that a synergistic interaction of $SO_2$ and ozone might cause the breakdown of chlorophyll *a* in the needles of the white pine (*Pinus strobus*).

The U.S. EPA Criteria Document on particulate matter and sulfur oxides briefly discusses effects on natural ecosystems (U.S. EPA 1982). Deleterious effects depend on concentrations as well as durations. For example, injury to vegetation in the vicinity of a Sudbury, Canada smelter happened when the following concentration-durations of $SO_2$ were reached or exceeded: 0.95 ppm for 1 hour, 0.55 ppm for 2 hours, 0.35 ppm for 4 hours, or 0.25 ppm for 8 hours. In another area of Canada, species diversity in the forest ecosystem was not affected by two gas plants, but white spruce seedlings close to the plants were reduced in number. In addition, the species diversity in the moss community was decreased. Concentrations of $SO_2$ above 52 μg/m$^3$ (0.02 ppm) can induce changes in the performance of producers, consumers, and decomposers. Several of the studies also indicate that susceptibility to $SO_2$ injury is greater during warm, moist weather conditions when growth is most rapid and the photosynthetic rate is high.

### 3.3.1.6 Acid Deposition

Incremental increases in atmospheric $NO_x$ and $SO_2$ contribute to the formation of acid deposition. In the atmosphere $NO_x$ and $SO_2$ can react with strong oxidizing agents such as $O_3$, OH, and $H_2O_2$ to form $HNO_3$ and $H_2SO_4$ both of which can be transported over long distances before being deposited as acid rain. Acid rain may impact both aquatic and terrestrial systems; however, the methodology is not yet available to assess the contribution of a single point source, such as a power plant, to environmental impacts.

Terrestrial systems. Terrestrial studies of acid deposition have focused 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 300-MW 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 in the exposed region.

Acid deposition, under some circumstances, may have beneficial effects in terrestrial systems; $H_2SO_4$ and $HNO_3$ can 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) are within the range of forest requirements (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).

**TABLE D-8. Effects of $SO_2$ on laboratory animals[a]**

| Species | Exposure | Effects |
|---|---|---|
| Rat | 10 ppm, 18-67 days, inhalation | Thickening of mucous layer of trachea |
| Rat | 12 ppm, 4-6 minutes, direct exposure to trachea | Cessation of ciliary beat; recovery a few minutes after exposure ceased |
| 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 |
| 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" |
| Guinea pig | 0.1 to 5.0 ppm for up to one year or more | No pulmonary pathology |
| 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) |
| Dog | 1 ppm for 1 year | Slowing of tracheal mucous transport |
| Dog | 5 ppm, 21 hours/day for 225 days | 50% increase in resistance; 16% decrease in compliance |
| 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 |
| Monkey | 0.1 to 5.0 ppm for up to one year or more | No pulmonary pathology |
| 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 |

[a] Compiled from Amdur 1986

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 susceptiblity 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 magnesium (Van Miegroet and Cole 1984; Ulrich et al. 1980). Occurring over the long life cyle of the forest, this alteration in soil chemistry would outweigh any short-term benefits of nitrogen fertilization of such soils (Brandt 1987; Abrahamsen 1980).

Aquatic Systems. Regional modeling for the evaluation of acid precipitation on aquatic resources 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 300-MW oil-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 oil-fired power plant is not expected to have a major ecological impact.

### 3.3.1.7 Particulates

Particulate emission rates for the hypothetical 300-MW oil-fired power plant using 1990 technology were set at 1.28 grams per sec. The resulting atmospheric concentrations at the southeastern site were calculated to be 0.83 $\mu g/m^3$ for a maximum 24-hr average, and 0.014 $\mu g/m^3$ for a maximum annual average. Ambient particulate concentration in the study area has been reported to be 108 $\mu g/m^3$ for the 2nd highest 24-hr average and 47 $\mu g/m^3$ for an annual average (particulate values from Appendix C). Operation of the power plant would result in an increase of about 0.03% in the average annual concentration.

There is very little experimental data on the ecological effects of high particulate concentrations. However, in one study it was found that deposition of particulate matter on the leaves of oak trees caused an indirect 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.

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 Smoky 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 Smoky National Park was 55 kilometers during 1980-1983 (Reisinger and Valente 1985). Located near the New Mexico site are Mesa Verde National Park, Chaco Culture National Historical Park, and Bandelier National Monument. Standard visual range in these areas exceeds 100 mi (161 km) (U.S. Department of the Interior 1982). Haze is generally considered to be caused by multiple emission sources (U.S. EPA 1988). A single 300-MW oil-fired power plant is unlikely to have direct visibility impacts on distant recreational areas.

### 3.3.2 Water Emissions

Potential water emissions from an oil-fired power plant include cooling tower blowdown, boiler water discharges, and general utility wastewater. Water pollutants contained in the wastewaters include BOD, COD, TSS, TDS, oil and grease, chlorine, zinc, copper, iron, and changes in pH (Section 5.2.2). 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, and overflow 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. Moreover, the water table at the southwestern site is located 200-500 feet below the surface (New Mexico Water Quality Commission 1990); at this depth the groundwater is relatively protected from surface contaminants. At the southeastern reference site the proximity of a large river system would probably result in direct discharges of wastewaters to the river.

### 3.3.2.1 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 (U.S. Department of Energy 1983). For mechanical draft cooling towers makeup water amounts to 1.5-4.5% of average condenser flow rate or about 250 acre-ft per $10^{12}$ Btu (about 1,800 acre-ft, or 5.9 x $10^8$ gal per year for a 300-MW facility) (U.S. Department of Energy 1983). 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 0.05% of river water flow. 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.

### 3.3.2.2 Wastewater

For an oil-fired power plant, the principal components of the wastewater discharge are boiler blowdown, washwater from chemical cleaning of boiler tubes, air preheater washwater, and boiler fireside washwater (Section 5.2.1). 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 an oil-fired power plant are expected to contain varying pH, high dissolved solids, high COD and BOD and metals such as iron and copper (U.S. Department of Energy 1983). 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.

## 3.4 TRANSPORTATION AND STORAGE

### 3.4.1 Crude Oil

Oil spills may occur during the transportation and storage of crude oil and crude oil products. Crude oil produced onshore near the two refineries would be transported to the refineries by small pipelines or trucks. The major impacts from pipelines occurs during their construction. Since the scale and probability of spills from onshore pipelines is minimal, onshore crude oil spills will not be considered in this report (Section 5.4).

Crude oil produced offshore in 2010 would be pumped from the Gulf of Mexico to a refinery near Houston through underwater pipelines that are laid on the bottom of the ocean. The pipelines are made of high-quality steel pipe welded together; the pipeline is usually covered with a protective coating and a layer of cement. Pressure pumps and compressors are placed along the pipeline at intervals to maintain a constant flow of oil. Near shore, or at depths of less than 200 feet, trenches are dug to contain the pipeline. Although there is local environmental disruption in coastal areas from dredging during placement of the pipelines, underwater pipelines have proved to be reliable and environmentally safe (Gates 1985).

Open ocean oil spills of <1,000 barrels do not cause appreciable environmental damage. (Most information on offshore spills combined platform spills, pipeline breaks, and seeps.) Between 1964 and 1988, there were 21 spills of 1,000 barrels or more from offshore operations on federal leases on the Outer

Continental Shelf. The number of barrels spilled ranged from 1,456 to 160,638. The most serious causes of accidents were anchor damage to pipelines and well blowouts (U.S. Department of Interior 1989). From 1964 to 1980 the average spill rate for pipelines was 1.6 spills per billion barrels produced (Lanfear and Amstutz 1983). According to Anderson and LaBelle (1990), the average spill size was 18,046 barrels for platform spills and 26,450 barrels for pipeline spills. Through 1987 spill rates were slightly lower: rates per $10^9$ barrels of oil handled were 0.60 and 0.67, respectively. Oil spill rates for platforms in state waters were not located. As in the case of platform spills, pipeline spills may impact local fisheries, but recovery is expected within one to two years.

The NRDAM/CME can be used to estimate injuries to marine and coastal resources from an underwater pipeline break. A break near the platform, 50 kilometers from the coast of Texas, would produce the same impacts as a platform spill. See Section 3.1.2.4 for the model description and Section 7.2.2 of Volume 1 for injuries to fisheries and other marine resources.

In experimental studies, crude oil added at rates of 1, 2, 4, and 8 liters/ $m^{-2}$ to enclosed plots in the Barataria Basin of Louisiana was not toxic to marsh grass (*Spartina alterniflora*) or sediment anaerobic bacteria. The added oil did not remain on the surface, but adhered to dead plant material on the marsh surface and in the sediments (Delaune et al. 1979).

Crude oil added to seawater separates into an oily layer and a water soluble fraction (WSF). With gentle mixing the oily layer mixes with water forming an oil-in-water dispersion (OWD). Studies on the toxicity of these mixtures to three estuarine crustaceans and three estuarine fish were performed by Anderson et al. (1974) (Tables D-9 and D-10). The lowest concentration acutely toxic (48-hr TLm or $LC_{50}$) to both shrimp (*Mysidopsis almyra*) and fish (*Menidia beryllina*) was 8.7 ppm (mg/L).

### 3.4.2 Residual Oil

#### 3.4.2.1 Water Transportation

Residual oil would be transported by tanker barges from the Deer Park refinery to the Clinch River site, a total distance of 1,320 miles. The proposed route is along the Gulf Coast from Houston, Texas to Mobile, Alabama, possibly utilizing the Gulf Intracoastal Waterway. From Mobile the barges would travel through the Tennessee-Tombigbee waterway and up the Tennessee and Clinch Rivers to the Clinch River site. One barge carrying 70,000 bbl every 7.8 days would be necessary to supply the southeastern power plant (calculations made from

Section 4.2.15.1). The most probable causes of inland barge accidents are collisons with bridges or other vessels and groundings. Barges in coastal areas would be vulnerable to storms. Spills could also occur during loading and unloading operations.

Residual oil #6 is a viscous black liquid with a specific gravity of 0.95. It is insoluble in water and usually floats on water. After 24 hours, 11 ppm may be in solution. Accidental spills are a potential danger to aquatic life and waterfowl; they result in fouling to shoreline and municipal and industrial water intake closures. The coating action of the oil is hazardous to waterfowl, plankton, algae and fish (CHRIS 1992, OHM/TADS 1992).

### TABLE D-9. Oil bioassays on three estuarine crustacean species

| | | *Mysidopsis almyra* | | *Palaemonetes pugio* | | | *Penaeus aztecus* (postlarvae) | | |
|---|---|---|---|---|---|---|---|---|---|
| Oil type | Value | 24 h | 48 h | 24 h | 48 h | 96 h | 24 h | 48 h | 96 h |
| South Louisiana crude | | | | | | | | | |
| OWD[a] | TLm (ppm)[c] | 165 | 37.5 | 1,700 | 1,650 | 200 | >1000 | >1000 | >1000 |
| WSF[b] | TLm (ppm)[d] | 11.7 | 8.7 | >16.8 | >16.8 | >16.8 | 19.8 | >19.8 | >19.8 |
| Kuwait crude | | | | | | | | | |
| OWD[a] | TLm (ppm)[c] | 72 | 63 | 13,500 | 9,000 | 6,000 | - | - | - |
| WSF[b] | TLm (ppm)[d] | 8.2 | 6.6 | >10.2 | >10.2 | >10.2 | - | - | - |

[a] Oil-in-water dispersion
[b] Water-soluble fraction
[c] Concentration expressed as ppm oil added to water
[d] Concentration expressed as ppm total oil-hydrocarbons in aqueous phase as determined by infrared analysis

From Anderson et al. 1974

## TABLE D-10. Oil bioassays on three estaurine fish species

| | | *Cyprinodon variegatus* | | | *Menidia beryllina* | | | *Fundulus similus* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Oil type** | **Value** | **24 h** | **48 h** | **96 h** | **24 h** | **48 h** | **96 h** | **24 h** | **48 h** | **96 h** |
| South Louisiana crude | | | | | | | | | | |
| a | TLm (ppm)[c] | 80,000 | 33,000 | 29,000 | 7,6000 | 5,000 | 3,700 | 6,610 | 6,000 | 6,000 |
| WSF[b] | TLm (ppm)[d] | >19.8 | >19.8 | >19.8 | 9.7 | 8.7 | 5.5 | 16.8 | 16.8 | 16.8 |
| Kuwait crude | | | | | | | | | | |
| OWD[a] | TLm (ppm)[c] | >80,000 | >80,000 | >80,000 | 20,000 | 15,000 | 9,400 | 17,500 | 14,800 | 14,800 |
| WSF[b] | TLm (ppm)[d] | - | - | - | 6.6 | 6.6 | 6.6 | >10.4 | >10.4 | >10.4 |

[a] Oil-in-water dispersion
[b] Water-soluble fraction
[c] Concentration expressed as ppm oil added to water
[d] Concentration expressed as ppm total oil-hydrocarbons in aqueous phase as determined by infrared analysis

From Anderson et al. 1974

Barge transportation accidents can occur at any point on the route. It is assumed barges travel close to the coastline or within the interacoastal waterway. The greatest impact from a spill of #6 residual oil at sea is probably to zooplankton in the immediate vicinity of the spill. Visual observations at the site of the *Argo Merchant* spill in shoal waters off Nantucket, Massachusetts, showed greatest impact on free-floating plankton (Kerr 1977). The oil did not reach the coast.

Impacts close to coastal areas would be much greater, with potential impacts on beaches, coastal vegetation, waterfowl, fish, and invertebrates. The coating action of the oil would be more destructive to wetland plants and biota than toxicity. On March 5, 1980, the barge *Ethel H.* collided with the oil tanker *Southwest Cape* in New York Harbor, resulting in a spill of #6 fuel oil. The beaches of nearby Sandy Hook, New Jersey were covered with oil and tar balls. No further details of the accident were located (Gates 1985).

Injuries to marine and coastal resources can be estimated using the National Resource Damages Assessment Model for Coastal and Marine Environments (NRDAM/CME). In December, 1986, a spill of #6 fuel oil occurred in the lower Savannah River at the Garden City Terminal, Savannah, Georgia (Brown 1989). A malfunctioning valve in the *Amazon Venture* allowed an estimated 500,000 gallons (12,000 barrels) of the oil to be discharged into the Savannah River during offloading operations. Efforts to contain the spill were relatively unsuccessful and strong river and tidal currents quickly spread the oil throughout the lower Savannah River and into numerous channels and wetlands in the Savannah National Wildlife Refuge. The oil remained on the water for approximately two weeks. There were no observable fish kills resulting from the spill, and only a few oiled birds were found; however, the most significant effect was the oiling of approximately 8,000 acres (3,200 hectares) of tidal marsh grasses throughout the lower Savannah River. Closure of the intake gates to the Savannah National Wildlife Refuge's impoundment system prevented the oil from reaching that location; however vegetation along approximately 58 miles of shoreline within the refuge had a heavy coating of oil. These impacts resulted in the temporary closing (2-3 weeks) of the refuge to hunting and fishing and the closing of shellfishing season in coastal waters downstream of the refuge by the State of Georgia. The Natural Resources Damage Assessment Regulations were applied following this accident. This was the first successful implementation of the NRDA regulations. The damage assessment process considered loss of use of wetlands, replacement services of the wetlands, damages to fish and wildlife, loss of hunting and fishing days, and other damages. A settlement was reached which provided damages to the U.S. government and the states of Georgia and South Carolina.

Using the NRDAM/CMA model, Opaluch and Grigalunas (1989) partially assessed the economic risk of large (> 1,000 barrels) crude oil spills for natural resources in the Eastern, Central, and Western Gulf of Mexico which constitute the Louisiana Province. Their assumptions and environmental parameters are provided in the paper. Their assessment did not include injury to public beaches, private facilities, or the cost of cleanup. They did not summarize injury to fisheries and biota. Costs varied with area of the Gulf coast, ranging from $11.40 per barrel of oil spilled in the Western Gulf of Mexico (corresponding to the offshore Texas site) to $37.60 in the Eastern Gulf of Mexico. Cost per billion barrels of oil developed ranged from $600,000 in the Western Gulf of Mexico to $3,000,000 in the Eastern Gulf of Mexico.

Several inland river spills have taken place; however, none involving #6 residual oil and river barges were located. Areas along the spill pathway that may be impacted include municipal and industrial water intakes, discharges, locks and dams, and river terminals. On Jan. 2, 1988, a major spill occurred near the Ohio River in which a storage tank containing >3.8 million gallons of #2 diesel oil collapsed, spilling nearly 800,000 gallons of fuel into the Monongahela River 25 miles upstream from Pittsburgh (Clark et al. 1990). (Diesel #2 contains 60% saturated hydrocarbons and 40% mono- and polycyclic aromatic hydrocarbons (API 1988a,b, cited in Cronk et al. 1990) and is lighter, but more toxic to aquatic organisms than #6. The Monongahela and Allegheny Rivers meet at Pittsburgh to form the Ohio River. Normal procedures for controlling oil spills were only partially successful (about 30 percent was recovered with booms and vacuums), and the fuel began to mix with the water. The oil also passed through several locks and dams and thus mixed vertically in the water column. The spill moved down the Ohio River toward Louisville, passing 39 municipal water intakes along the way. The intake valves were usually shut down until successful treatment of the contaminated water was possible. By January 4, the spill had moved 20-30 miles downstream from the origination of the Ohio River at Pittsburgh. On January 5, the slick was approximately 28 miles long, and oil was as deep as 16 feet. By January 27, the spill had reached Louisville, Ky, 600 miles downstream, but diesel oil concentrations had returned to background levels.

At Cincinnati, flows in the Ohio River normally range from 35,000 to 220,000 cfs. At the time of the spill, the flows were 95,000 cfs. Several days after the spill, the temperatures dropped into the single digits, causing freezing in the upper 100 mi of the Ohio River and slowing the flow to 25,000 cfs and the rate to <0.5 mph. On January 19, the Ohio River Valley experienced heavy rainfall and an extended warm spell and the river flows increased to >200,000 cfs and the rate to 3.1 mph. Ohio and Pennsylvania officials estimated that 10,000 fish and 2,000 ducks were killed.

Data on the toxicity of #6 fuel oil is important for predicting effects on aquatic organisms. The 48-hour median tolerance limit of #6 fuel oil for juvenile American shad in saltwater was approximately 2400 ppm. No effects occurred at 1300 ppm. Ninety-six hour $LC_{50}$ values for the marine species, menhaden and grass shrimp, were 10 and 26 ppm, respectively (CHRIS 1992, OHM/TADS 1992). Ninety-six hour $LC_{50}$ values were 160 ppm for a diatom, 5.1 ppm for a marine copepod, and 130 ppm for the Atlantic silversides (Hollister et al. 1980). Toxicity data for freshwater organisms were not located.

### 3.4.2.2 Land Transportation

Tank trucks will be used to transport residual oil from the Navajo refinery site to the southwestern power plant site, a distance of 450 miles. Oil spill rates of $4.5*10^{-4}$ bbl/$10^3$ bbl-mile have been calculated (Appendix B). The yearly transport of 3,260,000 barrels of oil over a distance of 450 miles results in 1,467,000,000 bbl-mile and a yearly spill rate of 660 barrels. Assuming the 660 barrels were divided over several small spills (three trucks at 220 barrels each is most likely), the impact due to spillage and spill cleanup in the sandy desert environment would be minimal. The most significant ecological impact would occur if a spill directly enters a stream; however, such effects would be localized and oil from a single truck would be diluted, even in the smallest average stream.

### 3.4.3 Air Emissions

Exhaust emissions from trucks hauling the fuel oil to the power plant and returning to the refinery, barges, and pumping equipment consist of hydrocarbons, $NO_x$, CO, particulates, $SO_2$, and $CO_2$. These emissions are not expected to have direct ecological impacts, but they would contribute to overall changes in air quality; therefore, they must be considered in relation to similar emissions from the power plant itself. Potential ecological effects of these emissions are discussed in Section 3.3.

### 3.4.4 Road Deterioration

The hypothetical 300-MW southwestern power plant would require 3.26 million barrels of residual oil in 1990 (Appendix B). This oil will be hauled to the power plant in trucks each having the capacity of 200 barrels; thus about 45 tank trucks per day or 16,300 delivery trips per year would be required. It is assumed that the average haul distance would be 450 miles; total roundtrip distance would be 7,335,000 miles. Most of this traffic will be on public roads. Therefore, excessive road deterioration is likely to occur.

### 3.4.5 Traffic Noise

As noted above, 16,300 truck deliveries would be required per year to furnish the oil to the power plant at the 1990 southwestern reference site. Assuming that the deliveries are made 5 days per week and 8 hours per day, the deliveries to and from the power plant would average about 7.8 per hour.

## 3.5 SUMMARY AND SELECTION OF KEY IMPACTS

Although quantitative information on many of the potential environmental impacts of the oil fuel cycle is limited, some general qualitative conclusions can be made based on the available data. Impacts from the oil-fuel cycle involve: (1) effects of wastewater and discharges from offshore drilling on local biota and regional fisheries, (2) the impact of a crude oil spill on marine and coastal resources, (3) the potential changes in crop yield from ozone formation from power plant emissions of hydrocarbons and $NO_x$, (4) damage to coastal wetlands and marine resources from potential spills of residual oil during transport along coastal areas, and (5) damage to freshwater aquatic resources from potential spills of residual oil during barge transport through the Tennessee-Tombigbee River system. Most quantitative data is available on the potential impact of ozone on crop yield at the southeastern site. However, the greatest ecological impact is to aquatic resources and biodiversity from marine and freshwater oil spills.

# 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 and the effects of oil on water quality and aquatic organisms can be partially quantified using both types of models as well as expert judgement. Highly site-specific effects can be quantified from site-specific data, but generic, predictive models do not exist. Poorly documented effects (such as changes in biodiversity or recreational opportunity) and poorly understood sources cannot be quantified using any of these approaches.

# 5. EVALUATION OF KEY IMPACTS

## 5.1 EFFECTS OF OFFSHORE OIL DRILLING AND PRODUCTION ON COMMERCIAL FISHERIES AND BENTHOS

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 a 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.

Oil spills from platforms and well blowouts produce regional short-term environmental impacts, but spill rates are low, especially for large spills (>1,000 barrels). Recovery via recruitment of fishery stocks takes from one to two years. On the other hand, 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 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. The combination of discharges of produced water, drilling fluids and cuttings, and oil from four oil platforms containing 16-17 wells would produce only chronic ecological impacts in a local area (within 1,500-2,000 meters of each well site) and result in an extremely small incremental impact on commercial fisheries of the Gulf.

The greatest measured 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 quantiry these incremental impacts on saltwater organism, these localized, continuous emissions should be of concern in an area experiencing decreased fisheries landings and increased oil development.

## 5.2 IMPACTS OF PLATFORM OIL SPILLS ON COASTAL AND MARINE RESOURCES

Oil spills in marine and coastal areas due to spills of crude oil from platforms would cause a direct and measurable ecological impact. Although effects would be site-specific and costs would depend on the economic value of the land and presence or absence of finfish and shellfish fisheries and wildlife, in general, these areas are considered valuable natural resources.

Injuries to marine and coastal resources from an oil spill can be estimated using the Natural Resource Damages Assessment Model for Coastal and Marine Environments (NRDAM/CME) (EA and ASA 1987). The NRDAM/CME provides a "Type A" natural resource damage assessment under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). A "Type A" assessment is a standard and simplified procedure in contrast to a "Type B" procedure which is used in individual cases. CERCLA provides that damages are compensation for injuries to natural resources. Injuries can be estimated for commercially and recreationally harvested fish, lower trophic biota (the food source for other animals), birds, fur seals, and public beaches. Damages are measured in terms of "willingness to pay" using established market prices.

The biological effects submodel calculates injury to biota and public facilities in the appropriate province, in this case the Louisianian Province (Gulf of Mexico) by season. The biological and physical injuries considered are:

(1) "direct, lethal effects on larvae, juveniles, and adult fish and shellfish, waterfowl, seabirds, shorebirds, fur seals, and lower trophic biota;
(2) indirect and long-term effects involving the eventual loss of fish and shellfish as a result of kills of larvae and juveniles, and birds, as a result of kills of lost broods;
(3) indirect effects resulting from kills of lower trophic level, non-commercial organisms (phytoplankton, zooplankton, and benthic biota); and
(4) direct effects resulting from oil or hazardous substances causing a closure of public recreational beaches, or a hunting or fishing area."

The biological data base contains the following information on biological abundance of various categories of finfish, shellfish, fur seals, and birds in the Louisianian Province in spring (Tables D-11 to D-13):

## Table D-11. Adult biomass (grams wet weight per square meter)

| Species/Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| Anadromous Fish | | | | |
| Subtidal | 0.0010 | 0.0010 | 0.0010 | 0.0010 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Planktivorous Fish | | | | |
| Subtidal | 11.4205 | 11.4232 | 11.4205 | 10.3178 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Piscivorous Fish | | | | |
| Subtidal | 0.0209 | 0.0303 | 0.0209 | 0.0116 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Top Carnivores | | | | |
| Subtidal | 0.0134 | 0.0134 | 0.0134 | 0.0134 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Demersal Fish | | | | |
| Subtidal | 0.0098 | 0.0098 | 0.0098 | 0.0098 |
| Intertidal | 0.0380 | 0.2500 | 0.2100 | 0.2300 |
| Semi-Demersal Fish | | | | |
| Subtidal | 0.6367 | 0.6367 | 0.6367 | 0.6367 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Mollusks | | | | |
| Subtidal | 0.0009 | 0.0009 | 0.0009 | 0.0009 |
| Intertidal | 5.2000 | 5.2000 | 5.2000 | 5.2000 |
| Decapods | | | | |
| Subtidal | 0.4315 | 0.4315 | 0.4315 | 0.4315 |
| Intertidal | 4.4000 | 4.4000 | 4.4000 | 4.4000 |
| Squid | | | | |
| Subtidal | 0.0086 | 0.0086 | 0.0086 | 0.0086 |
| Intertidal | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

## Table D-12. Larvae (numbers per square meter)

| Species/Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| **Anadromous Fish** | | | | |
| **Subtidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Planktivorous Fish** | | | | |
| **Subtidal** | 21.0000 | 10.0000 | 1.0000 | 21.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Piscivorous Fish** | | | | |
| **Subtidal** | 2.1000 | 2.0000 | 0.1000 | 0.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Top Carnivores** | | | | |
| **Subtidal** | 2.1000 | 0.0000 | 0.0000 | 0.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Demersal Fish** | | | | |
| **Subtidal** | 0.5000 | 1.0000 | 0.1000 | 1.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Semi-Demersal Fish** | | | | |
| **Subtidal** | 2.0000 | 3.0000 | 1.0000 | 2.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Mollusks** | | | | |
| **Subtidal** | 2.0000 | 20.0000 | 2.0000 | 0.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Decapods** | | | | |
| **Subtidal** | 0.0016 | 0.0042 | 0.0000 | 0.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Squid** | | | | |
| **Subtidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

**Table D-13. Mammals and birds (numbers per square kilometer)**

| Species/Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| **Fur Seals** | 0.00 | 0.00 | 0.00 | 0.00 |
| **Subtidal** | 0.00 | 0.00 | 0.00 | 0.00 |
| **Intertidal** | | | | |
| **Seabirds** | | | | |
| **Subtidal** | 2.30 | 2.30 | 2.30 | 2.30 |
| **Intertidal** | 0.00 | 0.00 | 0.00 | 0.00 |
| **Waterfowl** | | | | |
| **Subtidal** | 0.00 | 0.00 | 0.00 | 0.00 |
| **Intertidal** | 5450.00 | 2190.00 | 2520.00 | 23,900.00 |

**Table D-14. Productivity (grams carbon per square meter per day)**

| Category | Spring | Summer | Fall | Winter |
|---|---|---|---|---|
| **Primary Producers** | | | | |
| **Subtidal** | 0.6800 | 0.6800 | 0.6800 | 0.6800 |
| **Intertidal** | 0.0380 | 0.0380 | 0.0380 | 0.0380 |
| **Zooplankton** | | | | |
| **Subtidal** | 0.0879 | 0.0879 | 0.0879 | 0.0879 |
| **Intertidal** | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **Benthos** | | | | |
| **Subtidal** | 0.0481 | 0.0841 | 0.0841 | 0.0841 |
| **Intertidal** | 0.0080 | 0.0080 | 0.0080 | 0.0080 |

The NRDAM/CME was applied to a hypothetical spill of 18,046 barrels of medium crude oil from a platform located 50 km off the coast of Texas on June 1, 1990. For maximum damages, it was assumed that the spill would come ashore, thus impacting subtidal as well as intertidal biota. It was assumed that 20% of the oil was cleaned up from the water surface on the day following the spill. Based on direct kills of adults and young, reduced weights of adults and young, and loss of primary and zooplankton productivity, the model calculated a total catch losses in grams (Table D-15). This results in catch losses of 3,978,452 pounds of finfish and 33,779 pounds of mollusks and decapods over the next 20 years. In addition, approximately 140 adult seabirds and 3000 adult shorebirds would be directly killed. No ducks or geese were lost.

Because oil spills are episodic rather than continuous events, ecological impacts should not be annualized. Rather, the probability of such an event occurring given the site and time specific data for crude oil supplied to a 300-MW power plant should be considered. Using Anderson and LaBelle's (1990) spill rate of 0.60 spills per billion barrels handled, the probability of a major spill occurring during the handling of the yearly 3.66 million barrels needed for the power plant is 0.0022 (spills/3.66 million barrels).

**Table D-15. Lost catch of fish and invertebrates**

| Species | Category | Lost catch (g) |
|---|---|---|
| Anadromous Fish | | |
| | subtidal | 3,650 |
| | intertidal | 0.00 |
| Planktivorous Fish | | |
| | subtidal | 112,000,000 |
| | intertidal | 0.00 |
| Piscivorous Fish | | |
| | subtidal | 23,100,000 |
| | intertidal | 0.00 |
| Top Carnivores | | |
| | subtidal | 1,630,000,000 |
| | intertidal | 0.00 |
| Demersal Fish | | |
| | subtidal | 3,640,000 |
| | intertidal | 35,900 |
| Semi-Demersal Fish | | |
| | subtidal | 41,800,000 |
| | intertidal | 0.00 |
| Mollusks | | |
| | subtidal | 21,300 |
| | intertidal | 6,700,000 |
| Decapods | | |
| | subtidal | 65,200 |
| | intertidal | 8,540,000 |
| Squid | | |
| | subtidal | 8,470 |
| | intertidal | 0.00 |

## 5.3 EFFECTS 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 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 (9 a.m. to 4 p.m. and 9 a.m. to 9 p.m. standard time) 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).

The analysis of ozone-induced incremental changes in crop yields due to the operation of the proposed 300-MW oil-fired power plant was accomplished by using literature-derived ozone-exposure plant growth response functions, reported ambient ozone levels for the southeastern reference site, and estimations of incremental ozone increases attributed to the operation of the 1990 and 2010 oil-fired power plants at the southeastern site. Insufficient data were available to calculate incremental increases in ozone at the southwestern reference site.

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-16). For a given predicted increase in ozone, crop yield loss for a particular crop can be estimated by interpolation of the data presented in Table D-16. For the southeastern reference site the existing ambient ozone level within the region was determined to be 55 ppb (12-hr seasonal average, 9 a.m. to 9 p.m., May through September), and the incremental increase in the 12-hr seasonal ozone level associated with the 1990 technology was calculated to be 1.0 ppb, and that for the

**Table D-16. Crop yield losses estimated to result from various ozone concentration (in percent)**

| Crop | Mean ozone concentration during the growing season (ppb) 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|
| Soybeans<br>(Average of 22 experiments with about 10 cultivars) | 5.6 | 10.1 | 15.5 | 21.5 | 28.4 |
| Tobacco<br>(Average of 2 experiments) | 5.0 | 9.0 | 13.0 | 18.0 | 23.0 |
| Wheat<br>(Average of 5 experiments with 3 cultivars) | 9.0 | 15.0 | 20.8 | 26.8 | 33.2 |
| Corn<br>(Average of 3 experiments with mixtures of 5 cultivars | 1.7 | 3.7 | 6.7 | 10.3 | 15.7 |
| Hay<br>(Red clover, the main type of hay grown in the case-study area) | 9 | 19 | 31 | 44 | 59 |

2010 technology was calculated to be 0.1 ppb (see Appendix C).

The approach used to estimate crop losses 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 allowed for the use of a single increased ozone level averaged over the entire area, rather than for site-specific increases; it 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 lying about half or more than half within 50 km of the site were selected. Crop loss for each county was estimated, and then total losses for all counties was determined. The total county area (acres) was used to determine the proportional crop losses on acreage within 50 km of the power plant. The percent crop loss associated with existing ambient ozone levels (55 ppb) was subtracted from that associated with the estimated 1990 increased ozone level (1.0 ppb) occurring during power plant operation.

1990 Southeastern site. Applying the ambient and predicted ozone levels during power plant operation at the 1990 southeastern site to the exposure-response functions given in Table D-16 gave the results shown in Table D-17.

Table D-17. Percentage crop loss due to increased ozone (1990 southeastern reference site)

| Crops | Crop loss (%) | Loss due to power plant (%) |
|---|---|---|
| Soybeans | | |
| existing ambient | 12.8 | |
| predicted | 13.3 | 0.5 |
| Tobacco | | |
| existing ambient | 11.0 | |
| predicted | 11.4 | 0.4 |
| Wheat | | |
| existing ambient | 17.9 | |
| predicted | 18.5 | 0.6 |
| Corn | | |
| existing ambient | 5.2 | |
| predicted | 5.5 | 0.3 |

The crops listed in the preceding table 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.

Crop production and estimated losses associated with the 1990 oil-fired power plant are shown in Table D-18.

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 yield estimated crop losses within a 50-km radius of the power plant at the southeastern site. These estimated losses are shown in Table D-19.

## Table D-18. 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) | Tobacco (1,000s lb) |
|---|---|---|---|---|---|
| Anderson | 185,200 | | | | |
| production | | *a* | *a* | 15 | 170 |
| loss | | | | 0.045 | 0.680 |
| Blount | 347,516 | | | | |
| production | | 38 | 186 | 345 | 798 |
| loss | | 0.19 | 1.119 | 1.035 | 3.192 |
| Campbell | 253,373 | | | | |
| production | | *a* | *a* | 32 | 593 |
| loss | | | | 0.096 | 2.372 |
| Knox | 228,969 | | | | |
| production | | 6.3 | 16.5 | 89 | 587 |
| loss | | 0.032 | 0.099 | 0.267 | 2.348 |
| Loudon | 142,247 | | | | |
| production | | 14 | 51 | 80 | 730 |
| loss | | 0.07 | 0.306 | 0.240 | 2.920 |
| Morgan | 342,810 | | | | |
| production | | 20 | 13.2 | 84 | 78.3 |
| loss | | 0.1 | 0.079 | 0.252 | 0.313 |
| Roane | 172,533 | | | | |
| production | | *a* | *a* | 28 | 297 |
| loss | | | | 0.084 | 1.188 |
| Anderson, Roane, and Campbell[a] | | | | | |
| production | | 3.98 | 7.84 | | |
| loss | | 0.020 | 0.047 | | |
| *Total loss* | | 0.412 | 1.65 | 2.019 | 13.01 |

[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.

**Table D-19. 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 | 0.412 | 1.65 | 2.019 | 13.01 |
| Loss within a 50-km radius of the power plant | 0.478 | 1.914 | 2.343 | 15.095 |

2010 Southeastern site. Applying the ambient and predicted ozone levels during power plant operation at the 2010 southeastern site to the exposure-response functions given in Table D-16 gave the results shown in Table D-20.

**Table D-20. Percentage crop loss due to increased ozone (2010 southeastern reference site)**

| Crops | Crop loss (%) | Loss due to power plant (%) |
|---|---|---|
| Soybeans | | |
| existing ambient | 12.8 | |
| predicted | 12.85 | 0.05 |
| Tobacco | | |
| existing ambient | 11.0 | |
| predicted | 11.04 | 0.04 |
| Wheat | | |
| existing ambient | 17.9 | |
| predicted | 17.96 | 0.06 |
| Corn | | |
| existing ambient | 5.2 | |
| predicted | 5.23 | 0.03 |

The crops listed in the preceding table 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.

Crop production and estimated losses associated with the 2010 power plant are shown in Table D-21. The total acreage occupied by the seven counties 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 yield estimated crop losses within a 50-km radius of the power plant at the southeastern site. These estimated losses are shown in Table D-22.

**Table D-21. Crop production and the estimated crop losses (2010 southeastern reference site)**

| County | Acres | Soybeans (1,000s bu) | Wheat (1,000s bu) | Corn (1,000s bu) | Tobacco (1,000s lb) |
|---|---|---|---|---|---|
| Anderson | 185,200 | | | | |
| production | | *a* | *a* | 15 | 170 |
| loss | | | | 0.004 | 0.068 |
| Blount | 347,516 | | | | |
| production | | 38 | 186 | 345 | 798 |
| loss | | 0.019 | 0.112 | 0.104 | 0.319 |
| Campbell | 253,373 | | | | |
| production | | *a* | *a* | 32 | 593 |
| loss | | | | 0.01 | 0.237 |
| Knox | 228,969 | | | | |
| production | | 6.3 | 16.5 | 89 | 587 |
| loss | | 0.003 | 0.01 | 0.027 | 0.235 |
| Loudon | 142,247 | | | | |
| production | | 14 | 51 | 80 | 730 |
| loss | | 0.007 | 0.031 | 0.024 | 0.292 |
| Morgan | 342,810 | | | | |
| production | | 20 | 13.2 | 84 | 78.3 |
| loss | | 0.01 | 0.008 | 0.025 | 0.031 |
| Roane | 172,533 | | | | |
| production | | *a* | *a* | 28 | 297 |
| loss | | | | 0.008 | 0.119 |
| Anderson, Roane, and Campbell[a] | | | | | |
| production | | 3.98 | 7.84 | | |
| loss | | 0.002 | 0.005 | | |
| *Total loss* | | 0.041 | 0.166 | 0.202 | 1.301 |

[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.

Table D-22. Estimated crop losses due to increased ozone (2010 southeastern reference site)

| | Soybeans (1,000s bu) | Wheat (1,000s bu) | Corn (1,000s bu) | Tobacco (1,000s lb) |
|---|---|---|---|---|
| Total loss in 7 counties | 0.041 | 0.166 | 0.202 | 1.301 |
| Loss within a 50-km radius of the power plant | 0.048 | 0.193 | 0.234 | 1.51 |

## 5.4 EFFECTS OF TRANSPORTATION OIL SPILLS ON MARINE AND COASTAL RESOURCES

Oil spills in marine and coastal areas due to barge transportation accidents would cause a direct and measurable ecological impact. Although effects would be site-specific and costs would depend on the economic value of the land and presence or absence of wildlife and fisheries, in general, these areas are considered valuable natural resources. This evaluation considers effects and damages due to a spill of #6 residual oil in a Gulf of Mexico coastal area.

Ecological impacts to marine and coastal resources can be estimated using case studies and models (Brown 1989, Opaluch and Grigalunas 1989, Trudel et al. 1989). The Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME) (EA and ASA 1987) provides a "Type A" natural resource damage assessment under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). Injuries can be estimated for commercially and recreationally harvested fish, lower trophic biota (the food source for other animals), birds, fur seals (not present in the Gulf of Mexico), and public beaches.

Information on the effects of an accidental spill of #6 residual oil on the coastal wetlands of Georgia can be used to identify impacts of barge accidents along the Texas, Louisiana, and Alabama coast. In 1986, approximately 12,000 barrels of oil were discharged into the estuarine Savannah River, resulting in oiling of 58 miles of shoreline and 8,000 acres of tidal marsh grasses (Brown 1989). Hunting, fishing, and presumably other recreational activities were shut down. Shellfish beds were closed. This case was the first successful implementation of the NRDA regulations. The damage assessment process considered loss of use of wetlands, replacement services of the wetlands, injury to fish and wildlife, loss of hunting and fishing days, and other injuries. A settlement was reached which provided damages of $1.2 million to the U.S. government and the states of Georgia and South Carolina.

Using the NRDAM/CMA model, Opaluch and Grigalunas (1989) partially assessed the economic risk of large (1,000 barrels) crude oil spills for natural resources in the Eastern, Central, and Western Gulf of Mexico which constitute the Louisiana Province. Their assumptions and environmental parameters are provided in the paper. Their assessment did not include injury to public beaches, private facilities, or the cost of cleanup. Costs varied with area of the Gulf coast, ranging from $11.40 per barrel of oil spilled in the Western Gulf of Mexico to $37.60 in the Eastern Gulf of Mexico. Cost per billion barrels of oil developed ranged from $600,000 in the Western Gulf of Mexico to $3,000,000 in the Eastern Gulf of Mexico.

## 5.5 EFFECTS OF OIL SPILLS ON FRESHWATER AQUATIC RESOURCES

The Tennessee-Tombigbee waterway and the Tennessee and Clinch Rivers serve several functions: navigation, recreational fishing (bass, catfish, and crappie), other recreational activities, and municipal and industrial water sources. It is estimated that barges carrying 70,000 barrels of oil every 7.8 days would traverse this system. Information on accidents rates of inland oil-carrying barges was not located. With location of data on river flow rate, number of locks and dams, and predicted size and rate of spills, simple dilution models can be adequate to predict concentrations of oil and thus calculate effects on aquatic resources. In addition, information on park visitors and creel censuses would aid in quantifying recreational costs. Costs to municipalities for water replacement would be site-specific. Lack of an appropriate model and time constraints did not permit modeling of this type of spill.

## 5.6 CONCLUSIONS

This evaluation of the ecological impacts of the oil 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 oil production and refining and the method of transport of both crude and refined oil. The size determines the magnitude of point source emissions from the power plant, as well as the incremental amount of wastes and discharges from oil 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 any impacts) would contribute, on an incremental basis, to cumulative impacts caused by other sources and defined by ambient conditions. Therefore, the conclusions discussed below must be considered in terms of the size (300-MW) and location of the power plant.

Under the scenario created for this study, the parts of the oil fuel cycle that is likely to have the greatest potential for ecological impacts are oil spills, either from a platform or during transportation of crude or residual oil. The spill of large amounts of crude or residual oil can result in significant impacts on aquatic resources. In a coastal area, 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 as oil may remain on beaches for up to two years. In the river system, recreational fishing, other recreational activities, municipal and industrial water supplies, etc., would be impacted. The coating action and toxicity of the oil would result in fish and bird mortality. Populations would be replaced in a generation or two, but biodiversity would be temporarily reduced. These impacts could be modeled. The impact of chronic discharges 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 can be considered significant. 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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