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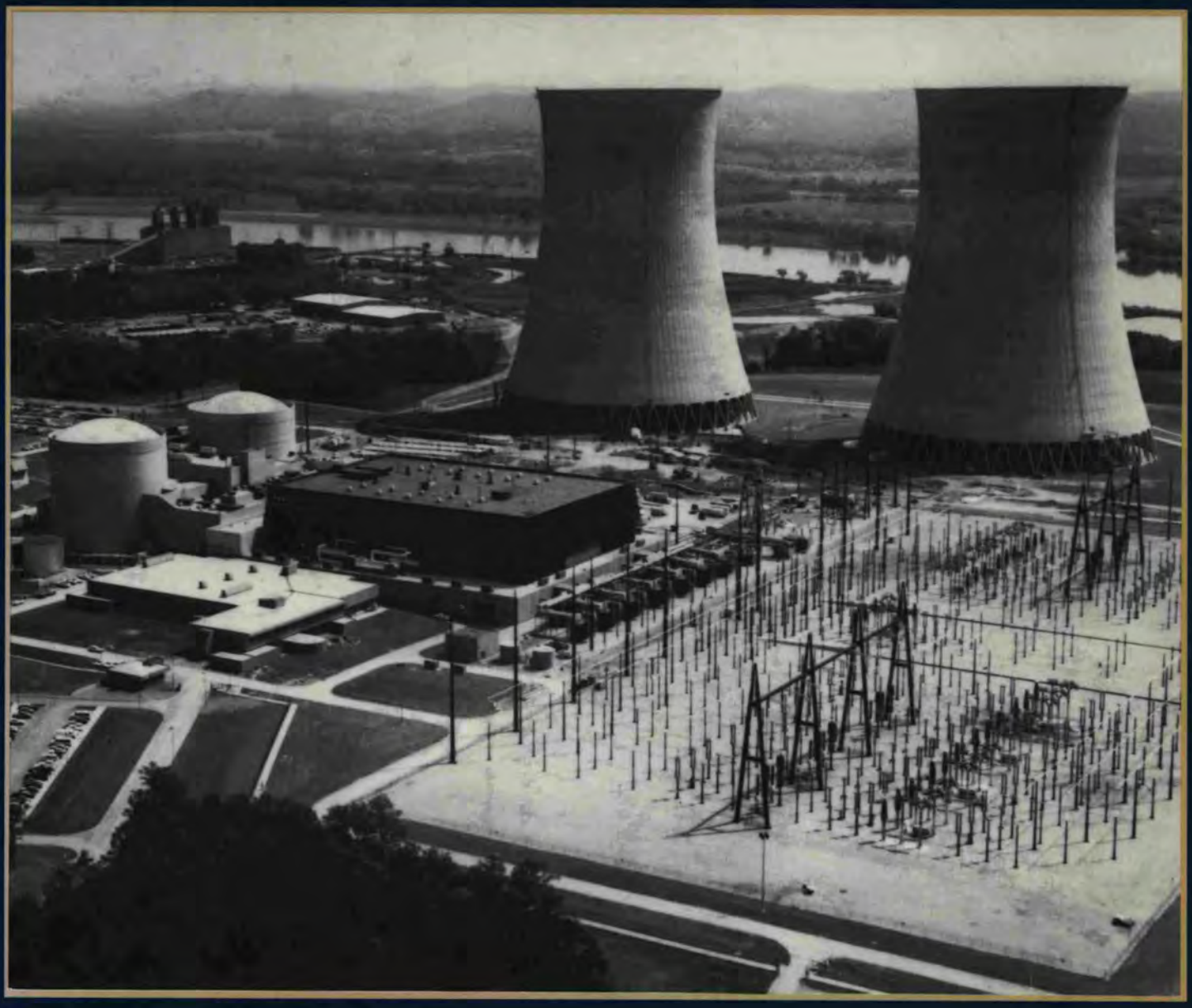
Estimating Externalities of Nuclear Fuel Cycles



Prepared by Oak Ridge National Laboratory and Resources for the Future

Report Number 8 on the External Costs and Benefits of Fuel Cycles: A Study by the U.S. Department of Energy and the Commission of the European Communities

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ESTIMATING EXTERNALITIES OF NUCLEAR FUEL CYCLES

OAK RIDGE NATIONAL LABORATORY
AND
RESOURCES FOR THE FUTURE

Report No. 8 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

April 1995

ORNL Author

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PREFACE

This report, and that of our colleagues in Europe, are the most detailed studies ever done on the externalities of nuclear fuel cycles.[1] These externalities are effects on the welfare of "third parties," that producers and consumers do *not* explicitly take into account in their decisions to produce and consume electricity from nuclear power plants. Many externalities, such as those associated with human health and ecological impacts, do not have a market. They are not exchanged using money. We nevertheless measure them in economic terms because empirical evidence on the risks that individuals voluntarily take, and on their use of their time and income, provide information for estimating the economic value of these impacts. Also, economic experiments directly provide information about individuals' willingness to spend part of their income to avoid different types of undesirable damages.

The nuclear technology that we use as a reference point in our analysis is a pressurized water reactor, common in the United States and elsewhere. This technology is not the state of the art and would not be used if a nuclear power plant were to be constructed in the future. However, it *is* representative of many currently operating plants. No new permits to construct nuclear power plants have been issued in many years, and none are imminent. Thus, this technology, though somewhat dated in terms of the latest engineering developments, is a useful point of reference for demonstrating the methodology that we develop to estimate externalities.

Nuclear fuel cycles have a number of stages: uranium mining and milling, conversion of uranium to uranium hexafluoride, enrichment, fabrication into fuel elements, use of the fuel to generate electric power, power plant decommissioning, and disposal of spent fuel. During each stage, radioactive material may be released, resulting in increased health risks and environmental damage. There are many possible "impact pathways" by which some release will lead to some impact on human health, the environment, or property. Our methodology focuses on the impact pathways that we assess a priori to be the more important, as well as those amenable to quantitative analysis. This latter consideration leads us to omit a number of impact pathways. These omissions are not so much shortcomings of our study, as they are current limitations in science and knowledge. For example, although considerable research has been done on the ecological impacts of radiation

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[1] The report by our European colleagues is by CEPN (Centre d'etude sur l'Evaluation de la Protection dans le domaine Nucleaire) 1994. *Nuclear Fuel Cycle: Estimation of Physical Impacts and Monetary Valuation for Priority Impact Pathways*. Report Number 3 of the Externalities of Fuel Cycles ExternE Project. Brussels, Belgium: European Commission, DG XII.

exposure, the ecological endpoints in these scientific studies are unsuitable for estimating broad ecosystem impacts, which this study requires for estimating externalities. Thus, as in the other fuel cycle reports, there are generally no quantitative estimates of ecological externalities, and this topic is a priority for further research.

Throughout the reports in this study, we emphasize that externalities are generally project- and site-specific. The nature of the externalities (e.g., whether they are primarily human health effects or ecological impacts), as well as their size, depend on the design of the power plant, the equipment that is installed, and the location of the power plant.[2] We find this to be the case in nuclear fuel cycles as well: the externalities are project- and site-specific. However, I think that, possibly more than any other fuel cycle, we can make certain generalizations about the externalities of nuclear fuel cycles. I invite readers to study this report, and to decide whether they agree.

Russell Lee

Oak Ridge, Tennessee
April, 1995

[2] Of course, some important externalities of fossil fuel cycles are not site-specific (i.e., the impacts do not depend on the location of the source of the emission), particularly the effects of CO_2 emissions on global climate.

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The report benefitted from the comments of many reviewers, particularly those on the DOE staff and the Fuel Cycle Peer Review Panel of the Secretary of Energy's Advisory Board (SEAB). DOE reviewers included David Boomsma, Richard Burrow, Paul Carrier, Richard Dye, Hilary Smith, and Walter Warnicke. SEAB Panel members J. Christopher Bernabo (Chair), Robert L. Dwyer, Donald C. Haney, Morton Lippmann, Joseph S. Meyer, Paulette Middleton, David Okrent, and Leonard H. Weinstein reviewed a draft of this report. I appreciate their efforts. I found their comments to be very illuminating. They provided us with considerable insight about the various perspectives that the readers of this report will have.

Our project also benefitted from the collaboration with our European colleagues, our "soul mates" in this endeavor. I especially wish to thank Mona Dreicer of CEPN, not only for the information and insights that she provided us, but for her warm collegiality as well. Thanks to Don Wilson of ORNL for providing the population data, and to Meg Talley of ORNL for her coordination of the publication effort. Thanks, too, to Corinne Boone of Ontario Hydro, who provided us with information on Ontario Hydro's activities, that we used in Chapter 2. Many others, to whom I apologize for not naming, provided us with useful information and insights. Finally, on behalf of all of the contributors, I wish to thank everyone who encouraged, supported and, yes, put up with us during this challenging project.

Russell Lee

Oak Ridge, Tennessee
February, 1995

TABLE OF CONTENTS

LIST OF TABLES xvii

LIST OF FIGURES xxv

ACRONYMS xxvii

EXECUTIVE SUMMARY ES-1
- ES.1 INTRODUCTION ES-1
- ES.2 PURPOSE OF STUDY ES-1
- ES.3 MAJOR ASSUMPTIONS AND CAVEATS ES-2
- ES.4 METHOD OF ANALYSIS ES-6
- ES.5 NUCLEAR FUEL CYCLE TECHNOLOGIES AND RELEASES ES-9
- ES.6 SELECTED IMPACT-PATHWAYS ES-11
- ES.7 SUMMARY OF NUMERICAL RESULTS ES-14
- ES.8 CONCLUSIONS ES-15
  - ES.8.1 Scope of the Study ES-15
  - ES.8.2 Usefulness of the DFA ES-25
  - ES.8.3 The More Important Marginal Impacts, Damages, and Benefits ES-25
  - ES.8.4 Information Needs ES-29

1. INTRODUCTION 1-1
   - 1.1 BACKGROUND 1-1
   - 1.2 U.S. NUCLEAR FUEL CYCLE 1-3
   - 1.3 STUDY PRIORITIES 1-6
   - 1.4 OVERVIEW OF IMPACT-PATHWAYS DAMAGE-FUNCTION APPROACH 1-11
   - 1.5 ECONOMIC VALUATION 1-14
   - 1.6 REPORT OUTLINE 1-20

2. PRIOR STUDIES OF DAMAGES AND BENEFITS FROM NUCLEAR FUEL CYCLES 2-1
   - 2.1 PACE REPORT 2-1
   - 2.2 HOHMEYER REPORT 2-4
   - 2.3 DELUCHI REPORT 2-8
   - 2.4 EWARS-RENNINGS STUDY 2-9
   - 2.5 NUCLEAR ENERGY AGENCY REPORT 2-11
   - 2.6 ONTARIO HYDRO'S ESTIMATES OF ITS NUCLEAR SYSTEM'S EXTERNALITIES 2-13
   - 2.7 PAST STUDIES PROVIDE MOTIVATION FOR STUDY PRIORITIES 2-18

2.8 MOST RECENT RESULTS OF EC NUCLEAR STUDY CONDUCTED BY CEPN 2-20

3. ORGANIZATION AND INTERPRETATION OF RESULTS . . 3-1
3.1 TYPES OF RESULTS 3-1
3.1.1 A Demonstration and An Account of the Methods 3-1
3.1.2 Identifying Information Quality and Gaps 3-2
3.1.3 Numerical Estimates of Damages and Benefits . . . 3-2
3.2 CAVEATS IN THE INTERPRETATION OF NUMERICAL RESULTS 3-4

4. NUCLEAR FUEL CYCLE OVERVIEW 4-1
4.1 REFERENCE NUCLEAR FUEL CYCLE TECHNOLOGIES 4-1
4.1.1 Uranium Mining and Milling 4-1
4.1.2 Electricity Generation 4-3
4.1.3 Transportation Shipments 4-4
4.1.4 Spent Fuel Disposal 4-4
4.1.5 Fuel Cycle Stages Not Addressed 4-5
4.1.6 Reference Fuel Cycle Material Requirements and Shipment Quantities 4-8
4.2 RADIOACTIVE EMISSIONS TERMINOLOGY FOR THE NUCLEAR FUEL CYCLE 4-10

5. URANIUM MINING AND MILLING 5-1
5.1 MINING AND MILLING TECHNOLOGY 5-3
5.1.1 Basis Used to Select Reference Technologies 5-5
5.1.2 Underground Mining 5-7
5.1.3 Acid Leach Milling 5-9
5.1.4 In-situ Mining 5-11
5.2 MINING AND MILLING SITE CHARACTERIZATION 5-11
5.3 OPERATIONAL EMISSIONS 5-15
5.3.1 Underground Mining Emissions 5-17
5.3.2 Acid Leach Milling Emissions 5-19
5.3.3 In-situ Mining Emissions 5-21
5.4 PERSISTENT EMISSIONS 5-24
5.4.1 Mill Tailings Pile 5-25
5.4.2 Mining Wastes 5-26
5.5 PRIORITY IMPACT-PATHWAYS 5-26
5.6 HEALTH EFFECTS 5-28
5.6.1 General Public Mortality and Morbidity 5-29
5.6.2 Nonradiological Occupational Health Effects . . . 5-30
5.6.3 Radiological Occupational Health Effects 5-34

5.6.4 Health Damages from Uranium Mining and Milling 5-35
5.7 ECOLOGICAL EFFECTS 5-43
5.7.1 Land Commitment 5-43
5.7.2 Water Quantity and Quality 5-46
5.7.3 Biota 5-47
5.8 EMPLOYMENT 5-48

6. ELECTRICITY GENERATION - NORMAL OPERATIONS . . . 6-1
6.1 Nuclear Reactor Technology 6-1
6.1.1 Generic Description of the Nuclear Power Generation Principle 6-1
6.1.2 Rationale for Selecting the Westinghouse PWR as the Baseline Reactor Plant for this Analysis . . . 6-2
6.1.3 Description of PWR Technology 6-6
6.1.3.1 Basic Energy Conversion Principle 6-6
6.1.3.2 The PWR Core 6-6
6.1.3.3 Heat Removal 6-9
6.1.3.4 Turbine/Generator 6-14
6.1.3.5 Control 6-14
6.1.3.6 Balance of Plant (BOP) 6-15
6.1.3.7 The PWR Life Cycle and Its Internalized Costs 6-16
6.1.3.8 Description of PWR Fuel and its Performance 6-19
6.1.3.9 Cooling Requirements 6-19
6.2 SITES 6-21
6.2.1 Introduction 6-21
6.2.2 Reference Plant Sites 6-21
6.2.3 Socioeconomic Parameters 6-22
6.2.3.1 Population 6-22
6.2.3.2 Economic Base, Housing, and Services 6-22
6.2.3.3 Transportation 6-22
6.2.3.4 Land Use 6-26
6.2.3.5 Fishing 6-26
6.2.3.6 Water Use 6-27
6.2.3.7 Other Sites and Structures 6-27
6.2.4 Environmental Parameters 6-27
6.2.4.1 Hydrology 6-27
6.2.4.2 Meteorology 6-31
6.2.4.3 Air Quality 6-31
6.2.4.4 Noise 6-31
6.2.4.5 Geology 6-31
6.2.4.6 Biodiversity 6-31

6.3 CONSTRUCTION MATERIALS REQUIREMENTS AND ASSOCIATED INDIRECT EMISSIONS 6-33
6.3.1 Material Requirements 6-33
6.3.2 Calculation of Emission 6-34
6.4 OPERATIONAL EMISSIONS 6-35
6.4.1 Airborne Radionuclides from Normal Operations 6-35
6.4.2 Liquid Radionuclides from Normal Operations . . 6-37
6.4.3 Non-Radioactive Emissions 6-39
6.5 DECOMMISSIONING EMISSIONS AND EXPOSURES 6-39
6.5.1 Airborne Radionuclides from Decommissioning . 6-40
6.5.2 Public and Occupational Exposures During Decommissioning 6-41
6.6 NUCLEAR FUEL CYCLE IMPACT PATHWAYS: CONSTRUCTION, NORMAL REACTOR OPERATIONS, AND DECOMMISSIONING 6-41
6.6.1 Pathway and Impact Tables 6-41
6.6.2 Priority Impact Pathways 6-46
6.6.2.1 Impacts from Reactor Construction . . . 6-46
6.6.2.2 Impacts from Reactor Normal Operations 6-47
6.6.2.3 Impacts from Reactor Decommissioning 6-47
6.6.3 Health Damages from Normal Operations and Decommissioning 6-47
6.7 HEALTH EFFECTS 6-50
6.7.1 General Public Mortality and Morbidity Due to Routine Releases of Radionuclides 6-50
6.7.1.1 Due to Atmospheric Releases 6-54
6.7.1.2 Due to Liquid Releases 6-55
6.7.2 Occupational Radiation Exposure 6-60
6.7.3 Latent Cancer Fatality Estimate 6-63
6.7.4 Nonradiological Health Effect 6-63
6.8 ECOLOGICAL EFFECTS 6-64
6.8.1 Land Commitment 6-64
6.8.2 Water Quantity and Quality 6-64
6.8.3 Aquatic Ecology 6-65
6.8.4 Agricultural Crops and Vegetation 6-67
6.8.5 Terrestrial Ecology 6-67
6.8.6 Priority Ecological Impacts 6-68
6.9 OTHER EFFECTS 6-68
6.9.1 Employment 6-68

7. SEVERE REACTOR ACCIDENTS - TECHNICAL EVALUATION
7.1 INTRODUCTION 7-1
7.1.1 Background 7-1

7.1.2 Nuclear Reactor Risk Assessment Methodology . . 7-1
7.1.3 Damage Estimation Methodology 7-3
7.1.4 Assumptions and Limitations of This Study 7-4
7.2 ACCIDENT SCENARIOS 7-6
7.2.1 Background 7-6
7.2.2 Post-Release Accident Scenario 7-8
7.2.3 Risks From External Initiating Events 7-11
7.2.4 Selection of Accident Sequences 7-11
7.3 ACCIDENT SOURCE TERMS AND PROBABILITIES . 7-12
7.3.1 Introduction 7-12
7.3.2 Fission Product Inventory 7-12
7.3.3 Source Term Characterization—MCF Case 7-13
7.3.4 Source Term Characterization - LCF Sequence . . 7-19
7.3.5 Comparison of Assumed Accidental Releases to TMI Source Term 7-19
7.3.6 Severity of LCF and MCF Source Terms 7-23
7.3.7 Severe Accident Probabilities (Internal Initiating Events) 7-23
7.4 SITE CHARACTERIZATIONS 7-26
7.4.1 General Modelling Assumptions and Features . . 7-27
7.4.2 Southeast Site Description 7-28
7.4.3 Southwest Site Description 7-31
7.5 PRIORITY IMPACT PATHWAYS 7-31
7.6 HEALTH EFFECTS 7-31
7.6.1 General Public Mortality and Morbidity 7-36
7.6.1.1 The Southeast Site and the Oak Ridge Reservation 7-37
7.6.1.2 The Southwest Site 7-41
7.6.2 Health Damages from Severe Power Plant Accidents 7-43
7.7 ECOLOGICAL EFFECTS 7-52
7.8 ENGINEERING ECONOMIC ESTIMATES OF OTHER CONSEQUENCES 7-52
7.8.1 Loss of Electricity Production Facility 7-55
7.8.1.1 Loss of Utility Assets and Site Cleanup Costs 7-55
7.8.1.2 Need for Replacement Power 7-56
7.8.1.3 Insurance Coverage 7-59
7.8.2 Evacuation and Temporary Relocation Costs . . . 7-59
7.8.3 Decontamination, Interdiction, and Condemnation Costs 7-60
7.8.3.1 Southeast Site Economic Consequences 7-62
7.8.3.2 Southwest Site Economic Consequences 7-64
7.8.4 Other MACCS-Calculated Costs 7-64

7.8.5 Costs for Disposal of Low-Specific Activity Wastes Resulting from Decontamination Activities 7-67
7.8.6 Summary of Engineering Economic Accident Costs for Southeast and Southwest Sites 7-70
7.8.7 Variability in Cost Estimates Due to Weather . . . 7-72
7.8.8 Conclusions 7-74
7.9 LEGAL LIABILITY, INSURANCE COVERAGE, AND THE CALCULATION OF EXTERNAL COST . . . 7-74
7.9.1 Incentives for Efficiency 7-77
7.9.2 Estimate of Externality 7-78

8. TRANSPORTATION SHIPMENTS 8-1
8.1 TECHNOLOGY 8-2
8.2 SITE CHARACTERIZATION 8-8
8.3 ACCIDENT SCENARIOS AND RELEASES 8-9
8.4 PRIORITY IMPACT-PATHWAYS 8-13
8.5 HEALTH EFFECTS 8-13
8.5.1 General Public Mortality and Morbidity 8-15
8.5.2 Occupational Health Effects 8-22
8.5.3 Health Damages from Fuel Transportation 8-23
8.5.4 Ecological Effects of Accidental HF Releases . . . 8-27
8.6 ENGINEERING-ECONOMIC ESTIMATES OF OTHER CONSEQUENCES 8-28
8.6.1 Emergency Response Costs 8-28
8.6.2 Decontamination and Property Condemnation Costs 8-29
8.6.3 Lost Productivity Costs, etc. 8-29
8.6.4 Impacts and Damages from Truck Traffic 8-33
8.6.4.1 Burden 8-33
8.6.4.2 Impacts 8-33
8.6.4.3 Economic Valuation 8-36
8.6.5 Summary of Engineering-Economic Risk 8-38

9. SPENT FUEL DISPOSAL 9-1
9.1 REPOSITORY SITE 9-2
9.2 REPOSITORY TECHNOLOGY 9-5
9.3 SPENT FUEL SOURCE TERM 9-9
9.4 PRECLOSURE RELEASES 9-10
9.4.1 Operational Releases 9-10
9.4.2 Accident Releases 9-12
9.5 POST-CLOSURE RELEASES 9-15
9.5.1 Groundwater Flow and Transport 9-17

9.5.2 Gas Flow and Transport 9-19
9.5.3 Human Intrusion 9-21
9.5.4 Volcanic Expulsion 9-25
9.6 PRIORITY IMPACT PATHWAYS 9-28
9.7 IMPACTS 9-28
9.7.1 Health Effects: Mortality and Morbidity 9-28
9.7.2 Land Commitment 9-32

10. NET NEW EMPLOYMENT BENEFITS 10-1

11. SUMMARY OF NUMERICAL RESULTS 11-1
11.1 TABULATION OF NUMERICAL RESULTS 11-1
11.2 THE MORE IMPORTANT MARGINAL IMPACTS . . 11-10
11.2.1 Scope of the Study 11-10
11.2.2 Usefulness of the DFA 11-10
11.2.3 The More Important Marginal Impacts, Damages, and Benefits 11-11
11.2.4 Information Needs 11-13

12. REFERENCES 12-1

Appendix A: ADDITIONAL ECONOMIC DAMAGE ESTIMATES EMPLOYING 5% DISCOUNT RATE A-1
A.1 INTRODUCTION A-1

Appendix B: RADIONUCLIDE INVENTORY METHODOLOGY: ORIGEN2 . . . . . B-1
B.1 ORIGEN2 DESCRIPTION B-1
B.2 BACKGROUND B-2
B.3 ORIGEN2 APPLICATIONS B-3

Appendix C: RADIONUCLIDE TRANSPORT METHODOLOGY . C-1
C.1 ATMOSPHERIC TRANSPORT C-1
C.2 AQUATIC TRANSPORT C-7

Appendix D: REACTOR ACCIDENT ANALYSIS: MACCS D-1

Appendix E: TRANSPORTATION RISK ANALYSIS: RADTRAN 4 E-1

Appendix F: ECOLOGICAL EFFECTS OF THE NUCLEAR FUEL CYCLE F-1
F.1 INTRODUCTION F-1
F.2 DEFINITIONS OF RESOURCE CATEGORIES F-1
F.2.1 Natural Biological Systems F-1

F.2.1.1 Biodiversity F-3
F.2.1.2 Commercially Valuable Natural Resources F-6
F.2.1.3 Recreationally Valuable Natural Resources F-9
F.2.2 MAN-MADE SYSTEMS F-10
F.2.2.1 Agricultural, Silvicultural, and Horticultural Industries F-10
F.2.3 NONBIOLOGICAL ENVIRONMENTAL CONDITIONS F-10

LIST OF TABLES

Table ES-1. Summary of occupational health impacts ES-17
Table ES-2. Summary of expected health effects to the general population for the southeast site ES-18
Table ES-3. Summary of expected health effects to the general population for the southwest site ES-19
Table ES-4. Expected cost of countermeasures and property losses for nuclear fuel cycle accidents ES-20
Table ES-5. Summary of nuclear fuel cycle damages and benefits estimated for the southeast site (1989$) ES-21
Table ES-6. Summary of nuclear fuel cycle damages and benefits estimated for the southwest site (1989$) ES-23
Table 1-1. Impact-pathway mappings 1-13
Table 2-1. Expected damages associated with nuclear power generation, estimated by Pace 2-3
Table 2-2. Possible variations of important parameters 2-6
Table 2-3. DeLuchi's estimates of CO_2-equivalent emissions of greenhouse gases from nuclear power plants and upstream processes in g/Kwh delivered to end user . 2-10
Table 2-4. DeLuchi's estimates of total CO_2-equivalent emissions for the nuclear fuel cycle in g/Kwh delivered to end user 2-10
Table 2-5. Estimated fatality rates per year for routine operations in the nuclear fuel cycle 2-12
Table 2-6. Nuclear fuel cycle: annual radiological health effects 2-15
Table 2-7. Nuclear fuel cycle radiological health & property externality costs (1992 cents/kWh - Can) 2-16
Table 2-8. External costs by station Dollars per tonne ($1992 - Can) 2-17
Table 2-9. Nuclear station radiological and fossil external environmental costs (1992 cents/kWh - $Can) 2-18
Table 4-1. Processed material quantities for reference fuel cycle stages 4-9
Table 4-2. Reference fuel cycle shipment quantities 4-9
Table 5-1. Ambient concentrations of airborne pollutants at the reference site 5-13
Table 5-2. Land use in the reference region 5-13
Table 5-3. Land ownership in the reference region 5-14
Table 5-4. Concentrations of chemical constituents of the water in the tributary river 5-15

Table 5-5. Air emissions from underground uranium mines (nonradioactive) 5-17
Table 5-6. Estimate of nonradioactive effluents contained in water discharges from underground uranium mines for a reactor year 5-18
Table 5-7. Nonradioactive emissions to air for an acid leach mill supporting the reactor year 5-20
Table 5-8. Composition of the nonradioactive liquid tailings slurry generated at the reference mill 5-20
Table 5-9. Major constituents in liquid waste streams for in-situ operations 5-22
Table 5-10. Annual emissions from an in-situ facility from gas or diesel powered equipment 5-23
Table 5-11. Annual nonradioactive atmospheric emissions from an in-situ leach facility 5-23
Table 5-12. Annual radioactive atmospheric emissions from an in-situ leach facility 5-24
Table 5-13. Primary emission or activities, pathways and impacts linked to the nuclear fuel cycle from uranium mining and milling 5-27
Table 5-14. Estimates of radon emissions and corresponding population health effects 5-32
Table 5-15. Nonradiological occupational accident risks 5-33
Table 5-16. Estimates of occupational radiological health effects 5-35
Table 5-17. Annual health damages from uranium mining and milling 5-40
Table 5-18. Primary emissions or activities, pathways and ecological impacts linked to the nuclear fuel cycle from mining and milling 5-44
Table 5-19. Land-use requirements for underground uranium mines 5-45
Table 6-1. U.S. power reactors and suppliers 6-2
Table 6-2. Capacities and geographic data for operating U.S. W-PWRs 6-3
Table 6-3. Domestic PWR power plant containment technology . 6-4
Table 6-4. Major PWR construction commodities 6-17
Table 6-5. Components of fuel portion of power generation cost for large W-PWRs 6-18
Table 6-6. Components of power generation cost for large W-PWRS 6-20
Table 6-7. Reference W-PWR fuel characteristics. 6-20
Table 6-8 Cumulative counts of people by radial distance and sector direction, Southeast Reference Site 6-24
Table 6-9 Cumulative counts of people by radial distance and

sector direction, Southwest Reference Site 6-25
Table 6-10. Crop production for the southeast reference environment 6-26
Table 6-11. Example of STORET (EPA water quality database) output 6-28
Table 6-12. Steel and concrete requirements 6-34
Table 6-13. Indirect emissions for reference nuclear power plant 6-35
Table 6-14. Emission factors for materials manufacture (lbs/ton). 6-35
Table 6-15. Average airborne radionuclide emissions from sample of 36 large W-PWRS 6-36
Table 6-16. Airborne radionuclide purge data 6-37
Table 6-17. Average liquid radionuclide emissions from sample of 36 large W-PWRS 6-39
Table 6-18. Radionuclides of concern during immediate dismantlement decommissioning option 6-40
Table 6-19. Summary of safety analysis for decommissioning the reference PWR by immediate dismantlement ... 6-42
Table 6-20. Primary emissions, environmental pathways, and ecologicalimpacts linked to the reactor electrical generation portion of the nuclear fuel cycle not examined in detail 6-43
Table 6-21. Emissions, environmental pathways, and ecological impacts linked to the reactor electrical generation portion of the nuclear fuel cycle not examined in detail 6-44
Table 6-22. Primary emissions, pathways, and health-safety impacts linked to the reactor electrical generation portion of the nuclear fuel cycle 6-45
Table 6-23. Emissions, pathways, and health-safety impacts linked to the reactor electrical generation portion of the nuclear fuel cycle not examined in detail 6-46
Table 6-24. Annual health damages from normal operations for the southeast reactor site 6-49
Table 6-25. Annual health damages from decommissioning for the southeast reactor site 6-51
Table 6-26. Annual health damages from normal operations for the southwest reactor site 6-52
Table 6-27. Annual health damages from decommissioning for the southwest reactor site 6-53
Table 6-28. Dose by pathway and nuclide (person-rem/yr)

for CRBR Site 6-56
Table 6-29. Dose by pathway and nuclide (person-rem/yr) for New Mexico Site 6-57
Table 6-30. Dose by pathway and nuclide (person-rem/yr) for New Mexico Site 6-58
Table 6-31. Annual average occupational dose for U.S. licensed PWRs 6-61
Table 6-32. Number of PWR workers receiving whole-body doses within specified ranges during 1989 6-62
Table 6-33. Latent cancer fatalities for normal reactor operation 6-64
Table 6-34. Primary emissions or activities, pathways and ecological impacts linked to the nuclear fuel cycle from electricity generation 6-69
Table 6-35. On-site employment levels at 37 W-PWR plants for which data are not available 6-70
Table 7-1. Mean PWR conditional containment failure probabilitiesfrom NUREG 1150 (NRC 1990) 7-7
Table 7-2. Total core inventory at the time of the accident (Becquerels) 7-14
Table 7-3. Time-dependent radionuclide class release fractions for MCF sequence 7-17
Table 7-4. Source term fission product groups 7-18
Table 7-5. Energy associated with source term for the MCF sequence 7-18
Table 7-6. Fission product group release fractions for the LCF case 7-20
Table 7-7. Source-term energies for the LCF case 7-21
Table 7-8. Comparison of LCF, MCF, and TMI fission product release fractions 7-22
Table 7-9. Comparison of total noble gas and iodine source terms for LCF, MCF, and TMI 7-22
Table 7-10. International nuclear event scale 7-24
Table 7-11. Site population characterization 7-27
Table 7-12. List of Major Impact-Pathways 7-33
Table 7-13. Health effects of direct pathways, Southeast site (MCF case) 7-38
Table 7-14. Health effects of direct pathways, Southeast site (LCF case) 7-39
Table 7-15. Total health effects (indirect plus direct pathways), Southeast site (MCF case) 7-39
Table 7-16. Total health effects (indirect plus direct pathways), Southeast site (LCF case) 7-40
Table 7-17. Health effects for Oak Ridge Reservation workers

(direct pathways, Southeast site, MCF case) 7-40
Table 7-18. Health effects of direct pathways, Southwest site (MCF case) 7-41
Table 7-19. Health effects of direct pathways, Southwest site (LCF case) 7-41
Table 7-20. Total health effects (indirect plus direct pathways), Southwest site (MCF case) 7-42
Table 7-21. Total health effects (indirect plus direct pathways), Southwest site (LCF case) 7-42
Table 7-22. Expected impacts of a nuclear power plant accident: Southeast site 7-44
Table 7-23. Expected impacts of a nuclear power plant accident: Southwest site 7-44
Table 7-24. Present value of total average cost per cancer patient assuming same risk across age groups (1989 $) 7-49
Table 7-25. Annual health damages from nuclear power plant accidents: Southeast site (1989 $) 7-51
Table 7-26. Annual health damages from nuclear power plant accidents: Southwest site (1989$) 7-51
Table 7-27. Primary emissions or activities, pathways, and ecological impacts linked to a severe reactor accident 7-52
Table 7-28. Historical replacement power costs at reference sites in same power pools as reference sites 7-58
Table 7-29. Evacuation and relocation costs: Southeast site 7-60
Table 7-30. Evacuation and relocation costs: Southwest site ... 7-60
Table 7-31. Southeast site (MCF case) costs 7-63
Table 7-32. Southeast site (LCF case) costs 7-63
Table 7-33. Southeast site (MCF case) costs Oak Ridge Reservation facility damage 7-65
Table 7-34. Southwest site (MCF case) costs 7-65
Table 7-35. Southwest site (LCF case) costs 7-66
Table 7-36. Sum of milk and crop purchase costs 7-66
Table 7-37. Costs and units affected for disposal of low specific activity materials resulting from post accident decontamination activities 7-69
Table 7-38. Summary of accident costs for Southeast and Southwest sites 7-71
Table 7-39. Total economic risk due to severe accidents 7-73
Table 7-40. Total accident costs 95th percentile weather variability 7-73
Table 7-41. Externalities of severe reactor accidents 7-80
Table 8-1. Transportation route analysis from HIGHWAY model 8-10
Table 8-2. RADTRAN 4 assumptions for the nuclear fuel

cycle externalities study transportation risk assessment 8-12
Table 8-3. Primary emissions or activities, pathways and ecological impacts linked to the nuclear fuel cycle from transportation of radioactive or hazardous materials 8-14
Table 8-4. Radiological risk per reactor year to the general population 8-16
Table 8-5. Health effects from intake of soluble uranium 8-19
Table 8-6. Effects of inhalation of HF on animals 8-20
Table 8-7. Toxic chemical risk per reactor year to the general population 8-21
Table 8-8. Incident-free radiological risk to occupational workers 8-22
Table 8-9. Annual health damages from transportation for the southeast reactor site 8-25
Table 8-10. Annual health damages from transportation for the southwest reactor site 8-26
Table 8-11. Emergency response costs per accident 8-29
Table 8-12. Decontamination and property condemnation costs for economic analysis using RADTRAN 4 8-30
Table 8-13. Decontamination and property condemnation cost for each dispersibility category 8-32
Table 8-14. Lost productivity costs for economic analysis using RADTRAN 8-32
Table 8-15. Transportation requirements 8-34
Table 8-16. Engineering-economic risk per reactor year 8-39

Table 9-1. Spent fuel source term for repository releases 9-9
Table 9-2. Operational repository releases due to failed spent fuel pins 9-11
Table 9-3. Operational repository release from excavated rock stored at the surface 9-12
Table 9-4. Preclosure repository accident scenarios involving radiation releases to the public 9-13
Table 9-5. Releases resulting from preclosure accidents at a spent fuel repository 9-15
Table 9-6. Cumulative aqueous releases from the Yucca Mountain repository for a 1,000,000 year time frame 9-18
Table 9-7. Conditional releases to the accessible environment for a human intrusion event 9-24
Table 9-8. Reference assumptions for volcanic expulsion scenario 9-29
Table 9-9. Primary emissions or activities, pathways,

	and impacts linked to the nuclear fuel cycle from spent fuel disposal	9-30
Table 9-10.	Release modes and environmental pathways used in EPA (Smith 1985) analysis of repository health effects	9-33
Table 9-11.	Number of fatal cancers per curie released from a repository	9-34
Table 9-12.	Number of genetic effects per curie released from a repository	9-36
Table 9-13.	Health effects from the Yucca Mountain repository due to long-term releases from the reference reactor spent fuel	9-36
Table 9-14.	Incremental long-term health effects from human intrusion and volcanic scenarios at Yucca Mountain repository attributable to 22.6 MT of spent fuel from the reference reactor	9-36
Table 10-1.	Matching of the input-output and unemployment table categories	10-3
Table 10-2.	United States unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990	10-5
Table 10-3.	East South Central region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990	10-7
Table 10-4.	Mountain Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990	10-9
Table 10-5.	East North Central Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990	10-11
Table 10-6.	Pacific Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990	10-13
Table 10-7.	United States input-output coefficients (multipliers) for earnings to industrial sectors	10-17
Table 10-8.	Percent probability that newly employed person was drawn from the pool	10-20
Table 10-9.	United States employment benefits (mills/kWh)	10-24
Table 10-10.	Best estimate and judgmental ninety percent uncertainty range for U.S. employment benefits (mills/kWh)	10-26
Table 11-1.	Summary of occupational health impacts	11-2
Table 11-2.	Summary of expected health effects to the general population for the southeast site	11-3
Table 11-3.	Summary of expected health effects to the general population for the southwest site	11-4

Table 11-4. Expected cost of countermeasures and property losses for nuclear fuel cycle accidents 11-5
Table 11-5. Summary of nuclear fuel cycle damages and benefits estimated for the southeast site (1989$) 11-6
Table 11-6. Summary of nuclear fuel cycle damages and benefits estimated for the southwest site (1989$) 11-8
Table C.1-1. Annual airborne radionuclide releasses for 36 W-PWRs (1988 data) C-2
Table C.2-1. Annual liquid radionuclide releasess for 36 W-PWRs (1988 data) C-8
Table F-1. Summary of resource categories and potential impacts for fuel cycle technologies F-2

LIST OF FIGURES

Figure ES-1. Impact-pathway damage function approach ES-8
Figure ES-2. Locations of the southeast and southwest reference sites ES-16
Figure 1-1. Schematic of nuclear fuel cycle 1-4
Figure 4-1. U.S. nuclear fuel cycle 4-2
Figure 4-2. Location of U.S. Gaseous Diffusion Plants 4-7
Figure 6-1. Basic PWR Arrangement 6-7
Figure 6-2. Heat Removal Loops in a Westinghouse PWR 6-10
Figure 6-3. Cooling System Schematic for 1300 MW PWR on Clinch River Site 6-12
Figure 6-4. Cooling System Schematic for 1300 MW PWR on New Mexico Site 6-13
Figure 6-5. Locations of the Southeast and Southwest Reference sites. 6-23
Figure 6-6. Wind rose at 60 m height, June-Sept, 11 a.m.-7 p.m., 1985-1990. 6-32
Figure 7-1. Atmospheric Dispersion and Removal Processes (from Till 1983) 7-9
Figure 7-2. Source term release fraction ranges from NUREG-1150. 7-16
Figure 7-3. The Southeast Plant site 7-29
Figure 7-4. The Oak Ridge Reservation and plant site. 7-30
Figure 7-5. The Southwest plant site. 7-32
Figure 8-1. Steel drum for transporting yellow cake 8-4
Figure 8-2. Truck spent fuel cask 8-7
Figure 9-1. Location of the Yucca Mountain site 9-3
Figure 9-2. Boundaries of the reference Yucca Mountain 9-4
Figure 9-3. Surface and underground facilities at the planned Yucca Mountain repository. 9-7
Figure 9-4. Expected temporal nature of repository aqueous releases in curies. 9-20
Figure 9-5. Scenarios for releases to the environment as caused by human intrusion. 9-22
Figure 9-6. Volcanic fields near the Yucca Mountain repository site. 9-26
Figure F-1. Relationship between damage and pollution. F-5
Figure F-2. Theoretical effect of the introduction of an incremental power plant on ecosystems which differ in existing deposition relative to their critical load. F-7
Figure F-3. Recovery of ecosystems following reduction of pollutant deposition to below critical loads/levels. F-8

ACRONYMS

AFUDC	allowance for funds used during construction
ANL	Argonne National Laboratory
AVLIS	Atomic Vapor Laser Isotope Separation
BNL	Battelle Northwest Laboratory
BOP	balance of plant
BRC	below regulatory concern
B&W	Babcock & Wilcox
BWR	boiling-water reactor
CE	Combustion Engineering
CEPN	Centre D'Etude sur l'Evaluation de la Protection dans le Domaine Nucleaire
CPI	consumer price index
CV	contingent valuation
DFA	damage function approach
DM	Deutsche mark
DOE	Department of Energy
DOL	Department of Labor
DOT	Department of Transportation
EC	European Community
ECCS	emergency core cooling system
EDF	Electricite de France
EPA	Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
FOAK	first-of-a-kind
FRG	Federal Repository of Germany
FTE	full-time-equivalent
FVC	Fisher, Violette, Chestnut study
GEIS	generic environmental impact statement
GWe-yr	gigawatt (electric) year
HF	hydrogen fluoride
HLW	high-level waste
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt-hours
LCF	limited containment failure
LCFs	latent cancer fatalities
LSA	low specific activity
LWR	light-water reactor
LLW	low-level waste
LLRW	low-level radioactive waste
MCF	massive containment failure
MSHA	Mine Safety and Health Administration
MT	metric tons
MW(e)	megawatt electric
MW(th)	megawatt-thermal

NERC	North American Electric Reliability Council
NMGS	New Mexico Generating Station
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
PCB	polychlorobiphenyl
PNL	Pacific Northwest Laboratory
PUC	Public Utility Commission
PWR	pressurized-water reactor
RFF	Resources for the Future
RRY	reference reactor year
SE	southeast
SF	spent fuel
SW	southwest
SWU	separative work unit
TG	turbine generator
TMI	Three Mile Island
TMI-2	Three Mile Island-2
TVA	Tennessee Valley Authority
TWh	terrawatt hour (one billion kilowatt-hours)
UF_6	uranium hexafluoride
VSL	value of a statistical life
WTA	willingness to accept
WTP	willingness to pay
W-PWR	Westinghouse pressurized-water reactor

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

Social accounting 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 of the social costs and benefits that result from production and consumption decisions. 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.

Externalities include benefits as well as damages. The benefits of nuclear power are largely reflected in what people pay for it. Therefore, these benefits are not externalities. Also, some of the damages of nuclear fuel cycles are "internalized," in the sense that utilities pay the costs of these damages. Damages that are internalized are not externalities.

The U.S. Department of Energy (DOE) and the Commission of the European Communities have recognized the importance of accounting for externalities in energy and environmental planning and policies. In a recent agreement they committed their respective organizations to develop a comparative analytical methodology to estimate the externalities of using different fuels to generate electricity.

ES.2 PURPOSE OF STUDY

This report documents the methodology developed for the nuclear fuel cycle. In this cycle uranium ore is extracted, milled to extract the uranium oxide from the host material, converted to uranium hexafluoride, enriched, fabricated into fuel pellets, shipped to the nuclear reactor, "burned" to generate electricity, and the spent fuel transported and stored. Uranium is transported between facilities between each stage of the fuel cycle. The normal operations at each stage involve processes that result in the potential release of radioactive material and other residuals; and there is the possibility

of reactor, transportation, or other accidents that result in the release of radioactive materials.

The purposes of the study are:

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

2. to identify, assess, compile, and illustrate the use of existing data and other information to develop, given the time and resources, a range of estimates of marginal (i.e., the incremental) damages and benefits associated with selected impact-pathways from a new nuclear power plant, using a representative reference technology, at two reference sites in the United States (the portion of damages and benefits not internalized in utility costs or electricity prices are externalities); and

3. to assess the state of the information available to support nuclear energy decision making and the estimation of nuclear fuel cycle 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 is the most important objective of the study. The specific numerical results are ***not*** generic. However, the models, exposure-response functions, economic valuation functions, and other analytical methods ***are***. Thus, a significant contribution of the study is the compilation of analytical methods, as well as illustrative data, that can be used in future nuclear technology-specific, site-specific studies.

ES.3 MAJOR ASSUMPTIONS AND CAVEATS

We hope that this study will be an important step towards a better understanding of the externalities of nuclear fuel cycles. This study is certainly not, however, the last word on that subject. In particular, the numerical results of this study should not be regarded as definitive estimates of the externalities of the nuclear fuel cycle. There are several reasons for this. Some of these apply to all of the fuel cycle studies:

1. Emissions, impacts, and damages are considered in the context of a fuel cycle associated with a single, new power plant. The study does

not consider the broader context of nuclear power in the country or of options other than expanding capacity.

2. All of the potentially important impacts were not necessarily addressed because of limitations in quantitative knowledge or in the resources for this study. Examples of priorities for future analysis include the issue of public perceptions of risk (as compared to estimates based on scientific and engineering analysis) of reactor accidents, impacts of the dedicated coal-fired power plants that provide electricity to the gaseous diffusion plants; impacts of the operational, decommissioning and depleted tails waste streams from enrichment processes; and the psychological/social costs to a locality of having a permanent high-level waste repository situated nearby.

3. Impacts are project-specific. Different technologies have different residual damages and benefits. It is inappropriate, for example, to apply radioactive-material release probabilities calculated for Chernobyl to modern U.S. plants. The Chernobyl design does not come close to meeting U.S. safety standards and would never be constructed in the United States or in any other country subscribing to U.S. standards.

Impacts are project-specific.

4. 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. Rather, the sites were selected so as to compare individual impacts across fuel cycles using a common geographic baseline. The sites may not be economically viable. For some of the other fuel cycles, the sites are physically implausible and alternative sites were considered. The purpose of the study is primarily to develop and demonstrate an appropriate methodology for quantitatively estimating externalities.

Impacts are generally site-specific.

5. 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.

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

Other limitations of the study pertain specifically to the analysis done on the nuclear fuel cycle:

1. Several stages of the nuclear fuel cycle were not addressed, including enrichment, conversion, and fabrication. That is not to say that these activities have no externalities. Rather, impacts associated with other stages were considered to be more important. Future study can address these other stages. The omission of the enrichment stage, in particular, may be significant and represents a high priority for future work.

2. One technology was considered - a Westinghouse pressurized-water reactor. This reactor is currently the most prevalent technology operating in the United States. In the future, other, more advanced technologies would likely be used. Their damages would be different from (presumably much less than) the ones calculated in this report. The advanced technologies are not sufficiently characterized to include in our study.

3. The study did not carry out a full probabilistic risk analysis. This type of analysis tries to account for the full range of possible parameter values in all of the sources of uncertainty. Thus, the analysis simplifies the characterization of nuclear plant risk. No externally-initiated events leading to possible reactor accidents, such as earthquakes, were considered because of the lack of applicable data.[1] Two nuclear reactor accident scenarios were used to approximate the range of possible accidents. The more severe accident had a massive containment failure (MCF) resulting in a Level 7 event (a "Major Accident") on the International Nuclear Event scale. The less severe accident, which we term a limited containment failure (LCF) case, resulted in a Level 5 event ("Accident with Off-Site Risk"). By comparison, the accident at Chernobyl was a Level 7 event and the

Two nuclear reactor accident scenarios were used to approximate the range of possible accidents.

[1]Note that reactors in the U.S. are built to meet specific earthquake standards.

Three Mile Island (TMI) accident was a Level 5 event—though our analysis was not generally based on Chernobyl or TMI data, per se.

4. Estimates of cancer were based on upper-limit coefficients, as is the practice in environmental impact assessments of nuclear facilities. Uncertainties in the source terms were not considered in the calculations - only the variability in weather conditions (which affect dispersion of released radioactive materials) and uncertainty in the economic valuation assumptions are treated. Otherwise, average estimates for impacts are generally provided rather than bounding estimates.

5. Estimates of some of the transportation and reactor accident damages, specifically the emergency response costs, evacuation costs, decontamination costs and losses from the disruption of private business activities, were based on data in the models used for the analysis, and were not independently verified in this study. These models were developed by the DOE national laboratories and are used by the Nuclear Regulatory Commission, but imbedded cost data and methodology need further review.

6. For modeling purposes, impacts for severe reactor accidents were estimated to a 1,000 mile radius. Most severe health and property damage is within 200 miles. However, some radionuclides are transported beyond 1,000 miles. In the modeling, we approximate the overall impact of this transport by completely depositing all of the radioactive emissions within the 1,000 mile radius. Environmental deposition of emissions from normal reactor operations (which, of course, are much less than releases from an accident) were tracked out to a 50 mile radius.

7. Health impacts associated with disposal of spent fuel in a geologic repository are explicitly addressed, but not economically valued. Temporary storage of spent fuel is not explicitly treated. However, all spent fuel in the U.S. is currently stored on the operating reactor sites, and occupational radiation exposure due to this temporary storage is included in the treatment of reactor operations in Chapter 6.

8. Differences between expert versus lay estimates of risk were not included in this report. Only expert estimates were used. Work on analysis of lay estimates is highly controversial. A paper that discusses this and related issues is given in ORNL/RFF (1994a).

9. Although the study distinguishes between damages and externalities (external damages are a *subset* of total damages), it is difficult to quantify the portion of the damages that are not internalized. Thus, summary Tables ES-5 and ES-6 list damages, not externalities per se.

ES.4 METHOD OF ANALYSIS

... external damages are a subset of total damages ...

The fuel cycle that was considered in this study involves the construction and operation of a new nuclear power plant. The reference nuclear technology that was analyzed is a Westinghouse pressurized-water reactor (PWR) with a large dry containment. The source of the uranium, and the conversion, enrichment, fabrication, and transportation facilities were assumed to already exist. It is unlikely that the incremental addition of one nuclear power plant would necessitate the construction of these other facilities. Other planning options such as adding units to other plants, purchasing power from other power producers, or integrated resource planning to meet system-wide or region-wide needs were not addressed in our analysis.

The damage function approach (DFA) is the methodology that is used to estimate the damages and benefits of the nuclear fuel cycle that are associated with (possible) residual emissions or other effects of fuel cycle activities. The DFA combines science and economics to estimate the expected changes in both environmental and non-environmental conditions which stem from an incremental investment (to build and operate a nuclear power plant). The DFA accounts for the various fuel-cycle stages, the nature of the engineering processes, the probabilities of accidents, environmental and meteorological baseline conditions, and findings in the economics literature on the monetary value of (avoiding) environmental, health and other impacts. The DFA uses appropriate models and other analytical tools to compute estimated damages and benefits associated with different sources of emissions and other residuals. The DFA is the most detailed and thorough approach for the purpose of estimating externalities. ORNL/RFF (1992; 1994b, Ch. 4) give additional information on the DFA.

Figure ES-1 is a flowchart that illustrates the DFA. It begins with an estimate of the residual emissions from each fuel-cycle activity and considers: (1) the probability of the release and the dispersion of released materials and the resulting increases in concentration; (2) the changes in human health, as well as in ecological and other resources which are caused by the changes in the concentrations; (3) the economic value that is placed on these impacts;

and (4) the distinction between social costs and benefits that are internalized within the market and the remaining externalities.

The concept of impact-pathways is used within the context of the DFA to define a specific 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 includes a particular emission (or set of emissions) from that activity; the dispersion and the possible physical or chemical transformation of the released material; the resulting change in its concentration in the environment; and the effect of that change, which results in a specific health, ecological or other impact. This impact is the endpoint of the pathway and the starting point for a monetary valuation of that impact.

The concept of impact-pathways is used within the context of the DFA to define a specific sequence of physical cause-and-effect linkages.

Monetary valuation in this study is done in two ways. One way is a straightforward estimate of the costs of an activity. Examples are evacuation costs based on lost work-time, and the cost of materials and resources used. The second approach is based on measuring the extent that individuals are willing to pay to avoid negative impacts or to obtain positive impacts - the so-called willingness to pay (WTP) criterion in economics that underlies modern benefit-cost analysis. Releases or other residuals from the nuclear fuel cycle result in health, environmental, and other impacts. In this study, the valuation of these impacts generally utilizes the results of past economic studies which have estimated the WTP to avoid different types of impacts.

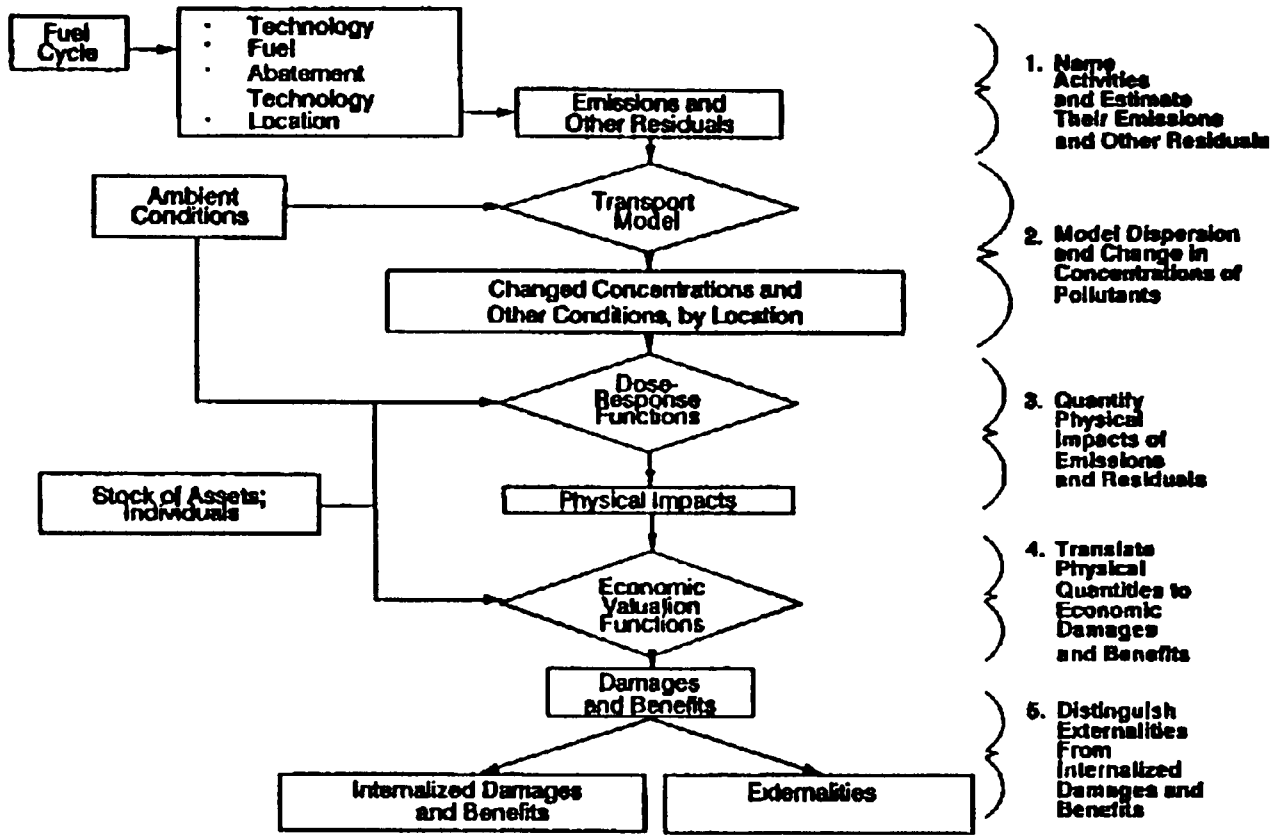

Figure ES-1. Impact-pathway damage function

ES.5 NUCLEAR FUEL CYCLE TECHNOLOGIES AND RELEASES

The benchmark technology that was used in the analysis of the nuclear fuel cycle is a Westinghouse pressurized water reactor (PWR) with a large dry containment.[2] A nominal 1300 MW(e) capacity plant with a lifetime of 40 years was assumed for each of the two reference sites. After accounting for the fact that typical operations only achieve a capacity of 1250 MW(e) and that about 100 MW(e) is used to meet on-site electric power demands, the actual net capacity of the Westinghouse PWR is 1150 MW(e). A capacity factor of 81% is assumed, resulting in net production of 8.16 billion kilowatt-hours of electricity per year. The 81% capacity factor is greater than the current industry average, but is a plausible approximation if a new plant were to be built. Many U.S. utilities are now realizing capacity factors in excess of 80%.

The benchmark technology that was used in the analysis of the nuclear fuel cycle is a Westinghouse pressurized water reactor (PWR) with a large dry containment. A nominal 1300 MW(e) capacity plant with a lifetime of 40 years was assumed for each of the two reference sites.

For other fuel cycles (e.g. coal, biomass, and small hydro), different capacities that are appropriate for those technologies are assumed. Damages, however, are all expressed on a mills/kWh basis.

Our study focuses on the stages of the fuel cycle that we have identified as potentially the most damaging in terms of their externalities: uranium milling and mining; reactor operations, including potential severe accidents; transportation of radioactive material; and permanent storage of spent fuel in a repository.

---

[2]Because of the lack of probabilistic risk assessments and projected emissions data on evolutionary advanced reactors at the time of the analysis (1993), we used conventional PWRs. This approach was consistent with our other fuel cycle studies in which, due to data constraints, we assumed that the power plant would begin operation in the year 1990. Design assessments indicate that new PWRs, advanced boiling-water reactors (BWRs), and other advanced concepts will have lower probabilities of severe damage and containment failure than those used in this study (i.e., PWRs, which already have a very low probability of severe accident). Similarly, advanced fossil-fuel and biomass technologies will have less emissions than the benchmark technologies that we assumed in those studies.

While most uranium is now imported, for the purpose of this analysis, our reference case assumes that the uranium is from domestic sources. Specifically, the uranium is assumed to be from an underground mine and associated mill, and from in-situ leaching, presently the two most likely sources in the United States. Generic sites are used for both. Mine waste includes silt, gravel, sand, volcanic ash, and lignite. Milling involves ore handling, mill concentration by hydrometallurgical reduction or leaching, and product recovery by chemical precipitation. The uranium mill tailings account for nearly all the material contained in the ore, and are thus the primary waste stream from uranium milling. In solution or in situ mining, uranium is recovered by introducing leaching solutions into the underground ore body to solubilize the uranium minerals. The primary environmental impact from solution mining is groundwater contamination.

... our reference case assumes that the uranium is from domestic sources.

The reference Westinghouse PWR uses uranium oxide fuel, fabricated into pellets, that has been enriched in the fissile ^{235}U isotope to a concentration of 4.7%. The reactor fuel is loaded and unloaded in a batch mode, with 4.5 years being the nominal length of time that each batch of fuel is in the reactor core. The reference reactor is assumed to operate in a high-burnup mode, typical of current fuel operating practice. The fuel burnup is assumed to be 52,000 MW-days of electricity per metric tonne of uranium fuel—resulting in higher concentrations of some radioactive isotopes in the fuel than for the lower burnup fuels that were standard throughout most of the 1970s and 1980s, but also resulting in lower quantities of spent fuel.

The eastern and western energy production sites were chosen to provide a commonality across the other fuel cycle documents. Due to the fact that the front and back end of each fuel cycle are not necessarily located near the energy production activity, selection of generic sites for these activities seemed appropriate.

Several options exist for reactor decommissioning, which is a stage of reactor operations for which little experience base exists. The reference decommissioning scenario is immediate dismantlement for which the reactor is assumed to be cut into sections for disposal in low-level and high-level radioactive waste repositories immediately after final shutdown of the reactor and unloading of its last batch of spent fuel.

There are five major transportation steps in a representative U.S. nuclear fuel cycle: (1) uranium oxide shipments between a uranium mine or mill and a conversion plant, (2) uranium hexafluoride shipments from a conversion plant to an enrichment plant, (3) enriched uranium hexafluoride shipments between the enrichment plant and the fuel fabrication facility, (4) shipments of assembled fuel from the fabrication facility to the nuclear reactor plant, and (5) radioactive spent fuel shipments from the nuclear reactor plant to a spent fuel storage facility. Material is transported by truck, in drums, cylinders, casks, or other packing. Our study considers accident scenarios and releases as the major potential source of damage from the transportation stage of the fuel cycle, but also includes evaluations of radiation exposure to the general public and transportation workers during incident-free transportation operations.

The spent fuel repository is assumed to be located at the proposed Yucca Mountain site in Nevada. The repository would be in the "unsaturated zone"—the rock mass between the surface of the land and the water table. The repository consists of surface facilities to receive and prepare the waste for disposal, underground facilities with "rooms" for waste emplacement, and shafts and ramps connecting the different facilities. Risks of releases of radioactive material stem from the possibility of different types of accidents during operations, prior to closure of the repository; and from possible groundwater flow and transport, gas flow and transport, human intrusion, or volcanic expulsion after closure of the repository. Most of these effects occur in the distant future, and any monetary damages would be eliminated if the wastes are discounted. Because of the legitimate concern about the effects of nuclear waste on future generations, detailed discussion of the repository is included.

ES.6 SELECTED IMPACT-PATHWAYS

Total fuel cycle externalities include those associated with the nuclear reactor plant itself, the "upstream" activities that take place to supply uranium to the plant, spent fuel disposal, and the secondary activities. Secondary activities are associated with the manufacturing of the materials and components used by the plant (particularly concrete and steel), and with the energy and materials required at various upstream stages of the fuel cycle (e.g. electricity used in uranium enrichment).

The analyses in this study indicate that the expected impacts from upstream activities (including transportation) are a significant portion of total fuel cycle externalities, as indicated by the estimates of damages given in this

report, and that any study that focuses exclusively on the generation stage underestimates total fuel cycle impacts.

Secondary emissions related to the manufacture of concrete and steel used for the reactor plant are of the same order of magnitude as those for a coal plant (on a per kWh basis) and are about two orders of magnitude less than the primary emissions from a coal-fired power plant.

Secondary emissions related to the manufacture of concrete and steel used for the reactor plant are of the same order of magnitude as those for a coal plant (on a per kWh basis) and are about two orders of magnitude less than the primary emissions from a coal-fired power plant. Electricity required in the gaseous diffusion uranium enrichment process amounts to a small but non-trivial fraction, about 2.5 to 5%, of the total electricity generated by the nuclear reactor plant.

There are many activities, processes, and potential releases associated with the nuclear fuel cycle. Due to limitations in scientific information, as well as time and resource constraints, only a subset can be addressed in any detail. Three major factors guided this setting of priorities: (a) impacts that were considered to be most important in terms of their potential damages or benefits (based on the existing literature and informed assessments); (b) impacts for which quantitative information is available; and (c) impacts that span all of the major stages of the fuel cycle. The following impact-pathways were selected for more detailed analysis.[3]

Impacts from uranium mining and milling:

- mortality and morbidity in the general population from radon emissions from operations of the mines and mills, and from persistent releases (releases that persist for long periods of time after operations have ceased) from mill tailings piles and from mining waste rock

- mortality and morbidity in mine and mill workers from inhalation of gaseous radon and radioactive airborne particulates

[3] Other impacts such as energy security and global climate change are appropriately omitted. These are not benefits of nuclear fuel cycles, but rather costs of oil and other fossil energy fuel cycles.

- occupational death and injuries due to nonradiological mining accidents.

Impacts from reactor operations:

- occupational mortality and disease from worker exposure to radiation
- occupational death and injuries due to nonradiological accidents
- mortality and morbidity in the general population due to airborne and liquid releases, particularly from radioactive xenon and argon gases, and by ingestion and inhalation of tritium.

Impacts from reactor accidents:

- public mortality and morbidity from releases of radioactive fission products into the air
- the costs of accident countermeasures such as evacuation, land condemnation and interdiction, decontamination of property, disposal of contaminated soil and other radioactive solid waste, and food and milk bans.
- the disruption to businesses and losses of property assets, including the loss of the reactor itself.

Impacts from transportation:

- mortality and morbidity to the general public, primarily due to radiation exposure when the truck shipment is at public rest stops
- public mortality and morbidity resulting from releases of radioactive material during transportation accidents
- deaths and renal injuries in the public caused by potential accidents during shipment of uranium hexafluoride, which reacts with air to form chemically toxic substances
- the costs of transportation accident countermeasures such as evacuation, land condemnation and interdiction, decontamination of property and food bans

- the disruption to businesses and losses of property assets in the locality of the accident.

- road wear from truck traffic associated with shipments.

Impacts from a permanent repository:

- health impacts from long-term releases of radioactive isotopes to the accessible environment via gaseous releases, groundwater transport, and potential disruptions to the repository such as volcanoes and human intrusion.

Impacts from employment:

- economic benefits to the site region resulting from employment of approximately 1,000 persons.

Some, but not all, of these impact pathways were identified from a review of the literature on nuclear fuel cycle externalities.

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, two specific reference sites were selected from the Southeast and Southwest regions. Figure ES-2 is a map showing the locations of the two reference sites used in the analysis.

ES.7 SUMMARY OF NUMERICAL RESULTS

The numerical analysis given in this report is illustrative of the type of analysis that is appropriate using the DFA for the nuclear fuel cycle. The numerical results are summarized in Tables ES-1 through ES-6. Tables ES-1 through ES.3 present summaries of the estimated health impacts on the general public and on the occupational workers. Table ES-4 summarizes the total cost of countermeasures, property losses and business disruption associated with severe reactor and transportation accidents. The damages in Table ES-4 attributable to limited containment failure reactor accidents are dominated by the loss of the asset value of the power reactor itself, and the replacement cost of electric power. The economic damages are summarized in Tables ES.5 and ES.6. For each of these six summary tables we show the results of the impacts and damage estimates that we calculated, but these

tables should **not** be interpreted to be a complete survey of **all** the impacts, damages, and benefits of the nuclear fuel cycle.

ES.8 CONCLUSIONS

ES.8.1 Scope of the Study

The main goal of the study is to compile a set of appropriate models and other analytical tools, and to demonstrate their use to estimate nuclear fuel cycle externalities. Analysis has focused on estimating damages. While consideration is given to externalities *per se*, additional analysis is warranted to estimate more precisely the extent these damages are already internalized through existing market, regulatory, tax, insurance, or other conditions.

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. Fuel cycle impacts are generally site-specific.

It is impossible to analyze every fuel-cycle activity, release of material, and subsequent impacts. Practical implementation of the DFA 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 expected damages or benefits. For the nuclear fuel cycle in particular, another criterion for selecting an impact-pathway is the severity of the impact should an accidental release occur.

Figure ES-2. Locations of the southeast and southwest reference sites

Table ES-1. Summary of occupational health impacts

Fuel cycle stage	Near-term health impacts		Long-term health impacts
	Deaths[b]	Injuries/ illnesses[b]	Genetic effects[b]
Uranium mining	0.0429	1.793	0.023
Uranium milling	0.0	1.230	a
Reactor operations[c]	0.2	7.7	a
Reactor decommissioning[d]	0.0128	0.1	a
Reactor accidents	a	a	a
Spent fuel disposal	a	a	a
Transportation (southeast site)	0.00029	a	a
Transportation (southwest site)	0.00013	a	a

[a]Not quantitatively estimated.

[b]Health effects are for annual operation of the reference reactor.

[c]Deaths include radiological and nonradiological causes. Injuries/illnesses are for nonradiological only.

[d]Health effects from the five years of decommissioning operations are spread over the 40 years of reactor operations.

Table ES-2. Summary of expected health effects to the general population for the southeast site

	Near-term health effects[c]		Long-term health impacts[c]	
Fuel cycle stage	Deaths	Injuries/illnesses	Deaths	Genetic effects
Uranium mining	0.0455	a	0.002	0.0015
Uranium milling	0.015	a	0.035	0.015
Reactor operations	0.00015	a	b	a
Reactor decommissioning[d]	0.00022	a	b	a
Reactor accidents	0.087	0.162	b	a
Transportation	0.0329	0.2222	b	a
Spent fuel disposal	a	a	0.304	0.0784

[a]Not quantitatively estimated
[b]No significant long-term fatalities are expected to result from this fuel cycle stage
[c]Health effects are for annual operation of the reference reactor
[d]Health effects for five years of decommissioning operations are spread over 40 years of reactor operations.

Table ES-3. Summary of expected health effects to the general population for the southwest site

	Near-term health effects[c]		Long-term health impacts[c]	
Fuel cycle stage	Deaths	Injuries/illnesses	Deaths	Genetic effects
Uranium mining	0.0455	a	0.002	0.0015
Uranium milling	0.015	a	0.035	0.015
Reactor operations	0.000007	a	b	a
Reactor decommissioning[d]	0.00022	a	b	a
Reactor accidents	0.00898	0.0169	b	a
Transportation	0.0128	0.2222	b	a
Spent fuel disposal	a	a	0.304	0.0784

[a]Not quantitatively estimated.
[b]No significant long-term fatalities are expected to result from this fuel cycle stage.
[c]Health effects are for annual operation of the reference reactor.
[d]Health effects for five years of decommissioning operations are spread over 40 years of reactor operations.

Table ES-4. Expected cost of countermeasures and property losses for nuclear fuel cycle accidents

	Number of expected accidents (per reactor year)	Conditional consequences (millions$/accident)	Expected cost ($/reactor year)
Southeast Site			
Severe reactor accidents			
Limited containment failure	4.6×10^{-5}	5,733	263,700
Massive containment failure	1.6×10^{-5}	23,809	380,940
Transportation accidents			
Spent fuel shipments	5.24×10^{-5}	9,630	504,000
All other shipments	1.5×10^{-4}	0.8	120
Southwest site			
Severe reactor accidents			
Limited containment failure	4.6×10^{-5}	6,039	277,800
Massive containment failure	1.6×10^{-5}	11,837	189,390
Transportation accidents			
Spent fuel shipments	1.18×10^{-5}	9,710	115,000
All other shipments	1.5×10^{-4}	0.8	120

Note: Most of these costs are calculated using standard models developed by the DOE national laboratories and used by the U.S. NRC, with some "default" values used for some cost parameters.

Table ES-5. Summary of nuclear fuel cycle damages and benefits estimated for the southeast site (1989$)[a,b]

Impact-pathway	Estimated damage, mills/kWh		
	Low[c]	Mid[c]	High[c,d]
Mining and milling			
Public cancer fatalities (radon)	0.00662	0.0145	0.0356
Occupational cancer fatalities	0.00521	0.0114	0.0280
Nonradiological occupational fatalities	0.00393	0.00860	0.0211
Occupational nonfatal accidents	0.00292	0.00767	0.0124
Electricity generation—normal operations			
Public cancer fatalities			
- Airborne radiation emissions	5.42×10^{-6}	0.000012	0.000029
- Waterborne radiation emissions	0.000011	0.000024	0.000058
Occupational: cancer fatalities	0.0130	0.0285	0.0700
Nonradiological occupational fatalities	0.0157	0.0343	0.0843
Nonradiological occupational injuries	0.00754	0.00971	0.0321
Electricity generation-decommissioning			
Public cancer fatalities-emissions	6.6×10^{-11}	1.4×10^{-10}	3.5×10^{-10}
Worker cancer fatalities-radiation exposure	0.000685	0.00150	0.00368
Worker fatalities-nonradiological accidents	0.000231	0.000505	0.00124
Worker morbidity-nonradiological accidents	0.000964	0.000964	0.000964
Public cancer fatalities-waste transportation	0.000012	0.000025	0.000062

Table ES-5. Summary of nuclear fuel cycle damages and benefits estimated for the southeast site (1989$)[a,b] (continued)

Impact-pathway	Estimated damage, mills/kWh		
	Low[c]	Mid[c]	High[c,d]
Severe reactor accidents			
Public fatalities	0.0098	0.0214	0.1435[c]
Public morbidity	0.0035	0.0035	0.0099[c]
Evacuation and relocation costs		0.0029	
Decontamination costs		0.0025	
Radioactive waste disposal costs		0.0108	
Interdiction costs		0.0135	
Condemnation costs		0.0052	
Crop and milk losses		0.0006	
Replacement power		0.0032	
Loss of utility assets		0.0205	
Decommissioning		0.0030	
Utility site cleanup		0.0167	
Transportation shipments			
Public cancer fatalities			
- Incident-free radiation exposure	0.00036	0.00079	0.00195
- Radioactive emissions: accidents	0.00261	0.00572	0.00141
Worker cancer fatalities (Incident-free radiation exposure)	0.00003	0.00007	0.00017
Public fatalities: accidental UF_6 releases	0.00107	0.00234	0.00574
Public renal injuries: accidental UF_6 releases		0.00025	
Cost of accident countermeasures/property loss		0.0618	
Road wear	0.00044	0.00155	.00545
Employment benefits	1.10	2.08	4.55

[a]The sum of the values is not a precise estimate of the total externalities. There would be some *under*-estimation because the table includes only those damages for which estimates were calculated; the table does not give a complete list of damages and benefits. On the other hand, some *over*-estimation may occur if the values are summed, due to the aggregation of economic values that are individually, rather than collectively, estimated.

[b]A large portion of the damages are internalized in the price of electricity, and are not externalities.

[c]The range of estimates is based on average estimates of impacts and only reflects uncertainty in economic valuation.

[d]The "high" estimates are based on 95% weather conditions with the use of high economic valuation parameters.

Table ES-6. Summary of nuclear fuel cycle damages and benefits estimated for the southwest site (1989$)[a,b]

Impact-pathway	Estimated damage, mills/kWh		
	Low[c]	Mid[c]	High[c,d]
Mining and milling			
Public cancer fatalities (radon)	0.00662	0.0145	0.0356
Occupational cancer fatalities	0.00521	0.0114	0.0280
Nonradiological occupational fatalities	0.00393	0.00860	0.0211
Occupational nonfatal accidents	0.00292	0.00767	0.0124
Electricity generation—normal operation			
Public cancer fatalities			
- Airborne radiation emissions	3.3×10^{-7}	7.1×10^{-7}	1.7×10^{-6}
- Waterborne radiation emissions	3.8×10^{-7}	8.3×10^{-7}	2.0×10^{-6}
Occupational: cancer fatalities	0.0130	0.0285	0.0700
Nonradiological occupational fatalities	0.0157	0.0343	0.0843
Nonradiological occupational injuries	0.00754	0.00971	0.0321
Electricity generation-decommissioning			
Public cancer fatalities-emissions	6.6×10^{-11}	1.4×10^{-10}	3.5×10^{-10}
Worker cancer fatalities-radiation exposure	0.000685	0.00150	0.00368
Worker fatalities-nonradiological accidents	0.000231	0.000505	0.00124
Worker morbidity-nonradiological accidents	0.000964	0.000964	0.000964
Severe reactor accidents			
Public fatalities	0.00100	0.00219	0.0118[c]
Public morbidity	0.00036	0.00036	0.0009[c]
Evacuation and relocation costs		0.000000767	
Decontamination costs		0.000354	

Table ES-6. Summary of nuclear fuel cycle damages and benefits estimated for the southwest site (1989$)[a,b] (continued)

Impact-pathway	Estimated damage, mills/kWh		
	Low[c]	Mid[c]	High[c,d]
Severe reactor accidents (continued)			
Radioactive waste disposal costs		0.00771	
Interdiction costs		0.00171	
Condemnation costs		0.00133	
Crop and milk losses		0.000251	
Replacement power		0.00557	
Loss of utility assets		0.0205	
Decommissioning		0.00304	
Utility site cleanup		0.0167	
Transportation shipments			
Public cancer fatalities			
- Incident-free radiation exposure	0.00036	0.00079	0.00194
- Radioactive emissions: accidents	0.00043	0.00094	0.00231
Worker cancer fatalities (incident-free radiation exposure)	0.00004	0.00003	0.00008
Public fatalities: accidental UF_6 releases	0.00107	0.00234	0.00574
Public renal injuries: accidental UF_6 releases		0.00025	
Cost of accident countermeasures/property loss		0.0141	
Road wear	0.000348	0.00123	0.00431
Employment benefits	0.41	0.99	3.04

[a]The sum of the values is not a precise estimate of the total externalities. There would be some *under*-estimation because the table includes only those damages for which estimates were calculated; the table does not give a complete list of damages and benefits. On the other hand, some *over*-estimation may occur if the values are summed, due to the aggregation of economic values that are individually, rather than collectively, estimated.

[b]A large portion of the damages are internalized in the price of electricity, and are not externalities.

[c]The range of estimates is based on average estimates of impacts and only reflects uncertainty in economic valuation.

[d]The "high" estimates are based on 95% weather conditions with the use of high economic valuation parameters.

ES.8.2 Usefulness of the DFA

... the negative externalities of nuclear fuel cycles are very small.

This study has demonstrated that the DFA is an operational method for estimating many of the damages and benefits of a nuclear fuel cycle. Also, as more studies are done using this approach, it will be easier and less costly to implement. In the future, many of the calculations can be "automated" further and perhaps "reduced-form" equations may be derived after the larger computer models are run many times.

Insofar as many Public Utility Commissions (PUC) in the United States, as well as many other countries, are considering ways of internalizing the external damages of fuel cycles, it seems all the more important to invest in thorough assessments to estimate the magnitude of those externalities. Regulatory burdens imposed on utilities and others are costly. They should be justified by thorough study. By the same token, the external damages to health and the environment should be accounted for and, many people feel that they should be internalized and reflected in energy prices. The DFA approach demonstrated in this study builds on insights gained from previous studies and is a further step in developing sound methodologies for estimating fuel cycle externalities. Thus, in spite of its limitations and gaps in scientific information, results gained from studies using this approach will add to the base of knowledge to support informed decisions about energy, and specifically about nuclear options.

ES.8.3 The More Important Marginal Impacts, Damages, and Benefits

In this section, we highlight the more important benefits, damages, and externalities. The overriding conclusion from Tables ES-5 and ES-6 is that the negative externalities of nuclear fuel cycles are very small, especially compared to the average cost of nuclear power, which is 5–6 cents/kWh.

Benefits. The only benefit analyzed was that of employment at the nuclear plant.[4] Because of the large staffing at nuclear plants (about 1,000 persons) and the large construction cost per MW of capacity for nuclear plants, the number of persons employed during the plant's life cycle is relatively large (on a per MW basis) compared to other power generation fuel cycles. For the SE site the benefit for the "mid" case is 2.1 mills/kWh. For

[4] The benefits of the electricity generated by the nuclear plant is internalized and reflected in the price of electricity.

the SW site, the benefit is 0.99 mills/kWh. The SE value is higher because of the higher construction unemployment rate in the SE and the fact that the model defines higher benefits to the employment of unemployed individuals. The benefit value calculated includes multiplier effects on the economy.

Damages. Occupational exposures to radiation among reactor staff resulted in estimates of about 0.12 deaths per reactor year and damages of 0.029 mills/kWh. Radiation exposure levels to the occupational staff are measured and are known unambiguously. Radiation doses to mine workers, primarily from inhalation of radon gas and other airborne particulates are also an important pathway, accounting for an estimated 0.043 deaths per reactor year with an estimated damage of 0.015 mills/kWh. Both radiological and nonradiological morbidity in the mining and milling work staff are estimated to be important, resulting in an estimated total of about 3.0 occupational injuries and illnesses per reactor year.

Nonradiological fatalities resulted in 0.08 deaths per reactor year and damages of 0.034 mills/kWh. The safety statistics (injury and fatality rate) for nuclear plants are actually somewhat lower than for a typical industrial facility. The occupational injury rate for nuclear plants is 7.7 accidents per reactor year, assuming a plant staff of 1,000 persons.

Potential severe reactor accidents had the highest estimated health impact upon the public, which was an expected number (probability multiplied by consequence) of 0.087 deaths per year for the southeast site. Our estimates were carried out to distances of 1,000 miles (1,609 km) with complete deposition of all radioactive releases. The majority of accident health effects were calculated to occur far from the reactor (from 50 to 1,000 miles), mostly due to indirect transport through food and water pathways. For example, in the massive containment failure (MCF) accident case for the southeast reactor site, 5,000 out of a total of 5,300 deaths occur at distances from 50 miles (80.5 km) to 1,000 miles (1,609 km). Overall, public cancer fatalities due to reactor accidents are estimated to have a damage of 0.021 mills/kWh.

Overall, public cancer fatalities due to reactor accidents are estimated to have a damage of 0.021 mills/kWh.

The costs of countermeasures and property losses from a severe reactor accident were calculated to be somewhat greater than the damages associated with public health impacts. As an example, the estimated cost of

countermeasures and property losses for the MCF accident at the southeast site was $23.8 billion, whereas the economic damages associated with public morbidity and deaths were estimated to be about $12.7 billion. For limited containment failure accident cases, the calculated damages are dominated by the cost of replacement power due to the loss of the reactor itself, and economic damages associated with public health impacts are relatively low.

The loss of the utility assets represents the single largest damage estimate (0.021 mills/kWh for the southeast site) for the impact pathways that have been evaluated to date.

The loss of the utility assets represents the single largest damage estimate (0.021 mills/kWh for the southeast site) for the impact pathways that have been evaluated to date. A major reason that this damage is large is that it occurs for both the LCF and MCF scenarios. Some, perhaps about 5%, of the utility on-site damages would be internalized through private insurance coverage and Price-Anderson provisions.

Another important impact was observed due to transportation accidents involving shipments of uranium hexafluoride, UF_6, to and from uranium enrichment plants. UF_6 reacts with air to form hydrogen fluoride (HF) gas and uranyl fluoride; both reaction products are gaseous and chemically very toxic. The expected impacts of public health effects from potential accidents involving shipments of UF_6 are about 0.0033 deaths from inhalation of HF and uranyl fluoride, and 0.22 permanent renal injuries, mostly from inhalation of uranyl fluoride. The estimated damage associated with permanent renal injuries is 0.00025 mills/kWh.

Emissions of radon from uranium mines are estimated to cause about 0.046 deaths to the general public per reactor year, resulting in estimated damages of 0.021 mills/kWh.

The expected value of direct financial consequences of accidents involving spent fuel shipments was estimated, at $504,000 per year or 0.062 mills/kWh for the southeast site, to be almost as high as the analogous financial consequences estimate for reactor accidents ($644,600 per year or 0.079 mills/kWh, including low specific activity waste disposal costs). This is a surprising result that may be partially explained by these factors:

- transportation accidents involving spent fuel shipments are estimated to be more probable by about a factor of three than reactor accidents involving major releases to the environment

- a small fraction of transportation accidents has the potential to occur in urban or suburban areas with higher population densities and property values than are found in the areas immediately proximate to the reference reactor sites

The expected value of direct financial consequences of accidents involving spent fuel shipments was estimated, at $504,000 per year or 0.062 mills/kWh for the southeast site, to be almost as high as the analogous financial consequences estimate for reactor accidents ($644,600 per year or 0.079 mills/kWh ...

- release fractions of radionuclides from breached spent fuel casks are higher than from damaged reactors, presumably due to the lesser containment offered by a shipping cask relative to a reactor system

- there may be inconsistencies or methodological problems with one or both estimates; though based on standard risk assessment models, additional review of the methodology is needed.

Aqueous releases of ^{99}Tc and ^{129}I and gaseous releases of ^{14}C from the repository are estimated to result in long-term health impacts of 0.304 deaths and 0.095 genetic effects to the public per reactor year. The high magnitude of these impacts may not translate into high economic damages, dependent upon whether discounting assumptions are used.

Externalities. We wish to make clear to the reader that the numerical estimates discussed thus far pertain to impacts and damages. Some of these damages are internalized, principally through legislation and private insurance. In general, all of the occupational damages are internalized, except for the decrease in quality of life. Latent health effects (both occupational and public) present a problem in terms of properly attributing them to actual cause. Thus, some of the latent health effects will likely not be internalized, even with the Price-Anderson Act.

This legislation limits the liability of nuclear operators for damages to third parties resulting from an extraordinary nuclear occurrence (ENO) that releases radioactive material that causes damages to third parties. The Act requires firms to carry $200 million in private insurance to compensate third

parties in the event of such accidents. For damages greater than $200 million and up to $7 billion, there is a pooling of liabilities shared among all nuclear operators. However, it is likely that the present financial costs of these operators do not reflect potential liability associated with the industry pool.

In the case of the risk of severe reactor accidents, 0.062 mills/kWh of the 0.104 mills/kWh in damages are externalities for the Southeast Reference case, and 0.018 mills/kWh of the 0.060 mills/kWh in damages are externalities for the Southwest Reference case.

Thus, as a result of these Price-Anderson provisions, the externalities associated with ENO's are the portions of the expected damages that are not internalized through the liability limit. In the case of the risk of severe reactor accidents, 0.062 mills/kWh of the 0.104 mills/kWh in damages are externalities for the Southeast Reference case, and 0.018 mills/kWh of the 0.060 mills/kWh in damages are externalities for the Southwest Reference case. These estimates assume that the $200 million is the effective limit to reimbursed damages.

ES.8.4 Information Needs

A major conclusion of this study is that while the base of scientific knowledge is reasonably good in some areas, it is certainly lacking in others. An important gap in our study is the lack of methodology for estimating the impacts upon public health and the environment of contaminated groundwater from in-situ leaching processes for uranium mining. This is probably the major environmental and health impact for this method of mining.

Another major need is for more realistic models of atmospheric dispersion over the long distances (1,600 km) relevant to reactor accident calculations. Current models ignore changes in wind direction and speed over the dispersion path, and are instead based upon the local weather at the reactor site at the time of the release. This simplification probably does not bias the result, but may not offer a realistic picture of dispersion transport.

A third need is to understand the effects of seismic events upon both the probability and the releases of severe reactor accidents. This effect, which is very site-dependent, may in fact dominate internally-initiated accident scenarios for some specific sites. No methodology is available to make estimates on this issue.

Another need is to examine further the UF_6 transportation accident scenario assumptions used in the estimates of health impacts (deaths and permanent renal injures). The resulting toxic cloud of chemicals formed in this accident is visible and would be readily visible under some conditions to the population at risk. Our current methodology makes some allowance for attempts of the population to avoid the relatively slow-moving cloud, but our assessment of population evacuation is subjective. Also, further research is needed on food chain effects.

In economics, a major issue in this area of research is the accuracy and precision of estimates of individuals' WTP to avoid certain health risks or ecological impacts. Estimates of the value of a statistical life and of the monetary value of morbidity vary by several factors.

The economic estimates of reactor and transportation accident costs due to countermeasures are based on scenario and parameter assumptions that require review to determine whether they are outdated. As an example, our review of the imbedded cost assumptions revealed that the cost of disposal of contaminated soil, crops, sod, and other low specific activity decontamination wastes was omitted from the reactor-accident computer code. Our rough estimate of these costs is $5.56 billion for the massive containment failure scenario at the Southeast Reference site, and $3.94 billion at the Southwest Reference site. The cost values reported in this report include these disposal cost estimates.

The crucial gap in the existence of reliable quantitative information is on the subjective or perceived risks of severe reactor accidents. Public perception of the risks of nuclear technology is pivotal to its eventual acceptance or demise.

The crucial gap in the existence of reliable quantitative information is on the subjective or perceived risks of severe reactor accidents. Public perception of the risks of nuclear technology is pivotal to its eventual acceptance or demise. The issue of WTP to avoid the perceived risk of accidents, and of its possible interpretation as an externality, is a special topic that needs to be studied further. The concept of considering public (lay) perceptions in a rigorous way, *in addition to* expert risk assessment, is an

untested approach.[5] The importance of public perception and the untested nature of the approach are all the more reason why more *social* and integrated science research should be done in this area, so as to put risk in a better social science perspective.

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 releases.
- Limitations in the knowledge base are likely to preclude quantitative estimates of subjective risk.
- The analyses are project- and site-specific (though we suggest that some degree of generalization is justified).
- 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.

Notwithstanding the above caveats, this study has demonstrated the application of the damage function approach to estimate the damages and benefits of nuclear fuel cycles. The study has identified important limitations in the quality of scientific information and in the feasibility of doing certain calculations, which preclude the possibility of quantifying all of the damages and benefits. Finally, the study has developed a range of estimates of many of the important social costs of a hypothetical nuclear reactor plant at two reference sites in the United States. These estimates form the basis for future study to distinguish more fully the external portions of these costs and benefits.

[5]ORNL/RFF (1994a) contains a paper by Markandya, Krupnick and Nickell that discusses this alternative approach.

1. INTRODUCTION

1.1 BACKGROUND[1]

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. 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, nevertheless, have value). External costs and benefits include environmental quality, health, as well as nonenvironmental considerations.

Estimating the externalities of energy production and consumption requires information about many complex factors. Information is needed about (1) the total fuel cycle for each energy source, beginning with the development and extraction of the energy resource and ending with the disposal of its wastes; (2) the production processes and technologies at each stage of the fuel cycle, particularly about emissions and other residuals; (3) changed concentrations and deposition in the environment that result from the emissions and residuals; (4) the incremental consequences, or impacts, that result from these changed concentrations, or from other physical changes, in the environment; (5) how these impacts are valued by individuals to derive the economic damages, as well as benefits, associated with these impacts; and (6) distinguishing between externalities and the damages and benefits that are already "internalized" within market prices. This series of information needs corresponds to the identification of "impact pathways," in which the effect of an emission is traced from its source to its ultimate damage or benefits. The term emission is used here to mean any residual or altered chemical or physical condition. Further discussion on these concepts is provided in the Background Document for this study (ORNL/RFF 1992) and in ORNL/RFF (1994b).

It has been recognized that "analysis is needed to account for the full costs and benefits of energy production and fuel consumption, especially taking into consideration environmental, public health, and safety concerns" (DOE 1991). The lack of high-quality information about external costs and benefits is a

[1] This report is self-contained. As such, it repeats information (such as that in Section 1.1) that is contained in other reports in this series.

handicap to making good decisions about energy. This problem was apparent both at the federal level, in terms of allocating energy research and development budgets, and at the state PUC level, in terms of conservation, fuel cycle, and technology choices. Both sets of decisions have large implications for the nation's energy future. Consequently, the U.S. DOE launched a major initiative to provide a foundation for sound decision making. The European Communities 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.

In 1991, DOE and the Commission of the European Communities (EC) signed a joint statement regarding the externalities of fuel cycles. This agreement committed their respective organizations 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 two research teams as follows:

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

A study team was created in the United States by bringing together research staff at Oak Ridge National Laboratory (ORNL) and Resources for the Future (RFF). A similar study team was organized for the EC effort. Given time and budget constraints, the U.S. and EC study teams, with the full agreement of the principals, moved to construct the foundation for improving our information about the external costs and benefits of energy fuel cycles. The study teams did not address the purely private-cost component of social costs. This activity is appropriately covered by individual DOE and other programs and involves a very different body of literature and analysis.

This foundation phase concentrated on the first five of the six areas of information needs presented in the preceding discussion—all except a complete distinction between externalities and internalized damages and benefits (discussed further in Section 1.5). Furthermore, 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.

The EC team has completed the first phase of their activity on the EC nuclear fuel cycle and have issued a draft report discussing methodology and preliminary results (Dreicer 1992).[2] Much of this methodology development has been of direct use to the U.S. nuclear fuel cycle analysis team, and we have adopted many of the general features of the EC approach. Early in the EC/US discussions on the nuclear fuel cycle project it was determined that many significant technology and site differences between the EC and U.S. nuclear systems exist and that a substantial parallel effort was required to apply the evolving methodology to the U.S. nuclear fuel cycle. Thus, this report on the U.S. fuel cycle, while similar in priorities and approach to the EC nuclear fuel cycle report, is intended to be a stand-alone report.

1.2 U.S. NUCLEAR FUEL CYCLE

This report documents the analysis of the U.S. nuclear fuel cycle. The consideration of impacts and damages due to nuclear power production must address both the nuclear reactor system itself as well as the surrounding nuclear fuel cycle. The U.S. fuel cycle has eight major operational stages, as is shown in Fig. 1-1, as well as several transportation stages.

1. The first step in the fuel cycle is **uranium mining**. In this step, uranium ore is extracted from the ground by one of several standard mining operations.

2. The uranium-bearing compounds are then separated from the raw ore and are purified and refined to "yellowcake" or uranium ore concentrate (UOC) at a **milling** facility that is often located close to the uranium mine.

3. UOC is then shipped to a **conversion** facility where it is combined with fluorine-based gases and transformed into uranium hexafluoride (UF_6) a gaseous compound at temperatures above 64°C.

4. The UF_6 is then shipped to a **uranium enrichment** plant where it is separated into a product stream and a waste stream. The product stream is concentrated, or enriched, in level of the fissionable isotope of uranium, ^{235}U, so that it may be used as fuel.

[2] The final draft of the EC report is expected to be published at about the same time as this report.

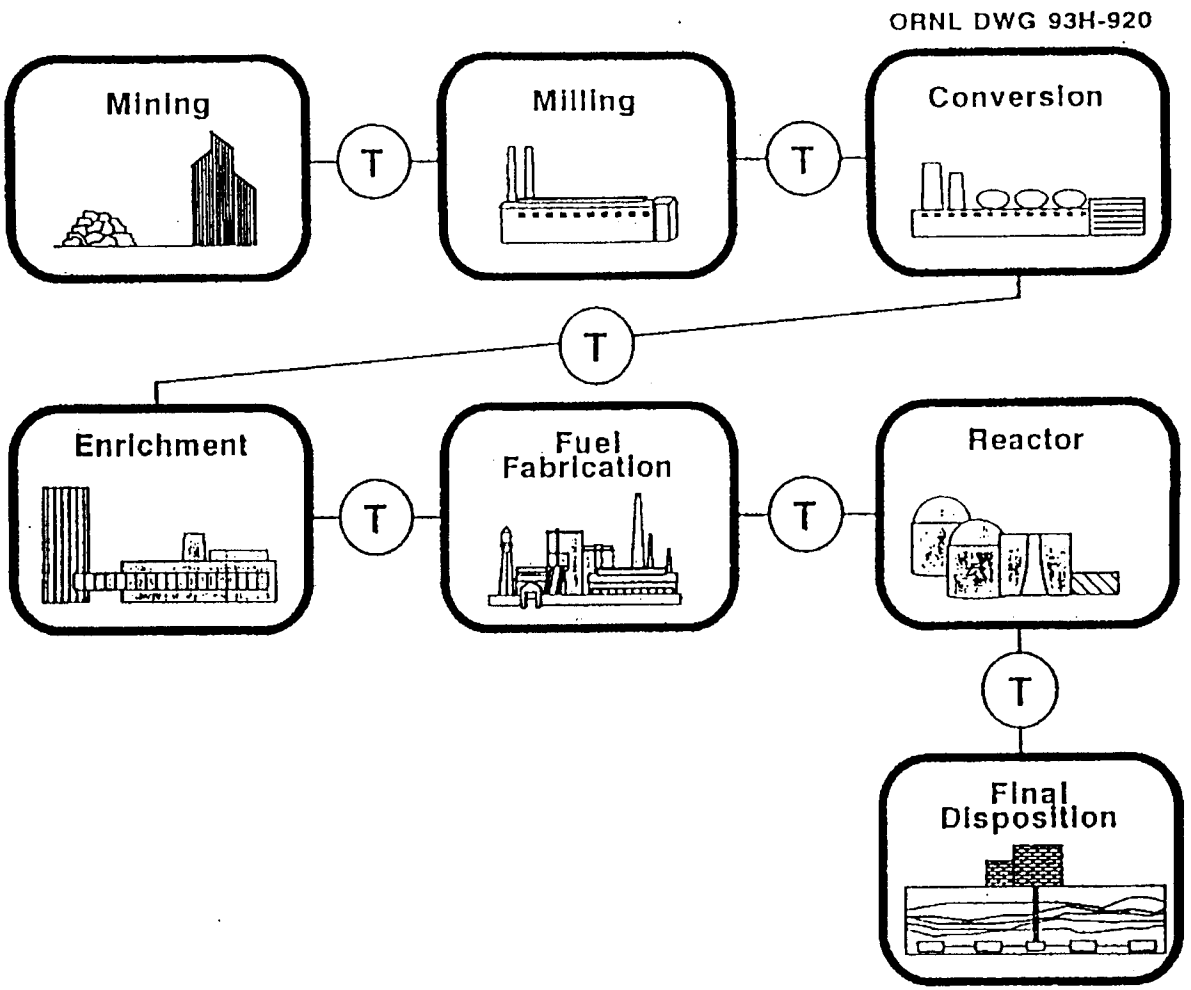

Figure 1-1. Schematic of nuclear fuel cycle

5. The enriched uranium hexafluoride is then transported to a **fuel fabrication** facility where it is converted back to a suitable chemical form and fabricated into highly engineered fuel pellets.

6. The fuel is shipped into a power reactor, which is the device used for **electricity generation.** The batch of new fuel is loaded into the reactor where it is irradiated or "burned" for a period of several years. Upon discharge, the spent fuel, which is referred to as spent fuel *(SF)*, has highly radioactive elements which pose an extreme health hazard. SF is stored on site to allow the radioactivity levels to decline with time.

7. According to current plans of the U.S. Government, SF is eventually shipped to a deep geologic **SF repository**, where it is to be placed into an engineered waste container and emplaced deep within the ground. The repository is the permanent storage site of the SF, and is intended to isolate the radioactive components from the accessible environment for periods of time that are long enough for the radiation to decay to negligible values.

8. The handling of radioactive fuel at the reactor site and handling of small amounts of radioactive materials formed by neutron activation yield a quantity of waste that is contaminated at relatively low levels with radioactive material. Such wastes include spent resins, maintenance materials, and contaminated personnel protection gear. This low-level radioactive waste (LLW) is shipped to a **LLW repository** where it is buried in near-surface facilities.

The **transportation** operations involved in shipping uranium and SF between fuel cycle facilities constitute another major type of operation (e.g., stage) in the nuclear power enterprise. In this report, the fuel cycle steps that are discussed in detail are uranium mining, milling, electricity production, the SF repository, and transportation. The fuel cycle steps that are omitted from this first phase of the study are conversion, uranium enrichment, fuel fabrication and the LLW repository. These stages were omitted because they were considered to be less important sources of fuel cycle emissions (Gotchy 1987).

Because of the hazardous materials that are present in the nuclear reactor and that are involved in several fuel cycle steps, the potential for severe accidents is an important consideration. This report addresses severe reactor accidents and transportation accidents in a quantitative way and discusses accidents at a SF repository in a qualitative manner.

1.3 STUDY PRIORITIES

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

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

2. to develop, given the time and resources, the best range of estimates of marginal damages and benefits associated with selected impact-pathways from a hypothetical nuclear reactor 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 compilation and demonstration of methods, modeling procedures, and use of scientific information is the most important objective of this study. It provides an illustrative example for those who will, in the future, undertake "actual" studies of "real" options at "real" sites.

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 necessarily addressed because of limitations in the state of quantitative knowledge or in the time and budget for this study.

2. Limitations in knowledge preclude quantitative estimates of subjective risks and of many ecological impacts. The effects of these limitations on the ability to derive quantitative estimates may vary among the different fuel cycles.

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. Of the two nuclear sites, one (the southeast site) is a likely option that has been considered for similar uses in the past, while the other (the southwest) may be economically marginal as a site. 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. Aggregation errors may arise from adding estimates of damages that are estimated separately for individual impacts.

5. This study is primarily a demonstration of methods, limited by time and budget constraints, rather than a conclusive comparison of alternative energy technologies.

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

Study Approach:

- The damage function approach (DFA) was selected by the study teams 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 a nuclear reactor plant. Figure 1-1 shows a flow chart that illustrates the DFA process. It is described further in Section 1.4 and in the Background Document (ORNL/RFF 1992) and in Chapter 4 of ORNL/RFF (1994b).

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

- Given the extreme challenges posed by dynamic modeling at the given level of knowledge, in terms of both data and the understanding of the physical and economic processes, the U.S. and EC teams chose to develop a static set of data and relationships. The term "static" describes the lack of feedback effects. For instance, we ignore the feedback effects of more impaired health on wage rates and on the demand for commodities.

Fuel-Cycle Assumptions:

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

- Fuel cycle stages encompass all of the activities involved in: (1) primary resource extraction (or growth) and preparation, (2) transport and storage of resources and materials, (3) conversion and processing, (4) power generation, (5) distribution of electricity, and (6) disposal. End-use activities are highly varied and should be addressed in future research.

- For the nuclear fuel cycle, the study focused on the following stages of activities: uranium mining and milling, electric power generation, severe reactor accidents, SF disposal in a geologic repository, and transportation interfaces between the fuel cycle stages, including refined uranium ore to the conversion plant, uranium hexafluoride to and from the enrichment plant, fresh fuel to the reactor and radioactive SF to the repository.

- The U.S. and EC teams have adopted, for simplicity, an incremental investment view of the problem, leaving the operations view to be applied in further extensions of the work. Investment and operation activities are not mutually exclusive but involve a substantially different perspective on the required information base necessary to examine pollution emissions and other effects. The operations view requires a completed characterization of the existing production system's activities to capture the change in emissions and other effects from an increase in electricity output associated with bringing a new plant on line. The investment view limits the analysis to characterizing emissions, impacts, and damages associated with the increment to output, holding the rest of the power system constant. This investment view is more appropriate in individual project decisions that, for example, a state PUC makes.

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

Scenario Assumptions:

- Two benchmark technologies had been intended for this study but only one technology, representing a current technology, has been analyzed. For the current 1990 timeframe, a Westinghouse PWR is assumed. For 2010, a

small passively safe advanced PWR was defined but not analyzed. These two technologies are generally considered to be the most likely for the two respective timeframes.

- Power plants come in many sizes, which influences their use in an existing electricity system. A review of current U.S. 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 80 megawatts electricity [MW(e]) or larger, while smaller scale is under 50 MW(e).

  The scale set for the benchmark nuclear plant is a 1,250 to 1,300 MW(e) in nameplate capacity, which, after adjusting for on-site power consumption and other factors, represents a net effective capacity of 1150 Mw(e). The benchmark plant was assumed to achieve a 81% capacity factor producing about 8,160 GWh of electricity per year for 40 years of operational life.

  Since impacts may have varied temporal distributions, the corresponding damages and benefits must reflect their placement in time: conventionally, this is done either by using a discount rate to derive present values or by using an interest rate for "levelization." The levelized cost is the amount which, when summed annually, equals the total present value of the cost over the life of the plant. This report generally uses a 3% discount rate, and puts all damages and benefits in levelized terms in mills/kWh.

This nuclear fuel cycle report is one in a series of reports that address the impacts, damages, and benefits of electricity production fuel cycles (e.g. coal, oil, gas, biomass, hydro, etc.). The study assumptions and methodology in this nuclear fuel cycle report are somewhat different than the assumptions and methodology in other fuel cycle reports, as explained below.

Methodology Differences from Other Fuel Cycle Reports

Discount Rates. The other fuel cycle reports used a 5% discount rate for the purposes of levelizing cumulative damages or damages distributed in ways other than annually for the lifetime of the plant. However, at subsequent meetings of the U.S. and EC teams, it was decided to use a 3% discount rate (social rate of time preference) as the basic rate. For this reason, this nuclear fuel cycle report has estimates of damages based on a 3% rate, but includes, as an appendix, damage estimates using a 5% rate for comparison with the fossil fuel cycle reports.

Some qualifications to this approach are necessary, however. First, a number of studies relied on in this report and in our other reports embed a discount rate in their calculations. Where the time stream of damages is irregular, there is no way of adjusting the results for a different discount rate. In this case, the most one can do is note the direction of bias. Second, the computer model used in this nuclear fuel cycle report to estimate the health and other costs associated with a severe accident embed a 12% rate of discount in the calculations. Note that the discount rate in this model has more than the usual function of bringing all damages to present dollars. It is used as part of a criterion function to decide on the extent and timing of decontamination and condemnation activities. This choice in turn determines the exposure of the population to radiation.

Treatment of Risks The issue of public perception of risk versus the expert perception of risk is important to the nuclear fuel cycle. Fears of nuclear proliferation, nuclear accidents at the plants and shipments, and concern over long-term storage have all been part of the public debate about the nuclear option and are the key issues underlying public opposition to new nuclear plants and relicensing of old nuclear plants. Much of this report has focused on addressing risks associated with nuclear accidents, but the risk estimates included in this report only correspond to the expert view of these risks. A paper in ORNL/RFF (1994a) develops a methodology to estimate damages based on the public perception of nuclear risks, and clarifies the differences between these estimates and those based on expert assessments.

In other fuel cycle reports, we have not included analyses of public perception of accident risk for events such as an oil spill, accidents at coal-fired power plants, and transportation accidents involving gas, oil, and coal. We feel that the issue of public risk perceptions is particularly important to the nuclear power option and justifies the development of the novel risk assessment methodology that is documented in ORNL/RFF (1994a).

Coverage. The reader will note that among the various possible health impacts and damages, estimates are not offered for each one in each stage of the fuel cycle. The fullest coverage is for severe accidents. The lack of impact estimates for health endpoints in particular stages is generally caused by the effect being judged insignificant. In some cases, primarily for genetic defects, an impact is estimated but cannot be valued.

Uncertainty. In other fuel cycle reports, we have tracked uncertainties in dose-response functions and valuation functions to give a range to the damage estimates. In the nuclear fuel cycle study, probabilities of accidents are explicitly modeled, but these lead to expected (midpoint) impact and damage estimates, not estimates analogous to the LOW and HIGH impact estimates found in the other

fuel cycle reports. The only uncertainty introduced is for weather conditions during a severe reactor accident. The only uncertainties that lead to LOW and HIGH *damage* estimates are those for the valuation functions. The reasons for this lack of symmetry vary by stage of the fuel cycle. For the severe accident estimates (chapter 7), the reason relates to the scope of the probabilistic risk assessment (PRA). Because of the expense of a full-blown PRA, we use two point-case scenarios to represent the range of severe accidents identified in the reference reactor. For the other fuel cycle stages we concentrate on providing the midrange, or expected, estimates for impacts.

1.4 OVERVIEW OF IMPACT-PATHWAYS DAMAGE-FUNCTION APPROACH[3]

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

The first concept, the total fuel cycle, refers to the approach in which all stages of the fuel cycle are explicitly considered, beginning with the development and extraction of a resource, and ending with the disposal of all wastes or residuals. The Background Document (ORNL/RFF 1992) describes a fuel cycle accounting framework that was developed to illustrate the stages of the coal fuel cycle and the subsequent impacts of fuel-cycle activities.

The second key concept is the DFA. This approach 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. The health effects are of the greatest direct importance and are the focus of the analysis in this report. Appendix H contains a general discussion of ecological impacts.

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, disposition, or chemical transformations of these emissions and other residuals, and the resulting changed concentrations of pollutants and other materials that are spatially and temporally distributed; (3) the physical response of ecological, human, and social resources (which are also spatially and temporally distributed) to these changes in concentrations; (4) the value that is placed on these impacts by the individuals affected; and (5) the

[3] This section repeats information contained in other volume(s) in this series of reports on fuel cycle externalities.

distinction between externalities and social costs and benefits which are internalized within the market.

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

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

Impacts are quantified using the available natural science literature to describe a pathway that may consider any or all of the following steps: the transport and chemical transformation of residual emissions, the deposition or changed concentrations of these emissions to these conditions, the exposure of environmental resources and people, and the biological and ecosystem responses. Responses may be positive or negative. The physical responses are then matched to endpoints that can be valued.

As in the other fuel cycle reports, averages or best estimates are used rather than bounding values. Exceptions to this rule are due to the great uncertainty in some estimates, and they err on the side of being conservative, i.e. larger impacts. These exceptions are made explicit in the text.

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.

- Impacts are generally site 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 nuclear

Table 1-1. Impact-pathway mappings

	Broad-level mappings	
Fuel cycle stages	→	activities
Activities	→	emissions and other residuals
Emissions	→	transport and change concentration
Transport and changed concentration	→	physical impacts
Impacts	→	economic damages and benefits
Damages and benefits	→	external costs and external benefits
	More specific mappings	
Emissions	→	source terms
Source terms	→	concentrations
Exposures	→	doses
Doses	→	responses
Responses	→	physical impact endpoints
Impact endpoints	→	valuation startpoints
Valuation startpoints	→	damages and benefits
Damages and benefits	→	external costs and external benefits

fuel cycle analysis, regional reference environments are defined for the southeast (Clinch River site, Tennessee) and southwest near Farmington, New Mexico. See Chapter 6 for the description of the regional reference environments.

1.5 ECONOMIC VALUATION[4]

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 WTP criterion in economics that underlies modern benefit-cost analysis. Emissions or other burdens imposed by the nuclear 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 depends on the type of policy in place to address these impacts and even on details of a plant's design. Because of these complexities (see Freeman, Burtraw, Harrington, and Krupnick 1992), the purpose of the current effort, insofar as health and environmental impacts are concerned, is to estimate marginal damages/benefits from a new plant and its supporting fuel cycle. It is not to estimate the extent to which such damage has already been internalized in the cost of building the plant or the electricity it produces.

The practical and conceptual problems of economic valuation are discussed fully in the Background Document. 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 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.

[4] Except for the latter part of this section, this section repeats information from other reports in this series.

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

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

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

The CV methods involve asking either open- or closed-ended questions to elicit individuals WTP 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

[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 contract, other methods must rely on realized (or *ex post*) information to infer *ex ante* values.

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 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 premia do exist. These premia 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 positively correlated 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 WTP for improvements in water quality at recreation sites.

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

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

approach have been avoided. Unfortunately, if the substitute good provides other benefits, the estimates could be too large.

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

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

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

We do not sum the damages associated with individual impacts and interpret the sum as an overall estimate of damage. One reason is that not all impact-pathways were valued. However, another reason is that in reality, individuals in the reference environment would be confronted with (offered) a package of impacts (both positive and negative) associated with the new plant. Their WTP to avoid or obtain this package may not necessarily equal the sum of their WTP for each impact, depending on complementarity or substitutability of

impacts (as well as physical interdependencies not picked up in the modeling of emissions to concentrations or concentrations to physical response).

The nonlinearity issue arises because many damage functions are nonlinear, in that the estimate of damage depends on baseline emissions, concentrations, or physical impacts. In the economic valuation, practical considerations have dictated that we generally use linear versions of nonlinear functions. Note here that we do not use a nonlinear valuation function for estimating WTP to avoid increased risks of premature death, where the nonlinearity is related to the size of the risk change.

The issue of non-use values, while not an issue special to this project, is nonetheless particularly controversial. One side in the debate over whether such values can be credibly estimated asserts that lack of familiarity with the "goods" at issue (such as an ecosystem, an endangered species, or a wilderness area) and the embedding effect (i.e., where WTP is sensitive to whether a good is valued by itself or as part of many other goods) make it inherently impossible to reliably estimate the WTP for such goods through hypothetical questioning. It is asserted (Kahneman and Knetch 1992) that observed WTP values are for the purchase of "moral satisfaction" not a WTP for marginal changes in the good. The other side suggests that the studies relied upon for these conclusions are faulty and that normal economic behavior can explain most of the observed allegedly inconsistent patterns of WTP responses (Smith 1992). Similar conclusions have also been reached about an Exxon-funded effort that concluded CV was an unreliable tool for eliciting non-use values.

Special Valuation Considerations Associated with the Nuclear Fuel Cycle

There are two issues in valuation that are special, if not unique, to the nuclear fuel cycle damage problem, at least in the context of the approach taken in this report. These include: (i) the use of large, non-transparent models to estimate impacts and damages and the divergence of these models from methodologies appropriate to the welfare theoretic paradigm, and (ii) the pervasiveness of health impacts with a latency period.

(i). Estimation of impacts and damages from severe nuclear accidents and accidents associated with the transport of nuclear material was undertaken using large computer models (MAACS for power plant accidents and RADTRAN for transportation accidents) that were developed by the DOE National Laboratories and are used by the Nuclear Regulatory Commission. These models generate estimates of health and other (e.g. evacuation related) impacts and then apply various unit values and algorithms to estimate damages associated with these impacts. The approaches followed do not generally conform to accepted principles of welfare analysis, where these principles otherwise lie at the heart of the DOE

Fuel Cycle Study. It is important to point out that, in the chapters in which these models are discussed and their results are presented, no attempt was made to adjust or modify these models to follow a more acceptable approach. It should also be noted that not all of the damage estimates made in the other fuel cycle studies conform to accepted welfare-theoretic principles.

However, a forthcoming chapter (which will be forwarded as a White Paper in the current round of research) does investigate at least some of the welfare-theoretic problems with using the approach taken by the MAACS model and makes some attempt to offer simulation results and correction factors. Resources were insufficient for any attempt at specifically adjusting or correcting for similar deficiencies in the computer model used to analyze transportation accident risk. The problems discussed in the forthcoming chapter relate to limitations in the current analysis: (a) implicitly using risk neutral utility functions (i.e., ignoring risk aversion), (b) taking an ex post rather than the conceptually correct ex ante approach to valuation, and (c) relying solely on expert assessments of risk rather than also considering lay assessments (informed by the experts).

(ii). In our previous fuel cycle studies, the latent effects of exposure to pollution on health did not figure prominently in the valuation sections because the primary latent health effect is cancer and pathways leading to cancer effects were not often judged to be priority pathways. In the nuclear fuel cycle, with cancers being such an important health effect, the issue of latency needs to be addressed more systematically.

Latent health effects can arise from two different sources: a one-time exposure to radiation (or other carcinogenic pollutant), which would be associated with a reactor or transportation accident; and a "normal" exposure to radiation (or other carcinogenic pollutant) over the course of an individual's life. In the first case, the conceptually correct measure of damage is the willingness to pay of individuals to avoid the possibility of a one-time exposure that, if it occurred, might result in a cancer developing sometime in the future (for most people, far into the future, or even in future generations). There are no studies providing such information. The closest we can get are studies that ask for the WTP to avoid an increased risk of cancer from an annual consumption of water that contains a carcinogen. And even these studies use scenarios where hypothetical cancer risks are larger than those applicable to the nuclear cycle. Thus, we must rely on studies that provide the WTP to avoid accidental death risks, i.e., death risks without a latency period.

Our approach to the latency issue for one-time exposures is necessarily ad hoc. It assumes that individuals would value reducing risks of accidental death x years in the future equivalently to reducing the risk today of developing cancer

and dying in x years. As the probability of an accident is assumed to be constant each year and cancer risks are estimated in annual terms, we simply use an estimate of the average latency period for cancer (if appropriate, varied by type of cancer) to date the onset of cancer and discount the accidental death WTP estimates from the date of onset to the present. Multiplying the discounted WTP estimate by expected deaths from cancer gives the annual expected damage from an accident.

In the second case, exposures are continuous. Here, the conceptually correct measure is the WTP to avoid a time stream of exposures that causes a cumulative increase in cancer risks. Given the lack of relevant valuation studies, we take a simple approach. First, we make the standard assumption that the dose-response function is linear, so cumulative risk is the sum of annual risk. Second, we assume that valuation is linear in risk. Thus, the WTP to avoid an increase in risks over two years is equivalent to the WTP to reduce twice the risk in one year. Then, the WTP to reduce annual cancer risk is the same as the levelized WTP to reduce cumulative risks. Finally, to address latency, as in the first case, we use an estimate of the average latency period for cancer to date the onset of cancer and discount the accidental death WTP estimates from the date of onset to the present. Multiplying the discounted WTP estimate by the annual expected deaths from cancer gives the annual expected damage for the annual exposure.

1.6 REPORT OUTLINE

This report summarizes the collection, assessment and application of existing literature to estimate selected damages and benefits from the nuclear fuel cycle. In Chapter 2, a brief review of other recent attempts to accomplish this goal is presented for contextual background. Chapter 3 provides a discussion of the organization of the results that is critical to interpreting the analysis which follows in Chapters 5 through 10. Chapter 4 defines the reference technologies and fuel cycle flows on which our analysis is based. Chapters 5-10 each present the technology, releases, priority impact-pathways, and impacts and damages associated with a portion of the nuclear fuel cycle. Chapter 5 treats both the uranium mining (extraction) and the milling steps of the fuel cycle. Chapter 6 reviews the normal operations of the nuclear reactor system while Chapter 7 discusses severe accidents associated with the reactor. Chapter 8 treats all the major transportation steps in the nuclear fuel cycle and evaluates both normal transportation operations and accident scenarios. Chapter 9 discusses the disposal of spent fuel. Chapter 10 presents employment benefits for the total fuel cycle. Chapter 11 presents a summary of the results and key conclusions.

The appendices present additional information on the methodologies and mathematical models used in the evaluation, as well as additional detailed information on severe accident scenarios for transportation and for the reactor.

2. PRIOR STUDIES OF DAMAGES AND BENEFITS FROM NUCLEAR FUEL CYCLES

Several studies share similar characteristics with this study. These studies include the *Environmental Costs of Electricity* by the Pace University Center from Environmental Legal Studies (1990), *Social Costs of Energy Consumption* by Olav Hohmeyer (1988), *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity* by M.A. DeLuchi (1991), "Abschatzung der Schaden durch einen sogenannten Super-GAU" by Ewars and Rennings (1991), the *Broad Economic Impact of Nuclear Power* published by the Nuclear Energy Agency (1992), Ontario Hydro's (1993) study, and the results of the European Commission's nuclear fuel cycle study. The following sub-sections briefly summarize the studies.

2.1 PACE REPORT

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 causes these impacts to be excluded from the computations of economic damages. The Pace report does not distinguish between damages and external costs. Based on a study of their analysis, we believe that Pace has estimated damages and not necessarily external costs.

The report examines the damages related to severe reactor accidents, as well as those associated with the routine operation of nuclear power facilities. Health impacts and property damage are both discussed. External costs accruing to the public sector (i.e., property damage and wildlife costs) are also discussed. Non-routine operations, including spills of mildly radioactive water, equipment failure, and the like, are also addressed.

The report discusses the damages of accidents in terms of reactor accident probability, health costs, and property damage. The damages associated with the possibility of severe reactor accidents comprise the major portion of total nuclear fuel cycle damages. Decommissioning and waste disposal costs contribute a significant, though much smaller portion.

The estimates derived for damages to human health rely on values of $4 million per premature death and $400,000 per major illness. The Pace dose-response functions appear to be linear over the range of 100 to 300 rem. That is, the probability of getting cancer increases in a linear fashion with increasing doses of radiation.

Health effects are divided into immediate and latent costs. Immediate injuries result from non-radiological accidents while latent injuries are caused by cancer. Pace states that "it is not clear whether any of these occupational injuries develop into deaths that would then be double-counted with latent injuries."

The results for immediate occupational mortality are derived using numbers from Shuman and Cavanagh (1982), Cohen and Pritchard (1980), and Spangler (1979). Pace states that "all the underlying sources of data for these studies are somewhat dated...thus none of these studies reflects the future level of occupational injuries and deaths because of the aging of nuclear power plants" (Pace). The results for latent occupational health impacts were derived using studies conducted by the Bonneville Power Authority, Shuman and Cavanagh, and Spangler.

Health costs from nuclear accidents were estimated using information from the U.S. DOE and data from the Chernobyl accident. Property damage was also estimated using Chernobyl data and studies conducted by Heising and George (1986) and Shuman and Cavanagh (1982).

Costs from decommissioning were derived using estimates for different decommissioning methods and different reactor sizes. Pace determined that these costs, which were derived for the year 1986, are likely to be significantly understated because of the escalation of decommissioning costs each year.

Table 2-1 summarizes the damages estimated by Pace for each of the stages discussed above. All numbers are expressed in cents/kWh. It is important to note that the analysis was not a complete examination of the total nuclear fuel cycle. The front-end, as well as other, fuel cycle costs were intentionally omitted. These costs include those from mining accidents, disposal of nuclear wastes, wildlife issues, thermal pollution damages, and property damage from routine operations. All were not estimated or not discussed due to lack of studies or information. Therefore, to obtain a more accurate estimate of total damages, further research is needed. Notwithstanding its limitations, the Pace (1990) report stands as a path-setting, though controversial, reference on the environmental costs of electricity. Pace estimates that the major impact from the nuclear fuel cycle is from projected fatalities resulting from low-level radiation doses to the population as a result of severe reactor accidents.

Table 2-1. Expected damages associated with nuclear power generation, estimated by Pace

		Expected damages (cents/kWh)
Routine operation		
(a)	Human health costs	
	Immediate occupational mortality	0.007
	Latent occupational mortality	0.07
	Occupational morbidity	0.02
	Public mortality	0.001
(b)	Wildlife costs	0.01
Accidents		
(a)	Human health	2.0
(b)	Property damage	0.3
Decommissioning and waste disposal		0.5
Total		2.908

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. DOE, Oceana Publications, Inc. New York.

As stated above, in its calculations, Pace uses radioactivity release from the Chernobyl accident as the basis for its damage calculations of U.S. reactors. The Chernobyl reactor did not have containment, whereas existing (and any future) U.S. reactors have containment structures. Thus, the Pace study equates the frequency of a core-meltdown accident with that of a catastrophic release of radioactive materials following a containment failure. However, these are two different types of events. If instead, containment were considered, then an estimate of the type of release postulated by Pace could be 1/300 the frequency that was estimated by Pace. The estimates in Pace for mortality and morbidity would thus be too large (by as much as a factor of 300 or more) to be applied to the types of reactors currently in use in the United States.

Also, Pace's estimates of the costs of decommissioning could be a factor of 10 too high because the extrapolation methodology that Pace uses may be inappropriate. Furthermore, the funds that are set aside by utilities, and that are thus internalized in the rates paid by consumers, may be adequate to cover decommissioning costs. Therefore, the external costs of decommissioning could be zero. See Chapter 6 for some discussion of such costs.

The Pace report is one of the important studies in the literature on fuel cycle externalities. Unfortunately, many readers of the Pace study have not heeded its warning that its numbers are "starting points," and are not definitive estimates of externalities.

2.2 HOHMEYER REPORT

One of the first attempts to develop fuel cycle-based social costs was by Hohmeyer (1988). The purpose of the Hohmeyer (1988) study is "to give a first systematic evaluation of the external effects of energy systems" (Hohmeyer 1988). The study's premise is that the market diffusion of energy systems using new and renewable sources of energy (such as solar and wind) is occurring much slower than the external costs and benefits would deem necessary. Hohmeyer (1988) proceeds differently from the research in the present volume. Our study applies the damage function approach (DFA) to estimate the marginal damage from an additional generation plant of a given technology operating in a specific reference environment (ORNL/RFF 1992). Hohmeyer (1988), on the other hand, estimates the total damage in the country [Federal Republic of Germany or FRG (Germany was not united at the time of the study)].

Hohmeyer's calculations of damage estimates concentrate mainly on possible failures of nuclear power plants and, as such, he believes that "they probably underestimate considerably the potential damages of nuclear power" (Hohmeyer 1988). The analysis quantifies the effects of large meltdown accidents, and does not address the effects of routine operation of a nuclear power plant. Hohmeyer indicates that this should lead to an underestimation of approximately 30% of total human health effects due to normal operations.

In this analysis, Hohmeyer uses the estimates of damages to human health resulting from the Chernobyl incident as a "starting point." Hohmeyer begins by assuming that the average working person's net domestic product is 50,000 DM/a (approximately $21,000 U.S. dollars). Each working person has an average working life of 40 years, and for an average cancer fatality there is a loss of half of this working life. Non-fatal cancers result in the loss of 10 working years. Hohmeyer also assumes a mortality rate of 50 percent for each cancer incidence. Using these assumptions, a fatal cancer incidence results in the loss of 1,000,000 DM ($420,000), while each non-fatal cancer incidence results in losses of 500,000 DM or $210,000.

In order to determine the losses resulting from a serious nuclear accident, Hohmeyer again uses data from Chernobyl. A 240 million person rem exposure is assumed as a result of the Chernobyl incident and approximately 200-3,700 cancer incidents are assumed to occur for each 1 million person rem (Bott 1987). These numbers yield a range of cancer incidents from 48,000 to 888,000 for the entire area affected by the Chernobyl accident. The share allocated to the Federal Republic of Germany is estimated to be 12 million person rem. Therefore, the corresponding numbers are 2,400 to 45,000 cancer incidents in the FRG. The health damages for the entire area affected by the Chernobyl accident are estimated to be $15,000 million to $280,000 million. The damages specific to the FRG area are $760 million to $14,000 million.

In order to calculate the damage per kWh, information is needed on the average probability of a major reactor accident and on the average electricity production per year. An average reactor size of 1250 MW is assumed with an average annual operation period of 6,000 hours at nominal load. This yields a production of 7.5 TWh/year. The probabilities for nuclear accidents range from 2,000 to 20,000 operation years per accident. Both of the resulting damage estimates are from 0.01 to 1.9 cents/kWh. These figures are a minimum damage range. Table 2-2 (adapted from Hohmeyer 1988) below illustrates other possible variations of important parameters such as nuclear accident probability and variation in the number of cancer incidents. The table shows the effect these variations can have on production losses due to the expected health effects of reactor accidents.

Table 2-2. Possible variations of important parameters

Cases considered	% of released radioactive inventory 1-50% (0.25-12.5)[1]	Population density (0.5-10)[2] Result in million person rem	Cancer incidents per 1 million pers. rem (200-3,700)[1]	Cancer incidents per nuclear accident	Production losses per nuclear accidents (million dollars)	Probability of nuclear accidents (one accident per 2,000-20,000 years of operation)	Electricity produced per nuclear accident	Production losses/kWh nuclear electricity produced (10^{-2} American dollars per kWh)
General nuclear accident based on the impact of Chernobyl (240 million person rem)	0.25	0.5	200	6000	1890	20000	150000	0.0013
						2000	15000	0.0126
			3700	111000	34980	20000	150000	0.0233
						2000	15000	0.2332
		10	200	120000	37815	20000	150000	0.0252
						2000	15000	0.2521
			3700	2220000	699580	20000	150000	0.4664
						2000	15000	4.663
	12.5	0.5	200	300000	94540	20000	150000	0.063
						2000	15000	0.6303
			3700	5500000	1733800	20000	150000	1.155
						2000	15000	11.558
		10	200	6000000	1890750	20000	150000	1.26
						2000	15000	12.605
			3700	111000000	34979000	20000	150000	23.31
						2000	15000	233.19

Table 2-2. Possible variations of important parameters (continued)

Cases considered	% of released radioactive inventory 1-50% (0.25-12.5)[1]	Population density (0.5-10)[2] Result in million person rem	Cancer incidents per 1 million pers. rem (200-3,700)[3]	Cancer incidents per nuclear accident	Production losses per nuclear accidents (million dollars)	Probability of nuclear accidents (one accident per 2,000-20,000 years of operation)	Electricity produced per nuclear accident	Production losses/kWh nuclear electricity produced (10^{-2} American dollars per kWh)
Chernobyl 10^3 cancer incidents/10^6 person rem	1	1	1000	240000	75600	2000	15000	0.5042
Accident like Chernobyl in the FRG. 10^3 incidents per 1 10^6 person rem	1	10	1000	2	756300	20000	150000	0.5042
						2000	15000	5.042

[1] 0.25-12.5 times the percentage released at Chernobyl.
[2] 0.5-10.0 times the population density of the western part of the USSR.
[3] 200-3,700 cancer incidents per 1 million person rem.

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

Hohmeyer's (1988) study is a seminal piece of work that galvanized interest in the issue of quantifying fuel cycle externalities. The methodology is a "back of the envelope" type of calculation that contrasts with the Damage Function Approach (DFA) used in our study. The DFA involves a much more thorough assessment of the technologies and of the risks of accidents, modeling the dispersion of released radioactive material, and explicitly accounting for the spatial distribution of the exposed population.

2.3 DELUCHI REPORT

M.A. DeLuchi's (1991) *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity* is a report on the results of a study that aims to help evaluate the effects of various energy options on greenhouse gas induced global climate change. The study includes estimates of greenhouse gas emissions from the nuclear fuel cycle. There are no estimates of other releases, impacts, or damages.

DeLuchi uses projections for the year 2000 and data from various sources in conjunction with an energy use and emissions model to develop estimates of emissions of greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), nonmethane organic compounds (NMOCs), carbon monoxide (CO), nitrogen oxides (NO_x), and carbon dioxide (CO_2). These estimates are developed for each of several scenarios that differ in assumptions about power plant efficiencies and other factors. The study also enables a comparison of each of the fuel cycles' global warming contributions by converting the estimates for non-CO_2 emissions into values for the CO_2 emissions that have the same temperature effect (CO_2-equivalent emissions).

The DeLuchi study takes into account emissions resulting from feedstock recovery and fuel production stages, from the transportation of feedstocks from the site of extraction to fuel production facilities, from the distribution of fuel from facilities to end users, and from the production and assembling of materials for facilities and other infrastructure. 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.

DeLuchi's estimates for the nuclear fuel cycle in terms of grams of CO_2-equivalent emissions per kWh of generated electrical energy have been tabulated for the study's base scenario in Table 2-3 below. The table lists the emissions values for both the fuel cycle's upstream processes (uranium mining, transport, etc.) and the power-generation stage. Each of the non-CO_2 gas

estimates were 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 emissions are the results of a detailed analysis of the fuel cycle. This analysis takes into consideration the emissions of power generation that drives the nuclear cycle's upstream stages, as well as emissions from standby generators and auxiliary boilers using diesel fuel. DeLuchi accounts for the latter emissions in the power plant stage. To convert the non-CO_2 equivalent 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).

Table 2-4 lists the total CO_2-equivalent emissions for the nuclear fuel cycle for the 100-year time period, as well as for 20- and 50-year periods. These totals can be obtained by summing the emissions of CO_2 and the CO_2-equivalent emissions of the other gases for all stages of the fuel cycle, including generation operations. It should be noted that in an addendum to the 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 2-4, therefore, should be regarded merely as estimates reflecting alternative scenarios for, or assumptions about, the warming potentials of the greenhouse gases.

2.4 EWARS-RENNINGS STUDY

Ewars and Rennings (1991) presented a paper in which they consider the economics of nuclear risks. Their study is for Germany, using a German power plant as a reference and with health effects reflecting German population density. The methodology is a broad, aggregate evaluation that is generally applicable to other contexts.

Ewars and Rennings focus on the health impacts of potential nuclear power plant accidents as being the dominant damage of the nuclear fuel cycle. Materials damages are estimated to be two orders of magnitude less than the health damages.

Health damages are estimated in a straightforward way. Ewars and Rennings assume, based on one of their previous papers, that a meltdown in Germany will release twice the radioactive material released at Chernobyl—a major assumption. The health effects, given a release of radioactive material, are estimated to be seven times greater than Chernobyl because of the greater

Table 2-3. DeLuchi's estimates of CO_2-equivalent emissions of greenhouse gases from nuclear power plants and upstream processes in g/kWh delivered to end user

Greenhouse gases from upstream processes	CO_2-equivalent emissions
CH_4	2.7
N_2O	0.7
NMOCs	0.0
CO	0.1
NO_x	4.6
CO_2	45.9
Upstream total	54.0
Greenhouse gases from power generation stage	
CH_4	0.1
N_2O	3.3
NMOCs	0.1
CO	0.1
NO_x	4.9
CO_2	6.5
Power generation total	14.9

Table 2-4. DeLuchi's estimates of total CO_2-equivalent emissions for the nuclear fuel cycle in g/kWh delivered to end user

Length of time period	CO_2-equivalent emissions
20-year case	101
100-year case	69
500-year case	60

population density in Germany. Thus, given a severe accident, mortality and morbidity are estimated to be fourteen times that at Chernobyl. This estimate, conditional on this type of release occurring, is also fourteen times the Pace (1990) estimate, which uses Chernobyl as its baseline.

The probability of this release is about one every 33,000 years, according to "Deutsche Risikostudio Kernkraftwerke," Phase B (a study of German nuclear power plant risks). This probability is an order of magnitude less than that used by Pace (1990) (which is one every 3,333 years), in which a U.S. Nuclear Regulatory Commission (NRC) estimate of the probability of a serious accident is equated to the probability of a Chernobyl type of release.

Ewars and Rennings use $4 million (U.S. dollars) as an estimate of the economic value of avoiding a fatality. This value is used by Pace (1990) and approximates the value Hohmeyer (1988) uses. Thus, the expected value of the health damage from nuclear power plants is about the same order of magnitude as that in Pace (1990); it is also within the range suggested by Hohmeyer.

The release probability of one every 33,000 years assumes that emergency impact-mitigation measures at the power plant will be ineffective. The German study of nuclear power plant risks, cited above, assumes that these internal plant emergency measures would greatly reduce the risks. Were these measures to be considered, the probability of a reactor meltdown would decrease by an order of magnitude to 1:250,000. The corresponding expected damages to health would decrease by an order of magnitude as well.

Using the 1:33,000 probability as their baseline, Ewars and Rennings conclude that internalization of these damages through insurance is impossible because a private insurance company could not insure the full amount of the potential damages—several trillion DM by Ewars and Rennings' calculations.

The methodology of Ewars and Rennings is similar to that of Hohmeyer. It is a broad-brush, aggregate, top-down approach. Its results rest on the key assumptions mentioned above.

2.5 NUCLEAR ENERGY AGENCY REPORT

A study by the Nuclear Energy Agency (NEA 1992) concluded that "for modern power plants operating under the current regulatory framework, the potential health and environmental costs are small relative to the direct generation costs, even when account is taken of hypothetical large-scale low-probability accidents." The study also suggests a number of benefits of the nuclear fuel cycle including employment, improved balance of payments, and

security of energy supply. The extent to which these benefits are externalities can be a matter of debate.

The Nuclear Energy Agency (1992) divides its discussion of environmental and health impacts into those which result from routine operations, and the risks associated with reactor accidents. [Our report follows a similar format (refer to Chapters 6 and 7, respectively).] In its calculations of the externalities from routine operations, the NEA uses Fritzsche's (1989) analysis, as accepted by the Senior Expert Symposium in Helsinki (1991). These estimates are summarized in Table 2-5.

Table 2-5. Estimated fatality rates per year for routine operations in the nuclear fuel cycle

Type of fatality	Immediate fatalities	Delayed fatalities
Occupational	0.09 - 0.5[1] 0.07 - 0.4[2]	0.13 - 0.37 0.07 - 0.33
Public	0.001 - 0.01	0.005 - 0.2

[1] Applies to underground mining conditions.
[2] Applies to surface mining conditions.
Source: Fritzsche (1989), as given in NEA (1992).

Assuming, for illustrative purposes, a high value of $5 million for the value of a statistical life, the NEA study calculated that the damage associated from statistical premature deaths from normal operations of the nuclear fuel cycle would be 0.1 to 0.6 mills/kWh, which the NEA compares to an overall generation cost of 30 mills/kWh. The report also notes that any portion of the risk which is compensated for in workers' wages, or through insurance or compensation schemes, would be internalized in the electricity price structure, and would thus not be an externality.

In its analysis of reactor accident risks, the NEA notes that in the United Kingdom, the design target is a probability of a core melt from all causes that is below one in 1 million per reactor per year. The NEA report also mentions that studies by the Federal Ministry of Research and Technology of the Federal Republic of Germany (1979 and 1990) and the U.S. NRC (NUREG 1150) conclude that the risks are low.

As a sample calculation to illustrate their point that the risks are low, the NEA study assumed a pessimistic reactor accident frequency of one per 100,000 reactor years. Although considered pessimistic by the NEA, this

probability is significantly more optimistic than the 1:33,000 used by Ewars and Rennings (1991) and the 1:3,333 used by Pace (1990). In the event of a severe accident, the NEA study assumes damages of the order of those estimated for Chernobyl, $200 billion. From these assumptions, the NEA estimates that, statistically, the costs associated with low-probability accidents are about 1 percent of the generation cost. Despite the fact that the risks are low, the severe accident remains the most contentious and publicized nuclear fuel cycle risk area both in the US and Europe. The fact that reactor accidents have high consequences certainly contribute to the public's perception.

2.6 ONTARIO HYDRO'S ESTIMATES OF ITS NUCLEAR SYSTEM'S EXTERNALITIES

In 1993, as part of its Full Cost Accounting initiative, Ontario Hydro[1] developed preliminary estimates of the externalities of its nuclear system over the full life cycle. Estimates were calculated for both fossil and radiological pollutant impacts.

Radiological Impacts

Six distinct segments of the fuel cycle were considered in the nuclear radiological analysis, including: upstream fuel (uranium mining and milling), routing operations, accidents, decommissioning, intermediate/low-level waste (I/LLW) and used fuel disposal. For the radiological emissions analysis, the impacts of Deuterium (D_2O_5) production and Tritium (HTO) recovery were also considered.

The dose-response function for radiological effects ranged from a low of 25 person-Sv/effect to a high of 9 person-Sv/effect, with a nominal value of 20 person-Sv/effect. The low values represent the estimates published by the International Commission on Radiological Protection (ICRP), the high by the Committee on the Biological Effects of Ionizing Radiations (BEIR V) and the nominal on the United Nations Scientific Commission on Radiological Protection (ICRP). These values are assumed to be for cases of cancer mortality. It is assumed there are an equal number of cases of cancer morbidity. This study did not require a formal pathways modelling of the emissions dispersion. The only damages modelled were human health and, in the case of accidents, property damage.

Using the range of values of the person-Sv/effect listed above, the estimated number of cancer cases for each stage of the fuel cycle, for both

[1] Ontario Hydro is Canada's largest utility.

mortality and morbidity, were estimated as shown in Table 2-6. Damages from upstream fuel were based on population dose values from the literature on radiological impacts from uranium mining, fuel fabrication and transportation. Damages from routine operations were based on historical population dose values calculated by Ontario Hydro. Damages from accidents were based on an Ontario Hydro Probabilistic Risk Analysis which modelled five categories of reactor accidents covering the full range of design basis and catastrophic accident consequences. The five accident categories were consolidated into an annual station health effect and property damage risk (which should be considered as bounding estimates). This was done by summing the product of the population dose and off-site damage costs multiplied by the frequency of occurrence. All probabilities of occurrence were increased by a factor 2 to account for external events, such as earthquakes and tornados. These calculations established the annual expected costs. There was not considered to be an engineering basis to apply further error factors to the accident analysis. In addition, it was not considered appropriate to relate the Chernobyl accident to CANDU reactors, which have completely different designs and massive containment systems. Damages from low-level wastes and from used fuel disposal were based primarily on potential health effects from contaminated groundwater from a hypothetical facility.

Table 2-7 summarizes preliminary estimates of radiological external costs (health and property damages) for each station for each stage of the fuel cycle based on projected station life and expected operating capacity. Impacts on lakes, animals and forests were expected to be small, difficult to quantify and therefore were not included in the estimates. The estimate of the value of a statistical life and of a statistical cancer morbidity impact were assumed to be $4,725,600 and $358,000 (Can.) respectively, based on estimates (adjusted for inflation) provided by VHB Consulting for Ontario Hydro's social cost of electricity export studies.[2]

Fossil Fuel Emission:

Fossil emissions associated with the nuclear generating system were also identified for six distinct segments of the fuel cycle: upstream fuel (uranium mining and transportation), station construction, routine operations, decommissioning, intermediate/low-level waste (facility construction, operation, closure) and transportation and used fuel disposal (construction of, and transportation to, disposal facility). The impacts of Deuterium (D_2O) production and Tritium (HTO) recovery were also considered.

[2] SENES Consultants, Ltd., *Effects on Human Health of Nuclear Generating Emissions Due to Electric Power Export*, October 1989.

Table 2-6. Nuclear fuel cycle: annual radiological health effects*

Station	Low (ICRP)	Nominal (BIER V)	High (UNSCEAR)
Pickering A			
Upstream	0.007320	0.017694	0.039319
Routine	0.026458	0.049608	0.166891
Accidents	0.001340	0.032530	1.449444
Decommissioning	0.005305	0.057844	1.243366
I/LLW	0.008412	0.010514	0.023365
Used Fuel	0.000263	0.000329	0.000732
Pickering B			
Upstream	0.009211	0.022265	0.049477
Routine	0.011791	0.021675	0.073213
Accidents	0.001340	0.032530	1.449444
Decommissioning	0.003619	0.035549	0.756985
I/LLW	0.008337	0.010421	0.023158
Used Fuel	0.000332	0.000414	0.000921
Bruce A			
Upstream	0.011750	0.028402	0.063116
Routine	0.002654	0.004424	0.014747
Accidents	0.000124	0.003150	0.039444
Decommissioning	0.000869	0.010419	0.249412
I/LLW	0.011928	0.014910	0.033132
Used Fuel	0.000423	0.000529	0.001175
Bruce B			
Upstream	0.015113	0.036530	0.081177
Routine	0.000910	0.001423	0.006322
Accidents	0.000136	0.003650	0.411111
Decommissioning	0.000794	0.009469	0.209873
I/LLW	0.013598	0.016998	0.037773
Used Fuel	0.000544	0.000680	0.001511
Darlington			
Upstream	0.014295	0.034552	0.076783
Routine	0.021528	0.034983	0.098567
Accidents	0.000656	0.017100	0.638889
Decommissioning	0.003799	0.036731	0.800403
I/LLW	0.012603	0.016998	0.035008
Used Fuel	0.000515	0.000643	0.001429

* Each entry in the table represents the number of fatal cancer effects and an equivalent number of additional non-fatal cancer effects.

Source: Ontario Hydro, "Full Cost Accounting for Decision Making," December 1993.

Table 2-7. Nuclear fuel cycle radiological health & property externality costs (1992 cents/kWh - Can)

Station	Low	Nominal	High
Pickering A			
Upstream	0.000406	0.000507	0.001128
Routine	0.002022	0.003792	0.012755
Accidents	0.000121	0.002603	0.095909
Decommissioning	0.000036	0.000045	0.005704
I/LLW	0.000283	0.000353	0.000785
Used Fuel	0.000001	0.000025	0.000055
Total	0.002869	0.007325	0.116336
Pickering B			
Upstream	0.000441	0.000551	0.001225
Routine	0.000669	0.001230	0.004155
Accidents	0.000104	0.002247	0.082786
Decommissioning	0.000041	0.000051	0.004968
I/LLW	0.000308	0.000384	0.000854
Used Fuel	0.000001	0.000035	0.000078
Total	0.001564	0.004498	0.094066
Bruce A			
Upstream	0.000419	0.000524	0.001164
Routine	0.000122	0.000203	0.000675
Accidents	0.000013	0.000094	0.001999
Decommissioning	0.000006	0.000008	0.000705
I/LLW	0.000292	0.000366	0.000812
Used Fuel	0.000001	0.000030	0.000065
Total	0.000853	0.001225	0.005420
Bruce B			
Upstream	0.000443	0.000553	0.001230
Routine	0.000031	0.000049	0.000218
Accidents	0.000011	0.000082	0.001642
Decommissioning	0.000002	0.000003	0.000721
I/LLW	0.000309	0.000387	0.000859
Used Fuel	0.000001	0.000037	0.000081
Total	0.000797	0.001111	0.004751
Darlington			
Upstream	0.000456	0.000571	0.001268
Routine	0.000772	0.001254	0.003537
Accidents	0.000046	0.000855	0.027627
Decommissioning	0.000040	0.000050	0.003730
I/LLW	0.000321	0.000401	0.000891
Used Fuel	0.000001	0.000036	0.000080
Total	0.001636	0.003167	0.037133

Source: Ontario Hydro, "Full Cost Accounting for Decision Making," December 1993.

The primary source of fossil pollutants reflects the burning of fossil fuels on-site at each of the nuclear plants. The pollutant emissions by nuclear plant were estimated by Energy Research Group Inc.[3] Their estimates were combined with the dollar per tonne estimates developed by Ontario Hydro for the fossil system as shown in Table 2-8.

The dollar per tonne estimates for Lakeview generation station (a coal-fired station located in metropolitann Toronto) were applied to the fossil emissions from the Darlington and Pickering nuclear stations. The dollar per tonne estimates for Lambton (a coal-fired station located in southwestern Ontario) were applied to the fossil emissions from the Bruce generating station. These estimates were chosen because it was felt they would better reflect the population surrounding each of the nuclear stations.

No explicit modelling of fossil emissions dispersion, physical damage, and dollar cost analysis was carried out for each nuclear station. Although these estimates should be considered approximations, the use of the fossil-system dollar per tonne estimates was considered to be a reasonable first approximation.

Table 2-8. External costs by station
Dollars per tonne ($1992 - Can)

Pollutant Station (Unit $)	Lakeview (1256)	Lambton (12)	Lambton (34)	Lennox	Nanticoke	Total System Average
SO_2*	2345	431	535	375	803	734
NO_3**	267	87	193	61	214	188
TSP	46	9	12	9	16	15

* Includes externality values of SO_4, which is derived from SO_2.
** Includes externality values of O_3, which is derived from NO_x.

Source: Ontario Hydro, "Full Cost Accounting for Decision Making," December 1993.

[3] Energy Research Group Inc. (in conjunction with Ontario Hydro). "Calculation of Environmental Externalities for Ontario Hydro's Nuclear Power Plants," September, 1993.

Table 2-9 summarizes the external environmental costs associated with Ontario Hydro's nuclear stations. It combines the radiological external costs with the fossil external costs associated with nuclear production.

Table 2-9. Nuclear station radiological and fossil external environmental costs (1992 cents/kWh - $Can)

Station	Low	Nominal	High
Pickering A			
Nuclear	0.002869	0.007325	0.116336
Fossil	0.002676	0.002676	0.002676
Total	0.005545	0.010001	0.119012
Pickering B			
Nuclear	0.001564	0.004498	0.094066
Fossil	0.002734	0.002734	0.002734
Total	0.004298	0.007232	0.096800
Bruce A			
Nuclear	0.000853	0.001225	0.005420
Fossil	0.000973	0.000973	0.000973
Total	0.001826	0.002198	0.006393
Bruce B			
Nuclear	0.000797	0.001111	0.004751
Fossil	0.000752	0.000752	0.000752
Total	0.001549	0.001863	0.005503
Darlington			
Nuclear	0.001636	0.003167	0.037133
Fossil	0.002968	0.002968	0.002968
Total	0.004604	0.006135	0.040101

Source: Ontario Hydro, "Full Cost Accounting for Decision Making," December 1993.

Ontaria Hydro recognizes that there are a number of limitations with this research. There is uncertainty associated with the above estimates. Further research is required and is being initiated to improve upon these estimates.

2.7 PAST STUDIES PROVIDE MOTIVATION FOR STUDY PRIORITIES

The major studies which have been reviewed in this Chapter provide much of the motivation for the emphasis given to various stages of the nuclear fuel cycle in this report. The Nuclear Energy Agency (1992), drawing on Fritzsche's (1989) well-known research, note the importance of not confining

an analysis to the generation stage of the fuel cycle. The NEA report notes that damages can result from both mining and transportation. These stages are considered in Chapters 5 and 8, respectively, of our report.

While the NEA (1992) and Pace (1990) reports state that damages from normal operations of the power plant are insignificant, Hohmeyer (1988) suggests that they may amount to 30% of total damages. Ewars and Rennings (1991) allow that non-accident risks may be as much as 20% of the total. Thus, the risks of normal operations are evaluated in our report in Chapter 6.

Of course, all studies agree that the potential damages from severe reactor accidents are the most significant of any in the nuclear fuel cycle. There is a considerably large range in estimates of expected damages, however. The NEA (1992) calculates them to be about 1% of the cost of generation. Pace (1990), Hohmeyer (1988), and Ewars and Rennings (1991), on the other hand, estimate that the externalities are the same order of magnitude as the total costs of electricity generation. Estimates by reviewers of the Pace (1990) report, who were commissioned by the U.S. DOE, generally agree with the NEA estimates. It is interesting to realize that this great variation in estimated damages is due to differences in technical scientific-engineering estimates—not due to any differences in the consideration of perceived or subjective risks. Chapter 7 of our report re-assesses severe reactor-accident risks from a technical standpoint.

Within the United States, the siting of the proposed permanent repository for spent fuel is a contentious issue. Chapter 9 of our report addresses that issue and estimates the potential long-term impacts.

Of the studies reviewed, Pace (1990) was one of the few to consider decommissioning. It estimated decommissioning-related externalities to be significant, about 5 mills/kWh. As discussed in Section 2.1, however, this estimate may be a factor of 10 too high. Decommissioning is considered in Chapter 6 of our report.

In discussing emissions from fossil-fuel plants used to generate electricity for enrichment facilities, the NEA (1992) report noted that these secondary emissions are much less (when divided by the electricity generated by the nuclear plant) than the per kilowatt-hour emissions from a fossil-fuel plant. Following that assessment, we did not consider the enrichment stage of the nuclear fuel cycle, though it remains as a top priority for future study, especially in terms of its waste stream.

The Ontario Hydro (1993) study appears to be the most sophisticated study of those done thus far. It follows a damage function approach and considers the nuclear fuel cycle on a full life cycle basis. The study even

includes the effects of emissions throughout the life-cycle from fossil fuel use associated with the nuclear fuel-cycle.

The results of the Ontario Hydro study indicate that:

- the order of magnitude of the externalities of the full fuel cycle (excluding on-site fossil fuel emissions) is about 0.01 to 0.07 mills/kWh for the mid-estimate case, depending largely on the size of the population in the vicinity of the power plant;
- in more heavily populated areas, the expected damages from routine operations are the largest of the possible impacts;
- the expected health effects of possible exposure to intermediate/low-level wastes appear to be the most significant impact from stations located in sparsely populated areas;
- the health risks of power plant accidents are the greatest among the externalities in the high accident-damage case; and
- in the mid-estimate case, the external costs associated with emissions from on-site fossil fuel use are the same order of magnitude as the sum of the rest of the nuclear fuel cycle externalities.

Ontario Hydro's estimates of externalities are significantly less than those of the other studies that we reviewed. The main source of the difference appears to be the probabilities of accidents. Further study is warranted, and the European Commission's study as well as ours offer further comparison.

2.8 MOST RECENT RESULTS OF EC NUCLEAR STUDY CONDUCTED BY CEPN

The technical approach of the EC nuclear fuel cycle study is very similar to ours, though they have recently had the opportunity to expand their analysis. The Centre d'Etude sur l'Evaluation de la Protection dans le Domaine Nucleaire (CEPN) was the lead organization that undertook the study. In 1994, CEPN decided to partition their damage estimate results by geographic proximity to the plant and by the time period in which damages occur. The three proximity categories are "local" (0 to 100 km), "regional" (100 to 1000 km), and "global" (1000+ km). The three timeframes for damage effects are "short-term" (under 1 year), "medium-term" (one to 100 years), and "long-term" (100 to 100,000 years).

Most of the monetized damages occurred in the long-term (in their base case with a zero discount rate) and are global effects. They result from the radiation dose to the world population from Carbon-14. Carbon-14 is formed in nuclear fuel by an n-p reaction with the 25 ppm or so of nitrogen-14 present in the fuel and cladding. This radionuclide is released during reprocessing or from leaky fuel elements during normal operations. CEPN found that reprocessing, which is not conducted in the U.S commercial nuclear fuel cycle, accounted for most of the Carbon-14 release.

CEPN estimated that over the next 100,000 years the health and environmental impacts from normal reactor and reprocessing operations amount to a maximum of 2.48 milliECU (3.12 U.S. mills) per kilowatt-hour. Adding in the effects of a low-probability, high-consequence severe reactor accident increases this value by only 5%. The results of the EC/CEPN study are covered in more detail in CEPN (1994). (It should be noted that the U.S. research team did not have the global dispersion models or funding resources to partition the damage estimates into time frame or distance categories.) A comparison table in *Nucleonics Week* (1994) shows that for the areas of similarity in the U.S. and EC fuel cycles and methodology, the numerical damage results were reasonably close. Preliminary results from our study are also summarized in two papers, Williams (1994) and Fisher (1994), from the same American Nuclear Society meeting where Mona Dreicer of CEPN presented the EC results.

3. ORGANIZATION AND INTERPRETATION OF RESULTS

This Chapter describes the organization of the results that follow, particularly in Chapters 5 through 9. 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."

In a report of this breadth, there are an enormous possible number of results. This Chapter identifies the most important types of results that are presented in this report and describes the format for their presentation.

3.1 TYPES OF RESULTS

3.1.1 A Demonstration and An Account of the Methods

There are three general types of results. The first are descriptions of the methods used to apply the damage function approach (DFA) to nuclear cycles. Whereas ORNL and RFF (1992) provided a general discussion of the approach and issues in estimating the externalities of fuel cycles, this 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 nuclear fuel cycle externalities.

Each stage of the nuclear fuel cycle tends to be dominated by a different class of radioactive releases. Mining and milling are dominated by uranium decay daughters that are not present at later fuel cycle stages. Reactor operations and accident impacts are dominated by short-lived gaseous radionuclides. The releases of a repository are dominated by very long-lived radionuclides. Most transportation steps involve assessment of the chemical and radiological hazards of uranium.

For this reason, the report is organized at the top level around the fuel cycle stages. The lack of commonality among the fuel cycle stage in terms of their releases causes there to be little duplication in the type of analysis required for each stage. Chapter 4 provides an overview on the nuclear fuel cycle and gives information on the choice of technologies for each stage. Chapter 5 is a

discussion of uranium mining and milling. Chapters 6 and 7 discuss the reference electricity generation system - the nuclear reactor. Chapter 6 defines the reference reactor and discusses the impacts and damages that result from the construction, normal operation, and decommissioning of that reactor. Chapter 7 is dedicated to a detailed treatment of potential severe reactor accidents. Chapter 8 discusses transportation operations between the fuel cycles, and Chapter 9 reviews the high-level waste repository to which the spent fuel (SF) from the reactor will report.

Within each of Chapters 5-9, the reference fuel cycle technology and site are defined and the releases associated with the fuel cycle stage are given. Impact pathways are identified, and priorities are assigned and explained. The high-priority impacts are then discussed with explanations of methodology and quantification of impacts. Finally, within each chapter, a methodology for estimating damages is explained and then illustrated. Employment benefits for the fuel cycle as a whole are estimated in Chapter 10.

3.1.2 Identifying Information Quality and Gaps

The second type of result is the identification of where important quantitative information does not exist, or is highly imprecise. Identifying these information gaps provides a research agenda for the future. Chapters 5 through 10 discuss the data and analytical methods used in this study - providing additional insight about data quality and the lack of information.

3.1.3 Numerical Estimates of Damages and Benefits

The third type of result, numerical results, are estimates of the marginal or incremental impacts and their corresponding 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 characteristics of the specific site.

Presentation of these results is in Chapters 5 through 9. Each chapter is dedicated to a stage of the nuclear fuel cycle and is organized according to the following format:

- The reference technology and reference site are described. For those fuel cycle stages for which accidents are recognized to be important (reactor operations, transportation shipments, and SF disposal), the accident scenarios are defined.

- The operational releases of the fuel cycle stage are characterized. In the case of the electrical generating system, the construction and decommissioning releases are characterized as well.

- The impact pathways are identified and priority impact pathways are chosen.

- The priority impact pathways are characterized and methodology for their estimation is presented. The impacts are then quantified. Valuation methodology is discussed and estimates of the damages are presented.

The results of the report are summarized in Chapter 11. The Appendices offer additional information about the methodologies used in the analysis and additional details on the calculations and estimates.

Estimates of impacts are in the physical units appropriate for the particular impact-pathway. Many of the impacts studied are health effects, and common units are latent cancer fatalities (LCFs), the number of genetic effects, and the number of non-fatal cancers. Estimates of damages and benefits are expressed in terms of mills/kWh, and as the dollar damages or benefits for each impact-pathway (in 1989 dollars).

In general there has not been a comprehensive effort to assign low, mid, and high values to numerical values, instead an average or medium value is generally selected. Assignment of low and high values would probably need to involve probabilistic risk assessment (PRA) calculations, where each input parameter is assigned a probability distribution of values and probability distributions of the output parameters are calculated. Such PRA calculations are possible, but are beyond the scope of this project. A limited PRA was performed for our analyses of severe reactor accidents (Chapter 7) and transportation accidents (Chapter 8). While a high-values scenario is presented for severe reactor accidents, this high value only addresses randomness in the effects of weather on the accident consequences and does not address uncertainty in the assumptions.

Also unlike the other fuel cycle reports, uncertainty in the dose-response functions are generally "hard-wired" in the computer codes used for this study. A priority in future work should be to identify and evaluate these functions.

3.2 CAVEATS IN THE INTERPRETATION OF NUMERICAL RESULTS

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

1. Only one particular reactor technology is analyzed in detail for the 1990 case. As discussed in Chapter 4, no reactors have been ordered since 1978 and the most recent reactor technology was insufficiently characterized to be able to support the needs of this report. Thus the reference Westinghouse PWR best represents 1978 reactor technology and is used as the technology for a 1990 need date. Current state-of-the-art and future technologies would presumably have lower externalities.

2. Some of the nuclear fuel cycle steps are not analyzed in this study, specifically uranium enrichment, fuel conversion, fuel fabrication and low-level waste disposal. These steps were assigned a lower priority than the steps that are analyzed based on the observation that past studies had shown that their impacts are small.[1]

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. The estimates do not include every emission or impact. A limited number of impact-pathways were considered in detail. The selected impact-pathways were regarded as being among the most important, but 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. ORNL/RFF (1994b) contains a discussion of the need for impact-pathway prioritization and the prioritization process used in the study.

[1] For some stages of the fuel cycle, past studies differ significantly in their results - particularly in the case of the risks of severe reactor accidents (see Chapter 2). We thus select severe reactor accidents as one of the priority impact pathways, especially in light of the public concern about this issue.

5. If we had estimates for every individual damage, then adding them to estimate a total damage for the fuel cycle would likely overestimate it. Estimates of damages 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. 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.

7. It is not always clear when damages are, in fact, externalities. This issue is discussed in ORNL/RFF (1992). The economic values derived in this study should be interpreted as some of the most significant marginal damages and marginal benefits associated with the addition of the nuclear plant and of operations needed to provide enriched new fuel and to dispose of SF. However, they may not be externalities. For example, utilities carry insurance for liabilities in the event of accidents - though all of the damages would not necessarily be covered. Chapter 7 contains a discussion of the Price-Anderson Act and of the extent to which it internalizes some of the expected damages. Chapter 11 includes brief comments on the extent to which the numerical estimates of damages (and benefits) are indeed externalities.

Notwithstanding these caveats, 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. The sums (really the partial sums) are also informative in terms of their general order of magnitude, keeping in mind the particular technology and site, the missing impacts that were not studied, as well as the likelihood of overestimation in adding estimates of damages. In any comparisons, the above-stated caveats should always be kept in mind.

This nuclear fuel cycle study does not explicitly treat uncertainty in the estimation approaches, which is a difference with other fuel cycle studies in this project. Nuclear risks and impacts have been studied in great detail, and models tend to be quite substantial and complex. The large literature on nuclear risks arguably enables a reasonable assignment of high and low values on most of the hundreds of parameter values that might affect the estimates. Perversely, while all of this detail and complexity might make a calculation of high and low values more meaningful for the nuclear fuel system, it also requires a much more

extensive effort in order to be faithful to the source material. A formal probabilistic calculation would be the ideal methodology for yielding probabilistic expectations of impacts and damages; such a calculation was beyond the resources of this study. Simpler approaches to estimating high and low values may be possible in future work.

In the results on severe reactor accident scenarios, we do present 95% confidence intervals on the impacts and damages; however, the calculation addresses only the basic randomness in weather conditions and the consequent uncertainty about weather inputs to be used for an accident scenario. No attempt was undertaken to systematically address parameter uncertainty with this calculation.

4. NUCLEAR FUEL CYCLE OVERVIEW

4.1 REFERENCE NUCLEAR FUEL CYCLE TECHNOLOGIES

The U.S. nuclear fuel cycle is shown in Fig. 4-1. The stages of the fuel cycle that are addressed in this report are uranium mining and milling, electricity production (the nuclear reactor), spent fuel disposal, and transportation operations that link many of the fuel cycle stages.

4.1.1 Uranium Mining and Milling

Although most uranium used in the United States is now imported, domestic uranium production continues.

Uranium mining technologies used in the United States include (1) underground mining, (2) open pit mining, (3) in-situ leaching, and (4) extraction as a by-product from other mineral mining operations. Past environmental assessments such as Gotchy (1987) and current EPA regulatory tables for fuel cycle emissions (EPA 1990) assume that uranium mining production is due to 67% underground mining and 33% open pit mining. In our survey of the uranium mining industry, reported in Section 5.1, we determined that the production from open pit mines has declined dramatically during the 1980s, while the relative importance of in-situ leaching has increased significantly. Thus, for our 1990 reference technology case, we define that uranium mining production is 50% underground mining and 50% in-situ leaching. We have also defined the acid leach milling process to be our reference milling technology. Uranium milling is the process that extracts the uranium from the mined uranium ore. In the case of in-situ mining, this extraction process occurs as an integral part of the in-situ mining operation. In other words, the production of uranium needed for the nuclear fuel cycle, in our reference technology, occurs by either underground mining and acid-leach milling, or by in-situ mining.

Based on the current strong trend, we expect that underground mining production will continue to decline, and that by the year 2010, virtually all U.S. production will be from the lower cost in-situ leaching technology. Although the impacts and damages of the nuclear fuel cycle technology in the year 2010 have not been explicitly estimated in this report, the reference 2010 technology for uranium mining was defined to be 100% in-situ leaching.

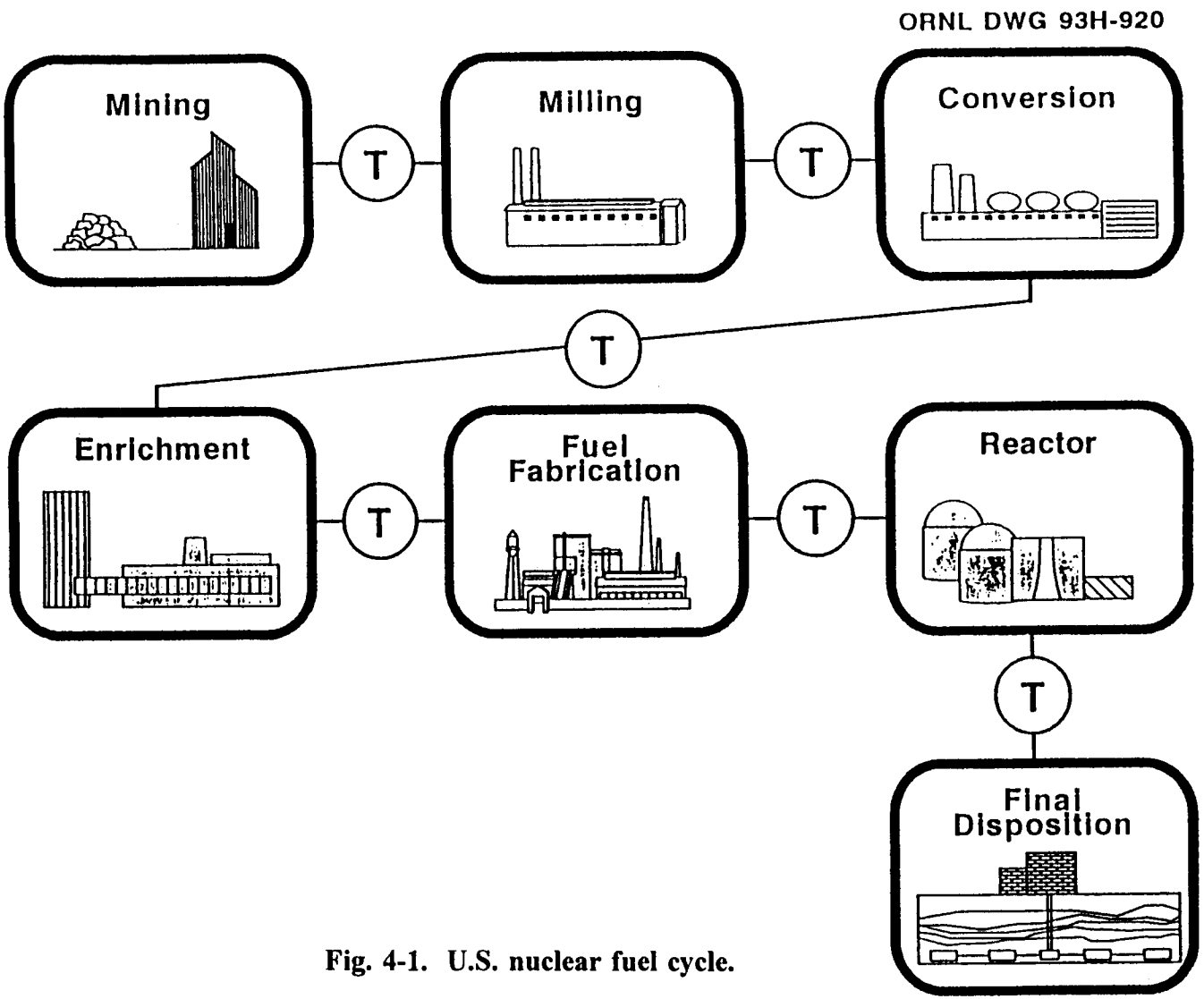

Fig. 4-1. U.S. nuclear fuel cycle.

The use of the same sources of uranium for both reference power plants represents somewhat of a departure from the fuel cycle studies. One reason for this different approach is that with so few production centers in the United States there is a reasonable chance that some domestic producers would supply uranium to different utilities (our generic site represents a composite of these producers). A second reason is that the initial source of the uranium may be unclear, due to so-called flag swaps, inventory drawdown, and other factors. Thus, unlike the other fuel cycle analyses, we do not identify specific locations as being the sources of the fuel or feedstocks.

4.1.2 Electricity Generation

Presently there are 111 operating commercial nuclear power stations that are licensed to generate electricity for resale in the United States. All are based on the use of light water as the moderator and coolant and are usually referred to as light-water reactors (LWRs). There are two major types of LWRs, the pressurized-water reactor (PWR) and the boiling-water reactor (BWR). Of the 111 U.S. nuclear reactors, 52 are PWRs, as designed by Westinghouse, 36 are BWRs, as designed by General Electric, and 23 are PWRs, as designed by either ABB/Combustion Engineering (CE) or Babcock & Wilcox (B&W).

The choice of a 1990 technology is made more difficult by the fact that no reactors have been bought (ordered) during the period 1978–1992. Thus, all of the above reactor technologies represent technology that is no more recent than 1978. New LWR technologies are under development by reactor vendors and the U.S. Department of Energy, but are not expected to be licensed until 1996 or later. These new LWR systems are believed to have significant safety advantages over the 1978 technologies that are in current use, especially with respect to the probability of a potential severe reactor accident. However, because these reactors are not available in the 1990 timeframe, and are incompletely characterized in any case, they were not chosen as the reference 1990 technology. It can be expected that the damages calculated in this study for a severe accident will be an upper bound for those anticipated from new reactor technology.

Use of a non-advanced/evolutionary reactor for the reference reactor will likely cause the monetized damages from a reactor accident to be overestimated compared to those that would be expected from an advanced/evolutionary reactor. The latter are expected to have severe-accident probabilities at least an order of magnitude lower than today's operating reactors, and the source terms (amounts and types of escaping radionuclides) are expected to also be lower. The lower probability and lower source term would significantly reduce the health and property damages from any severe accident. It is expected that probabilistic risk

analysis (PRA) data on advanced/evolutionary reactors will be available before 1996 and perhaps form the basis for new studies in this area.

The Westinghouse PWR was selected as the technology that would hypothetically come on line in 1990. This reactor is defined as having a dry containment system, typical of 38 of the 52 Westinghouse PWRs, and is assumed to operate with high "burnup" of its fuel, as is typical of the current operating mode of LWRs. This high-burnup mode is defined as meaning that 52,000 megawatt-days of electricity are produced for each metric ton of heavy metal (uranium) fuel. Consistent with this definition, it is assumed that the initial fuel that is loaded into the reactor has been enriched in the fissile ^{235}U isotope to a concentration, or assay, of 4.7%. This higher level of enrichment will, in turn, require a larger quantity of uranium to be extracted from the ground in order to meet the input requirements of the uranium enrichment stage of the fuel cycle.

The nuclear reactor plant is assumed to have a nameplate capacity of 1300 MW(e), an actual capacity of 1250 MW(e), and a net capacity of 1150 MW(e) after onsite use of 100 MW(e). These assumptions are explained in more detail in Section 6.1. An average fuel requirement for the reactor would be 340.8 MT of U_3O_8, assuming on enrichment tails assay of 0.4 wt%.

As noted earlier, this report does not explicitly address the future 2010 technology case. However, the reference technology that had been defined for that case is a 600 MW(e) passively-safe Westinghouse AP-600 PWR reactor, or alternatively a small BWR such as the General Electric SBWR. These reactor systems have design goals that include reduced probability and emissions for severe reactor accidents, reduced radiological occupational exposures, and reduced radiological emissions to the environment. These design features would be expected to reduce the estimated levels of damages to society relative to the 1990 case Westinghouse PWR technology that is evaluated herein.

4.1.3 Transportation Shipments

Transportation shipments are all defined as truck shipments in NRC-approved shipping containers. No significant differences between 1990 technology and 2010 technology for transportation are foreseen. The impacts of exposure to radiation from incident-free transportation and postulated transportation accidents have been evaluated in this study.

4.1.4 Spent Fuel Disposal

Spent fuel is currently stored in pools or dry cask storage at the reactor sites. However, the long-term plan for spent fuel in the United States is to dispose

of it in a deep geologic repository. Although no repository currently exists, all spent fuel from currently operating and future civilian reactors is planned to go to a deep geologic repository. A significant national program is underway to examine feasibility of a candidate site (Yucca Mountain, Nevada) and to develop and design the necessary component technologies for a geologic repository. Thus, the reference spent fuel disposal technology is defined as being a deep geologic repository for both the 1990 and 2010 cases.

This fuel cycle stage differs from the others because it involves a *proposed* facility rather than an existing facility even for the 1990 case. This is deemed to be appropriate because the 1990 reactor case involves electricity generation and spent fuel discharges during the period 1990 through 2030; discharged spent fuel is planned to be stored for a minimum of 5 to 10 years before shipment to a geologic repository. Thus, a geologic repository that begins acceptance of spent fuel in 2010 (as is currently planned) will significantly overlap the desired timeframe for spent fuel disposal from the 1990 case reference reactor; this argument is even stronger for a 2010 case reactor.

Interim on-site storage of spent fuel, in either pools or dry casks, is a standard reactor site operation and, in this study, is defined as being part of normal operations for the reference reactor and not part of the spent fuel disposal stage. Occupational radiation exposures are virtually the only impact of interim on-site storage, and are included in the occupational radiation exposures for normal reactor operations as provided in Chapter 6.

4.1.5 Fuel Cycle Stages Not Addressed

The fuel cycle stages that are not addressed are *uranium enrichment*, *fuel fabrication*, and *disposal of low-level radioactive wastes (LLW)* that are generated in the reactor and throughout the rest of the fuel cycle. The first two of these fuel cycle stages were not selected as priorities for this study due to the low emissions and health effects that have been identified for them in prior studies, such as Gotchy (1987). LLW disposal is also not believed to pose significant impacts to the public health or environment, but almost no quantitative literature methodologies or estimates were found that are suitable for the analysis of this fuel cycle stage.

The most important omission from the fuel cycle analysis may well be the *uranium enrichment facility*. Although most literature agrees (Gotchy 1987, Michaels 1992a) that the U.S. enrichment plants are not significant sources of either radiological or chemical emissions, there are at least five impacts that warrant further study. One impact is from the coal-fired power plants that are dedicated to support the gaseous diffusion plants (gaseous diffusion is the only

U.S. enrichment technology in production today). Gaseous diffusion is a power-intensive process, and typically 25 to 50 MW(e) is required from the electric grid to support the increment of enrichment operations necessary to produce 1 GW(e) of nuclear electricity generation (Gotchy 1987). Electric power is provided to the Portsmouth, Ohio and Paducah, Kentucky gaseous diffusion plants from dedicated coal-fired plants that are generally regarded as being among the most pollution intensive plants in the country. A detailed evaluation of the impacts of these coal-fired plants would need to involve characterization of the emissions and site of the actual plants; generic coal-fired plant emissions and sites would probably not be adequate. A preliminary estimate of these emissions is offered in the following paragraphs.

Both the conversion and enrichment steps of the nuclear fuel cycle were not considered in detail in the first draft of this study. Plants that convert yellowcake (U_3O_8) to UF_6 and uranium enrichment plants are large, and they service dozens of large LWR plants. The health and environmental impacts of a single conversion or enrichment plant are thus spread over many plants, and the marginal effect of adding another LWR to their servicing capability is rather small. The enrichment plant, however, has one associated issue that is technology dependent, i.e., its power consumption.

In the U.S., all domestic enrichment capability is currently provided by energy-intensive gaseous diffusion plants (GDPs) originally constructed by the U.S. Government for military purposes. At their peak production levels, the three U.S. plants consumed the output of several 1000 MW(e) power plants. These three plants are located at Oak Ridge, TN; Paducah, KY; and Piketon (Portsmouth), OH. The Oak Ridge plant has been permanently shut down, and the Portsmouth Plant may be shut down in the near future. (These plant shutdowns have occurred because of reduced military needs, more foreign enrichment capacity now on-line, the cancellation of many U.S. reactor projects, reduced U.S. market share, and anticipated use of excess enrichment uranium from U.S. and Russian military stockpiles). The remaining Paducah plant utilizes nearly 2000 MW(e) of coal-fired electrical capacity when at full production. Figure 4-2 shows the location of U.S. GDPs and the utilities and plants providing their power. (The Paducah plant could service approximately 56 of the "reference PWRs" described in this report.)

It would take a hypothetical coal-fired plant of 50 MW(e) capacity operating at 75% capacity factor to supply the electrical energy needed to enrich uranium for the reference PWR in this study. This coal plant is one-tenth the size

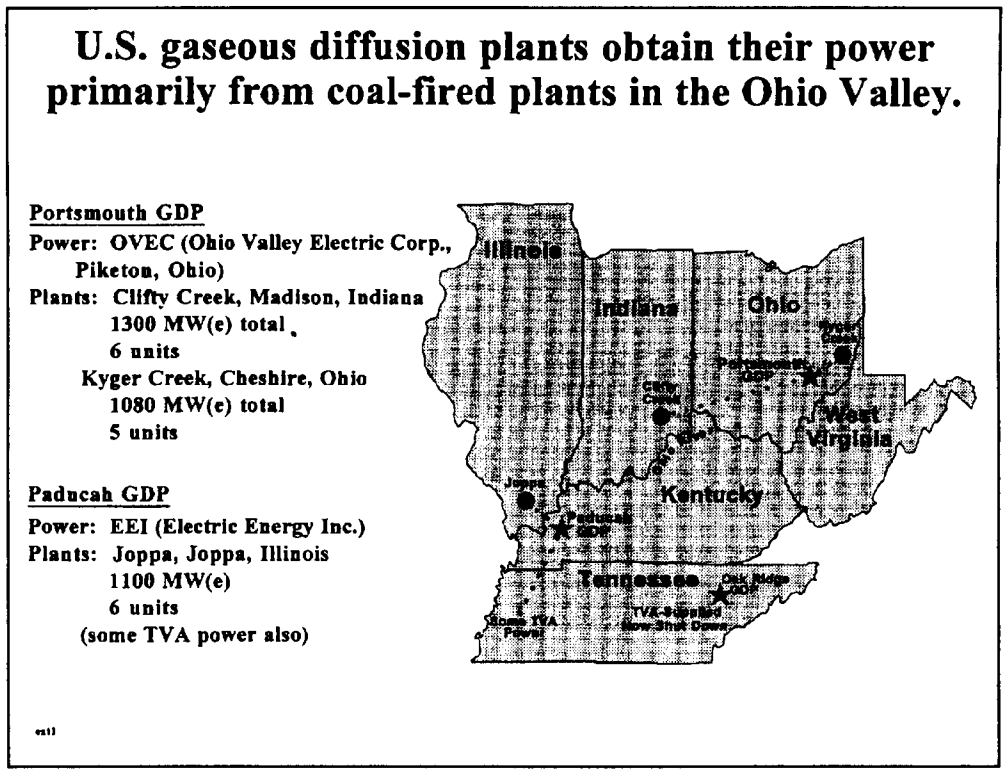

Figure 4.2 Location of U.S. Gaseous Diffusion Plants.

of the 500 MW(e) coal plant described in the May 1992 Draft Coal Fuel Cycle Report: *Residual Damages and Benefits of the Coal Fuel Cycle: Estimation Methods, Impacts, and Values.* Based on one-tenth of the emissions listed in this report, and an adjustment for higher sulfur coal used in the lower Ohio River Valley, the following emissions result[1]:

CO_2	336,000 tons CO_2 /yr 304,000 MT CO_2 /yr 82,900 MT C/yr
SO_2	2,393 tons SO_2 /yr
No_x	957 tons NO_2/yr
Particulates	53 tons/yr

[1] These emissions estimates are generally greater than those used in the final report, which used estimates based on analysis of the coal quality and power plant characteristics, rather than on estimates that were previously published elsewhere.

Any new enrichment plants located in the U.S. would probably not use the power-intensive gaseous diffusion technology. Both gas centrifuge and Atomic Vapor Laser Isotope Separation (AVLIS) technologies utilize a small fraction (4–15%) of the power per unit of enrichment (i.e., per SWU of separative work unit) of the gaseous diffusion plant. For this reason, the health and environmental damages of the enrichment step would be considerably smaller.

A second potentially important impact is from the potentially large LLW streams associated with *decommissioning gaseous diffusion plants*. U.S. gaseous diffusion plants are contaminated from operations involving the enrichment of natural uranium for both civilian and defense purposes, as well as the reenrichment of reprocessed uranium (also for defense purposes). The portion of decontamination wastes attributable to civilian power production is not cleanly separable from the wastes attributable to defense-related operations.

Other potentially important effects of uranium enrichment involve fluorocarbon emissions, disposal of PCB-contaminated wastes, accident scenarios, and non-internalized costs related to the storage and eventual disposal of large inventories of depleted uranium as uranium hexafluoride (UF_6).

4.1.6 Reference Fuel Cycle Material Requirements and Shipment Quantities

An important aspect of analyzing the nuclear fuel cycle is the development of assumptions that determine the material requirements of each fuel cycle stage. Table 4-1 lists the processed material quantities for each stage of the fuel cycle. Development of this table required assumptions about uranium ore grade, efficiency of extraction and manufacturing processes, assumptions about enrichment plant operations, and annual fuel requirements for PWRs.

Also important to the fuel cycle analysis is the development of assumptions related to the quantities transported between each fuel cycle stage. Table 4-2 lists assumptions about the total number of shipments required for a reference reactor year (RRY) and to support the generation of 1 giga-watt of electricity.

Table 4-1. Processed material quantities for reference fuel cycle stages

Material	Form	Per reactor year[1] (MT)	Per GWe-yr[1] (MT)
Ore[2] mined	Ore	271,200	291,143
U_3O_8 milled	U_3O_8	340.8	365.9
Conversion to UF_6	U-natural[3]	280.09	310.3
Enrichment[4]	U-enriched	21.09	22.64
Fabrication	U, in UO_2	21.09	22.64
Reactor	U, in UO_2	20.98	22.52

[1]A reactor year is defined as 1150 MW(e) * 0.81 capacity factor = 0.9315 GWe-yr. Therefore, a GWe-yr = RRY/0.9315.
[2]Uranium ore is assumed at 0.135 U_3O_8 wt%, and 93.1% recovery factor.
[3]Assumes 0.848 factor to convert U_3O_8 to uranium (U).
[4]Assumes a 0.4 wt% tails assay, which translates to a feed-to-product ratio of 13.709 from the gaseous diffusion plant.

Table 4-2. Reference fuel cycle shipment quantities

	Basis	Per RRY	Per GWe-yr
Ore; mine to mill[a]	25 tons/truck (22.73 MT/truck)	11,933 trucks	12,800 trucks[b]
Yellowcake to conversion plant	0.35 MT/drum	974 drums	1046 drums
UF_6 to enrichment	12.7 MT/cylinder	22.76 cylinder	24.4 cylinder
UF_6 to fabrication	9.0 MT/cylinder	2.34 cylinder	2.5 cylinder
Fuel assemblies[c]	0.4614 MT/assemblies	45.5 assemblies	49 assemblies

[a]Reference case assumes mine and mill are co-located; thus, truck shipments are all on site. Mine is assumed to be 15–20 miles from mill.
[b]Translates to 51.2 trucks per day for mine operating 250 days/year.
[c]Fresh fuel to reactor or spent fuel to repository.

4.2 RADIOACTIVE EMISSIONS TERMINOLOGY FOR THE NUCLEAR FUEL CYCLE

The nuclear fuel cycle differs from other electricity production options in that it involves the handling and production of large quantities of radioactive materials. Emissions of radioactive materials normally occur during all stages of the nuclear fuel cycle. The emitted materials, called **radionuclides**, may be ingested, inhaled, or otherwise taken into the body and become trapped in body tissue. Alternately, impacts to human health may arise when radioactive materials remain in the environment and serve as a continuing source of external (to the body) radiation exposure.

The nuclear fuel cycle is also characterized as having **persistent** emissions; that is, emissions that continue to occur long after the facility operations have ceased. An important example of this is mill tailings piles which contain radioactive daughters of uranium, as found in uranium ore. The radioactive daughters in the mill tailings piles decay into radon, a radioactive gas which is particularly hazardous due to its mobility and potential for inhalation. Mill tailings piles will continue to emit radon gas for thousands of years; thus small annual emissions can accumulate into large integrated numbers. Other sources of persistent emissions of radioactivity are waste rock from mining, and geologic repositories for spent fuel disposal.

The nuclei of all heavy elements and many direct fission products are unstable and emit radiation. Radiation from radionuclides can differ in its penetrating power and in its health impact, depending upon the nature and the energy of the radiated particle. The unit of radioactivity used in this report is the **Curie**, which is defined as:

$$1 \text{ Curie} = 3.7 \times 10^{10} \text{ disintegrations per second.}$$

The curie is used as a measure of radiation regardless of the nature and energy of the radiated particle. An alternative unit of radiation found in the general literature is the becquerel which is defined as one disintegration per second.

Generally, as radiation interacts with biological tissue, it gives up energy, which can alter and damage the molecules present in cells. Of particular importance is that the DNA that carries genetic information necessary for cell development and replacement can be damaged, thus altering the function of the cell. Human health consequences can be death (usually only in cases of high radiation doses), cancer, or intergenerational genetic effects. The amount of cell damage depends on the type of radiation, its specific energy, and the total integrated dose of radiation received. Disparate types of radiation are converted

into units of biological impact called the (Roentgen Equivalent Man) rem. A **rem** is a measure of the total integrated intensity of the radiation and the relative biological damage of the radiation. For each of the more than one hundred radionuclides that may be present in the nuclear fuel cycle, standard methodologies are available for converting radiation doses into rems.

Death due to massive cell damage resulting from high radiation doses is referred to in this report as **early fatalities**. The term **latent cancer fatalities** is used for deaths resulting from cancer; those cancers that do not result in death are counted as illnesses. The monetary valuation aspects of latency and of intergenerational illnesses are discussed and treated as part of the economic valuation sections of the report.

5. URANIUM MINING AND MILLING

The nuclear fuel cycle consists of mining and milling uranium ore, processing the uranium into a form suitable for generating electricity, "burning" the fuel in nuclear reactors, and managing the resulting spent nuclear fuel. In mining and milling, uranium-bearing ore is removed from the host geology (mining) and processed to extract the uranium oxide (U_3O_8) from the host material (milling). This chapter provides a description of uranium mining and milling, and estimates of environmental releases, occupational and public exposures, and projected health effects.

The rest of this section summarizes the key health impact equation and key assumptions used to estimate the tons of uranium ore required to supply the annual fuel requirements of the reference reactor. Section 5.1 provides detail on mining and milling technology, and how they lead to both radioactive and nonradioactive residuals. Section 5.2 describes the sites affected by these activities. Section 5.3 describes the emissions during mining and milling operations and Section 5.4 describes emissions that persist after operations are concluded. Section 5.5 summarizes the major impact pathways discussed in the previous sections. Section 5.6 gives the calculation of health effects. Section 5.7 describes, in qualitative terms, the main ecological effects. Section 5.8 lists the employment levels.

An extensive literature of hundreds of reports was used to describe and quantify the health and environmental impacts of uranium mining and milling technologies. Where possible, we have updated the information to account for changes in estimates or technology.

In simplistic terms, the health impact may be estimated by the following equation:

$$HE = Q * TF * DCF * HF \qquad (1)$$

where:	HE	=	health effect (e.g., fatalities etc.)
	Q	=	source term (quantity released)
	TF	=	transport or dispersion factor that results in exposure quantity
	DCF	=	dose conversion factor (population dose per exposure)
and	HF	=	health effects factor (health effects per population dose)

We updated the source terms (Q) based on the fuel cycle requirements and changes in technology assumptions that were used in literature written in the mid–1970s to mid–1980s. The site is assumed to be the generic site described in the Generic Environmental Impact Statement (GEIS) on Uranium Milling (NRC 1980). Some justification for using a generic site is given in Chapter 4 and is discussed further in Section 5.1.1. The transport factors (TF) were not updated since this activity would require a significant resource commitment to provide an assessment that would be an improvement to the comprehensive GEIS on uranium milling (NRC 1980). The TF include such parameters as the local site meteorology, population density, and other site-specific parameters. The dose conversion factors (DCF), on a population dose basis, determine the population dose response resulting from radiation releases to the environment. For simplicity, TF and DCF were combined into a single factor to account for environmental transport and population exposure, so as to relate environmental release to population dose in a single factor. This combined factor is reported in NRC (1981) and was originally derived in the GEIS on uranium milling (NRC 1980). The health effects factors (HF) (i.e., those factors that convert the population dose to health effects) we used were updated from those used in the GEIS on uranium milling (NRC 1980), which were derived from (NAS 1972). The updated factors are derived from ICRP (1991) and BEIR-V (NAS 1990). The values of these factors are given in Section 5.6.1.

In this assessment. the environmental impacts of uranium mining and milling have been normalized to a reactor year which generates 0.9315 gigawatt years (GWe-yr) of electrical power or 8.16×10^9 kWh/yr. The study is based on a reference 3411 megawatt thermal (MWth) pressurized-water reactor (PWR) operating on an 18-month refueling cycle at an 81% capacity factor (i.e., the plant is operating at full capacity 81% of the time, and 19% of the time, the reactor is shut down for maintenance outages and refueling). The average annual fuel requirements have been estimated to be 20.98 metric tons (MT) of uranium in the form of uranium oxide (UO_2) enriched to 4.7 wt% ^{235}U. The reference PWR generates 1250 megawatts of electric power [MW(e)], of which 100 MW(e) is utilized by plant operations and 1150 MW(e) is provided to the transmission grid.

With the product stream fractions provided in DOE (1991c, Appendix A) and an assumed enrichment plant tails assay of 0.4 wt%, the average annual fuel requirement for the reference reactor would be 340.8 MT of U_3O_8. The enrichment tails assay is commonly assumed to be between 0.2 and 0.3 wt%. However, a value of 0.4 wt% was used in this study because uranium prices have been steadily falling over the past few years, partly due to increases in low cost, foreign imports, and partly resulting from decreased demand for uranium. Another factor influencing the selection of 0.4 wt% tails assay is the fact that the operating

costs per separative work unit (SWU) of the enrichment plant are less with 0.4 wt% tails than with a lower tails assay.

The uranium ore grade is assumed to be 0.135 wt% U_3O_8, with 93.1% of the U_3O_8 recovered in the product stream. This ore grade was a typical ore grade in 1990, but current uranium market conditions in 1993 make extraction impractical for grades less than 0.20 to 0.30. Thus, a total of 271,200 MT of uranium ore must be mined and milled to supply the annual fuel requirements for the reference PWR.

The present day (1990) uranium mining and milling industry is composed of a combination of domestic production and foreign imports. Since the mid-1980s, domestic production has suffered severe cutbacks brought on by lower costs of foreign ores and a stagnant commercial nuclear industry. For this study, we have made a broad assumption that uranium resource needs for the generic nuclear generating stations would be strictly derived from domestic production. Our assumed mining and milling technologies for the nuclear fuel cycle are that 50% of the uranium is produced by underground mining and acid leach milling and the other 50% of the uranium production is achieved by in-situ leaching. These assumptions vary from past studies, which typically assumed 2/3 of uranium production was from underground mining, 1/3 from surface mining, and little production from other technological sources. The uranium mining industry has undergone significant changes (and large cutbacks in production) since the 1970s and early 1980s. The 50% underground mining/acid leach milling and 50% in-situ leaching assumption, while perhaps overly simplistic, provides a reasonable picture of domestic uranium production technologies in the U.S. Production volumes from each technology are driven by economics and are tied to uranium prices in the world market. The following sections describe each technology, characteristics of representative sites, and quantify key emissions, occupational, and public exposures, and health effects associated with each technology.

5.1 MINING AND MILLING TECHNOLOGY

Uranium is a naturally-occurring silvery-white radioactive heavy metal that is present in small concentrations as various U compounds in rocks and minerals of the earth's crust and whose compounds are dissolved in the world's oceans. In a nuclear reactor, heat produced by the fissioning of ^{235}U is used to generate steam, which is then used to generate electricity.

Typically, uranium-bearing ore is mined by methods similar to those used for other metal ores. The uranium content of ores that have been milled in the U.S. have ranged from 0.05 to 0.8 percent U_3O_8. In foreign countries, the

uranium content of ores varies widely, from 0.035 percent in South West Africa to 14 percent at Cigar Lake in northern Saskatchewan, Canada. In general, foreign ores are of higher grade than those mined in the U.S. Commercially significant amounts of uranium are also obtained by other methods, such as solution (or in-situ) mining and as a byproduct of phosphate mining (DOE 1991a).

After processing to extract the uranium, the mill tailings contain most of the radioactivity contained in the original ore. The mill tailings are composed of a small fraction of the original uranium (5–10%) but nearly 100% of the daughter products (e.g., thorium and radium, and the short-lived isotopes of radon, polonium, bismuth, and lead). ^{222}Rn has a half-life of 3.8 days; ^{210}Po has a half-life of 138 days; ^{210}Bi has a 5 day half-life; and ^{210}Pb has a 22 year half-life. The long-lived parent controlling the rate of decay is ^{230}Th with a half-life of 83,00 years. The radioactivity of this material is typically about 3 nanocuries per gram (nCi/g) of tailings. A nanocurie is one billionth of a curie. This very low level of radioactivity would not normally be of concern, except for the fact that two of the daughters of ^{230}Th are the soluble ^{226}Ra and the gaseous ^{222}Rn. The ^{226}Ra could be dissolved by rain and eventually distributed in the biosphere where it may be ingested by the general population. The porosity of the tailings piles allows a significant fraction of the ^{222}Rn to escape to the atmosphere, where it could be inhaled by the general population. Of these two uranium daughter-products, ^{222}Rn seems to be of greater concern, especially since ^{226}Ra eventually decays to ^{222}Rn. Also of concern is the dust from the mill tailings pile.

The principal states in which uranium-bearing ores have been mined (including in-situ mining) are Arizona, Colorado, New Mexico, South Dakota, Texas, Utah, Washington, Wyoming, and most recently, Nebraska, which initiated commercial production in 1991. Both open pit and underground mining methods are used to produce uranium ores from the ground. Open pit methods are used to produce ore from deposits located near the surface or at shallow depths, depending on the local subsurface conditions. Underground mining methods are generally used for deposits that are deeper and contain ore of a higher grade. Ore mined by these methods is hauled to mills for processing or to stockpiles for future processing. Underground mines generally do not mine the ore unless they plan to process it and, thus, have smaller stockpiles.

In addition, significant amounts of uranium concentrate are produced by other methods, such as solution (in-situ) mining and as a byproduct of phosphate and copper mining. In-situ leaching methods involve leaching uranium from the ore "in-place" without removing the ore from the ground. A leaching solution is circulated through the in-place ore and is then chemically processed to concentrate the uranium ore (called yellowcake). In-situ mining involves processes that are very similar to the chemical extraction processing steps found in uranium milling.

The uranium-bearing leaching solution is then pumped to the surface, and the uranium is recovered. Leaching solutions commonly employed in solution mining consist of water containing small quantities of oxygen and carbon dioxide or sodium bicarbonate. Uranium is also recovered as a byproduct from the processing of uriniferous phosphate ore. Uranium has also been recovered in the U.S. as a byproduct of copper and beryllium production (DOE 1991d).

At uranium mills, usually located near the mines, uranium is extracted from the ore by chemical leaching to obtain the uranium concentrate, with the uranium content expressed as percent U_3O_8. Milling of mined ore begins with crushing and grinding of the ore to a particle size required for nearly complete chemical extraction of uranium. The prepared ore is then leached in a dilute slurry with acid or alkaline reagents to extract the uranium. After leaching is completed, uranium is concentrated from the slurry by solution-extraction techniques. The uranium is recovered from solution by chemical precipitation as uranium ore concentrate, which is then dried and packaged for shipment. The mill product, called uranium ore concentrate or "yellowcake," is then marketed and sold as pounds of U_3O_8. The concentrate from mills, in-situ mining, and byproduct recovery is shipped to conversion facilities, where it is purified and converted to uranium hexafluoride (UF_6) (DOE 1991d).

The following sections provide a basis for the reference mining and milling technologies chosen for assessment, and provides a more detailed description of each technology.

5.1.1 Basis Used to Select Reference Technologies

Selection of reference technologies for mining and milling is complicated. Many reports (Wymer 1981, Schneider 1982, NRC 1980, AEC 1972, Sears 1975) published in the 1970s and early 1980s indicated that most uranium production would result from underground and open-pit mining, and uranium production from other methods, such as solution (in-situ) mining or as a byproduct of other mineral production. would never be expected to play a major role in the total domestic uranium production. More recent surveys, (DOE 1991d; DOE 1991a; DOE 1990) however, indicate that uranium production by these other methods now accounts for nearly half of the annual domestic production of U_3O_8, and it is expected that this trend will continue in the near future.

During the last decade, many changes have occurred in the uranium industry that support our selection of a reference mining/milling technology based on 50% underground mine with acid leach mill and 50% in-situ leaching sources. At the end of 1990, only 39 uranium mining sources remained in operation (DOE 1991d), down considerably from 247 sources in 1981. These included 27

underground, 2 open pit, 7 in-situ leaching, and 3 others (composed of heap leaching, mine water, mill tailings, and low-grade stockpiles).[1]

Most operations are in the western U.S. Therefore, we have selected an underground mine in the western U.S. as the reference underground mining technology. The site description for the underground mine is assumed to be similar to that of the acid leach mill.

In the early 1980s, the average ore grade processed was between 0.12 and 0.16 percent U_3O_8. We have selected an ore grade of 0.135 percent for the reference uranium production operation. This assumption, coupled with a enrichment plant, tails assay of 0.4 wt% leads to relatively high ore volume requirements of the fuel cycle.[2] However, these assumptions are reasonable in lieu of current economic conditions. In-situ leaching would typically extract uranium with an ore grade of as low as 0.05 percent, but under more recent economic conditions, in-situ mining facilities must also extract uranium ore grades in the range of 0.20 to 0.30 percent U_3O_8.

In 1981, there were a total 20 operating and 3 inactive uranium mills (DOE 1987), with a total capacity of 54,000 tons of ore/day; and 77% of this total capacity was utilized. In 1990, only 2 mills remained in operation (DOE 1991d), and 12 were inactive. Only 7% of the total milling capacity in 1990 was utilized. Both mills presently in operation (Chevron Resources in Hobson, Texas, and Pathfinder in Shirley Basin, Wyoming) utilize the acid leach process, as did the Umetco mill in Blanding, Utah, which ceased operation as a uranium mill in 1990, although some uranium production continues as a byproduct of vanadium mining. Most uranium mills, both active and inactive, have utilized the acid leach process. Therefore, the acid leach process selected as the reference milling technology.

The reference uranium mill described in the Final Generic Environmental Assessment on Uranium Milling (NRC 1980, p. 5-1) was selected as the basis for this study. The generic reference mill was developed from a comprehensive accumulation of data and is probably more representative of the future industry than picking between the only two uranium mills in operation at the end of 1990.

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[1]The massive reduction in mining was in part a repercussion of the Three Mile Island accident in 1979, with many utilities canceling reactors in the early 1980s. All commercial reactors ordered in 1974 or later have been canceled (DOE 1991b). More recently, the two factors most responsible for the decline of domestic uranium production are the low-cost reserves recently developed in Canada and Australia and the sale of inventories by electric utilities and others. Use of U.S. and Former Soviet Union weapons-grade uranium in the commercial fuel cycle may cause further decline in the domestic uranium production.

[2]Since 1986, the average ore grade has been about 0.30 percent.

Uranium mines in almost all states, except Texas and Washington (i.e., Colorado, New Mexico, and Utah), are underground mines, which accounted for about 40% of the total mine production in 1990. Wyoming has both surface and underground mines. The number of byproduct and in-situ uranium production facilities in operation has also declined during the 1980s. In 1986, 12 of 15 facilities were operating (DOE 1987), compared with only 5 of 15 facilities (2 in-situ and 3 phosphate byproduct) in operation at the end of 1990 (DOE 1991d), although 7 in-situ mines were in operation during part of 1990.

Uranium production from "other" methods totaled 4 million pounds of U_3O_8 in 1990, although specific data on production by in-situ leaching was not available. Overall, production of uranium concentrate by other methods has remained fairly steady throughout the 1980s, with in-situ leaching facilities in Wyoming and Texas, and as a byproduct of phosphate recovery facilities in Louisiana and Florida. Also, an in-situ leaching facility in Nebraska started commercial operation in 1991. Most recently, the poor economic climate seems to have forced curtailment of uranium production as a byproduct of phosphate mining. With production of uranium concentrate from these other methods nearly equaling production from uranium mills, the assumption that 50% of the uranium production results from in-situ leaching is justified. Again, with only two or three in-situ facilities in production (or beginning production) in 1990, selection of one of these existing sites as reference is dubious. Therefore, for a reference in-situ mining site, we have chosen the generic description presented in NRC (1978a, p. 4-1), which is similar to the conventional reference mill site described in NRC (1980). Some of the specific details for in-situ mining facilities have been taken from White (1984).

5.1.2 Underground Mining

Deeper ore deposits require underground mining. A variety of techniques are used because of differences in the shape, size, altitude, and grade of the ore bodies. For small ore deposits, a number of mines employ simple inclined entries driven into the canyon wall or sloping ground. Mining is done by open-cast methods supported or unsupported by roof bolting; in wider spaces, pillar supports may be used. Ore is recovered by hand mucking and tramming and with the use of such equipment as front-end loaders and mucking machines (NRC 1980).

For larger deposits, most mines require a vertical shaft entry sunk to ore-bearing formations at depths of from 185 to 430 m (600 to 1400 ft). From the shaft, stopping, or the driving of various levels or tunnels, is performed to gain access to the ore deposits. The mining techniques used include the room-and-pillar, longwall retreat, and panel methods. The mining method selected for each

ore body depends on the stability of the ground, the size and shape of the ore body, and the cost of extraction (NRC 1980).

Groundwater intrusion is a problem with underground mining, and dewatering is usually required. The volume of water pumped from mines may range from 0.75 to 11 m^3/min (200 to 3000 gpm). The mine water is usually used as process water in the mill if the mill is adjacent to the mine. If the mine is further away or produces more water than the mill can use, the mine water is used for dust control, and is sometimes run through ion exchange processes to recover the uranium.

Mines are required to have proper ventilation to prevent the buildup of ^{222}Rn gas (a uranium daughter product) to concentrations hazardous to miners' health. Ventilation holes, typically 0.9 to 1.8 m (3 to 6 ft) in diameter, are drilled to connect the underground workings. A large fan installed at the top of the hole on the surface exhausts the mine air which enters the shaft. This is a principal source of radon emissions from uranium mining.

Uranium mining produces large amounts of bulk material. Surface mining produces far more wastes than underground mining. In surface mines, the bulk materials include excavated topsoil, overburden, and low-grade ore (sometimes called sub-ore). Topsoil is the natural soil overlying the area which is being mined. Overburden, which is beneath the topsoil and overlies the ore deposit, contains diffuse levels of naturally-occurring radioactive materials (NORM) and, thus, is a potential source of radon emissions. Overburden materials must be removed in order to expose the underlying ore bodies. Overburden is sometimes used to backfill mines, but is generally just discharged to the mine waste piles. Low-grade ore is usually stored (for later processing), and thus, is not considered as waste material. Underground mining, chosen as our reference technology, limits the amount of bulk materials generated in the mining operation, since far less of these materials are generated during construction of shafts than result from totally exposing the ore body in surface mining. For underground mining, the material removed from the shafts constructed to reach the ore body is called mine waste, not overburden, even though both overburden and mine waste contain quantities of naturally-occurring uranium at concentrations too small to allow economic extraction. Both materials are also part of the bulk waste materials that result from mine operations, although underground mine wastes are frequently not hauled to the surface.

The characteristics of uranium mine wastes vary with the geologic formation from which they are extracted. The majority of uranium ore is mined from geologic formations which include sandstone, claystone, siltstone, and shale deposits. Mine wastes also include silt, gravel, sand, volcanic ash, and lignite.

Rock and waste materials vary in size from small particles to large boulder size rocks. Typically, such wastes are piled up at the mine or spread out to be unobtrusive. The mine wastes have poor textural properties, do not support vegetative growth, and have poor water-holding capacities.

The mine waste to ore ratio is typically less than one for underground mines, and generally ranges from 1:20 to 1:1, with an average mine waste to ore ratio of about 1:9. This ratio has also been steadily decreasing over the past 40 years. For the 1990 mine production, we assume a mine waste to ore ratio of 1:9 to be indicative of the mine waste production from underground mining operations.

Mine wastes are the vast majority of waste materials from a mining operation, just as the mill tailings form the major waste stream from uranium milling. The potential for the mine waste to cause exposure to the general public or become redistributed in the environment depends, in part, on the location of the waste piles and whether they have undergone any reclamation. Surface mining is responsible for better than 90% of all overburden or mine wastes sent to waste piles. Whether produced by surface or underground mining, however, only a small fraction of mines have undergone reclamation, due to a lack of state regulations in all but Texas and Wyoming. Most mines remain unreclaimed today.

Mine wastes would typically be stored on-site. Because of the large volume involved, materials are moved only short distances from the mining areas. Mine wastes have been used on-site to construct roads. Past experience has shown that by far the most prevalent misuse of any uranium wastes involves construction of buildings using the mill tailings sands. It is fairly unlikely that mine wastes or overburden wastes would find use in construction of residential structures, since these materials would first need to be sorted to remove large boulders, then crushed to a suitable form. Other types of construction materials are readily available, and at much lower costs. Therefore, the other more likely exposure pathways involve land use, such as use for grazing, crop production, or residential or commercial developments.

5.1.3 Acid Leach Milling

The milling process involves the following basic steps: (1) ore handling and preparation, (2) mill concentration, and (3) product recovery. Ore handling and preparation include such processes as ore blending, crushing, fine ore storage, and grinding. Mill concentration consists of leaching with dilute sulfuric acid, followed by purification and concentration of leached uranium by solvent extraction. The product is recovered from solution by chemical precipitation, followed by drying and packaging for shipment.

Overall uranium recovery from the acid leach process is around 91 to 93% based on the uranium content of the ore feed, with the remaining 7 to 9% lost to the tailings (DOE 1991c, Sears 1975). The uranium mill tailings account for nearly all the material contained in the uranium ore, and is thus the primary waste stream from uranium milling. Ore contains only about 0.1% uranium; therefore, the tailings consists of 99.9% of the ore, including all the radioactive decay products (EPA 1986a, EPA 1986b).

About 10 percent of the ^{238}U and virtually all of the other radionuclides in the ore are contained in the tailings. Tailings represent the largest and longest lasting source (persistent source) of ^{222}Rn emissions from uranium milling because of the large exposed area and the significant concentrations of ^{226}Ra present.

Virtually all tailings are disposed of in impoundments. Some impoundments are constructed below-grade in mined-out or excavated pits, but most licensed mills use above-grade dams, where site topography dictates the general shape of the impoundments. Constructing impoundment with earthen embankments or below-grade is the preferred method at new milling operations.

Tailings are typically covered with raffinate, which effectively controls dusting and reduces ^{222}Rn emissions during the mill's active life. Upon closure of the mill, the tailings impoundment began to dry out, chiefly due to evaporation. This results again in an increase of ^{222}Rn release. In our reference mill, we have assumed this period lasts 5 years after mill closure. At 5 years, we have assumed that the mill tailings impoundment is stabilized. Stabilization involves covering the dry tailings impoundment with layers of rock, and if available, topsoil (to allow vegetation to grow). Mill tailings covering is designed to return ^{222}Rn emissions to background levels. Stabilization greatly reduces the radon emissions, but does not eliminate the emissions.

^{222}Rn is emitted from all exposed tailings in impoundments. Emission rates vary over time. ^{222}Rn and ^{226}Ra both have much shorter half-lives than their precursor ^{230}Th; therefore, their radioactivity remains the same as that for ^{230}Th. The ^{222}Rn emissions decrease only as the ^{230}Th, which has a half-life of 75,400 years, decreases. It would require about 265,000 years for the ^{222}Rn emissions to be reduced to 10 percent of its initial value. If control techniques are not imposed, the ^{222}Rn emissions remain relatively constant for many tens of thousands of years. Using covers, it is possible to reduce ^{222}Rn emissions to near background levels after the tailings are stabilized.

5.1.4 In-situ Mining

Solution, or in-situ, mining is employed to recover uranium from low-grade ores not economically recoverable by conventional mining methods. Essentially, the process consists of introducing suitable leaching solutions into the underground ore body to solubilize the uranium minerals and then recovering the enriched solution by pumping it to the surface for further processing[3]. Advantages of this method include the elimination of hazards associated with normal underground mining and elimination of the need for handling large quantities of material and disposing of solid waste products. Possible objections to undesirable open pits and structures are eliminated, a consideration of special importance when the mine is near populated areas (NRC 1980).

NRC (1978a) contains a detailed description of the in-situ mining process. This reference states that the largest environmental impact from in-situ mining is due to airborne exposures resulting from the drying and packaging of the yellowcake product. Groundwater contamination, resulting from excursions of the mining solution, is remediated by backwashing the well field with fresh water, which is then processed to removed the chemicals.

5.2 MINING AND MILLING SITE CHARACTERIZATION

Most of the nation's known uranium resources are located in the West, with about 90% of the potential uranium resources distributed among New Mexico, Wyoming, Colorado, Utah, and Texas. Hence, it is reasonable to assume a single, generic site for uranium production located somewhere in the western U.S. as a reference site for a conventional (underground) uranium mine, a conventional (acid leach) uranium mill, as well as an in-situ leach (solution mining) operation. Both the GEIS on uranium milling (NRC 1980) and the environmental report on the Irigaray solution mining project (NRC 1978a) present site descriptions that are essentially the same. Therefore, the reference site, as described in the uranium milling GEIS, is used for our site description.

The mine or mill site is postulated to be situated at the center of a hypothetical reference site with a radius of 40 km (25 miles). Surrounding the

[3]Solution mining is usually carried out by drilling inflow wells into the ore body upstream of a production well based on the direction of groundwater flow. Salt solutions of ions, such as sulfate, bicarbonate, carbonate, and ammonium, known to form stable aqueous complexes with hexavalent uranium, are pumped to the inflow well; simultaneously a slightly greater volume of water is withdrawn from the production well. A solution of oxidant ($NaClO_3$) may be added to increase leaching efficiency. The inflow of solution is continued until the leach zone is depleted, as indicated by a decrease in uranium concentration in the leach solution.

reference site is an annular region with an inner radius of 40 km (25 miles) and an outer radius of 80 km (50 miles). The area of the site is thus about 5000 km^2 (2000 mi^2) and that of the region is about 15,000 km^2 (6000 mi^2) (NRC 1980).

The following paragraphs describe the general characteristics of the environment at the generic reference site that would be impacted by mining and milling operations. When possible, these descriptions are based on weighted averages of the pertinent characteristics of the six physiographic regions of the U.S. within which uranium is milled. More detailed information may be found in NRC (1980).

Climate. The climate is semi-arid and the seasons are distinct, with mild summers and harsh winters. As is typical of much of the western U.S., the weather is dominated by influences of elevation and of the high- and low-pressure systems that pass through the area during the year. The average annual precipitation at the reference site is 31 cm (12 inches), but relatively large variations in the monthly and seasonal totals occur from year to year. Thunderstorms, frequent in spring and summer, occasionally spawn tornadoes that tend to be less destructive than ones occurring further east.

Air Quality. Present air quality is considered to be good. Data on concentrations and applicable standards for airborne pollutants are presented in Table 5-1 (NRC 1980). The entire basin is classified as an "air quality maintenance area", meaning that it is viewed by the EPA as having the potential for significant decline in air quality because of the projected increases in mining and industrial activity. The high wind speeds and sparsity of vegetation often result in wind erosion and, thus, in high concentrations of suspended particulates. The low population density, lack of industrial pollution sources (other than fossil-fired electrical generating plants at West City and East City), and the dispersive characteristics of the region account for the current air quality in the basin. East City and West City are fictitious population centers in the model region.

Topography. The reference site is located on plains of moderate relief, ranging in elevation from 1200 m (4000 ft) to 1300 m (4300 ft). The plains are dissected by the Tributary River and its associated streams. The base of the Northern Mountain Range, with elevations up to 1200 m (4000 ft), lies at the northern tip of the reference region (some distance from the site). The southern boundary reaches the rim of the Wide Plateau, which rises almost vertically from an elevation of 1300 m (4300 ft) to 2000 m (6000 ft) (NRC 1980).

Table 5-1. Ambient concentrations of airborne pollutants at the reference site

Pollutant	Concentration $\mu g/m^3$	Applicable standard $\mu g/m^3$
Suspended particulates		
24-hour average	4-90	150
Annual average	31	60
SO_2 (annual average)	6	60
NO_x (annual average)	15	100
Hydrocarbons		
3-hr average	45	160
Annual average	<5	

Source: NRC 1980, p. 4-5.

Land Resources and Use. Most of the land within the reference site is in public domain and administered by the Bureau of Land Management (BLM). This land and that of the few scattered private ranch holdings are primarily in the following land use categories: desert shrubland, subhumid grassland, and semiarid grazing land. The primary uses of the land in the reference region are shown in Table 5-2 (NRC 1980). Ownership patterns are shown in Table 5-3 (NRC 1980).

Table 5-2. Land use in the reference region

Land use	Percent of region
Subhumid grassland and semiarid grazing land	30
Desert shrubland grazed	25
Forest and woodland grazed	15
Open woodland grazed	20
Irrigated land, cropland, and cropland mixed with grazing land	10

Source: NRC 1980, p. 4-6.

Table 5-3. Land ownership in the reference region

Ownership	Percent of region
Public domain managed by Bureau of Land Management	30
Public domain managed by National Forest Service	25
Indian Reservation	15
Private	25
State	6

Source: NRC 1980, p. 4-6.

Water Resources and Use. The surface water resources in the region include ephemeral streams, small ranch impoundments used for livestock watering, four major reservoirs, and a river (Tributary River). The average and maximum concentration of chemical constituents in Tributary River are given in Table 5-4 (NRC 1980).

Socioeconomic Profiles. In general, the aggregated area of the reference site and reference region is sparsely populated. The current population is about 65,000, with a density of 3.25 persons per km^2. There is no major metropolitan center within 80 km (50 miles) of the mine/mill site, but about 70% of the population are town dwellers. The largest city, West City, has a population of about 25,000. It is about 80 km (50 miles) west of the mine/mill. East City, about 50 km (30 miles) east of the mine/mill, has a population of about 15,000. There are four towns in the reference region with populations ranging from 500 to 2000.

Three towns in the reference site all have populations of ~500. The only permanent residences within 20 km (12 miles) of the mine/mill are two ranches—one 2 km (1.2 miles) to the NE and the other about 10 km (6 miles) to the ENE (NRC 1980).

The region is primarily agricultural, principally ranching, and hay production, with an industrial center located in West City. More descriptive information about economic, cultural, and political aspects of the reference region are provided in NRC (1980).

5.3 OPERATIONAL EMISSIONS

In the early 1970s, the Atomic Energy Commission, in efforts to establish a technical basis for consideration of environmental effects of the uranium fuel cycle, published a draft (AEC 1972) and final (AEC 1974) report on the subject. One of the summary tables within the reports, Table S-3, "Table of Uranium Fuel Cycle Environmental Data," was codified in 10 CFR Part 51. Recently, the nonradiological environmental parameters have been updated (Habegger 1987) for uranium mining, milling, and enrichment.

Table 5-4. Concentrations of chemical constituents of the water in the tributary river (all concentrations in μg/L except as noted)

	Annual average concentration	Annual maximum concentration
Hg	2	2
AS	15	95
Cd	3.5	8
Cr	11	34
Cu	20	44
Fe	300	1,500
Pb	37	65
Mn	135	300
Zn	65	85
Se	3	7
Mg (mg/L)	30	50
SO_4 (mg/L)	115	430
B	380	950
F	380	500
Mo	3	7
NO_3 (mg/L)	20	40
Al	100	100
Ba	30	30
PO_4 (mg/L)	40	
Ni	25	25
V	6000	65,000
$CaCO_3$	350	1,200

Source: NRC 1980, p. 4-8.

Wastes (i.e., emissions) generated during mining and milling can be categorized as airborne, liquid, and solid. The emissions can be further divided into nonradiological and radiological. Nonradiological emissions primarily result from the operations of equipment at mines and the industrial and chemical processes at mills. Radiological emissions, particulate releases of U, ^{226}Ra, ^{230}Th, and ^{222}Rn, result from mining and milling processes that liberate uranium and its decay daughters from the ore. Radon is released directly during the operational period of the mine or mill. Persistent releases of radon from tailings piles and mine waste piles continue essentially forever. However, the rate of radon release is a function of the condition of the tailings or mine waste. During facility operation, the release rate of radon from tailings ponds and mine waste piles continues at a rate dictated by the rate of the decay of the parent radioactive species. In order to mitigate the release of radon from tailings impoundments, the impoundment is frequently covered with water, thus reducing the radon release rate as well as limiting the dispersion of dusts that would result from a dry tailing impoundment.

Most radiological assessments of uranium mining or milling discuss the impact of exposure to ^{222}Rn. In nature, almost all soils contain some uranium, which decays to thorium and radium and, hence, to ^{222}Rn. ^{222}Rn is a naturally occurring daughter product of ^{238}U, and is the only member of the decay chain that is a gas. Furthermore, it is a noble gas and, therefore, does not usually combine with other elements to form nongaseous compounds. As a gas, radon can be released to the atmosphere if it escapes the mineral matrix containing its parent, ^{226}Ra. It can also migrate through soil gas (the space between soil particles occupied by air), which is how it is found in basements. Since ^{222}Rn has a half-life of only 3.8 days, most radon generated underground decays into nongaseous daughters before it can escape to the atmosphere. When uranium is mined, the ore that is brought to the surface is much richer in uranium than average soil. On the surface, the radon emitted by the radium is much more likely to escape into the atmosphere. In terms of radiological impact, exposure to radon is of primary concern, far outweighing other radiological exposure mechanisms unless a dry tailings impoundment allows the dispersion and exposure to wind blown dusts from the tailings impoundment.

Solution mining operations, which extract the uranium from the uranium ore body while it is still underground, do not generate the large tailings impoundments needed by acid leach mills. However, solution mines have the potential of contaminating the groundwater. These effects have not been quantified in this report.

5.3.1 Underground Mining Emissions

Most non-radiological emissions to air result from the combustion of hydrocarbons in the heavy-duty diesel-powered equipment used in mining operations. These emissions are primarily NO_x, SO_x, and hydrocarbons. The dust emitted to the atmosphere is primarily silica, with small amounts of uranium, thorium, and trace elements from the soil overburden. Table 5-5 is a summary of the emissions to air based on a reference underground mine of the same capacity to meet the annual uranium ore needs of this study.

Table 5-5. Air emissions from underground uranium mines (nonradioactive)

Type of emission	Tons/reactor-year[a,b]
Particulates	0.54
SO_x	1.12
CO	9.25
NO_x	14.9
Hydrocarbons	1.49
Fugitive dust	148

[a] A reactor year is a means of normalizing production requirements to a common basis, in this case, the airborne wastes generated by the production of 271,200 MT of uranium ore.

[b] Values in this table have been adjusted to account for production of 271,200 MT of ore, not 200,000 tons as reported in Habegger (1987, p. 11).

The estimated contaminants in the water discharged from uranium mines, presented in Table 5-6, are based on a reference uranium mine and a discharge volume of 3800 x 10^6 gal/yr. The contaminants can be transported to the other geographic areas by stream migration in perennial or ephemeral streams. As the water evaporates from ephemeral streams, it also leaves behind its dissolved and suspended materials, which can subsequently percolate into the groundwater.

The amount of residual solid material at uranium mines is determined by the amount of overburden and waste rock that is not backfilled and the sub-ore that is not processed. It is assumed that the sub-ore produced is equal in quantity to the ore produced (270,000 tons per reactor-year) and that one-half (135,000 tons per reactor year) remains unused. The waste rock is assumed not to be backfilled.

Using an ore-to-waste rock ratio of 9:1, the quantity of residual waste rock is thus estimated at 30,000 tons per reactor year.

Table 5-6. Estimate of nonradioactive effluents contained in water discharges from underground uranium mines for a reactor year

Constituent	Tons/yr[a]
Total suspended solids	485
Sulfate	2030
Arsenic	0.21
Cadmium	0.12
Selenium	1.33
Zinc	0.75

Source: Habegger 1987.
[a]Based on average reference mine and discharge volume of 4200 x 10^6 gal/yr.

Mine ventilation is necessary to control concentrations of radon and radon daughters in the mine air to which miners are exposed; ventilation is generally provided by large exhaust fans drawing air from the mine through vertical ventilation shafts to exhaust into the atmosphere at the surface. All radon released from underground mine surfaces will either be contained in the ventilation exhaust or will decay in underground airways because of stagnation in some locations. In addition, radon will be released by ore and sub-ore stockpiles on the surface and by small amounts of waste that are brought to the surface and accumulated during the mine life. Measurements of radon contained in ventilation air from 27 underground mines were made by Pacific Northwest Laboratory. Based on 340.8 MT of U_3O_8 required to support a reactor year, it is estimated that during mine operation, ~9765 Ci/reactor year of radon is released from mine vents, and an additional 235 Ci/reactor year are released from ore piles, wastes, and handling operations, for a total of 10,000 Ci/reactor year. After shutdown of the mine, small releases of ^{222}Rn will continue at ~10 Ci over the first 100 years after mine shutdown (NRC 1981). This is due to the fact that most underground mines are left open after shutdown, possibly to expedite re-use in the future.

5.3.2 Acid Leach Milling Emissions

In the uranium milling process, uranium is extracted from the ore and concentrated into a semirefined product called "yellowcake". After the ore is pulverized and has gone through a process of wet grinding, it goes through an acid leach process. The resultant slurry is then decanted to remove the suspended solids, and the uranium is removed from the resulting liquid by solvent extraction. The residual liquids from the solvent extraction and the decanted solids, washed and resuspended, are sent to the mill tailings pond for disposal. The NRC has performed a major study of the environmental impacts of uranium milling (NRC 1980).

Since 1976, the NRC has made a concerted effort to bring uranium mill tailings under control. Performance objectives were issued in 1977, providing location criteria, requiring the elimination of wind-blown tailings, and requiring the reduction of post-reclamation radiation exposures on off-site areas to essentially background levels. The same NRC guidance discouraged the use of upstream dam construction and specified the use of clay or artificial liners in tailings ponds to minimize seepage. The EPA promulgated a requirement in 1983 that radon emissions be limited to 20 pCi per m^2/s.

Gaseous emissions from milling come from fuel combustion and the chemicals used in the acid-leach procedure. The use of fuels, such as natural gas or fuel oil results in the emission of hydrocarbons, SO_x, NO_x, CO, CO_2, and particulates. The primary effluents given off to the atmosphere from the chemical processes at the mill are SO_x, kerosene, ammonia, and amines. Also, vapors of organic chemicals enter the atmosphere via evaporation from the tailings ponds. The published emissions to the air for the reference mill (NRC 1980) were scaled to account for a mill producing 341 metric tons/yr of U_3O_8 and are listed in Table 5-7 (Habegger 1987).

When discharged from the mill, the slurried tailings material is pumped through pipes to the tailings pond. The slurried tailings at the reference mill contain equal parts by weight of the uranium-depleted ore and water. Therefore, about 915 tons/day of slurry are released to the tailings pond for the mill supporting the reactor year. In addition to the radiological residue in the tailings pond (which gives rise to radon gas emissions), materials are leached from the ore and from the chemicals used in the acid-leach process. The composition of the slurry generated at the reference mill is quantified in Table 5-8 (Habegger 1987).

Table 5-7. Nonradioactive emissions to air for an acid leach mill supporting the reactor year

Air emission	Tons/yr
Ore dust plus tailings dust	240
Hydrocarbons - organic solvent (92% kerosene)	160
Fuel oil burning	
SO_x	4.9
NO_x	1.1
SO_2 (acid leach tank vent)	0.22

Source: Habegger 1987, p. 17, scaled to reactor year production.

Table 5-8. Composition of the nonradioactive liquid tailings slurry generated at the reference mill

Chemical element	Composition (mg/L)
Aluminum	2000
Arsenic	0.2
Chloride	300
Copper	50
Fluoride	5
Iron	1000
Lead	7
Manganese	500
Mercury	0.07
Selenium	20
Sulfate	30,000
Zinc	80

Source: Habegger 1987, p. 18.

Solid wastes from the reference mill are generated at a rate of 140,000 tons per year for a mill supporting a reactor year. In regions where mills are generally found, the mill tailings slurry will tend to dry out and form a waste deposit. This material is normally too high in chemical content and too low in nutrients to support vegetation. To control the radon release, the tailings area is allowed to dry out, contoured, covered with earth and top soil, then planted and fertilized. In many western U.S. sites, insufficient rainfall for plant growth may require that the tailings be covered with a thick rock layer.

The only significant sources of radon emissions from an operating mill (excluding the tailings pile) are ore stockpiles and the operation of ore unloading, crushing, and grinding, which can be expected to release all of the contained radon. It is estimated that ore storage, crushing, and grinding account for radon releases of 102 Ci per reactor year (NRC 1981), and continue for the duration that the mill is in operation. The tailings pond, during operation of the mill, releases 1475 Ci per reactor year (NRC 1981), and the windblown ore and tailings provide an additional 1.7 Ci/yr until decay (NRC 1981).

5.3.3 In-situ Mining Emissions

The in-situ process is designed to recycle process chemicals as much as possible; however, some liquid, solid, and atmospheric emissions are produced.

The amounts and constituents in liquid effluent streams depend on the chemical processes used in the plant, constituents in the groundwater, and characteristics of daily operations. The major liquid waste streams include filter, reverse osmosis, and deionizer backwashes when these are used to treat the lixiviant solutions (or leach liquors); decant solutions from precipitation tasks, bleed or purge waters; and scrubber system effluents. Table 5-9 gives the approximate chemical compositions of liquid waste streams.

Amounts and kinds of solid waste generated by an in-situ operation vary depending on the constituents of the groundwater, the chemical processes used, the waste treatment and contamination control systems, and the daily operations. Solid wastes are generated from (1) the carbonate removal process, (2) the evaporative concentration of impounded liquid wastes, (3) supplemental contaminant control, (4) sediments trapped in filters and surge tanks, (5) well acidification, and (6) daily plant operations. Potentially radioactive solid waste is either drummed as it is produced or is discharged to the solid waste storage pit. This pit is lined and has a leak detection system. A berm, constructed at the top of the pit, diverts runoff from rainfall into the waste pond. The storage pit is kept

Table 5-9. Major constituents in liquid waste streams for in-situ operations

Constituent	Concentration (mg/l)[a]
Ca	120 - 3060
Mg	27 - 600
Na	150 - 5100
HC3	450 - 5400
SO_4	600 - 7050
Cl	525 - 66,000
NH_4	75 - 34,500
Mo	0 - 150
V	0 - 38
As	0 - 115
K	38 - 900
SiO_2	-
Al	-
U_3O_8	1.5 - 45
^{226}Ra	900 - 3750

Source: Cowan 1980, p. 2.21, derived from NRC 1978a.
[a]For ammonium carbonate-bicarbonate lixiviant, based on annual production of 340.8 MT of U_3O_8.

moist to prevent wind erosion. This also restricts ^{222}Rn and ^{226}Ra from becoming airborne. Periodically, the wastes are removed, mixed with concrete, drummed, and shipped to a licensed radioactive disposal site (Cowan 1980).

The primary sources of atmospheric emissions from an in-situ facility include the open surfaces of ponds and tanks, the product drying and packing unit, the internal combustion engines in vehicles and drilling rigs, dust from vehicular traffic on unimproved roads, and releases during process chemical handling (Cowan 1980). Emissions also occur from operation of diesel and gasoline powered engines used during construction and operation. For example, trucks are used frequently in in-situ operations to transport materials and to inspect equipment. All of these sources result in nonradiological atmospheric emissions. Table 5-10 contains a listing of the levels of primary pollutants expected from diesel and gas powered equipment operations. Table 5-11 shows ranges of values of nonradioactive emissions to the atmosphere during operations of selected components from an in-situ leach facility, based on 340,800 kg/year yellowcake production. Table 5-12 shows example values for radon and uranium atmospheric emissions during normal in-situ leach operations.

Table 5-10. Annual emissions from an in-situ facility from gas or diesel powered equipment

Emission	MT/yr
Particulates	1.29
CO	6.3
Hydrocarbons	1.8
NO_x	25.8
SO_x	1.8

Source: Cowan 1980; NRC 1978a, based on production of 340.8 MT U_3O_8.

Table 5-11. Annual nonradioactive atmospheric emissions from an in-situ leach facility

	Annual emission rates, MT/yr			
Source	NH_3	CO_2	NH_4Cl	H_2O
Recovery processes	4.1 - 6.0	1020 - 2040	20.4 - 36.8	—
Calcium control unit	1.5 - 2.7	4.1 - 6.0	0.045 - 0.06	266 - 320
Calcite storage pond	1.7 - 2.4	6.0 - 6.8	6.5 - 7.2	5400
Liquid waste ponds	6.0 - 7.5	4.8 - 5.4	18.3 - 21	6300

Source: Cowan 1980; NRC 1978a, based on 340.8 MT U_3O_8 production.

Table 5-12. Annual radioactive atmospheric emissions from an in-situ leach facility

Source	Annual Emission Rates(Ci/yr) ^{238}U	^{222}Rn
Recovery process	0.23	—
Calcium control unit	—	0.06
Calcite storage pond	—	2.04
Surge tanks	—	114

Source: Cowan 1980; NRC 1978a, based on 340.8 MT U_3O_8 production.

5.4 PERSISTENT EMISSIONS

During uranium mining, the soil and mine waste must first be removed to gain access to the underlying uranium ore. Mine waste, which is beneath the topsoil and overlies the ore deposit, contains limited amounts of natural uranium and its progeny. Mine waste usually does not have a high enough uranium concentration to make milling economically feasible, and is usually stored in piles near the mine. Many times, these piles remain after the mining operations cease, with little or no remedial action to stabilize the mine waste pile. The concentration of uranium results in radon releases to the atmosphere.

When uranium ore undergoes crushing and grinding at a uranium mill, literally all of the ^{222}Rn is liberated. The acid-leach milling process removes about 93% of the uranium from the ore, but leaves behind nearly 100% of the long-lived thorium and radium isotopes that were in secular equilibrium with the uranium parent. These materials are discharged to the mill tailings pond. Since the tailings contain essentially all of the thorium and radium initially contained in the uranium ore, releases of radon return to pre-milling release rates if the tailings pond dries out. After stabilization, the radon exhalation rate is impeded by the use of cover materials which trap radon until it has the opportunity to decay away. Herein lies the problem. Whether at the mine or mill, the mine waste pile and mill tailings pile provide a persistent source of radon emissions. Tailings represent the largest and longest lasting source (persistent source) of ^{222}Rn emissions from uranium milling because of the large exposed area and the significant concentrations of ^{226}Ra present. In surface mining, overburden is also of concern, but for somewhat different reasons. Overburden provides a smaller source of radon than tailings during the operational phase of the uranium mining/milling operation due to the

fact that overburden has a substantially lower concentration of uranium than that of uranium ore.[4]

In summary, the persistent emission problem is twofold. First, mill tailings and uneconomical ore piles (mine wastes, low grade ore) contain significant concentrations of uranium or uranium daughters, respectively, that provide a substantial and persistent source of radon emissions as a result of radioactive decay. Second, releases of radon are a function of the degree that either the mill tailings or mine wastes have been reclaimed or stabilized. For this report, we will assume that during facility operation, releases of radon from mine waste are minor (noise level) in relation to radon emissions from the mine. Milling, on the other hand, liberates all the radon in the ore, mostly during the crushing and grinding phases. We then assume, for the first 5 years after facility shutdown, that no reclamation or stabilization occurs, followed by stabilization that significantly reduces the radon emissions.

5.4.1 Mill Tailings Pile

The mill tailings pile is the primary source of ^{222}Rn emissions from uranium processing. Mill tailings include about 99% of the original weight of the ore, but less than 10% of the uranium content. However, mill tailings contain over 99% of the uranium daughters (thorium and radium).

The radon emission rate from tailings is based on a reference tails impoundment described in the GEIS (NRC 1980), except that an average tailings depth of 12 m is assumed, in line with current practice, and a correspondingly smaller tailings area is projected. The estimate for a reference tailings pond is normalized to 1 reactor year. Consideration is given to the contribution of windblown ore and tailings. After mill shutdown, there is a period of up to 5 years during which the water in the pond evaporates and there is an increased rate of radon emission and wind blown tailings dust (these impacts have been included in the projected impacts). Finally, the tailings area is reclaimed. There may be degradation of the tailings cover after a longer period of time, leading to increased emission rates (NRC 1981). It is estimated that the radon emission rate, per reactor year, for drying tailings is about 700 Ci/yr for up to 5 years before the tailings pile is reclaimed. The radon release from reclaimed tailings is estimated to be 1.7 Ci/yr for as long as the tailings pile cover remains intact. If the cover degrades, the radon release could be expected to increase by an order of magnitude.

[4]Reclamation of abandoned uranium mines varies greatly between states, however, only about 15% of the overburden has been reclaimed on the average. In addition, significant amounts of uranium still remain at older mines.

5.4.2 Mining Wastes

Mine wastes contain diffuse levels of NORM, and thus are a potential source of radon emissions (as is the ground on which these piles sit). Underground mines are exploited in a way that minimizes the removal of waste rock, resulting in much smaller waste storage piles than those of surface mines. The waste to ore ratio is typically less than one for underground mines, and generally ranges from 1:20 to 1:1, with an average ratio of about 1:9. This ratio has also been steadily decreasing over the past 40 years. For the 1990 mine production, we assume a ratio of 1:9.

Mine wastes are, by far, responsible for the vast majority of waste materials from a mining operation. Mine wastes are also a source of ^{222}Rn emissions. Because waste rock contains much less radium than either the ore, sub-ore, or tailings pile, and because the mine waste area is only about 6% of the total area at a mine/mill complex, it is conservatively estimated that radon releases from the mine wastes during operation of the mine will be about 52 Ci per reactor year.

5.5 PRIORITY IMPACT-PATHWAYS

This section gives the priority impact-pathways associated with the reference uranium mining and milling technologies. Table 5-13 lists the primary emissions or activities, their associated environmental pathways and impacts, and the evaluation status of each impact.

Underground Mining. Mining operations result in emission of SO_x, NO_x, and hydrocarbons from the operation of diesel equipment at the mine. The impact of these emissions is expected to be low because of low population densities in the relatively remote areas of the western U.S. Mine water discharges are expected to be treated before discharge, thus minimizing the impacts. Mines generate solid wastes on the surface, which provide a persistent source of ^{222}Rn from the waste piles. The mining operation also liberates a large quantity of ^{222}Rn that is transported to the surface with the mine ventilation air.

Solution Mining. Solution mining operations also result in the release of SO_x, NO_x, and hydrocarbons. Again, the impact of these emissions is expected to be low due to the remote operation of the in-situ well fields. Liquid wastes, and the possibility of groundwater contamination from excursions of the leach solution that is injected into the ore body is an important aspect of this type on mining. It is expected, however, that this type of mining operation would not be located

Table 5-13. Primary emission or activities, pathways and impacts linked to the nuclear fuel cycle from uranium mining and milling

Emissions/ activities	Environmental pathway	Impact	Impact evaluation
Underground mining			
SO_x, NO_x, hydrocarbons	Atmospheric dispersion, deposition on land surfaces	Human health	Minimal impacts due to low releases in isolated population areas
		Damage to wildlife and biosystems	Not quantified, minimal impact expected
Dusts from mining operations	Atmospheric dispersion	Human health	Qualitative
Mine water discharges	release to surface or groundwater leaching	Damage to aquatic habitat, degrade water quality	Qualitative
Solid wastes	Diffusion, atmospheric dispersion, persistent source of ^{222}Rn	Human health	Quantified
	Direct effect	Loss of land use, loss of aesthetic value	Not yet evaluated
^{222}Rn emissions from mine operations	Atmospheric dispersion and inhalation	Human health	Quantified
Solution mining (in-situ leaching)			
SO_x, NO_x, hydrocarbons, CO, particulates	Atmospheric dispersion and land deposition	Damage to wildlife and biosystem	Minimal impacts expected due to remote location
		Human health	Minimal impacts expected
Liquid wastes	Leaching to groundwater	Degrade groundwater quality	Qualitative
^{222}Rn emissions	Atmospheric dispersion and inhalation	Human health	Quantified

Table 5-13. Primary emission or activities, pathways and impacts linked to the nuclear fuel cycle from uranium mining and milling (continued)

Emissions/ activities	Environmental pathway	Impact	Impact evaluation
Acid leach milling			
SO_x, NO_x, hydrocarbons	Atmospheric dispersion and land deposition	Damage to wildlife and biosystem	Not quantified
		Human health	Not quantified
Liquid waste	Release to surface water or leaching to groundwater	Degrade surface and groundwater quality	Qualitative
^{222}Rn (operations)	Atmospheric dispersion and inhalation	Human health	Quantified
^{222}Rn (tailings)	Diffusion, atmospheric dispersion and inhalation	Human health	Quantified
General			
Socioeconomic	Direct effect	Benefits of employment	Quantified
Land use	Direct effect	Loss of aesthetic value and recreational use of land	Not yet determined
	Direct effect	Loss of biota habitat	Not yet determined

near potable water supplies and that backwashing would be used to mitigate impacts. Some ^{222}Rn is liberated by this type of mining, but in quantities far lower than that in underground mining.

Acid-Leach Milling. Milling also results in the release of SO_x, NO_x, and hydrocarbons. Again, the impact of these emissions is expected to be low due to the remote operation of the milling operations. The primary source of liquid wastes is the water and chemicals used to extract the uranium from the ore. This liquid is discharged to the tailings pond which is designed to minimize possible discharges to the environment. Milling releases ^{222}Rn, and the mill tailings pond provides a persistent source of ^{222}Rn. The impacts of ^{222}Rn have been quantified.

5.6 HEALTH EFFECTS

This section summarizes the health impacts resulting from mining and milling of uranium. This information is derived from the extensive body of literature on the subject. In many cases, the results have been updated to reflect changes in technology, the availability of more recent information, or, at the very

least, changes in the production basis for the 1990 technology. Emphasis is given to radiological impacts on the workers and population during facility operation.

5.6.1 General Public Mortality and Morbidity

Most uranium mining and milling facilities are located in sparsely populated areas of the country. Operation of these facilities results in emissions of non-radiological and radiological effluents. Most literature on mining and milling focus on the impact of the radiological (namely ^{222}Rn) exposure on the public. The literature tends to neglect potential impacts from non-radiological exposure pathways (e.g., SO_x and NO_x emissions). Historically, mining and milling assessments have neglected to assess exposures to chemicals released from facilities, thus, non-radiological exposure pathways are generally only given qualitative assessment in the available literature.

The release of ^{222}Rn from the processing of uranium ore appears to be the dominant health impact from the front end of the nuclear fuel cycle. Nearly all of the available radon is released from the mining and milling processes[5]. In earlier sections of this chapter, radon release estimates from mining and milling were reported. Using these estimates as the source term, it is then possible to determine the environmental dose commitment to the U.S. population resulting from radon release.

The method used to determine the dose commitment involves calculation of the environmental concentrations, based on dispersion of the radon (and daughters) through the environment, taking careful note of the environmental pathways leading to humans. The dose commitment is then calculated using assumptions on the distribution of the U.S. population, the pattern of food consumption in different parts of the U.S., the distribution of radon and its daughters in human body organs, and the size of the dose delivered to body organs per unit of radon and its daughters when ingested or inhaled. This methodology, in some form, has been utilized in every fuel cycle environment assessment, as represented by the GEIS on uranium milling (NRC 1980), the environmental assessment of the Irigaray solution mining project (NRC 1978a), and the work of Gotchy (1987). By utilizing the modeling efforts performed for the GEIS, one can simplify calculation of the environmental dose commitment to the following equation:

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[5]In 1978, the Nuclear Regulatory Commission (NRC) deleted from Table S-3 (Table of Environmental Data on the Uranium Fuel Cycle) the value for radon emissions during mining and milling operations. This was done because the value in the table was limited to radon releases during operation of the mill. It did not include the radon release from the tailings piles after the milling operations had stopped nor did it include the radon released from mining (NRC 1981).

$$EDC = Q * ETM * HRE \quad (2)$$

where

EDC = environmental dose commitment (health effects);
Q = radiological release, Ci;
ETM = environmental transport modeling, person-rem/released Ci;
and
HRE = health response estimator, mortalities/person-rem

This equation is analogous to the one on p 5-1, with TF and DCF combined as ETM. The ETM accounts for generic site information, transport modeling of the environmental pathways, and population uptake and dose conversion parameters. From GEIS, as reported in U.S. NRC (1981), a value for ETM of 0.041 person-rem/Ci is assumed. For somatic cancers, HRE is assumed to be 500 mortalities per million person-rem (ICRP 1991) and 400 mortalities per million person-rem for occupational exposure (ICRP 1991). For genetic risk, HRE is assumed to be 200 genetic defects per million person-rem (NAS 1990). Table 5-14 reports the population health effects for radon releases from mining and milling.

5.6.2 Nonradiological Occupational Health Effects

The U.S. Department of Labor (DOL) maintains occupational mortality, injury, and illness data for all types of U.S. mining industries, including uranium. This data represents the best source of occupational data and is used as the basis for nonradiological occupational health effects in this study.

The U.S. DOL data for uranium mining is reported in terms of number of fatalities, accidents, illnesses, and lost work days for the following broad categories: (a) underground mining, (b) surface at underground, (c) surface mining, (d) processing plants, and (e) office. The data does not have a unique category for (in-situ) mining. Therefore, in order to calculate different risk factors for underground and in-situ mining, it is assumed that underground mining is composed of data from groups (a), (b), and (e), while in-situ mining consists of data from groups (b) and (e) only. It is assumed that the "surface at underground" category would be reference of surface activities at an in-situ mine. The processing plant data, category (d), is defined as uranium milling, and is used that way in this study. Note that in-situ mining also involves a processing step, synonymous with milling.

The U.S. DOL injury data does not provide a listing of total mine production (DOL 1987a, DOL 1987b, DOL 1988, DOL 1989, DOL 1990). These

data for the years 1985 to 1989 were obtained from DOE (1991d). On average, about 60% of the uranium production was the result of surface or underground mining, with 40% from other mining sources. This is in rough agreement with our assumption of a 50/50 mix of underground and in-situ uranium production methods.

Table 5-15 provides a listing of the estimated non-radiological occupational health effects for uranium mining and milling. The data for illnesses were primarily the result of exposure to dusty conditions or other repeated trauma that resulted in an occupational illness or disability, as reported to the Mine Safety and Health Administration (MSHA).

For perspective, we have compared the values listed in Table 5-15 with Table 14 of the Gotchy (1987) report and with Table 3-6 of the Chapter 3 draft on Mining and Milling from CEPN (1992). The Gotchy report indicates the mortality rate for occupational accidents of mining to be 0.2 per Gwe-yr, but our data indicates a value of 0.023 for underground mining and 0.012 for in-situ mining. Gotchy reports the mortality health effects from milling (processing) to be 0.001. Our data, for the years 1985 through 1989, did not indicate any deaths. The Gotchy value of 0.001 per GWe-yr for milling occupational fatalities is not inconsistent with this observation.

For non-fatal accidents, the Gotchy report indicates a range from 4.6 to 13 for mining and 0.76 to 2.1 for milling. Our data tends to show a value for underground mining (3.14) somewhat lower than the Gotchy range and considerably lower for in-situ mining (0.40). However, our data shows non-fatal accident health effects from milling to be somewhat higher than the Gotchy range (2.4). The occupational health effects reported by the Gotchy report come from estimates reported in 1979 by the National Academy of Sciences, Committee on Nuclear and Alternative Energy Systems. We presume that the generally lower health effects values reported herein are the result of improvements in mine and occupational safety over the last two decades.

When comparing our data with the recent Chapter 3 draft from CEPN, our data indicate a mortality rate from accidents of 2.84E-3 per TWh for conventional mining, and 1.43E-3 per TWh for in-situ mining, somewhat lower than the CEPN

Table 5-14. Estimates of radon emissions and corresponding population health effects

Radon emissions	During operation	First 100 years after shutdown
Underground mining	10,000 Ci/reactor year	10 Ci
Milling*	1579 Ci/reactor year	-
In-situ leaching	116 Ci/reactor year	-
Tailings piles	-	3662** Ci
Overburden	-	422*** Ci
Calculated population health effects****		
Underground mining		
Fatalities	0.101	0.00010
Genetic defects	0.08	0.00008
Milling		
Fatalities	0.015	-
Genetic defects	0.013	-
In-situ leaching		
Fatalities	0.001	-
Genetic defects	0.001	-
Tailings piles		
Fatalities	-	0.036
Genetic defects	-	0.03
Overburden		
Fatalities	-	0.004
Genetic defects	-	0.003

*Includes tailings emissions during operation.

**Release is 700 Ci/yr for first 5 years after shutdown of facility; reduced to 1.7 Ci if tailings and/or overburden is stabilized.

***Release is 52 Ci/yr for first 5 years after shutdown of facility; reduced to 1.7 Ci if tailings and/or overburden is stabilized.

****Calculated health effects = Curies released x person-rem/Ci x health effects/person-rem.

Table 5-15. Nonradiological occupational accident risks

Risk basis	per reactor year
Underground mining	
Fatal accidents	0.0232
NFDL accidents*	1.984
NDL accidents**	1.160
Illnesses	0.0464
Lost work days (LWD)	72.95
In-situ mining	
Fatal accidents	0.0116
NFDL accidents	0.267
NDL accidents	0.128
Illnesses	0
Lost works days (LWD)	5.26
Milling (processing)	
Fatal accidents	0
NFDL accidents	1.462
NDL accidents	0.916
Illnesses	0.0812
Lost works days (LWD)	30.90

*NFDL accidents are non-fatal accidents that result in work days lost.
**NDL accidents are non-fatal accidents that did not result in loss of work days.

value of 6.16E-3 per TWh[6]. For the available accident data, our data indicate an average of 12.7 lost work days per TWh for underground mining, and only 4.42 LWD per TWh for in-situ mining, quite a bit lower than the CEPN value of 66 LWD per TWh. Some of the differences may originate from differences in the U.S. and French systems for acquiring occupational health data. In France, the national health system provides a data base of medical treatments; the U.S. DOL depends upon reporting by the mine operators.

5.6.3 Radiological Occupational Health Effects

The main source of radiation exposure to underground uranium miners is radon and its daughters. This exposure results in an average annual effective dose equivalent of 1.3 rem (13 mSv) (UNSCEAR 1988). Surface miners have a lower exposure to radon and daughters, with annual doses estimated to be about 0.3 to 0.4 rem (3-4 Msv). Both underground and surface miners are also exposed to external gamma radiation from the ore body. Estimates for underground miners range from 0.1 to 1.0 rem (0.6 rem assumed); for surface miners, the estimate is 0.1 to 0.2 rem. For underground mining, the total effective dose equivalent is assumed to be 1.9 rem.

We assume that occupational doses from an in-situ mining and processing operation may be conservatively represented by occupational doses from uranium milling. In-situ leaching utilizes similar leaching processes that occur at a conventional uranium mill. It is estimated that the annual effective dose equivalent to uranium mill workers is 0.27 rem (2.7 mSv) (UNSCEAR 1988).

In 1990, the total U.S. worker population of 664 uranium miners, 304 uranium mill workers, and 293 uranium processing workers, was responsible for the production of 4.65 million pounds of U_3O_8 (conventional) and 4.24 million pounds of U_3O_8 (nonconventional) in 1990. For production of 340.8 MT of U_3O_8 needed to supply our reactor year, this translates into 107 uranium miner workers and 49 mill workers for conventional production and 52 uranium processing workers.

Taking all the above information and utilizing the same dose conversion factors applied to the general population, we calculate that the total effective

[6]Because mortality from occupational diseases is usually the result of chronic exposures, the U.S. Department of Labor data do not indicate mortality from diseases. Thus, the Labor Department data do not provide data for lost work days (LWD) as a function of occupational diseases. In fact, occupational diseases are usually not fatal, but the fatal diseases tend to be preceded by a permanent disability. The MSHA has statutory limits of 6000 LWD for death or permanent total disability.

occupational dose from underground mining and acid leach milling uranium production is 217 person-rem/reactor year. For in-situ leaching uranium production, the total effective occupational dose is calculated to be 14 person-rem/reactor year. The occupational radiological health effects are shown in Table 5-16.

Table 5-16. Estimates of occupational radiological health effects

	Somatic fatalities*	Genetic defects**
Conventional mining/milling	0.09	0.043
Nonconventional (in-situ) mining	0.006	0.003

*Somatic health effects (fatalities) assume 400 fatalities per million person-rem (ICRP 1991).
**Genetic health effects assume 200 genetic defects per million person-rem (NAS 1990).

5.6.4 Health Damages from Uranium Mining and Milling

At the uranium mining and milling stage, miners, millers, and the general public are at risk, both in terms of mortality and morbidity, from radiation. In addition, the miners and millers are at risk from occupational injury. In this section, the expected fatalities and morbidity effects are valued to estimate damages. Note that, as in other fuel cycle valuation exercises, we make no attempt to identify the extent to which damages have been fully internalized in the price of uranium. There is a presumption that occupational health damages are likely to be more internalized than effects on the general public, however. Nevertheless, we present all damage estimates here.

Unit Values for Mortality. Unit values for immediate deaths and premature deaths from cancer are developed in this section (but see Chapter 7 for a fuller explanation). The damages associated with immediate deaths are based on the average value of a statistical life (which we take from the literature review by Fisher, Chestnut, and Violette 1989). This study is considered to be the primarily wage compensation studies analyzing the premiums paid to workers in relatively risky jobs for the excess accidental death risks they bear. It also considers contingent valuation studies of the willingness to pay (WTP) to avoid automobile death risks. Low, Mid, and High values are $1.6 million, $3.5 million, and $8.6

million, respectively. As these values are taken from studies involving accidental and immediate deaths in the workplace, we feel these estimates are reasonably appropriate for application to occupational death risks, somewhat less appropriate for immediate death risks to the public, and still less appropriate for applying to risks of death from cancer to workers and the public.

The unit values for cancer-related premature mortality in miners and the public from radon exposure can be calculated in three ways: (1) multiplying estimates of the value of a statistical life (from Fisher, Chestnut, and Violette 1989) by the number of premature deaths and adjusting for latency; (2) multiplying an estimate of the average value of a life-year saved (Viscusi and Moore 1988) by the total life-years lost and adjusting for latency; and (3) multiplying the value of a statistical life associated with a disease with a twenty-year latency period (Mitchell and Carson 1986) by the number of premature deaths. The third approach is clearly the most appropriate as premature death from radon exposure will occur after a long latency period. Unfortunately, the risks faced by miners as a result of their occupational exposure exceed the risks examined in the Mitchell and Carson study, making this approach infeasible. We also reject the life-years saved approach, because the number of life-years saved is unclear and these studies were conducted in the workplace setting where risks of accidental death were at issue.

We use the first and simplest approach. To address latency, we use an estimate of the average latency period for cancer (20 years) to date the onset of cancer and discount the accidental death WTP estimates from the date of onset to the present. Multiplying the discounted WTP estimate by the annual expected deaths from cancer gives the annual expected damage for the annual exposure.

With radon exposures of the general public, there are exposures that outlast the use of the uranium mine to provide fuel for the plant. In the previous section, these are defined as "cancer fatalities during the first hundred years after plant shutdown." We assume, for purposes of simplification, that all exposures occur in the first year after shutdown, i.e., year 40, with a 20 year latency period from there. This effectively means that the WTP is being discounted over a 60 year span. This is a conservative assumption in that it overestimates damages. To obtain an annual value, this resulting damage estimate is then levelized using a 3% rate of interest.

Unit Values for Morbidity. The only morbidity effects we can value are nonradiological impacts to both miners and millers, called Non-Fatal Days Lost (NFDL) accidents and lost work days. The former are simply occupation accidents leading to injuries and involving at least one day absence from work. Non-fatal cancer estimates were not made for this stage; hence, no unit value is

offered here (see Chapter 7 for these values). Because the mining was assumed to occur in present day timeframe, it was assumed that mining safety practices would avoid many of the chronic health effects that were more common in past years. There are two approaches taken in the literature for estimating the willingness to pay (WTP) for reduction in nonfatal injuries [translated into value of a statistical injury (VSI) by dividing the WTP by the risk change]. One approach, exemplified by Rossman, 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, pain and suffering, etc. The second approach is a hedonic wage approach, which may be called a top-down approach, where variation in injury rates across types of jobs and industry classes and other variables is used to explain variation in wage rates and labor force participation. This is the identical 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.

Since no injury incidence information of sufficient specificity is available for the uranium mining and milling industry, we apply an across-industry average cost per injury, as provided by the Urban Institute (UI) in Rossman, Miller, and Douglass (1991), for using a bottom up approach of VSI estimates. The UI has developed their cost file from an analysis of the Detailed Claims Information (DCI) database of the National Council on Compensation Insurance (NCCI). Their cost file includes (1) medical costs, (2) wage loss, (3) household productivity loss, and (4) administrative costs, which we do not include since they are likely to be fully internalized. If the injuries included in the DCI database are of the same kind (severity, injury type distribution, cost) as the injuries in the uranium mining and milling industry, then we can assume that the industry-wide average cost of $10,301 per injury is applicable to this industry. (For a fuller description of the methodology used to determine these costs, see Appendix F.2 in the draft Coal Fuel Cycle Report.)

We found nine studies using the hedonic wage approach to estimate the value of avoiding a statistical injury (VSI). These models include personal and job characteristics and most include corrections for workers compensation benefits (which are tax-exempt) by assuming full earnings replacement from workers compensation and using after tax wage rates. These researchers generally assume that job risks are exogenous. If individuals with higher earnings capacity choose less risky jobs, this assumption will result in a downward bias to the VSI.

The studies, as a group, indicate that workers do receive higher wages as a result of working in occupations or in industries with higher injury rates. The one study that disaggregated injuries by major and minor injuries (Martinello and

Meng 1992) found that wage compensation was insignificant (actually negative and significant) for minor injuries, but was positive, significant, and large for major injuries, implying VSI's ranging from $116,000 to $138,000 in 1989 U.S. dollars. For the studies that do not differentiate injury severity, values range from $10,000 to $70,000, although the bulk of the studies are in the $20,000 range.

There are two studies that stand out from the rest: Martinello and Meng (1992) and Moore and Viscusi (1988).[7] The Martinello and Meng study, although simple in its estimation techniques, provides an analysis with by far the most recent database (1986 vs the 1970s, except for some of the Viscusi papers, which are based on 1982 data, but are for the chemical industry only). The model contains terms for both fatal and non-fatal injuries. The sample is blue-collar workers in logging, mining, and manufacturing, a reasonable sample for occupational injury damage estimation in the fuel cycles, providing estimates of both fatal and non-fatal risks in excess of those for a random sample of occupations and industries.[8] Unfortunately, the model does not include worker compensation adjustment, uses pre-tax wage rates, and is estimated using ordinary least squares (OLS) techniques, a relatively unsophisticated approach. Given these problems, one would expect that the Martinello and Meng estimates of VSI for aggregate injury rates (not by severity) would be below those of the other studies, which they are. Without controlling for severity, Martinello and Meng estimate a VSI ranging between $8,000 and $10,000. However, their VSL estimates of from $1.6 to $4.9 million (1989 U.S. dollars) are not out of line with the VSL literature.

The other, more theoretically sophisticated study, is by Moore and Viscusi (1988). They apply non-linear least squares techniques to estimate the discount rate being applied to life cycle decisions, use the after tax wage, correct for workers compensation programs, and contain dummy variables to reflect self-assessed hazard. The drawbacks of this study are that it uses data from 1977 and the sample is relatively small—only 317 non-farm household heads who worked more than 20 hours per week. Their best estimate of VSI is $26,000 (1989$), with a range $17,000 to $34,000 for average baseline risks of about 4.7 lost work days per 100 days.

We have a clear preference for the "revealed preference" analyses using hedonic wage techniques. Given the fact that the bottom-up approach yields

[7] The remaining studies are less sophisticated and older studies and so will not be discussed further.

[8] Occupational injury rates average 6.3 days/100 days for this sample versus 4.68/100 for a more representative sample.

estimates within the range given by the hedonic studies, but with no clear preference among the two best hedonic studies (one uses more recent and more relevant data, the other is more sophisticated from a theoretical and econometric point of view), we construct a judgmental confidence interval for a VSI spanning the range of these two studies, from $8,000 to $34,000. When applied to the electricity generation sector, for a best estimate, we choose the UI study's across industry average value of a VSI of $10,300, which falls within this range. However, because mining and milling are more dangerous activities than the industry average, we use a best estimate value of $21,000 per injury, based on the average of Moore and Viscusi (1988) and Martinello and Meng (1992). We ignore the estimate of Section 5.6.2 for lost work days, because such losses are already subsumed in the unit damage estimates.

Mortality Damage Calculations. As shown on Table 5-17 for the southeast reference environment, based on the estimate of 0.02 immediate occupational deaths to miners and millers expected annually and a VSL midpoint estimate of $3.5 million, we offer a midpoint estimate of $70,000/year, or 0.009 mills/kWh. Expected annual occupational cancer fatalities of 0.048, valued at $1.9 million, result in damages of $93,000/year, or 0.0114 mills/kWh. Premature deaths to the public are twice as large each year of the mine's operation as the sum of all cancer deaths to the public expected from 100 years of exposure after the mine closes. The annual effects result in damages of 0.014 mills/kWh as a midpoint estimate. The latter, "100 year" effects, after discounting over 60 years and levelizing, result in trivial damages, even with the assumption that all exposures are compressed into the year following mine closure. The results are identical for the southwest reference environment since it has the same sources of uranium.

Morbidity Damage Calculations. For the southeast reference environment (Table 5-17), the damages associated with nonfatal injuries in the mining and milling of uranium are $63,000/year as a best estimate, or 0.008 mills/kWh. The analogous information for the southwest reference environment is identical.

Uncertainties. Table 5-17 also presents judgmental LOW and HIGH estimates of damage based entirely on ranges of unit values for the VSL's and VSI's, as discussed above. For this stage for the southeast reference environment, total damages range from 0.019 mills/kWh to 0.097 mills/kWh with a midpoint estimate of 0.042 mills/kWh. For the southwest reference environment, total damages are identical because the mining and milling is assumed to be located in the same areas irrespective of reference environment of the power plant.

Table 5-17. Annual health damages from uranium mining and milling

Startpoint	Radon emissions				Radiological Occupational Risk		Nonradiological occupational risk				
Exposure	Public				Miners		Miners and millers				
General endpoint	Mortality		Morbidity		Mortality	Morbidity	Mortality	Morbidity			
Specific endpoint	Cancer fatalities during plant lifetime	Cancer fatalities during 1st hundred yrs after shutdown (a)	Genetic defects during plant lifetime (a)	Genetic defects during 1st hundred yrs after shutdown (a)	Cancer fatalities	Genetic defects	Fatalities	NFDL accidents	NDL accidents	Illnesses	Lost work days (LWD)
Yr of first exposure to risk	1	40	1	40	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	1	40	1	40	40	40	40	40	40	40
Latency period (yrs)	20	20	#N/A	#N/A	20	#N/A	0	0	0	0	0
Expected cases resulting from each annual exposure	0.0605	0.039045	0.0535	0.039045	0.048	0.023	0.02007515	2.9812131	1.798175	0.12034	80.687
LOW											
Damage per case valued at time of exposure (1989$)	$885,881	$885,881	#N/A	#N/A	$885,881	#N/A	$1,600,000	$8,000	#N/A	#N/A	#N/A

Table 5-17. Annual health damages from uranium mining and milling (continued)

Startpoint	Radon emissions				Radiological Occupational Risk		Nonradiological occupational risk				
Exposure	Public				Miners		Miners and millers				
Damage levelized over plant lifetime (1989$/yr)	$53,596	$459	#N/A	#N/A	$42,522	#N/A	$32,120	$23,850	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.00656367	5.61795E-05	#N/A	#N/A	0.00520754	#N/A	0.00393364	0.0029208	#N/A	#N/A	#N/A
MEDIUM											
Damaged per case valued at time of exposure (1989$)	$1,937,865	$1,937,865	#N/A	#N/A	$1,937,865	#N/A	$3,500,000	$21,000	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (1989$/yr)	$117,241	$1,003	#N/A	#N/A	$93,018	#N/A	$70,263	$62,605	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.01435802	0.000122893	#N/A	#N/A	0.01139149	#N/A	0.00860483	0.007667	#N/A	#N/A	#N/A
HIGH											
Damage per case valued at time of exposure (1989$)	$4,761,611	$4,761.611	#N/A	#N/A	$4,761,611	#N/A	$8,600,000	$34,000	#N/A	#N/A	#N/A

Table 5-17. Annual health damages from uranium mining and milling (continued)

Startpoint	Radon emissions				Radiological Occupational Risk		Nonradiological occupational risk				
Exposure	Public				Miners		Miners and millers				
Damage levelized over plant lifetime (1989$/yr)	$288,077	$2,466	#N/A	#N/A	$228,557	#N/A	$172,646	$101,361	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.03527971	0.000301965	#N/A	#N/A	0.02799051	#N/A	0.0211433	0.0124133	#N/A	#N/A	#N/A

(a) Assumes all the exposure occurs in the first year after shutdown.

5.7 ECOLOGICAL EFFECTS

This section discusses the priority impact-pathways for ecological impacts associated with uranium mining and milling (Table 5-18, see also Appendix F).

5.7.1 Land Commitment

Underground Mining. The land required for underground uranium mining largely consists of land used for long-term storage of waste rock and, during operation, of land used for storage of sub-ore (containing a smaller percentage of uranium than ore), and the ore itself. Land requirements for the mining activities are dependent on the particular mining technique utilized and the resource characteristics. For underground mines, the mined surface area is negligible. The amount of waste rock produced from underground mining is much less than the overburden produced at surface mines. In fact, the amount of waste rock produced is less than the amount of ore produced, with an estimated average ore-to-waste rock ratio of 9.1:1. Assuming production of 270,000 MT of ore per reactor year, the land requirements for a mine extended to a 30-yr lifetime are 12 acres for waste rock (overburden) storage, 1.3 acres for 41-day ore storage, and 23 acres for sub-ore storage. Land for other facilities at the underground mine is estimated at 4 acres. It is assumed that the land commitments for sub-ore storage are permanent. Also, it is assumed that waste rock is not backfilled and, thus, the land is permanently committed. The land use requirements are summarized in Table 5-19 (Habegger 1987).

One of the major impacts associated with mining is the withdrawal of groundwater to prevent flooding of the mine. Declining water levels in the tapped aquifers, and possibly adjacent formations, are immediately noticed. Lowering of the water table may also affect the flora and fauna, especially in the West, where many of the plants are dependent on subsurface water. Water levels in the aquifers generally return to premining conditions after mining operations cease. The discharge of water pumped away from the mining area and into the neighboring environment is one of the major impacts of uranium mining. This water is often released to the environment without processing or being allowed to reside in a settlement pond prior to release. The discharge of mine water may transform dry washes and ephemeral streams in perennial streams. The relative amounts of water that evaporate and go to surface and groundwater sources vary with the climate and the topography. For underground mines, water discharges are estimated at 4200 x 10^6 gal/yr for production of 271,200 MT of ore for the

Table 5-18. Primary emissions or activities, pathways and ecological impacts linked to the nuclear fuel cycle from mining and milling

Emissions/activities	Environmental pathway	Impact	Impact evaluation
Air emissions:			
Radionuclides	Deposition on land surface	Changes in biodiversity; contamination/ damage to wildlife and crops	Qualitative evaluation; minimal impacts due to low concentration
Water quality:			
Mine water; process water	Discharge to surface water or impoundment	Create or damage aquatic habitat, degrade water quality	Qualitative evaluation
Other factors:			
Solid waste	Leaching to ground water	Degraded water for irrigation, livestock and wildlife	Qualitative evaluation
Land use change	Development of roads, mine openings, tailings piles, impoundments, buildings	Changes in biodiversity; loss of biotic habitat, loss of grazing land	Land use change quantified but not evaluated

Table 5-19. Land-use requirements for underground uranium mines

Requirement[a]	Temporary acres/reactor year	Permanent acres/reactor year
Mined surface area	—	—
Overburden, waste rock storage	18	18
Ore storage	1.3	—
Sub-ore storage	23	23
Associated facilities	4	—
Total	46	41

[a]Land-use estimates are values extended over the 30-yr lifetime of the mine.
Habegger 1987, adjusted to account for production of 271,200 MT of ore.

reactor year. The water discharged from a mine is generally pumped into alluvial stream beds. How far it proceeds through above-ground streams and rivers is highly dependent on the specific location, hydrology, topography, and climate of the mine. It is assumed that 40% of the discharged water goes to surface water, 50% to groundwater, and 10% to the air.

Acid Leach Milling. For the reference mill with a 30-yr lifetime that produces 340.8 MT of U_3O_8 needed per reactor year, about 165 acres will be permanently committed to the mill disposal area (pond). This entire area could be committed to tailings initially or in several stages during the lifetime of the mill. In addition, about 17 acres could become contaminated by wind-blown tailings (i.e., greater that 5 pCi/g of radium). During operation, about 82 acres would be devoted to the milling process and allied activities. This is a temporary land commitment independent of mill lifetime (Habegger 1987).

Each day, the reference mill processes 875 tons of ore, resulting in nearly equal daily tailings and nearly equal daily water weights for slurrying the tailings. On the average, 30% of the tailings liquid is recycled, so that the net consumption of water is 615 tons (155,000 gal) per day. This water typically comes from deep wells or possibly from supplies available from nearby mining operations. When discharged from the mill, the slurried tailings materials are pumped in pipes to a tailings pond. A well is normally drilled for potable water, but potable water requirements are small compared with those for the milling itself. The use of wells to supply process water results in a decrease in the amount of water available in aquifers for other uses, but the quantities withdrawn are not expected to have major long-term effects on regional water supplies. The use of water from mining operations for process water at the mill reduces the need for process water

wells and also reduces the volume of mine water discharged to the environment (Habegger 1987).

The amount of seepage to groundwater from the tailings pond, which serves as an evaporation pond, varies from as much as 85% to as little as 7% in properly engineered clay-lined ponds. There are generally no routine releases to surface water from uranium mills, if the tailings pile is properly sited and minimal engineering controls are used. In the unlikely event that excess liquids exist in the ponds (precipitation and the influx from the mill exceeds seepage and evaporation), these liquids would be discharged, after treatment, to streams and underground wells. Standing water in adjacent intermittent streams has been found with elevated concentration of toxic materials. Also, contaminated groundwater can conceivably find its way to nearby surface streams and lakes (Habegger 1987).

At equilibrium operating conditions, a seepage rate of 0.1 million tons of water per year for the reference mill has been estimated. It is further estimated that after the mill is shut down, about 5% of this amount will continue to percolate annually. About 90% of the water evaporates during the operation, after which the dissolved chemicals retard evaporation, requiring that the remaining water be drained from the pond before stabilization. Of the 47 million gallons of water required annually, about 90% evaporates and the remainder seeps into the groundwater (Habegger 1987).

The reference uranium mill requires electrical energy and fuel oil or natural gas for the milling process. It is estimated that 3500 MWh/yr of electrical and 90 x 10^9 Btu/yr from natural gas and/or fuel oil is required by the reference uranium mill processing 271,200 MT of ore per year (Habegger 1987).

In-situ Leaching. For a reference in-situ uranium processing plant that produces 340.8 MT U_3O_8 needed for the reactor year, the well field of the facility takes up about 1500 acres. Approximately 150 acres of the well field will be in production at any one time, using about 1800 injection wells and about 300 production wells. The tailing pond only requires about 2 acres. For in-situ mining in Texas, wastes are reinjected into deep wells.

5.7.2 Water Quantity and Quality

Mining uranium-bearing ore and disturbing the overburden associated with the uranium deposits will disrupt local aquifers. Groundwater will flow into the pits and mine tunnels and have to be removed. Water collected by wells and sumps would be pumped to settling ponds on the surface, and may be used for mill processes and dust control on roads and tailings piles (NRC 1978a). Rates

of groundwater pumping from uranium mines are expected to range from 0.75 to 11 m^3/min (200 to 3000 gpm).

Some of the groundwater removed from the mine will return to the aquifer via seepage in the settling pond. However, seepage will likely be limited by impermeable soils, such that most water pumped from mines is expected to be lost through evaporation in the settling ponds or consumption in the mining and milling processes. The effect of groundwater pumping on surface water quantity will depend on the permeability and depth of the aquifer. Shallow, highly permeable aquifers may be an important source for permanent surface water in arid regions. Loss of groundwater by evaporation or consumption could reduce the amount of water that would otherwise be available from groundwater inflow to streams and ponds near the pumping site. On the other hand, deep or relatively impermeable strata may have little influence on surface waters. When pumping rates exceed evaporation rates and the process water needs of mines and mills, runoff of mine water from the settling ponds would provide a relatively high-quality source of surface water in nearby perennial or ephemeral streams (Table 5-6).

Mill tailings are transported to lined tailings ponds as an aqueous slurry (Section 5.1.3). The slurry water contains suspended materials (fine-grained minerals), milling reagents (especially sulfuric acid), and dissolved ore solids, including radionuclides and metals (Table 5-8). Slurry water is not discharged to stream channels from the tailings ponds, but rather is recycled or allowed to evaporate. After mill tailings have dried out, they are stabilized with rock and topsoil. Therefore, under normal operations, there is no discharge of contaminated mill process waters to streams or ponds.

5.7.3 Biota

Site construction and maintenance will result in the removal or disturbance of about 351 acres of terrestrial vegetation; 128 acres would be temporary land-uses during operations, whereas 223 acres would be permanently committed to waste rock and tailings storage (Section 5.7.1). Secondary impacts would be caused by deposition of fugitive dust from mining and milling activities and road surfaces. Deposited dust may lower plant vigor by slowing photosynthetic rates, and will cause the plants to be less palatable to animals.

Mining and milling activities will result in the destruction or impairment of habitat for terrestrial animals. Small animals (e.g., mice, ground squirrels, insects, and reptiles) will be destroyed in the disturbed areas, whereas larger, more mobile animals (e.g., antelope, deer, and birds), would be displaced to other areas. These losses would be similar to those from construction and operation of other,

similar-sized industrial or commercial installations in the area (U.S. NRC 1980). Restoration of vegetation following cessation of operation would also restore much of the lost terrestrial animal habitat. Under normal operations, discharge or seepage of process waters in the mill tailings ponds will be prevented, so the risk to wildlife of contaminated drinking water should be small.

Aquatic habitats in arid regions are often maintained by inflowing groundwater. Removal of groundwater from the aquifer by mining operations, followed by its loss through evaporation, dust suppression, and milling processes, could reduce the quantity of water available for nearby aquatic habitats. Project-generated soil erosion and dust could increase the turbidity of streamflows following rainstorms, but these systems already carry high suspended sediment loads. Compared to normal suspended sediment loads, project-related increases would probably be slight in small nearby tributaries and undetectable in larger streams (U.S. NRC 1980). Because there will be no discharges of process water under normal operations, no surface water quality degradation or direct losses of aquatic biota from toxic contaminants are expected. Similarly, adequate lining of the mill tailings pond should prevent transport of contaminated water into the aquifer and subsequently to surface waters downgradient from the site.

5.8 EMPLOYMENT

Based on uranium production requirements in support of an reactor year (340.8 MT U_3O_8), it is estimated that 119 person-years of mining and 49 person-years of milling is needed for conventional mining/milling, and 52 person-years of processing is needed for nonconventional uranium production. Chapter 10 gives estimates of the employment benefits for the entire nuclear fuel cycle.

6. ELECTRICITY GENERATION - NORMAL OPERATIONS

6.1 Nuclear Reactor Technology

6.1.1 Generic Description of the Nuclear Power Generation Principle

Like biomass and fossil-fuel fired central station electric generating plants, nuclear power plants are based on a thermal steam cycle where the heat produced in a "furnace" vaporizes water and the steam produced drives a turbine-generator. The heat produced in the nuclear "furnace" or reactor core, however, is derived from nuclear rather than chemical reactions.

For nuclear plants, most of the products of the "burning" process (nuclear fission products, neutron activation products, and transuranic elements) are highly radioactive and, in many cases, toxic. These radionuclides cover many elements of the Periodic Table of the Elements having differing chemical and physical properties. It is the ionizing radiation emitted by these radionuclides, which is not detectible by human senses, that is of most concern to regulators and the public. In sufficient quantities, this radiation can damage living tissue and lead to mortality or morbidity. For this reason, the radionuclide products from nuclear power production must be carefully isolated from the environment.

Under normal operation nearly 100% of the products of "burning" from a nuclear plant's operation reside within the reactor core and are not continuously released to the environment. A major task in nuclear reactor design is to protect people and the environment from the detrimental effects of these radionuclides both during normal operations and during an inadvertent release of radionuclides from the reactor core. The environmental and health consequences of an accidental radionuclide release are so serious that the nuclear reactor accident issue becomes a major consideration in describing and evaluating the social and environmental effect of nuclear electric power generation. (For fossil- or biomass-fueled power plants, even a serious mishap, such as a boiler explosion, will have minimal environmental/health impacts beyond the boundaries of the power plant itself.)

The following paragraphs now describe a typical nuclear plant in more detail, with emphasis on the reactor core and heat removal portions, i.e. the systems where most of the radioactivity resides or can find pathways to the environment.

6.1.2 Rationale for Selecting the Westinghouse PWR as the Baseline Reactor Plant for this Analysis

Presently there are 111 operating nuclear power stations that are licensed to generate electricity for resale in the United States. All are based on the use of light water as the moderator and coolant; thus, such plants are usually referred to as light water-reactors (LWRs). (The term "light" water refers to the hydrogen isotope in the water (H_2O) coolant/moderator and is discussed later in this Section) Within this classification there are two major types of LWRs—the PWR and BWR. The major reactor suppliers are shown in Table 6-1 along with the number of operating units of each type.

Table 6-1. U.S. power reactors and suppliers

Reactor technology	Supplier	Number in the United States
PWR	Westinghouse	52
PWR	ABB/Combustion Engineering	15
PWR	Babcock & Wilcox	8
BWR	General Electric	36

As noted above, the Westinghouse-PWR (W-PWR) represents the largest number of operating plants in the United States (52 out of 75 operating PWRs). Forty of these W-PWRs are over 850 MW(e) in capacity and are listed in Table 6-2 along with their generating capacities, geographic locations, cooling water sources, and utility owner/licensees. [Most U.S. reactors are named for nearby geographic entities such as cities (e.g. Zion, Illinois), counties (e.g. Salem, New Jersey), or reservoirs (e.g. Watts Bar, Tennessee). Some are given persons' names, e.g. Joseph Farley (Alabama), a utility executive, and Sequoyah (Tennessee), a famous Cherokee Indian leader.] The W-PWR is also the design upon which the French power system is most dependent, i.e. the Westinghouse PWR technology originally licensed to Framatome and ordered by Electricite de France (EDF). This latter similarity is important in that it provides an excellent basis for comparison for the U.S. DOE and European Community (EC) fuel cycle studies.

Table 6-2. Capacities and geographic data for operating U.S. W-PWRs

#	NAME OF SINGLE-UNIT FACILITY	NAMEPLATE CAPACITY (MWE)	NET CAPACITY	LOCATION (COUNTY) [STATE ABBREVIATION IN PARENTHESES]	OWNER/LICENSEE (UTILITY)	COOLING WATER SOURCE
1	BEAVER VALLEY 1	923	810	BEAVER CO. (PA)	DUQUESNE LIGHT CO	OHIO RIVER
2	BEAVER VALLEY 2	923	810	BEAVER CO. (PA)	DUQUESNE LIGHT CO	OHIO RIVER
3	BRAIDWOOD 1	1175	1120	WILL CO. (IL)	COMMONWEALTH EDISION CO	KANKAKEE RIVER
4	BRAIDWOOD 2	1175	1120	WILL CO. (IL)	COMMONWEALTH EDISION CO	KANKAKEE RIVER
5	BYRON 1	1175	1105	OGLE CO. (IL)	COMMONWEALTH EDISION CO	ROCK RIVER
6	BYRON 2	1175	1105	OGLE CO. (IL)	COMMONWEALTH EDISION CO	ROCK RIVER
7	CALLAWAY 1	1236	1125	CALLAWAY CO. (MO)	UNION ELECTRIC CO	MISSOURI RIVER
8	CATAWBA 1	1305	1129	YORK CO. (SC)	DUKE POWER CO	LAKE WYLIE
9	CATAWBA 2	1305	1129	YORK CO. (SC)	DUKE POWER CO	LAKE WYLIE
10	COMANCHE PEAK	1161	1150	SOMERVELL CO. (TX)	TEXAS UTILITIES GENERATING CO	SQUAW CREEK RESERVOIR
11	COOK 1	1152	1020	BERRIEN CO. (MI)	INDIANA & MICHIGAN ELECTRIC CO	LAKE MICHIGAN
12	COOK 2	1133	1090	BERRIEN CO. (MI)	INDIANA & MICHIGAN ELECTRIC CO	LAKE MICHIGAN
13	DIABLO CANYON 1	1137	1073	SAN LUIS OBISPO CO. (CA)	PACIFIC GAS & ELECTRIC CO	PACIFIC OCEAN
14	DIABLO CANYON 2	1164	1087	SAN LUIS OBISPO CO. (CA)	PACIFIC GAS & ELECTRIC CO	PACIFIC OCEAN
15	FARLEY 1	860	814	HOUSTON CO. (AL)	ALABAMA POWER CO	CHATTAHOOCHEE RIVER
16	FARLEY 2	860	824	HOUSTON CO. (AL)	ALABAMA POWER CO	CHATTAHOOCHEE RIVER
17	HARRIS 1	951	860	WAKE & CHAPMAN COs. (NC)	CAROLINA POWER & LIGHT	MAKE-UP RESERVOIR
18	INDIAN POINT 2	1013	939	WESTCHESTER CO. (NY)	CONSOLIDATED EDISON CO	HUDSON RIVER
19	INDIAN POINT 3	1013	965	WESTCHESTER CO. (NY)	POWER AUTH. OR THE STATE OF NY	HUDSON RIVER
20	MC GUIRE 1	1305	1129	MECKLENBURG CO. (NC)	DUKE POWER CO	LAKE NORMAN
21	MC GUIRE 2	1305	1129	MECKLENBURG CO. (NC)	DUKE POWER CO	LAKE NORMAN
22	MILLSTONE 3	1253	1137	NEW LONDON CO. (CT)	NORTHEAST NUCLEAR ENERGY CO	LONG ISLAND SOUND
23	NORTH ANNA 1	947	911	LOUISA CO. (VA)	VIRGINIA ELECTRIC POWER CO	LAKE ANNA
24	NORTH ANNA 2	947	909	LOUISA CO. (VA)	VIRGINIA ELECTRIC POWER CO	LAKE ANNA
25	SALEM 1	1170	1106	SALEM CO. (NJ)	PUBLIC SERVOCE ELECTRIC & GAS CO	DELAWARE RIVER
26	SALEM 2	1170	1106	SALEM CO. (NJ)	PUBLIC SERVOCE ELECTRIC & GAS CO	DELAWARE RIVER
27	SEABROOK	1197	1150	ROCKINGHAM CO. (NH)	NORTHEAST UTILITIES	ATLANTIC OCEAN
28	SEQUOYAH 1	1221	1122	HAMILTON CO. (TN)	TENNESSEE VALLEY AUTHORITY	TENNESSEE RIVER
29	SEQUOYAH 2	1221	1122	HAMILTON CO. (TN)	TENNESSEE VALLEY AUTHORITY	TENNESSEE RIVER
30	SOUTH TEXAS 1	1311	1251	MATAGORDA CO. (TX)	HOUSTON LIGHTING & POWER CO	RESERVOIR
31	SOUTH TEXAS 2	1311	1251	MATAGORDA CO. (TX)	HOUSTON LIGHTING & POWER CO	RESERVOIR
32	SUMMER 1	900	885	FAIRFIELD CO. (SC)	SOUTH CAROLINA ELECTRIC & GAS CO	MONTICELLO RESERVOIR
33	SURRY 1	848	781	SURRY COUNTY (VA)	VIRIGINIA ELECTRIC POWER CO	JAMES RIVER
34	SURRY 2	848	781	SURRY COUNTY (VA)	VIRIGINIA ELECTRIC POWER CO	JAMES RIVER
35	TROJAN	1216	1095	COLUMBIA CO. (OR)	PORTLAND GENERAL ELECTRIC CO	COLUMBIA RIVER
36	VOGTLE 1	1215	1100	BURKE CO. (GA)	GEORGIA POWER CO	SAVANNAH RIVER
37	VOGTLE 2	1215	1097	BURKE CO. (GA)	GEORGIA POWER CO	SAVANNAH RIVER
38	WOLF CREEK 1	1236	1135	COFFEY CO. (KS)	WOLF CREEK NUCLEAR OPER. CORP.	COOLING LAKE
39	ZION 1	1085	1040	LAKE CO. (IL)	COMMONWEALTH EDISON CO	LAKE MICHIGAN
40	ZION 2	1085	1040	LAKE CO. (IL)	COMMONWEALTH EDISON CO	LAKE MICHIGAN

Within the W-PWR class there is a further sub-classification by containment type. (As will be explained in more detail later, the containment is the very large and thick structure which is designed to isolate radioactive materials from the environment in the event of a severe reactor accident.) The selection of containment type is very important to the reactor accident evaluation process which is discussed in Chapter 7. Table 6-3 presents a summary of the domestic PWR containment designs for completed, but not necessarily operating, W-PWRs. It is clear from the table that the Zion plant has the most representative reactor and containment technology (38 of 80 constructed PWR units are like Zion) of the three PWRs studied in recent comprehensive U.S. NRC safety studies: NUREG/CR-4624 (NRC 1986) and NUREG-1150 (NRC 1990). Thus, similarity concerns would argue in favor of selection of Zion as a reference design technology.

Table 6-3. Domestic PWR power plant containment technology

Number of units	Reactor vendor	Containment type	Representative NUREG-1150 plant
38	Westinghouse	Dry	Zion
15	Combustion Engineering	Dry	None
10	Westinghouse	Ice condenser	Sequoyah
10	Babcock and Wilcox	Dry	None
7	Westinghouse	Sub-atmospheric	Surry

It was also decided by both the U.S. and the EC research teams to evaluate existing PWR reactor technology for this particular stage of the Fuel Cycles Study. For the United States, the assumed nameplate electrical generation capacity is on the order of 1250 MW(e) for a single unit. This translates to gross maximum utilized generating capacity of 1250 MW(e). (Note: This same W-PWR design is sometimes utilized up to a gross capacity of 1300 MW(e), hence, the basic design concept is sometimes referred to as the Westinghouse 1300 MW design. The fuel cycle data for this study is for the 1250 MW(e) design capacity.) After subtracting the 100 MW(e) "house load" required for pumps, heaters, and other electrical equipment, a net generating capacity of 1150 MW(e) remains. Assuming an 81% capacity factor, which is attainable for a baseloaded plant using an "extended burn" fuel cycle, this plant can generate 8.16 billion kilowatt-hours

(8160 GWh) of electricity per year. The total thermal power output of this plant is 3411 MW(th) with a thermodynamic efficiency of 33.7%. (Because the steam produced in a fossil-fired plant is somewhat hotter, a higher efficiency, i.e. around 38%, is attained in a fossil plant.) A 40-year life for the plant is assumed, since this is the basis for licensing by the NRC.

The PWR technology described here represents that utilized for the most-recently completed (1990) Westinghouse PWRs. U.S. PWR vendors and regulators (NRC) are also in the process of designing and certifying reactors utilizing improved engineered safety systems (evolutionary plants such as the Combustion Engineering System 80+) and safety systems relying on natural thermal-hydraulic principles (passive plants such as the Westinghouse AP-600). These plants are projected to have severe accident probabilities significantly smaller than for existing PWRs. In later phases of the Fuel Cycles Study, and when more data on these designs are available, these "Year 2010" options may be evaluated.

There are other reasons for choosing the generation of PWRs that are currently operating as the reference technology:

1. The reactor system and its overall fuel cycle requirements are well characterized.

2. The safety characteristics of these PWRs, including accident scenarios, accident source terms, accident probabilities, and accident consequences have been studied extensively by the U.S. NRC. Much of this analysis, such as that documented in NUREG-1150 (NRC 1990), was a direct regulatory response to the Three Mile Island reactor accident in 1979.

3. Historical data on PWR reactor performance and radionuclide emissions are readily available.

The choice of the PWR rather than the BWR, and the choice of the Westinghouse system over CE's and B&W's was not meant to show favoritism toward one system. The intent was to simply evaluate a benchmark reactor plant. There was also no intent to select a system on the basis of anticipated small (or large) impacts, especially since the differences in impacts between today's LWR reactor systems would be expected to be very small. (Advanced reactors, such as those that have passive safety features, may have smaller calculated damages due to their smaller size and reduced accident probabilities.)

6.1.3 Description of PWR Technology

6.1.3.1 Basic Energy Conversion Principle

As with any thermal power plant the PWR must: (1) convert to heat, control, and recover the energy generated by the fission reaction within the nuclear "furnace" (in this case nuclear transmutation processes within the static reactor core), (2) transfer as much of this heat as possible to mechanical/electrical energy via a turbine-generator, and (3) discharge the waste heat in an environmentally acceptable fashion. Light water (as opposed to the rarer "heavy water" used in other nation's reactor programs) is both the circulating coolant, which transfers heat to the steam generators, and the moderator, which slows down the neutrons generated in the fission reaction and allows these neutrons to take part in additional fissions, thus sustaining the nuclear chain reaction for energy production. The PWR coolant passes through the very hot core where it is heated to approximately 600°F (316°C). Because of the high pressure of 2235 psig (15400 KPa), it stays in the liquid state (as opposed to the BWR where steam is produced in the reactor core). Via a steam generator, the heat from the hot side of the pressurized-water loop (primary loop) downstream of the core is used to produce dry, saturated steam (840-1000 psig, ~540 of 280°C) in the secondary loop. This secondary loop contains the turbine-generator (T-G), which produces electrical energy, and the condenser (where the lower energy steam leaving the T-G is cooled and condensed back to water). This water is pumped back to the steam generator to complete the secondary loop. Approximately 14 million lb/hr (30.9 million kg/h) of steam circulates in this secondary loop at full power. The condenser downstream of the T-G must be cooled by an external heat sink, such as the atmosphere or a natural or artificial body of water. Typically, 66% of the heat produced in the core is eventually discharged into this heat sink. The remaining 34% is converted to electrical energy. (The second law of thermodynamics limits the amount of heat energy that can be converted to mechanical/electrical energy.) Figure 6-1 illustrates the basic PWR system arrangement described above. The following subsections describe PWR technology in greater detail and are based on descriptions in an NRC PWR Technology Manual (NRC 1992).

6.1.3.2 The PWR Core

In the reactor core, solid pellets of slightly-enriched uranium dioxide ceramic fuel are converted to fission products, additional neutrons, and gamma radiation. (Note: enriched uranium is uranium that has been enhanced in the fissile isotope ^{235}U.) The kinetic energy of these nuclear species produced, such

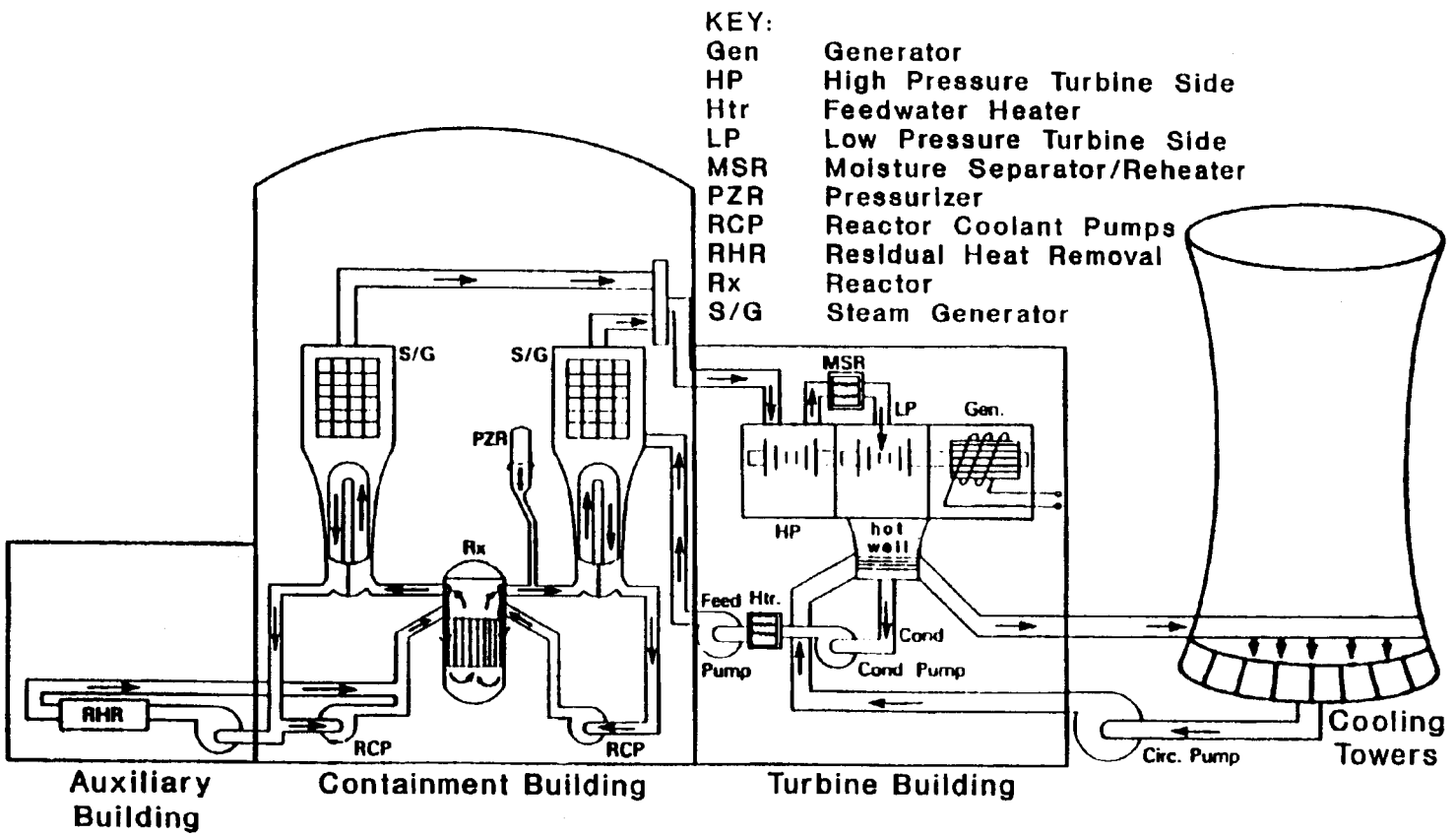

Figure 6-1. Basic PWR Arrangement

as fission product fragments, is converted to prodigious amounts of heat. Unlike fossil fuel thermal plants to which the fuel is continuously fed and combustion products withdrawn, the nuclear plant core is a batch reactor consisting of a static core. The products of the fission reaction are contained by the ceramic fuel pellet itself, the cladding of the fuel rod, and the pressure vessel which holds the core and the circulating coolant. The fission products consist of dozens of different elemental/isotopic species of varying physical and chemical properties. In addition to being highly radioactive, many of these are far more volatile than uranium oxide fuel and, because of the high temperature in the core, will attempt to escape or react with the cladding or coolant. The first line of defense against such fission product release is the zircaloy cladding tube enclosing the stacked UO_2 fuel pellets. This alloy is corrosion resistant and can be welded to produce strong leaktight fuel rods. The tubes are strong enough to contain the noble gas fission products which diffuse out of the fuel pellets as fission proceeds. In general, the normal operation leak rate from these tubes is quite small, thus keeping the normal operation radionuclide emissions very small. The second line-of-defense between the fission products and the environment is the reactor pressure vessel itself. This very thick-walled structure, along with the primary piping and pumps, contains any fission products that leak from the cladding into the primary water coolant. [A PWR pressure vessel can typically hold 108,000 gallons (410 cubic meters)]. The water primary coolant in the pressure vessel flows axially upward past the fuel rods, thereby cooling them and keeping their maximum internal or "centerline" temperature less than 3000°F (1650°C). The temperature of the fuel rod cladding must be kept below 1000°F (538°C). If the internal fuel temperature were to exceed 5000°F (2760°C), the fuel would begin to melt and a severe accident situation would commence.

The W-PWR core consists of 193 fuel assemblies or bundles, each consisting of 289 rod positions. These rod positions are arranged in a 17 x 17 square array within each assembly. Of the 289 positions, 264 are occupied by fuel rods with the remainder being control or diagnostic positions. A fuel rod is typically 12 ft (3.66 m) long and consists of stacked UO_2 fuel pellets clad in a zircaloy sheath. A typical core has over 100 miles (161 km) of fuel rod.

The fission reaction in the core is allowed to proceed until enough fission products have built up that core performance (heat output per unit mass) begins to degrade due to neutron absorption. At this point the reactor is shut down and, typically, one-third of the "spent" fuel elements are replaced by new ones. This refueling step, which generally takes several weeks, is performed every 12 to 18 months. The spent fuel rods are then transported to an in-plant storage pool where the water removes the decay heat. After a cooling period of several years, the rods are transferred to out-of-containment pool storage or dry cask storage awaiting ultimate transfer to the U.S. DOE and its civilian high-level waste

management system [a monitored retrievable storage facility (MRS) or a geologic repository]. Section 6.1.3.8 describes the reactor fuel and its burnup characteristics in more detail.

6.1.3.3 Heat Removal

Heat from the core is removed by the pressurized primary-loop water which is circulated by four large, leaktight pumps in a four-loop Westinghouse plant. Within each loop is a steam generator, which is a very large, vertically mounted heat exchanger. Liquid water entering the secondary side of the heat exchanger is evaporated to 540°F, 1000 psia steam; this steam is subsequently routed to the high-pressure steam header for use in the steam turbine. The exit steam from the turbine is condensed via another large heat exchanger simply called the condenser. The condenser must be cooled by water from an external source or heat sink. The method used to cool the condenser is site specific and depends on the availability of natural or artificial water sources and their temperatures and flowrates. (Air could also be used for condenser cooling; however, air-cooled condensers are larger and more expensive than water-cooled condensers.) For a "run-of-river" plant, river water is used to directly cool the condenser and the river is the main heat sink. For a cooling tower plant, the condenser water is recirculated through a cooling tower and the atmosphere is the sink for most of the heat. River or other water is used for makeup.

For the reference PWR, 410,000 gpm (1553 cubic meters/hr) must flow through the condenser. In doing so, the temperature of the entering water is raised from typically 72°F to 110°F, an increase of 38°F for a condenser load of 7.8 billion BTU/hr (8.23 Tj/hr). Figure 6-2 is a schematic of the heat removal system for a W-PWR.

For the Southeast reference site (Oak Ridge, Tennessee), there is a large, relatively cool river nearby—the Clinch River. As is the case with other PWRs in the Tennessee River valley (Sequoyah and Watts Bar), the reference Southeast site PWR can use both the river, but mainly the atmosphere, as its heat sink. Recirculating water can be pumped directly over the condenser tubes and to a natural or mechanical draft cooling tower. (It is the massive hyperbolic design cooling tower that has become the common graphic symbol for a nuclear power plant. Actually, many such towers are also used for coal-fired power plants.) The Clinch River is the source of makeup water. In order to avoid mineral/salt buildup, an amount of water less than the makeup is discharged to the river as blowdown. The temperature of the blowdown water exiting the cooling tower is not high enough to significantly disturb aquatic ecosystems, except for organisms

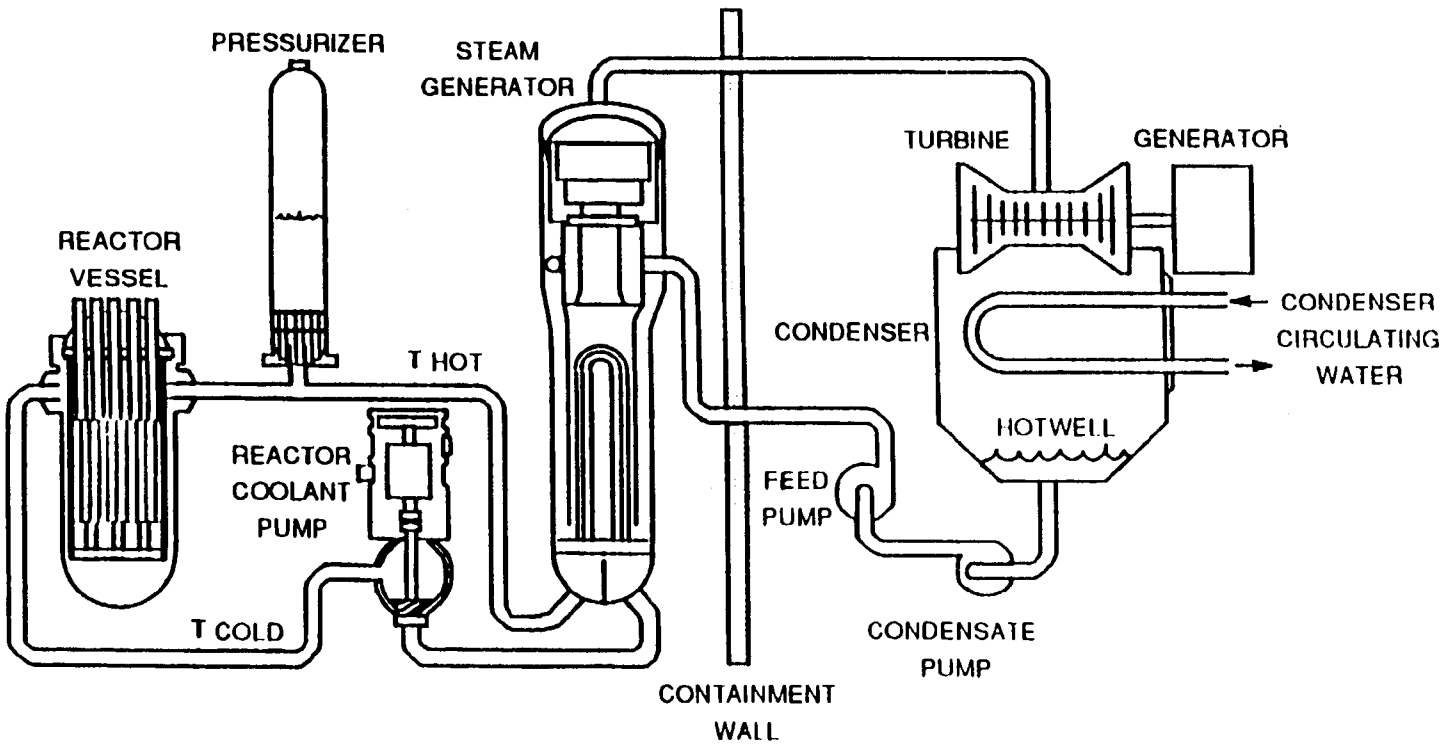

Figure 6-2. Heat Removal Loops in a Westinghouse PWR

found in the near-field area of thermal discharge plumes. Blowdown is usually discharged downstream of the makeup water intake. If, for environmental reasons, the condenser discharge water must be stored and further cooled before discharge, large holding ponds can be used on a temporary basis. Because the Clinch River site lies on a Tennessee Valley Authority (TVA) reservoir (Watts Bar Lake), upstream dam flow can be used to optimize power plant cooling. Figure 6-3, which is based on the design (TVA 1975) for TVA's Watts Bar PWR, shows a schematic and a material balance for a possible recirculating cooling system at the SE Reference site.

For the Southwest reference site (Farmington, New Mexico), provision of cooling water is more difficult because there is no large river nearby in this desert environment. The heat sink in this case could only be the atmosphere or the atmosphere in conjunction with water pumped from a remote location. The former option requires air-cooled or "dry" cooling towers which are massive, less efficient, and very expensive. The latter option entails building a cooling tower similar to that for the Clinch River site and the construction of large holding ponds. Make-up water, i.e. the 13,300 gpm (50 cubic meters/min) of water which must be provided to make up for recirculating water lost by evaporation, could be pumped from the San Juan reservoir. This was the option suggested for the large coal-fired plant (New Mexico Generating Station or NMGS) (BLM 1983) suggested for this site. Because there is no river or lake into which the cooling water discharge can be pumped, dissolved salts, minerals, and reactor liquid effluents concentrate in the recirculating water loop as a significant fraction (around 3%) of the circulating water evaporates. In order to keep the recirculating water useable, a very small fraction of the loop, perhaps a blowdown stream of 1000 gpm, can be withdrawn continuously to evaporation ponds. As the water evaporates, individual ponds can be isolated and the minerals, salts, etc. precipitated out by evaporation. These sludges could then be drummed and sent to a facility for burial of slightly radioactive and slightly toxic wastes. For makeup water with a hardness of 7625μg per liter, about 100-200 barrels of sludge would be produced annually. Figure 6-4 shows a cooling scheme (Williams 1993) and material balance for a hypothetical recirculating water system for the New Mexico-located PWR. (Another option might be to pipe the blowdown stream back to the San Juan Reservoir, but this option may entail water quality and cost problems.)

It should be noted that many pumps, valves, and auxiliary systems are needed to ensure that heat is removed efficiently and that the reactor core is always covered by water and adequately cooled. Some of these systems are discussed in more detail under the Balance of Plant (BOP) Section 6.1.3.6. One should also note that similar recirculating water systems for condenser cooling would be needed for fossil plants of the same thermal capacity; hence, the effects

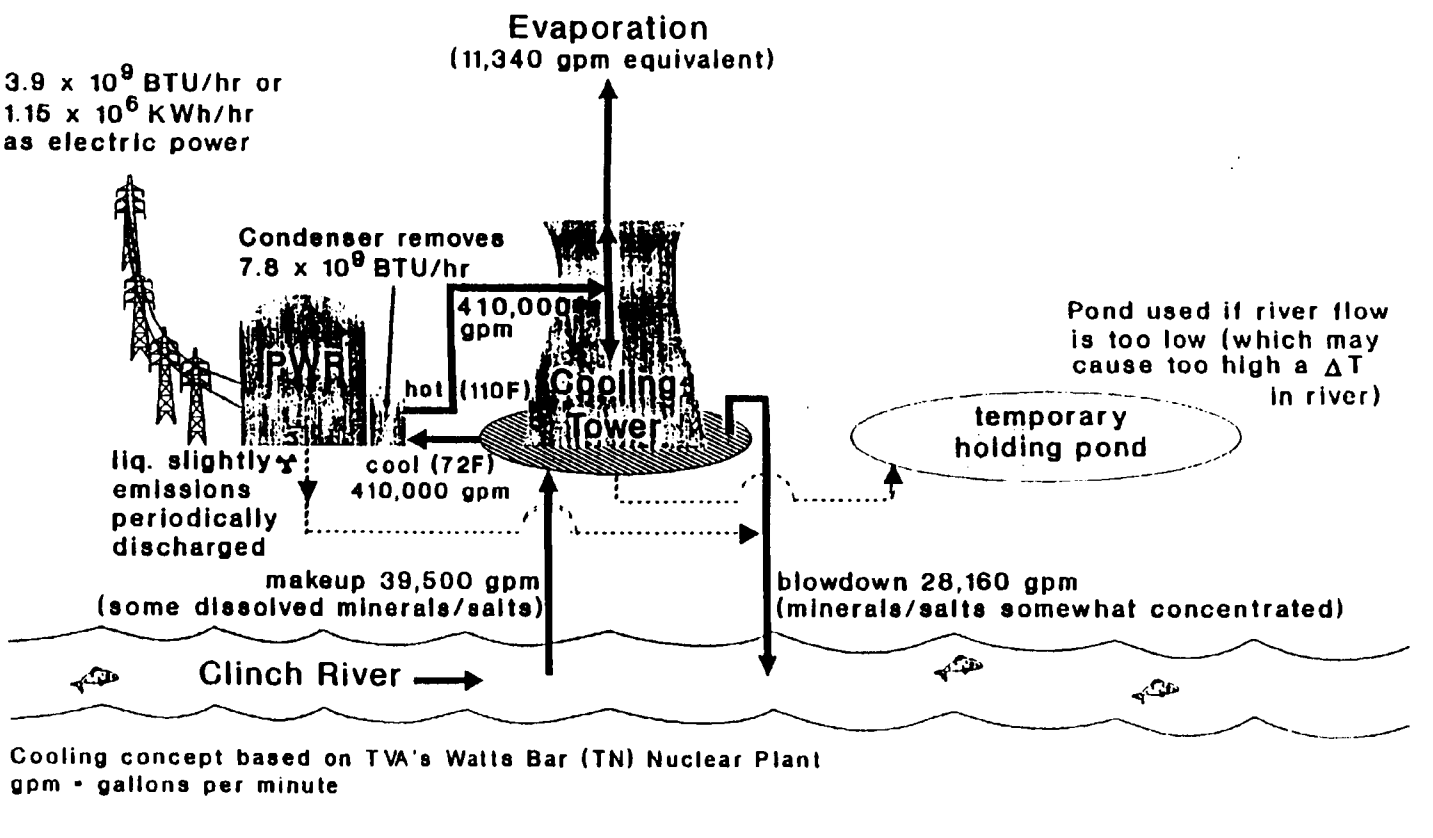

Figure 6-3. Cooling System Schematic for 1300 MW PWR on Clinch River Site

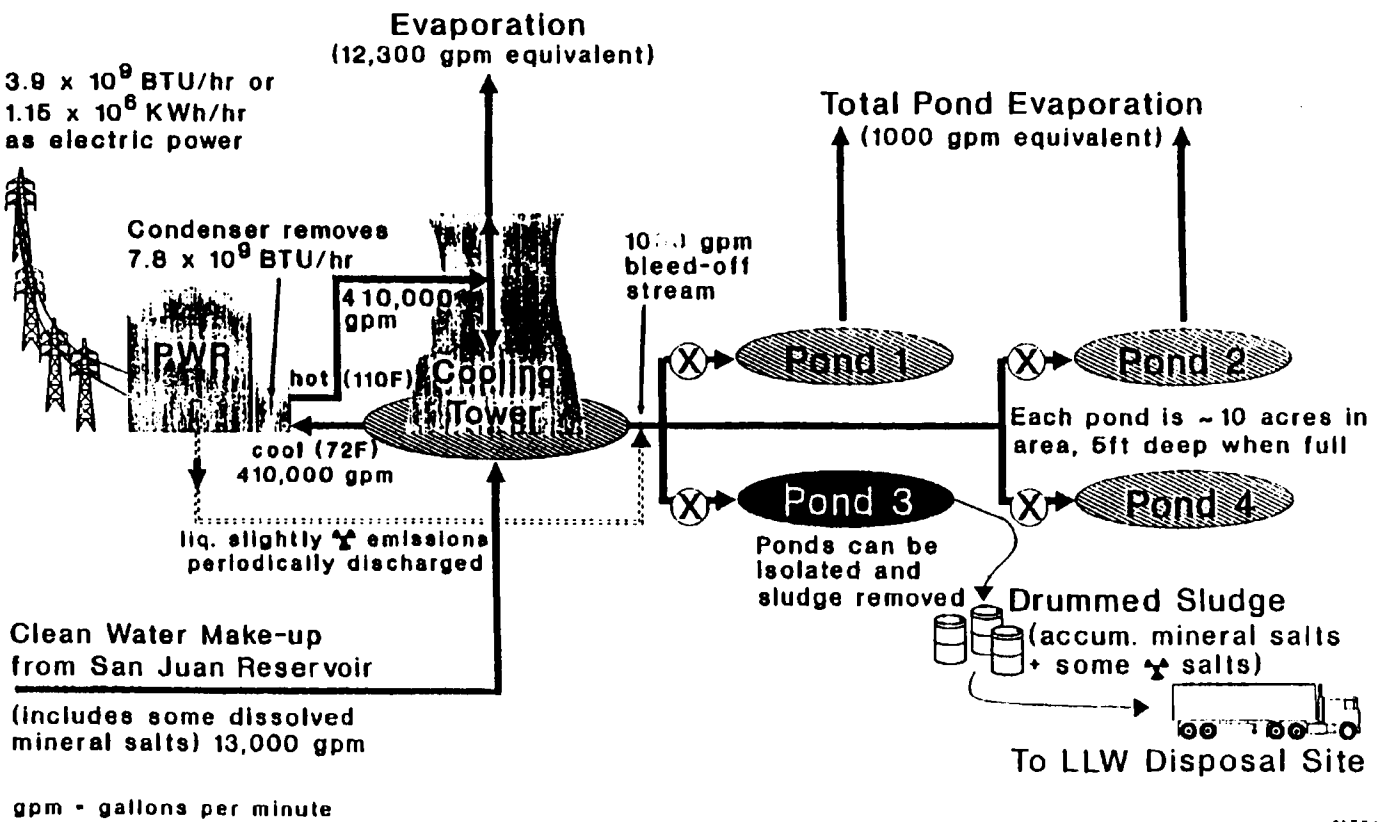

Figure 6-4. Cooling System Schematic for 1300 MW PWR on New Mexico Site

on local meteorology and local aquatic resources would be expected to be similar. In fact, the New Mexico site was originally proposed for a 2000 MW(e) project [4 units @ 500 MW(e)] coal-fired plant—the New Mexico Generating Station (NMGS)].

6.1.3.4 Turbine/Generator

This system converts the energy content of the high-pressure steam to mechanical energy via the steam turbine. The turbine, in turn, drives the generator which converts the mechanical energy to electrical energy for feed to the switchyard and grid. This system of the PWR plant is most similar to that of fossil-fuel fired thermal power stations. The major differences are that precautions must be taken to isolate any secondary coolant side radioactivity from the environment and that water must always be circulated in the secondary side to keep the steam generator working. The latter is important to removing decay heat from the core in the event of a turbine trip and the sudden shutdown of the fission reaction. In a fossil plant, this consideration is minor since the combustion furnace cools rapidly in the event that the fuel feed to the combustor stops.

6.1.3.5 Control

The heat production within the core is controlled by increasing or reducing the number of neutrons made available for further nuclear fission reactions. If the number of neutrons absorbed relative to the number fissioned increases, the nuclear reaction will slow down and eventually cease. This fact allows two methods of control in a PWR. The most familiar method is the use of control rods which, when inserted more fully into the core, absorb neutrons. In a PWR these are made of a silver-indium-cadmium alloy. These elements have a strong affinity for thermal neutrons and act as "poisons" to the fission reaction. (Thermal neutrons are former "fast" neutrons from the fission process that have been slowed down by collisions with moderator molecules.) The light water in the reactor itself has a property which tends to slow down the fission reaction. As water is heated it expands and becomes less dense. This decreases the moderating or "neutron slowing-down" effect of the water and tends to reduce the fission reaction. This property of light water is called a negative temperature coefficient of reactivity. The addition of boron in the form of boric acid to the coolant pushes the temperature coefficient of reactivity in the positive direction and can itself be used to control the fission reaction. (Boron addition makes the moderator temperature coefficient of reactivity less negative, but this is compensated for by boron's affinity to absorb neutrons.) These two control methods are coordinated to provide optimal control which maximizes reactor safety and energy production at the same time.

6.1.3.6 Balance of Plant (BOP)

Most of the BOP systems in a PWR are related to engineered safety systems such as the Emergency Core Cooling System (ECCS). These systems ensure that the core is always covered with water and that sufficient coolant flow capacity is maintained to remove the decay heat. Other electrical/mechanical systems ensure that electric power is always available to drive the pumps, valves, and motors needed to activate and maintain these safety-related systems. There are also sources of cooling water outside of the main recirculating water cooling system, such as the refueling water storage tank. These auxiliary systems can be called upon during an accident situation. Other BOP systems of importance are the water chemistry control system, the refueling system (and its residual heat removal system), the feedwater reheat system, reactor diagnostic systems, and the systems for storing and packaging low-level radioactive wastes produced by the plant. Many of the other systems, such as security, potable water, process and instrument air, etc., are similar to those in other power plants or industrial facilities.

A major BOP item that is a structure rather than a system is the reactor containment, which is the third line-of-defense against release of radionuclides to the environment. In the event of a core melt and a subsequent breach of the pressure vessel or primary piping, the containment volume serves to contain the fission products. The containment is designed to withstand significant overpressure resulting from the primary coolant flashing to steam when the primary loop is depressurized and possible chemical reactions, such as steam-zircaloy or uranium-concrete occur. It is constructed of 3.5 ft (1.05 m) thick reinforced concrete capable of an overpressure of 47 psig (425 KPa). This design pressure should handle the "blowdown" case where the pressurized primary water flashes to 269°F (132°C) steam. Many PWR containments now have a water spray system which helps to cool the containment and immobilize the fission products in the event of a severe accident. (In the TMI-2 accident it was the containment that prevented significant health consequences to the public. At Chernobyl, which was of a different design than a PWR, it was the lack of a containment that allowed for such tragic consequences to the public and property over a wide area of Europe.) The explosion and ensuing graphite/uranium fire that occurred at Chernobyl lofted the fission products higher into the atmosphere than would likely be the case for a PWR containment breach. For this reason, the Chernobyl accident would fall into the very low-probability, worst-case classification of possible PWR accidents.

6.1.3.7 The PWR Life Cycle and Its Internalized Costs

Design. Many U.S. Westinghouse PWRs are based on the four loop design for the reactor steam supply (core, pressure vessel, primary coolant loops, and steam generators). The other plant systems and the sites are sufficiently different, however, that each plant is, in essence, a first-of-a-kind (FOAK) plant and requires a very large detailed design effort. (This is in contrast to France where the PWRs are similar enough that they can be considered replicate rather than FOAK plants.) Design experience in the United States shows that design, from the time of plant order to issuance of an NRC construction permit, takes 48 months (DOE 1988). The cost of the entire design effort, including engineering activities during construction, incurs a cost of $315M in 1989$ (DOE 1988). Resolution of regulatory issues has been a major contributor to design costs. This design cost, and the other life cycle costs listed below, are considered internal rather than external costs since they are covered by the revenues received by the utility from the sale of electricity.

Construction. In recent years the time required to construct a PWR (from receipt of construction permit to issuance of the operating license) has increased to an average of 120 months (DOE 1988). Most of the schedule slippage has been due to regulation-mandated design changes made during construction, problems with utility financing, slowdowns mandated by less-than-anticipated need for new power, and legal intervention by environmentalist and anti-nuclear groups. Such schedule slippages have also increased PWR capital costs. The portion of the capital cost most affected by schedule slippage is the allowance for funds used during construction (AFUDC), which is essentially the interest during construction. In addition to schedule slippage, the AFUDC was also impacted by the higher interest rates of the early 1980s. Another portion of the capital cost is escalation, which is represented in "as spent" dollars. The overnight cost is the other portion of the capital costs and represents the actual costs of the labor, materials, equipment, and services purchased to construct the reactor. (The term "overnight" means that the cost is represented as if the facility were built overnight, i.e. with no time dependent AFUDC charges.) Based on post-TMI, median-cost experience historical PWR data (EEDB 1987), the overnight, escalation, and AFUDC costs are approximately $3.3B (1989$), $1.4B (as spent dollars), and $3.4B (as spent dollars) respectively for a total of $8.1B (DOE 1988). For better cost/schedule experience plants, the total is on the order of $4.1B (DOE 1988).

The two major commodities used in construction of a typical PWR are shown in the following Table 6-4 (EEDB 1987). Section 6.3.1 gives further detail.

Table 6-4. Major PWR construction commodities

Commodity	Quantity
Steel	40,000 Tons (39020 MT)
Concrete	260,140 Cubic yards(199,030 m^3)

Studies to date (Baron 1981) have shown that the energy use needed to produce these commodities is a very small fraction of the electrical energy produced by the reactor over its 40-year production lifetime. A typical PWR takes on the order of 22 million craft man-hours to construct, and the on-site work force reaches a maximum of a few thousand workers, including craft workers and white-collar construction support staff (EEDB 1987).

Commercial Operation: Operations and Maintenance. A U.S. reactor is licensed by the NRC for 40-years of commercial operation. For the reference PWR, a capacity factor of 81% is assumed. This is higher than the historical average capacity factor; however, improvements in reactor operations and extended fuel cycles are increasing this average factor every year. The number of persons employed at such plants has increased markedly over the last ten years. The number of employees now on site is on the order of 1000 per unit. (On-site employment levels are discussed later). Response to regulatory and safety concerns has been the main contributor to higher employment and operations costs. A typical PWR now costs on the order of $100M per year in 1989$ to operate exclusive of fuel costs. Non-personnel costs included are taxes, insurance, operating materials, training, refueling labor, security, low level waste disposal, and overheads.

Commercial Operation: Fuel Costs. When a utility reports fuel costs to the Federal Energy Regulatory Commission (FERC), it includes the costs for all steps of the nuclear fuel cycle, i.e. mining & milling, conversion, enrichment, fabrication, and HLW disposal combined. (Transportation costs are imbedded in these costs.) Table 6-5 lists the typical per kilowatt-hr internalized fuel cycle costs for a PWR (DOE 1988, UDI 1992). The labor costs for refueling are included in O&M costs above.

Table 6-5. Components of fuel portion of power generation cost for large W-PWRs

Front- and back-end fuel cycle steps (once-through cycle)	Mills/kWh (1989$)
Yellowcake purchase (mining and milling)	2.9
Conversion	0.3
Enrichment	1.9
Fuel fabrication	0.8
High-level waste disposal	1.0
Total	6.9

Total fuel cost based on average from Table 6-6.
Component values based on fractions from DOE "Nuclear Energy Cost Data Base," 1988.

Decommissioning. Unless a utility licensee requests and receives extension of its operating license, a utility must begin the decommissioning process 40 years from issuance of an operating license. (Because of litigation, issuance of an NRC operating license and actual operation of the plant have not always coincided.) The NRC has approved various methods of accomplishing decommissioning such as: (1) safe storage followed by dismantlement, (2) entombment, and (3) immediate dismantlement followed by returning the site to "greenfield" condition. In any case, the utility is required to collect funds in an escrow account to pay for decommissioning. Costs for decommissioning are not well known because of the limited experience in this area. There is also the problem of disposing of the low level radioactive waste (LLW) from decommissioning. The fees charged by LLW handlers under the various interstate regional compacts have been rising significantly. There is now a question whether the decommissioning escrow accounts will have enough money to cover the actual costs. The NRC will, in the near future, adjust the formula used to define the decommissioning sinking fund (escrow account) so that projected, more realistic costs will be covered. [Older utility data submitted to the NRC suggests large PWR decommissioning costs on the order of $230M (1989$) (Reid 1993)]. Recent increases in LLW disposal costs, from $50/ft^3 to upwards of 300 $/ft^3, are driving projected D&D costs significantly upward. For a PWR in the 1100 MW(e) to 1300 MW(e) size class, the total in today's dollars is projected to be on the order of $400M in 1989$ (Williams 1991). To recover these costs in the electrical power generation costs, a surcharge on the order of 0.5

mills per kWh (in constant $) is required. To the extent to which these costs are passed on in the charge to the utility customer, they are also internalized.

Summary of Internalized Power Generation Costs. Table 6-6 shows a breakdown of the power generation costs for several PWRs. These costs are based on data published by the Utility Data Institute (UDI 1992) for year 1991 and are in 1991$. These are internalized costs only and do not include any added external environmental or social costs.

6.1.3.8 Description of PWR Fuel and its Performance

Power Generation. The reference current generation W-PWR operates at 3411 megawatts (thermal) [MW(th)] and has a net generation capacity of 1150 MW(e). A capacity factor of 81% is used. This is considerably higher than the latest average PWR capacity factor but has been exceeded by several individual plants and is common in many foreign PWRs. Other calculations could be done using lower capacity factors, increasing the sizes of the damages that are computed.

Material Balance. Fuel cycle economics are pushing utilities toward use of the 18-month extended burnup fuel cycle. This cycle would also have somewhat higher consequences during a severe accident with radionuclide release, since the radionuclide inventory would be higher at end-of-cycle than for the 12-month refueling cycle. Table 6-7 lists the reference fuel characteristics given a capacity factor of 81% (Delene 1991). This information can be used to define input parameters to the ORIGEN2 computer model which, in turn, defines the radionuclide composition of the core (useful for accident analyses) and of the spent fuel.

The amount of total radionuclide build-in is important to the severe accident source term, as well as to the characteristics of the HLW generated.

6.1.3.9 Cooling Requirements

The suggested cooling options were described above under Heat Removal in Section 6.1.3.3. Essentially, 2160 MW(th) of heat must be dealt with in an environmentally acceptable manner. For reactors, or any thermal power plant using cooling towers, the atmosphere becomes the ultimate reservoir for most of the heat dumped. The Environmental Safety and Health (ES&H) effects of power plant heat removal, such as fog formation, warm water effects on fauna, etc., are very site specific and must be analyzed on that basis.

Table 6-6. Components of power generation cost for large W-PWRS

#	W-PWR UNIT NAME	NAMEPLATE RATING (MWE)	NET GENER CAPACITY (mwe)	EXPERI'ED CAPACITY FACTOR	POWER GENERATION COST COMPONENTS (MILLS PER KILOWATT-HR)			
					CAPITAL RECOVERY	O&M	FUEL	TOTAL
1	BEAVER VALLEY 1	923	810	0.70	89.97	13.76	13.47	117.20
2	BEAVER VALLEY 2	923	810	0.70	89.97	13.76	13.47	117.20
3	BRAIDWOOD 1	1175	1120	0.71	96.67	11.78	8.15	116.60
4	BRAIDWOOD 2	1175	1120	0.71	96.67	11.78	8.15	116.60
5	BYRON 1	1175	1105	0.70	59.74	10.17	6.11	76.02
6	BYRON 2	1175	1105	0.70	59.74	10.17	6.11	76.02
7	CALLAWAY 1	1236	1125	0.86	49.39	10.19	8.40	67.98
8	CATAWBA 1	1305	1129	0.70	33.75	10.82	7.10	51.67
9	CATAWBA 2	1305	1129	0.70	33.75	10.82	7.10	51.67
10	COOK 1	1152	1020	0.59	18.10	13.51	7.46	39.07
11	COOK 2	1133	1090	0.59	18.10	13.51	7.46	39.07
12	DIABLO CANYON 1	1137	1073	0.77	67.88	14.57	7.20	89.65
13	DIABLO CANYON 2	1164	1087	0.77	67.88	14.57	7.20	89.65
14	FARLEY 1	860	814	0.85	23.07	11.23	7.00	41.30
15	FARLEY 2	860	824	0.85	23.07	11.23	7.00	41.30
16	HARRIS 1	851	860	0.77	106.32	11.63	6.15	124.10
17	INDIAN POINT 2	1013	939	0.70	16.22	21.01	5.56	42.79
18	INDIAN POINT 3	1013	965	0.66	14.99	16.09	8.30	37.38
19	MC GUIRE 1	1305	1129	0.71	24.58	12.17	6.99	43.72
20	MC GUIRE 2	1305	1129	0.71	24.58	12.17	6.99	43.72
21	MILLSTONE 3	1253	1137	0.78	44.34	12.38	9.88	68.60
22	NORTH ANNA 1	947	911	0.79	19.51	7.80	4.84	32.15
23	NORTH ANNA 2	947	909	0.79	19.51	7.80	4.84	32.15
24	SALEM 1	1170	1106	0.66	26.76	13.63	7.68	48.07
25	SALEM 2	1170	1106	0.66	26.76	13.63	7.68	48.07
26	SEQUOYAH 1	1221	1122	0.53	25.71	15.50	9.32	50.53
27	SEQUOYAH 2	1221	1122	0.53	25.71	15.50	9.32	50.53
28	SOUTH TEXAS 1	1311	1251	0.68	135.94	13.27	5.79	155.00
29	SUMMER 1	900	885	0.71	33.46	14.29	6.24	53.99
30	SURRY 1	848	781	0.51	24.68	16.17	6.58	47.43
31	SURRY 2	848	781	0.51	24.68	16.17	6.58	47.43
32	TROJAN	1216	1095	0.62	14.75	17.12	5.25	37.12
33	VOGTLE 1	1215	1100	0.80	80.26	11.09	11.05	102.40
34	WOLF CREEK 1	1236	1135	0.81	60.24	9.38	4.07	73.87
35	ZION 1	1085	1040	0.60	12.87	12.78	6.29	31.94
36	ZION 2	1085	1040	0.60	12.87	12.78	6.29	31.94
	AVERAGE	1110	1025	0.70	44.51	12.89	7.36	64.77

Table 6-7. Reference W-PWR fuel characteristics.

Initial core fuel loading:	88,128 kg U as uranium oxide (UO_2)
Fuel burnup:	51.7 MWD/kg U
Fuel core residence time:	4.5 years (1/3 of core replaced every 1.5 years for equilibrium cycle)
Uranium in reload core:	29,376 kg U
Average enrichment level:	4.7% ^{235}U at beginning of life (BOL)

6.2 SITES

6.2.1 Introduction

This section delineates the locations of the PWR nuclear plant and describes the sites in terms of their baseline socioeconomic and environmental characteristics. These same two sites were used for most of the other fuel cycle studies so as to facilitate comparisons. Two sites were chosen as regional reference environments for the nuclear plants to illustrate the differences in the analyses that result from different socioeconomic and environmental conditions. One site is in the southeast United States and the other in the Southwest. The sites are selected solely for the purpose of illustrating the methodology for our fuel cycle analysis. The sites are not intended to be representative or "typical." No two sites, anywhere, are representative of all possible sites in the country.

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. Some information in the EIS was updated (e.g., population, income).

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.

6.2.2 Reference Plant Sites

The site of the nuclear 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 southwest of Oak Ridge (hereafter referred to as the Southeast Reference site). The site of the nuclear 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 6-5 is a map showing the locations of these two reference sites in the United States.

6.2.3 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.

6.2.3.1 Population

U.S. Bureau of the Census 1990 population data were used to derive population densities for both site-specific areas. The data are estimates of population in specified distance intervals in 16 directions. The total number of people within 50 miles of the Southeast Reference Site plant is 866,406, and 98,168 people are estimated to be within a 50 mile radius of the Southwest Reference Site plant. Tables 6-8 and 6-9 contain cumulative populations for given distances for the Southeast and Southwest Reference Sites, respectively.

6.2.3.2 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.

6.2.3.3 Transportation

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

Figure 6-5. Locations of the Southeast and Southwest Reference sites.

Table 6-8 Cumulative counts of people by radial distance and sector direction, Southeast Reference Site

	Miles								
Sector	0-1	0-2	0-3	0-5	0-10	0-20	0-30	0-40	0-50
N	0	0	0	6	2520	4091	5051	10131	17211
NNE	0	0	0	0	7450	13307	22481	44205	51758
NE	0	0	0	0	1678	30885	47990	57059	64138
ENE	2	7	7	7	475	35211	163817	196974	211164
E	2	25	74	163	1987	54093	126094	152206	179920
ESE	0	29	75	340	4354	11702	64288	70285	73425
SE	0	21	79	302	9572	13210	20523	21114	23704
SSE	1	12	67	497	2045	7843	11573	12808	14216
S	14	34	52	273	1076	7441	18238	26744	30540
SSW	0	27	61	254	664	3880	11520	37250	47884
SW	1	22	73	337	881	2639	6227	13259	29420
WSW	0	57	159	463	4628	8042	13619	17464	24638
W	13	78	325	968	5971	15272	17946	34109	41294
WNW	52	136	206	542	6739	9524	12070	17413	22719
NW	4	13	13	127	1548	4799	6931	9212	18049
NNW	5	13	13	77	1382	5556	7903	13160	16326
Total	94	474	1204	4356	52970	227495	556271	733393	866406

Table 6-9 Cumulative counts of people by radial distance and sector direction, Southwest Reference Site

	Miles								
Sector	0-1	0-2	0-3	0-5	0-10	0-20	0-30	0-40	0-50
N	0	0	0	0	4	115	1208	40967	49464
NNE	0	0	0	0	11	207	661	6881	9834
NE	0	0	0	0	2	123	420	588	746
ENE	0	0	0	0	2	144	311	450	566
E	0	3	20	25	25	252	476	861	1109
ESE	0	1	3	3	3	202	463	1198	2155
SE	0	0	0	0	16	66	72	161	433
SSE	0	0	0	0	20	76	164	417	545
S	0	0	0	0	14	162	590	3136	5030
SSW	0	0	0	1	7	13	301	712	2880
SW	0	0	0	11	65	97	148	1566	3724
WSW	0	0	1	1	17	76	550	2065	2616
W	0	0	0	2	8	8	164	1680	2160
WNW	0	0	0	0	5	125	312	1117	2555
NW	0	0	0	4	5	101	259	875	4456
NNW	0	0	1	9	18	24	841	7790	9895
Total	0	4	25	56	222	1791	6940	70464	98168

6.2.3.4 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 the Southeast Reference site are shown in Table 6-10. Crop data were not collected for the southwest. An additional source of annual crop information at the county-level is the U.S Department of Agriculture's publication, *Census of Agriculture*.

Table 6-10. Crop production for the southeast reference environment

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

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

6.2.3.5 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 and the New Mexico Department of Game and Fish.

6.2.3.6 Water Use

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

6.2.3.7 Other Sites and Structures

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

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

6.2.4 Environmental Parameters

6.2.4.1 Hydrology

Hydrology data for the Southeast Reference site are available from the 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 U.S. Geological Survey (USGS) and the hydrology technical report prepared for the Southwest Reference site draft EIS (1982).

The EPA maintains and updates a water quality data base, for surface and ground water, called STORET. STORET contains information on a multitude of variables, among which are geographic data about the site of collection of water quality, the water's physical and chemical characteristics, municipal waste sources and disposal systems, pollution-caused fish kills, and daily stream flow. Table 6-11 is a printout of water quality data for a point on the Clinch River near the Southeast Reference site (specifically, Clinch River mile marker 14.4). There is also a water quality technical report that was prepared for the Southwest Reference EIS. If desired, hydrological data obtained from a source other than STORET can be matched with STORET data by dates and times. Additionally, the Tennessee State Division of Public Water Supply performs regular chemical analyses on all public water supplies.

Table 6-11. Example of STORET (EPA water quality database) output

```
1STORET RETRIEVAL DATE 91/07/30                    FGM=INVENT                                                    PAGE:     1
                                                    4:8052          5337
                                                    35 53 30.0 084 23 00.0 2
                                                    WATER SUPPLY INTAKE AT OLD DR ST
                                                    07145   TENNESSEE        ROANE
                                                    TENNESSEE RIVER BASIN    040101
/TYPA/AMBNT/STREAM                                  CLINCH RIVER 14.4
                                                    131IVAL                          06010207003 0003.710 DN
                                                    0000 FEET DEPTH
```

	PARAMETER			MEDIUM	RMK	NUMBER	MEAN	VARIANCE	STAN DEV	MAXIMUM	MINIMUM	BEG DATE	END DATE
00002	USAMPLOC	1 FROM	RT BANK	WATER		185	50.00000	440.2200	20.98100	95.0	5.0	75/03/11	77/10/12
00010	WATER	TEMP	CENT	WATER		187	16.56300	14.96000	3.867800	23.0	5.8	74/08/27	77/10/12
00011	WATER	TEMP	FAHR	WATER	P	187	61.81200	48.62300	6.973100	73.4	42.4	74/08/27	77/10/12
00061	STREAM	FLOW,	INST-CFS	WATER		8	6520.000	12875000	3223.300	15830	920	74/12/19	77/09/07
00070	TURB	JRSN	JTU	WATER		77	8.142800	79.81700	8.930900	55.0	1.5	74/02/18	77/10/12
00080	COLOR	PT-CO	UNITS	WATER		75	6.651600	15.64900	3.955900	20	1	74/12/19	77/10/12
00081	AP COLOR	PT CO	UNITS	WATER		76	24.72900	221.0000	14.86600	100	5	74/12/19	77/10/12
00095	CNDUCTVY	AT 25C	MICROMHO	WATER		178	219.8300	2010.700	44.84100	280	100	74/02/18	77/10/12
00300	DO		MG/L	WATER		186	8.544500	3.433100	1.852900	12.2	.1	74/08/27	77/10/12
00301	DO	SATUR	PERCENT	WATER	P	186	83.75400	195.9500	13.99800	108.0	1.0	74/08/27	77/10/12
00310	BOD	5 DAY	MG/L	WATER		20	1.205000	.0594490	.2438200	7.0	1.0	75/07/15	77/10/12
					K	37	1.000000	.0000000	.0000000	1.0	1.0	74/02/18	77/10/12
					101	57	1.071900	.0299130	.1729500	2.0	1.0	74/02/18	77/10/12
00335	COD	LOW LEVEL	MG/L	WATER		74	9.283800	5.712900	2.390200	12.0	1.0	74/02/18	77/10/12
00400	PH		SU	WATER		179	7.415600	.0944740	.3073200	8.50	6.50	74/08/27	77/10/12
00410	T ALK	CACO3	MG/L	WATER		162	88.14700	297.1800	17.23900	140	9	74/12/19	77/10/12
00415	PHEN-PH-	LTIN ALK	MG/L	WATER		162	.0000000	.0000000	.0000000	0	0	74/12/19	77/10/12
00530	RESIDUE	TOT NFLT	MG/L	WATER		77	9.836100	88.06800	9.384500	51	1	74/02/18	77/10/12
00605	ORG N	N	MG/L	WATER		75	.0980000	.0010460	.0323020	.200	.050	74/02/18	77/10/12
					K	1	.0100000			.010	.010	76/03/09	76/03/09
					101	76	.0968420	.0011340	.0336740	.200	.010	74/02/18	77/10/12
00610	NH3+NH4	N TOTAL	MG/L	WATER		73	.0294520	.0017914	.0423240	.360	.010	74/02/18	77/10/12
					K	5	.0100000	.0000000	.0000000	.010	.010	77/05/10	77/05/10
					101	76	.0286840	.0017347	.0416440	.360	.010	74/02/18	77/10/12
00612	UN IONIZD	NH3 N	MG/L	WATER	P	75	.0005312	.0000011	.0010519	.009	.00003	75/03/11	77/10/12
00619	UN-IONIZD	NH3 NHS	MG/L	WATER	P	25	.0006459	.0000016	.0012790	.011	.00004	75/03/11	77/10/12
00630	NO2&NO3	N-TOTAL	MG/L	WATER		76	.4318100	.0176310	.1327800	.95	.17	74/02/18	77/10/12
00665	PHOS-TOT		MG/L P	WATER		74	.0186890	.0001187	.0108950	.060	.010	74/02/18	77/10/12
					K	2	.0100000	.0000000	.0000000	.010	.010	76/07/15	76/07/15
					101	76	.0184210	.0001174	.0108390	.060	.010	74/02/18	77/10/12
00666	PHOS DIS		MG/L P	WATER		33	.0109070	.0000085	.0029194	.020	.010	75/03/11	77/10/12
					K	32	.0100000	.0000000	.0000000	.010	.010	75/03/11	77/07/13
					B	1	.6975000	.2082900	.9563900	1.000	.020	76/07/15	77/04/12
					101	69	.0502900	.0353500	.1880200	1.000	.010	75/03/11	77/10/12
00680	T ORG C	C	MG/L	WATER		70	1.859600	.5108800	.7147600	5.2	.9	74/02/18	77/10/12
					B	4	1.200000	.0066681	.0816580	1.3	1.1	76/08/05	76/08/05
					101	24	1.823000	.5056300	.7110800	5.2	.9	74/02/18	77/10/12
00681	D ORG C	C	MG/L	WATER		26	1.019200	.2048200	.4525700	1.9	.2	75/03/11	76/03/09
00916	CALCIUM	CA-TOT	MG/L	WATER		48	28.31300	16.98500	4.121300	38.0	18.0	74/02/18	77/10/12

Table 6-11. Example of STORET (EPA water quality database) output (continued)

STORET RETRIEVAL DATE 91/07/30 (GM:INVEN) PAGE:

476652 3339
35 51 30.0 084 23 40.0 2
WATER SUPPLY INTAKE AT OLD BR ST
47145 TENNESSEE ROANE
TENNESSEE RIVER BASIN 040101
ELOWEN RIVER 14.4
ICITYDC
6000 FEET DEEP

/19FA/AMBNT/STREAM

PARAMETER			MEDIUM	KM	NUMBER	MEAN	VARIANCE	STAN DEV	MAXIMUM	MINIMUM	BEG DATE	END DATE
00927 MAGNESIUM	MG,101	MG/L	WATER		48	7.591600	1.225000	1.129500	9.4	3.2	74/02/18	77/10/12
00929 SODIUM	NA,101	MG/L	WATER		47	3.357000	3.560700	1.881700	12.00	2.00	74/12/19	77/10/12
00937 POTASSIUM	K,101	MG/L	WATER		47	1.270700	.9410540	.2084600	2.10	.90	74/12/19	77/10/12
00940 CHLORIDE	TOTAL	MG/L	WATER		51	3.156900	3.774900	1.942900	16	2	74/12/19	77/10/12
00945 SULFATE	SO4-101	MG/L	WATER		51	15.29400	18.09200	3.753700	22	7	74/12/19	77/10/12
00951 FLUORIDE	F,TOTAL	MG/L	WATER		1	.0000000			.08	.08	74/12/19	74/12/19
00955 SILICA	DISSOLVED	MG/L	WATER		50	4.254000	1.126600	1.061400	6.2	1.5	75/03/11	77/10/12
00956 SILICA	TOTAL	MG/L	WATER		5	4.800000	.9230000	.9607500	6.2	4.0	74/02/18	75/03/11
01002 ARSENIC	AS,101	UG/L	WATER	R	2	5.000000	.0000000	.0000000	5	5	74/02/18	74/12/19
01007 BARIUM	BA,101	UG/L	WATER	R	2	100.0000	.0000000	.0000000	100	100	74/02/18	74/12/19
01012 BERYLLIUM	BE,101	UG/L	WATER	R	2	10.00000	.0000000	.0000000	10.00	10.00	74/02/18	74/12/19
01022 BORON	B,101	UG/L	WATER		1	160.0000			160	160	74/12/19	74/12/19
01027 CADMIUM	CD,101	UG/L	WATER		4	1.500000	.1333300	.5773500	2	1	75/09/16	76/10/13
				R	44	1.000000	.0000000	.0000000	1	1	74/02/18	77/10/12
01034 CHROMIUM	CR,101	UG/L	WATER	101	48	1.041700	.0407820	.2019500	2	1	74/02/18	77/10/12
					12	8.000000	6.363600	2.522600	12	5	75/05/22	77/04/12
				R	36	5.000000	.0000000	.0000000	5	5	74/02/18	77/10/12
01042 COPPER	CU,101	UG/L	WATER	101	48	5.750000	3.217800	1.797400	12	5	74/02/18	77/10/12
					28	51.78600	8333.700	36.52000	170	10	74/12/19	77/10/12
				R	29	10.00000	.0000000	.0000000	10	10	74/02/18	77/07/15
01045 IRON	FE,101	UG/L	WATER	101	48	31.37500	1199.600	34.63500	170	10	74/02/18	77/10/12
01046 IRON	FE,DISS	UG/L	WATER		48	473.7100	522730.0	560.1000	2400	50	74/02/18	77/10/12
					9	98.44500	627.7000	25.05600	140	60	74/02/18	77/04/12
				R	39	50.00000	.0000000	.0000000	50	50	75/03/11	77/10/12
				R	1	280.0000			280	280	76/07/15	76/07/15
01047 FERROUS	IRON	UG/L	WATER	101	48	64.31000	1550.700	39.37900	280	50	74/02/18	77/10/12
					25	66.40000	2449.000	49.48700	220	20	75/03/11	75/10/15
01051 LEAD	PB,101	UG/L	WATER		11	19.81000	102.2700	10.13700	45	10	74/02/18	77/01/11
				R	33	10.00000	.0000000	.0000000	10	10	74/12/19	77/10/12
				101	48	12.25000	39.25500	6.265400	45	10	74/02/18	77/10/12
01055 MANGANESE	MN	UG/L	WATER		45	48.88500	613.4400	24.76800	140.0	20.0	74/02/18	77/10/12
01056 MANGANESE	MN,DISS	UG/L	WATER		5	22.00000	120.0000	10.95500	40.0	10.0	75/04/16	77/10/12
				R	3	10.00000	.0000000	.0000000	10.0	10.0	74/02/18	77/10/12
				R	1	60.00000			60.0	60.0	76/07/15	76/07/15
				101	44	17.68300	85.12200	9.225200	60.0	10.0	74/02/18	77/10/12
01067 NICKEL	NI,TOTAL	UG/L	WATER		5	110.0000	4600.000	67.82300	230	30	74/12/19	77/01/11
				R	43	50.00000	.0000000	.0000000	50	50	74/02/18	77/10/12
				101	48	56.25000	734.5000	27.10300	230	50	74/02/18	77/10/12
01077 SILVER	AG,101	UG/L	WATER	R	2	10.00000	.0000000	.0000000	10.0	10.0	74/02/18	74/12/19

Table 6-11. Example of STORET (EPA water quality database) output (continued)

Table 6.2-4 Example of STORET (EPA water quality database) output (continued)

```
STORET RETRIEVAL DATE 91/07/30                FGM:INVENT                                                    PAGE:     1
                                                          476012          3339
                                                          35 53 30.0 084 23 40.0 2
                                                          WATER SUPPLY INTAKE AT DIO DR SI
                                                          47145   TENNESSEE        ROANE
                                                          TENNESSEE RIVER BASIN    040101
/11FA/AMBNT/STREAM                                        CLINCH RIVER 14.9
                                                          ICETVAC                          060102:47003 0003.710 PM
                                                          0000 FEET DEPTH

            PARAMETER                    MEDIUM      RMK   NUMBER    MEAN  VARIANCE STAN DEV MAXIMUM MINIMUM  BEG DATE END DATE
01092 ZINC      ZN,TOT     UG/L   WATER                     34 95.88200 102560.0 320.2500    1900      10 74/12/19 77/10/12
                                                       L    14 10.00000 .0000000 .0000000      10      10 74/02/18 77/07/13
                                                     TOT    48 70.82300 23565.00 271.2300    1900      10 74/02/18 77/10/12
01105 ALUMINUM  AL,TOT     UG/L   WATER                      1 400.0000                      400     400 74/12/19 74/12/19
                                                       L     1 200.0000                      200     200 74/02/18 74/02/18
                                                     TOT     2 300.0000 20000.00 141.4200    400     200 74/02/18 74/12/19
01132 LITHIUM   LI,TOT     UG/L   WATER                      1 10.00000                       10      10 74/12/19 74/12/19
01147 SELENIUM  SE,TOT     UG/L   WATER                      2 2.000000 .0000000 .0000000      2       2 74/02/18 74/12/19
01152 TITANIUM  TI,TOT     UG/L   WATER                      1 1000.000                     1000    1000 74/12/19 74/12/19
31501 TOT COLI  MF(MENDO   /100ML WATER                      9 1278.900  6268600 2503.700    7600      10 75/08/16 75/09/16
                                                       L    11 10.00000 .0000000 .0000000      10      10 75/03/11 75/07/15
                                                       L     1 6000.000                     6000    6000 75/09/16 75/09/16
                                                     TOT    21 839.0500  430430 2074.700    7600      10 75/03/11 75/09/16
31616 FEC COLI  MFM-FCBR   /100ML WATER                      5 62.00000 4370.000 66.10600     160      10 75/08/07 77/10/12
                                                       L    23 25.65200 1216.600 34.88000     100      10 75/03/11 77/07/13
                                                     TOT    28 32.14300 1839.700 42.89200     160      10 75/03/11 77/10/12
32730 PHENOLS   TOTAL      UG/L   WATER                      1 1.000000                        1       1 74/02/18 74/02/18
46570 CAL HARD  CA MG      MG/L   WATER                     48 101.7500 200.6600 14.16600     120      58 74/02/18 77/10/12
70300 RESIDUE   D155-180 C MG/L   WATER                     77 174.8100 722.6700 17.96300     230      90 74/02/18 77/10/12
71900 MERCURY   HG,TOTAL   UG/L   WATER                      1 2.500000                       2.5     2.5 76/07/15 76/07/15
                                                       L    44 .2000000 .0000000 .0000000      .2      .2 74/02/18 77/10/12
                                                     TOT    45 .2511100 .1175600 .3428600     2.5      .2 74/02/18 77/10/12
74041   NOF     SAMPLE     UPDATED WATER                     6 970600.0 .0000000 .0000000   870803   870803 75/09/16 76/08/05
84002   CODE    GENERAL    REMARKS WATER                     5    TEST     TEST     TEST     TEST     TEST 75/09/16 76/08/05
```

6.2.4.2 Meteorology

Meteorological data (e.g., temperature, wind direction and speed, precipitation, incidences of hurricanes and tornadoes) are available from the National Oceanic and Atmospheric Administration (NOAA). There is a publication titled *Climates of the States* (1985) that contains NOAA data for each state for selected weather stations. According to the Southeast Reference site EIS, for the nearby ORNL weather station, mean average annual temperature is 58.5°F, annual relative humidity is 70%, and average annual precipitation is 51.52 inches. Wind speed and direction distributions (wind roses) for the southeast plant site are shown in Figure 6-6. 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.

6.2.4.3 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.

6.2.4.4 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.

6.2.4.5 Geology

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

6.2.4.6 Biodiversity

For the biodiversity of the area, including both aquatic and terrestrial ecology, we are concentrating on threatened and endangered species at this point.

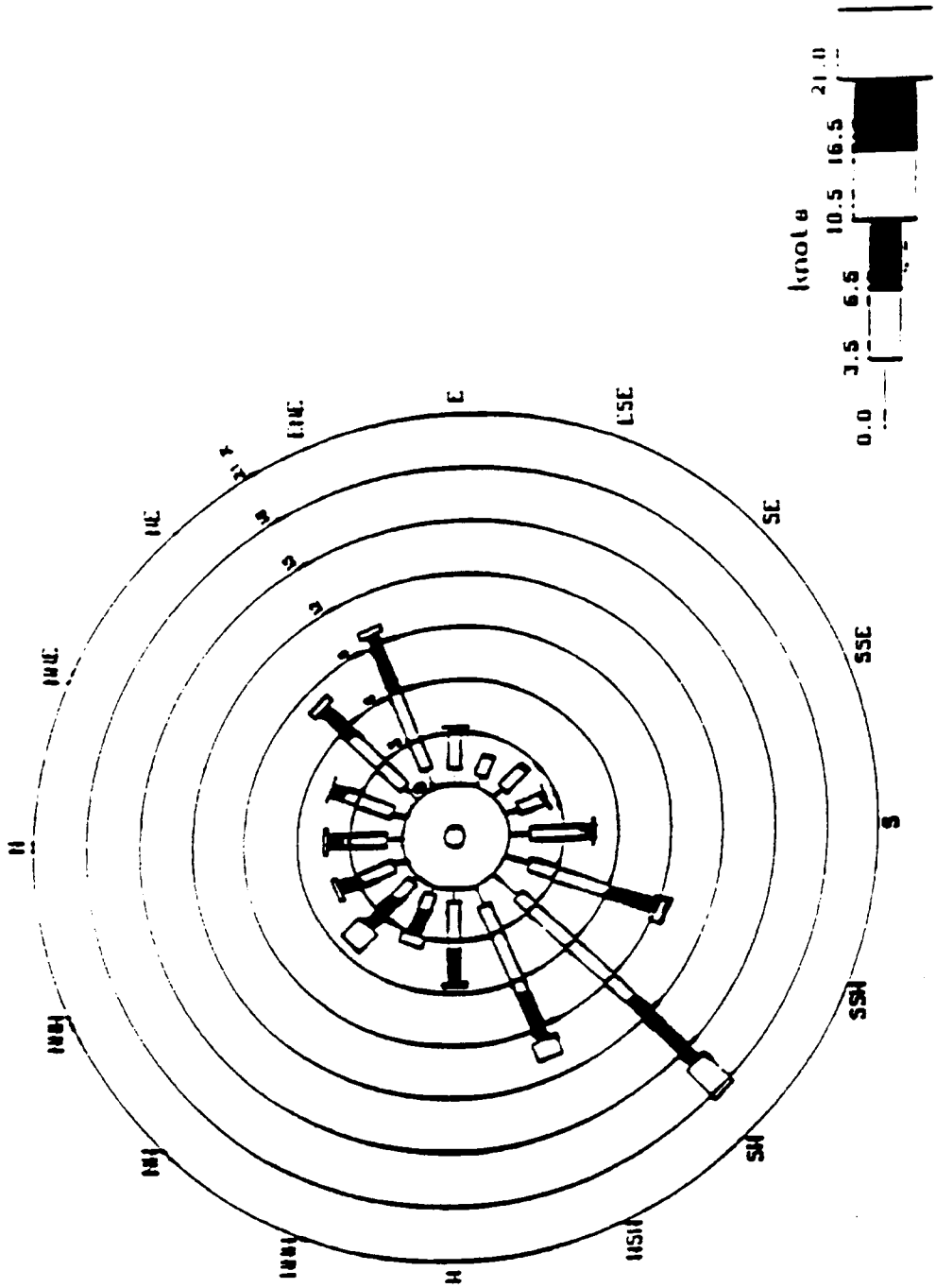

Figure 6-6. Wind rose at 60 m height, June-Sept, 11 a.m.-7 p.m., 1985-1990. Data were taken from the K-25, DOE facility which is located 4.5 km north of the Southeast Reference Site.

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.

6.3 CONSTRUCTION MATERIALS REQUIREMENTS AND ASSOCIATED INDIRECT EMISSIONS

"Indirect emissions" here refer to the pollutants released during the manufacture of the materials required to construct energy production projects. Steel and concrete constitute the largest portion of the materials required to construct nuclear power projects, and thereby are the major sources of indirect emissions. Thus, the emissions from the manufacture of these two construction materials are examined in this section. This section does not examine the emissions associated with the construction activities themselves (e.g., construction equipment operation, fugitive dust emissions, or noise during construction). This section also does not examine the emissions associated with providing the raw materials to manufacture the construction materials (e.g., mining of ore, extraction from quarries, or transport of raw materials to manufacturers). Adequate data on indirect emissions from construction activities and raw materials extraction and delivery were not available.

If the reference plant were *not* built, some—but not all—of these quantities of materials would still be produced and used for purposes other then building a nuclear power plant. Nevertheless, estimates of emissions are derived so as to indicate the order of magnitude of the emissions (and, thus, of their effects) compared to other fuel cycles.

6.3.1 Material Requirements

The quantities of steel and concrete required to build a 1144 MW(e) PWR were obtained from the Energy Economic Data Base (EEDB 1987), Version IX, compiled by United Engineers and Constructors (Table 6-12).

Table 6-12. Steel and concrete requirements

Reinforcing steel	25,328 tons
Embedded steel	1,922 tons
Structural steel	10,906 tons
Other iron	843 tons
Steel pipe	376 tons
Other	625 tons
Total steel	40,000 tons
Concrete fill	97,794 cubic yards
Structural concrete	159,346 cubic yards
Other (paving, panels)	3,000 cubic yards
Total concrete	260,140 cubic yards

Source: EEDB-IX (1987)

6.3.2 Calculation of Emissions

Atmospheric emissions were calculated for the production of steel and concrete (Table 6-13). Carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM) emission coefficients are supplied in The Meridian Corporation's version of the Total Emission Model for Integrated Systems (TEMIS) database. These coefficients relate the tons of a given construction material to the pounds of pollutants emitted during its manufacture. The emission factors used are given in Table 6-14.

The TEMIS emission coefficients are based on data for Germany and Western Europe. However, according to Kevin DeGroat (Meridian Corporation, personal communication to A. J. Schaffhauser, ORNL, September 17, 1992), these European coefficients are better than those available for the United States because the manufacture processes for the United States and Europe are very similar, and the European coefficients account for the process emissions as well as the emissions associated with the energy input to the process. In calculating emissions from concrete, cubic yards of concrete is converted to tons based on the conversion factor of 127 lbs per cubic foot (Meridian Corporation 1991), which corresponds to 1143 lbs per cubic yard.

Table 6-13. Indirect emissions for reference nuclear power plant

	Emissions from steel (million lbs)	Emissions from concrete (million lbs)	Total emissions (million lbs)
CO_2	240.00	267.61	507.61
SO_2	0.24	1.49	1.73
NO_x	0.40	4.46	4.86
PM	0.04	0.30	0.34

Table 6-14. Emission factors for materials manufacture (lbs/ton).

	Steel	Concrete
CO_2	6,000	1,800
SO_2	6	10
NO_x	10	30
PM	1	2

Source: Pace (1990), Appendix A

6.4 OPERATIONAL EMISSIONS

Because of fact that the amount of nuclear fuel consumed per year is very small compared to fossil plants and the fact that great effort is expended in nuclear fuel design and manufacture to contain radionuclides, the emissions from normal (non-accident) nuclear plant operations are also small when compared to fossil. Any radionuclide releases to the environment are the result of minor fuel pin leakage or activation of materials in the reactor coolant and piping.

6.4.1 Airborne Radionuclides from Normal Operations

Every year nuclear utilities are required by NRC to report their airborne radionuclide emissions to the environment for the entire year. This data is compiled by Brookhaven National Laboratory (BNL) for the NRC and is reported in document NUREG/CR-2907 (NRC 1988). In addition to data summaries,

which partition the airbornes into (1) fission and activation gases, and (2) ^{131}I and particulates, there are release statistics (expressed in annual curies released per plant) for individual radionuclides. Some utilities report as few as ten radionuclides, others report as many as 30 radionuclides. Since the models to be used for transport and dose-effect calculations require data on a radionuclide basis, a decision had to be made about which utility data to use. It was decided to prepare a data base of airborne releases for all U.S. Westinghouse PWRs of 800 MW(e) or greater. For the 1988 NUREG data used, this consisted of 36 reactors. This large sample should well characterize the gaseous waste handling capability of the reference PWR. The 31 radioisotopes that were most often reported, or which had the longest half-lives, were selected for analysis and tabulated. The amounts of radionuclide produced did not appear to correlate with the MW-hrs (thermal) produced or the reactor capacity. Amounts produced are more likely affected by random events within the reactor, such as fuel pin cladding failures, leaks in the primary coolant loop, steam-generator tube leaks, etc. The amount of each radionuclide released for one reactor year (1988) at each plant is reported in curies in Appendix C.1 and the average (mean) for all 36 reactors is reported in Table 6-15 below. Where a utility reported a total for two units, half that value for each unit was tabulated.

Table 6-15. Average airborne radionuclide emissions from sample of 36 large W-PWRS (Expressed in annual Curies)

Isotope> Half-life>	T-3 (12.3 y)	Ar-41 (1.8 h)	Cr-51 (27.7 d)	Mn-54 (312 d)	Co-57 (272 d)	Co-58 (71 d)	Co-60 (5.2 y)	Kr-85 (10.7 y)	Kr-85M (4.48 h)	Kr-87 (1.27 h)
	5.98E+01	2.55E+01	1.60E-03	2.27E-05	4.30E-06	5.49E-05	4.13E-04	4.23E+01	2.05E+00	7.63E-01
	Rb-88 (17.7 m)	Kr-88 (2.84 h)	Br-89 (50.5 d)	Br-90 (29.1 y)	Nb-95 (35 d)	Zr-95 (84 d)	Tc-99M (6.01 h)	Ag 110M (250 d)	I-131 (8 d)	Xe-131M (11.9 d)
	8.38E-03	3.58E+00	2.95E-06	1.20E-06	9.02E-07	2.33E-06	1.21E-07	2.69E-08	1.93E-03	3.45E+00
	I-132 (2.3 h)	Xe-133 (5.24 d)	I-133 (20.8 h)	Xe-133M (2.19 d)	Cs-134 (2 y)	I-134 (53 m)	Xe-135 (9.1 h)	I-135 (6.6 h)	Xe-135M (15.3 m)	Cs-137 (30 y)
	3.92E-04	4.98E+02	1.79E_00	3.31E+01	8.10E-05	2.03E-03	1.88E+01	1.02E-04	3.59E-01	6.11E-04
	Xe-138 (14 m)									
	1.19E+00									

(1988 DATE FROM NUREG-/CR-2907 VOL 9)

Units for half-lives
d - days
h - hours
m - minutes
y - years

The noble gas radionuclides are not released continuously, but are rather held up in tanks for about 60 days. When the containment is periodically purged, these tanks are emptied into the high flowrate purge stream. The following data [based on the Watts Bar Final Safety Analysis Report (FSAR) (TVA 1975)] were used for the transport calculation (Table 6-16).

Table 6-16. Airborne radionuclide purge data

Purges per year:	6
Purge gas flowrate:	28,000 cfm
Stack height:	130 ft. above grade
Stack cross-section:	2 ft x 7-1/2 ft
Timing of nuclide analysis:	Just prior to purge

Some of the non-noble gas radionuclides may be purged continuously; however, no data was provided on which nuclides were treated in this manner. A case where one-sixth off all the annual airborne nuclides are "stacked" to the atmosphere in an hour's time has been assumed. The dose at the site boundary, however, must be limited to the allowable standard. Therefore, a utility will stagger or slow down the release rate, if necessary, to meet this criterion. These assumptions, while relatively standard, might result in an overestimate of the health impacts.

6.4.2 Liquid Radionuclides from Normal Operations

NUREG/CR-2907 (NRC 1988) also has data on liquid radionuclide emissions to the environment for the entire year. In addition to data summaries, which lump the liquid radionuclides into (1) fission and activation products, and (2) tritium, there are tables of individual radionuclides (expressed in curies per year released) for each radionuclide. Some utilities report as few as 15 radionuclides, others report as many as 45 radionuclides. Since the models to be used for transport and dose-effect calculations require data on a radionuclide basis, a decision had to be made as to which utility data to use. It was again decided to prepare a data base of liquid releases for all U.S. Westinghouse PWRs of 800 MW(e) or greater. For the 1988 NUREG data, this database consisted of 36 reactors. This large sample should well characterize the liquid waste emissions and liquid waste handling capability of the reference PWR. The 35 radioisotopes that were most often reported, or which had the longest half-lives, were selected. The amounts of radionuclide produced did not appear to correlate with the MW-hrs (thermal) produced or the reactor capacity. Amounts produced are more likely affected by random events within the reactor, such as fuel pin cladding failures,

leaks in the primary coolant loop, steam-generator tube leaks, etc. The amount of each radionuclide produced for one reactor year is reported in curies in Table 6-17 and is the average (mean) for all reactors reporting the nuclide. The data for each plant is reported in Appendix C.2. Where a utility reported a total for two units, half that value is used for each unit. Tritium, which is produced by ternary fission or activation of deuterium or Li-6, is by far the largest liquid effluent radioisotope with an average annual emission of 447 curies per reactor-yr. The temporarily dissolved fission product noble gases are second at 65 curies per reactor-year. Iodine and other dissolved fission products account for only 1.08 curies per reactor-yr. Considering the large volumes of dilution water added, the amount of radioactivity added to the cooling water source is quite insignificant.

The liquid radionuclides are not released continuously, but are rather held up in tanks for around five days. When the tanks are periodically purged, their contents and significant dilution water are emptied into the blowdown line to the cooling towers. For the Southeast reference site PWR there will be considerably more dilution water available than at the Southwest reference site. For the SE site, the Sequoyah PWR dilution data can be used (see Appendix Table C.2). At the SW site there is no large river into which purged liquids can be dumped. Many acres of evaporation pond, however, might be constructed, and could be used for liquid discharge. (Approximately 22,000 acre-feet per year or 2.7 million cubic meters per year of water will be needed to make up for evaporation losses from these ponds and the cooling towers). Non-volatile radionuclides and evaporation blowdown products will accumulate in the ponds. The solids which settle out may occasionally need to be collected and drummed for disposal. Even though the amounts of radionuclide should be small, the drums may need to be treated as LLW. (Depending on the ratio of non-radioactive sludge to radionuclide-contaminated salts, the drummed material might alternatively be treated as "below-regulatory-concern" BRC waste. The regulatory issues concerning BRC have not yet been successfully resolved. For the SW site, the dilution water available will probably be on the order of 1000 gpm or 2 million cubic meters per year. The noble gas radionuclides in the water effluent will be rapidly released from the evaporation ponds and will become an additional airborne source term. The other radionuclides will eventually be collected with the pond sludge and treated as low-level or possibly BRC waste. (The reader should note that the LLW facility associated with the nuclear fuel cycle is not treated in this study.)

Table 6-17. Average liquid radionuclide emissions from sample of 36 large W-PWRS (Expressed in annual Curies)

Isotope> Half-life>	T-3 (12.3 y)	Na-24 (15 h)	Cr-51 (27.7 d)	Mn-54 (312 d)	Fe-55 (2.73 y)	Co-57 (272 d)	Co-58 (71 d)	Fe-59 (44.5 d)	Co-80 (5.27 y)	Zn-85 (244 d)	Kr-85M (4.48 h)	Sr-89 (50.5 d)
	4.47E+02	2.24E-03	6.07E-02	4.00E-02	1.43E-01	1.47E-03	5.98E-01	7.34E-03	1.57E-01	6.75E-04	3.78E-02	2.42E-03
	Sr-90 (29.1 y)	Nb-95 (35 d)	Sr-95 (64 d)	Mo-99 (2.75 d)	Tc-99M (6.01 h)	Ru-103 (39.3 d)	Ag-110M (250 d)	Sn-113 (115 d)	Sb-124 (60.2 d)	Sb-125 (2.76 y)	I-131 (8.04d)	Xe-131M (11.9 d)
	5.69E-04	1.03E-02	6.27E-03	7.55E-04	8.78E-04	1.26E-03	1.47E-02	1.39E-03	1.26E-02	5.02E-02	2.80E-02	4.60E-01
	I-132 (2.3 h)	Xe-133 (5.24 d)	I-133 (20.8 h)	Xe-133M (2.19 d)	Cs-134 (2.07 y)	I-135 (6.6 h)	Xe-135 (9.1 h)	Cs-136 (13.2 d)	Cs-137 (30 y)	Ba-140 (12.75 d)	La-140 (1.88 d)	
	1.06E-02	7.07E+01	1.20E-02	5.79E-01	3.37E-02	8.61E-03	5.27E-01	1.35E-03	5.06E-02	9.34E-04	1.00E-03	

(1988 DATE FROM NUREG-/CR-2907 VOL 9)

Units for half-lives:
d - days
h - hours
m - minutes
y - years

6.4.3 Non-Radioactive Emissions

There must be some quantities of non-radioactive chemicals released into the recirculating cooling water. These are not listed in the NRC NUREG-2907 document on plant emissions and consist of chemicals used for coolant water pH control and biocides for the cooling towers.

6.5 DECOMMISSIONING EMISSIONS AND EXPOSURES

U.S. reactors are licensed for 40 years of operation after issuance of their operating license. Unless the case can be made to the NRC for life extension, the reactor enters the decommissioning phase of its life cycle. The NRC now allows three modes of decommissioning: (1) immediate dismantlement of the reactor; (2) safe storage of the reactor for 40 or more years (to allow radionuclides to decay) followed by dismantlement; and (3) entombment of the reactor inside the containment building. In this discussion of decommissioning we will focus on the immediate dismantlement option only. (Immediate dismantlement would have the most health effects and, thus, represents a conservative assumption.)

Dismantling a reactor begins with removal of the fuel followed by a planning period of a few years in which radionuclides can decay. Work crews then go inside the reactor containment and begin disassembling the reactor steam-supply system. This work is anticipated to use many manual cutting and welding torch operations but also some robotic techniques. In 1978 the NRC performed an extensive study on the technology, ES&H aspects, and costs of decommissioning PWRs (NRC 1978). It is from this report that the following data on emissions and public and occupational exposures are obtained.

6.5.1 Airborne Radionuclides from Decommissioning

Nearly all of the worker and public exposure is from airborne radionuclides released during the various dismantling and cutting operations. Liquid wastes are held-up in tanks and appropriately treated at a later time. The sources of exposure are radionuclides from the following sources: (1) isotopes formed by activation of piping and core component elements, (2) fission products plated out on piping and other internal surfaces, and (3) other radionuclides formed by activation of miscellaneous substances such as water, air, organics, etc. Among the radionuclides formed are the following listed in Table 6-18. (Quantities in curies are not listed since they are given for each major reactor component and would fill several pages of text. Appendix J of NUREG/CR-0130 Vol 2 gives these data in detail.)

Table 6-18. Radionuclides of concern during immediate dismantlement decommissioning option

Argon-39	Nickel-59	Molybdenum-93
Calcium-41	Nickel-63	Niobium-94
Manganese-54	Zinc-65	Niobium-95
Iron-55	Chromium-51	Zirconium-95
Iron-59	Yttrium-90	Tellurium-129
Cobalt-58	Strontium-89	Iodine-131
Cobalt-59	Strontium-90	Cesium-137
Cobalt-60	Cesium-134	Cerium-141

It should be noted that the contaminated or activated LLW generated by decommissioning must be sent to a certified low level waste burial facility. This particular facility (LLW processing and burial site) is not part of this nuclear fuel cycle study.

6.5.2 Public and Occupational Exposures During Decommissioning

The results of the NUREG/CR-0130 safety evaluation of immediate dismantlement decommissioning operations are summarized in Table 6-19. The principal radiation dose to the public arises during transportation of radioactive materials from the reactor station to the disposal facilities. The estimated public dose from actual dismantlement operations is very small.

The largest aggregate dose is the 1200 man-rem to the workers actually doing the dismantling. Less than 6 lost-time injuries from industrial type accidents are predicted during the 6-year decommissioning effort. Based on industrial safety averages, very few of these injuries prove to be fatal. Thus, using the sum of the occupational fatality figures on Table 6.19, we can assume that 0.10 deaths will occur during the six-year decommissioning effort (decommissioning operation plus transportation).

6.6 NUCLEAR FUEL CYCLE IMPACT PATHWAYS: CONSTRUCTION, NORMAL REACTOR OPERATIONS, AND DECOMMISSIONING

6.6.1 Pathway and Impact Tables

Table 6-20 lists the emissions, environmental pathways, and ecological impacts that are discussed in Sections 6-3, 6-4, and 6-5 and Appendix C, and gives the reasons why these were evaluated. Table 6-21 lists the emissions, environmental pathways, and ecological impacts that were not discussed in the above sections, and gives the reasons why these were not evaluated.

Table 6-22 lists the emissions, pathways, and health-safety impacts that are discussed in Sections 6-3, 6-4, and 6-5 and Appendix C, and gives the reasons why these were evaluated. Impacts, which were discussed in detail, are given in italics. Table 6-23 lists the emissions, pathways, and health-safety impacts that were not discussed in the above sections, and gives the reasons why these were not evaluated.

Table 6-19. Summary of safety analysis for decommissioning the reference PWR by immediate dismantlement[b]

Type of safety concern	Source of safety concern	Units	Immediate dismantlement[d]
	Public safety[a]		
Radiation exposure	Decommissioning operations	man-rem[c]	0.0001
	Transportation	man-rem	22
	Safe storage	man-rem	--
	Occupational safety		
Serious lost-time injuries	Decommissioning operations	no. injuries	4.0
	Transportation	no. injuries	1.1
	Safe storage	no. injuries	--
Fatalities	Decommissioning operations	no. fatalities	0.029
	Transportation	no. fatalities	0.068
	Safe storage	no. fatalities	--
Radiation exposure	Decommissioning operations	man-rem	1200
	Transportation	man-rem	100
	Safe storage	man-rem	--

[a]Radiation doses from postulated accidents are not included.
[b]Data is from NUREG/CR-0130.
[c]The **rem** is a dose unit for ionizing radiation.
[d]Estimates are of total impacts over a six-year decommissioning period, with five years of risk exposure

Table 6-20. Primary emissions, environmental pathways, and ecological impacts linked to the reactor electrical generation portion of the nuclear fuel cycle not examined in detail

Emissions	Environmental pathway	Ecological impact	Impact evaluation
Impacts during reactor construction:			
Gases created during steel and concrete mfg. (CO_2, No_x,SO_2)	Atmosphere dispersion	Global warming, effects on plant growth, wildlife	These indirect emissions are quantified, but effects are not
Particulate matter created during steel and concrete mfg	Atmosphere dispersion	Effects on plant growth, wildlife	These indirect emissions are quantified. but effects are not
Impacts during normal reactor operations			
Concentrated non-radioactive salts and liquid radionuclides concentrated in evaporation ponds at SW site	Leaching from pond sludges if sludges are not properly handled.	Effects on desert biota if released to desert floor.	Sludges are assumed drummed and shipped to LLW or BRC site, thereby preventing qualitative discussion of impact aversion

Table 6-21. Emissions, environmental pathways, and ecological impacts linked to the reactor electrical generation portion of the nuclear fuel cycle not examined in detail

Emissions	Environmental pathway	Ecological impact	Impact evaluation
Impacts during construction:			
Dusts and gases created during construction	Atmospheric dispersion	Effects on plants and wildlife	No evaluation (impacts are small and confined)
Impacts during normal operations:			
Thermal discharges (heat)	Condenser to cooling water	Effects on aquatic biota	Qualitative evaluation, regulation of thermal discharge minimizes impact
Cooling tower drift (water and salt particulates)	Cooling towers to atmosphere via wind	Fog and deposited particulate matter can affect biota	No evaluation (effects are small and not specific to nuclear plants)
Airborne radionuclides	Periodic releases to atmosphere from plant stack	Radiation exposure to plants and wildlife	No evaluation
Liquid radionuclides	Periodic releases to cooling water source in blowdown stream	Radiation exposure to aquatic plants and wildlife	No evaluation
Impacts During Decommissioning:			
Airborne radionuclides (mostly particulates)	Cutting, dismantlement operations to atmosphere, atmospheric dispersion	Radiation exposure to plants and wildlife	No evaluation
Liquid radionuclides	Possible release to nearby waters	Radiation exposure to aquatic plants and wildlife	Minimal qualitative evaluation

Table 6-22. Primary emissions, pathways, and health-safety impacts linked to the reactor electrical generation portion of the nuclear fuel cycle

Emissions	Environmental pathways	Health-safety impact	Impact evaluation
Impacts during reactor construction:			
Gases created during steel and concrete mfg. (NO_x, SO_2,) particulate matter	Atmospheric dispersion	Respiratory illnesses	Indirect emissions are quantified
Impacts during normal reactor operations:			
Airborne radionuclides	Atmospheric dispersion	Morbidity-mortality due to radiation exposure (public)	Qualitative evaluation (effects on health modeled).
Liquid radionuclides	Intake of water or fish or plants living in water	Morbidity-mortality due to radiation exposure (public)	Quantitative evaluation (effects on health modeled).
In-plant radiation sources plus on-site airborne/liquid radionuclide emissions	Worker access to on-site sources	Morbidity/mortality (occupational) due to radiation exposure	Qualitative evaluation
Impacts during decommissioning:			
Airborne radionuclides (mostly particulates)	Cutting, dismantling operation to atmosphere, followed by dispersion	Morbidity-mortality due to radiation exposure (occupational and public)	Qualitative evaluation (results of 1978 NRC study presented)

Table 6-23. Emissions, pathways, and health-safety impacts linked to the reactor electrical generation portion of the nuclear fuel cycle not examined in detail

Emissions	Environmental pathways	Health-safety impacts	Impact evaluation
Impacts during construction:			
Dust and gases from construction activity	Atmospheric dispersion	Mortality-morbidity	No evaluation (generic to all types of outdoor construction.)
Impacts during normal reactor operations:			
Cooling tower drift	Cooling tower to atmosphere via wind	Fog hazards (vehicle accidents) or inhalation morbidity/mortality	No evaluation (Not specific to nuclear. Effects would be negligible.)
Non-radioactive liquid effluents (biocides, misc. chemicals, etc.)	Discharge into cooling water source	Mortality/morbidity	No evaluation
Impacts during decommissioning:			
Non-radioactive gases and chemicals	Inhalation or ingestion after dispersion or contact	Mortality/morbidity	No evaluation (impact no worse than other non-reactor demolition activity.

6.6.2 Priority Impact Pathways

This section lists the priority impact pathways from the reactor portion of the nuclear fuel cycle during normal operations. All were selected based on an assessment of the emission and assumptions stated earlier in this report and upon 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.

6.6.2.1 Impacts from Reactor Construction

Indirect emissions are the most significant impact contribution but are not generic to nuclear or any other electricity generation technology. Emissions from the steel and concrete industries come under EPA regulation. Estimates of emissions are in Section 6.3.

6.6.2.2 Impacts from Reactor Normal Operations

Normal reactor operations produce non-radioactive emissions that are thought to be negligible in terms of amounts, ecological impacts, and health and safety impacts.

6.6.2.3 Impacts from Reactor Decommissioning

There is not much historical experience on reactor decommissioning emissions on which to base an assessment. The NRC, however, will strictly regulate radionuclide emissions to reduce public exposure to radiation. NRC will also insist that worker exposure during decommissioning be minimized. The anticipated 1200 man-rem exposure is considered small.

6.6.3 Health Damages from Normal Operations and Decommissioning

The health damages from normal operations of a nuclear reactor are defined to also include decommissioning, which itself is divided into operations, waste transport and safe storage. No estimates of health effects were made for storage. Damage categories include (i) mortality from immediate causes and injuries in the operations and in the decommissioning operations and waste transport stages, and (ii) cancer fatalities to the public and workers from normal operations and decommissioning stages.

Unit values for mortality. Unit values for immediate deaths and premature deaths from cancer are developed in this section (but see Chapter 7 for a fuller explanation). The damages associated with immediate deaths are based on the average value of a statistical life (which we take from the literature review by Fisher, Chestnut, and Violette 1989). This study considered primarily wage compensation studies analyzing the premia paid to workers in relatively risky jobs for the excess accidental death risks they bear. It also considers contingent valuation studies of the WTP to avoid automobile death risks. Low, Mid, and High values of statistical lives are $1.6 million, $3.5 million, and $8.6 million, respectively. Being taken from studies involving accidental and immediate deaths in the workplace, we feel these estimates are reasonably appropriate.

Cancer deaths are valued following the approach discussed in Section 5.6.4, which involves correcting the above VSL estimates for latency. To address latency, we use an estimate of the average latency period for cancer (20 years) to date the onset of cancer and discount the accidental death WTP estimates from the date of onset to the present. Multiplying the discounted WTP estimate by the annual expected deaths from cancer gives the annual expected damage for the annual exposure.

All exposures in the decommissioning phase are assumed to begin in year 41 and continue for 5 years. The sum total of damages are then levelized using a 3% discount rate to assign an estimate of decommissioning damages to each year of plant operation.

Unit values for Morbidity. The only morbidity effects we can value are on the job injuries from nuclear power plant operations and "serious lost-time injuries" during the decommissioning stage.

Section 5.6.4 has presented a discussion of the valuation of injuries. Since no injury incidence information of sufficient specificity is available for the electricity generation sector, we apply an across-industry average cost per injury as provided by the Urban Institute in Rossman, Miller and Douglass (1991) for the value of a statistical injury (VSI). If the injuries included in this study are of the same kind (severity, injury type distribution, cost) as the injuries in the electric generation sector, then we can assume that the industry-wide average cost of $10,301 per injury is applicable to this industry. We construct a judgmental confidence interval for a VSI spanning the range of the two hedonic studies reviewed in Section 5.6.4, from $8,000 to $34,000. These unit values would apply to injuries to workers engaged in normal plant operations.

Whether these values also apply to the "serious lost-time injuries" to workers engaged in decommissioning depends on the meaning of "serious." On the assumption that "serious" means "major injuries," as defined by Martinello and Meng (1992), each statistical case would be valued at $127,000, the average of two estimates developed by these researchers (see section 5.6.4 for a complete discussion of valuing injuries). Alternatively, it is possible that "serious" simply means injuries involving at least one day absent from work. Subject to further clarification, we take the first meaning, providing only a midpoint estimate of the value of serious injuries. Note that non-fatal cancer estimates were not made for this stage; hence, no unit values are offered here (see Chapter 7 for these values).

Mortality Damage Calculations. As shown on Table 6-24 for the Southeast Reference environment, based on the estimate of 0.08 immediate occupational deaths each year to workers engaged in normal plant operations, and a VSL midpoint estimate of $3.5 million, we offer a midpoint estimate of $280,000 per year, or 0.034 mills/kWh. Expected annual occupational cancer fatalities of 0.12, valued at $1.9 million given the 20 year latency assumption, result in damages of $233,000 per year, or 0.028 mills/kWh. Premature deaths to the public are trivially small.

Table 6-24. Annual health damages from normal operations for the southeast reactor site

Startpoint	Airborne radionuclide emissions	Waterborne radioncuclide emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6-33				
Section No.	6.7.3		6.7.2	6.7.4	
Specific endpoint	Latent cancer fatalities			Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	5.00E-05	1.00E-04	0.12	0.08	7.7
LOW					
Damage per case valued at time of exposure (1989$)	$885,881	$885,881	$885,881	$1,600,000	$8,000
Damage levelized over plant lifetime (1989$/yr)	$44	$89	$106,306	$128,000	$61,600
Damaged levelized over plant lifetime (mills/kWh)	$5.4245E-06	1.0849E-05	0.01301884	0.01567565	0.007544
MEDIUM					
Damage per case valued at time of exposure (1989$)	$1,937,865	$1,937,865	$1,937,865	$3,500,000	$10,300
Damage levelized over plant lifetime (1989$/yr)	$97	$194	$232,544	$280,000	$79,310
Damaged levelized over plant lifetime (mills/kWh)	1.1866E-05	2.3732E-05	0.02847872	0.3429049	0.009713
HIGH					
Damage per case valued at time of exposure (1989$)	$4,761,611	$4,761,611	$4,761,611	$8,600,000	$34,000
Damage levelized over plant lifetime (1989$/yr)	$238	$476	$571,393	$688,000	$261,800
Damaged levelized over plant lifetime (mills/kWh)	2.9157E-05	5.8314E-05	0.06997628	0.08425664	0.032062

In the decommissioning activities, shown on Table 6-25, immediate fatality risks to workers are very low and occur after 40 years, thus damages are insignificant. The risks to workers of death from cancer in this stage are higher, however, resulting in a midpoint estimate of 0.0014 mills/kWh annualized. The risks to the public of decommissioning activities are also trivially low.

Tables 6-26 and 6-27 provide the analogous information for the Southwest Reference environment.

Morbidity Damage Calculations. For the Southeast Reference environment (Tables 6-24 and 6-25), the damages associated with nonfatal injuries through normal power plant operation are $79,000 per year as a midpoint estimate, or 0.01 mills/kWh. Even valuing serious injuries in the decommissioning stage at $127,000 per injury, their low number and the fact that they occur far in the future results in extremely small annual damage estimates. Tables 6-26 and 6-27 provide the analogous information for the Southwest Reference environment.

Uncertainties. Tables 6-24 through 6-27 also present judgmental LOW and HIGH estimates of damage based entirely on ranges of unit values for the VSL's and VSI's, as discussed above. For this stage for the Southeast Reference environment, total damages range from 0.038 mills/kWh to 0.192 mills/kWh with a midpoint estimate of 0.076 mills/kWh. For the Southwest Reference environment, total damages are very similar. At three significant digits, only the midpoint estimate (0.075 mills/kWh) is different. This similarity occurs because the occupational effects are identical and the populations affected by the radiation are very similar in total, although the close-in population around the southwestern site is smaller.

6.7 HEALTH EFFECTS

6.7.1 General Public Mortality and Morbidity Due to Routine Releases of Radionuclides

During normal operation of a nuclear reactor, a variety of radionuclides may be released to the environment in atmospheric and liquid discharges. These releases are described in Sections 6.4.1 and 6.4.2. This section presents the radiation doses and risks to the public from such releases.

Table 6-25. Annual health damages from decommissioning for the southeast reactor site

Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
Table No.	6-19											
Section No.	6.5.2, 6.6.2.3, 6.6.3											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
LOW												
Damage per case valued at time of exposure (1989$)	$1,600,000	$127,000(a)	$885,881	$885,881	$1,600,000	$127,000(a)	$885,881	$885,881	$1,600,000	$127,000(a)	$885,881	$885,881
Damaged levelized over plant lifetime (1989$/yr)	$564	$6,171	$5,165	$0	$1,322	$1,697	$430	$95	$0	$0	$0	$0
Damaged levelized over plant lifetime (mills/kWh)	6.9028E-05	0.000755733	0.00063259	6.5895E-11	0.00016186	0.000207827	5.2716E-05	1.1597E-05	0	0	0	0
MEDIUM												
Damage per case valued at time of exposure (1989$)	$3,500,000	$127,000(a)	$1,937,865	$1,937,865	$3,500,000	$127,000(a)	$1,937,865	$1,937,865	3,500,000	127,000(a)	$1,937,865	$1,937,865
Damaged levelized over plant lifetime (1989$/yr)	$1,233	$6,171	$11,299	$0	$2,891	$1,697	$942	$207	$0	$0	$0	$0
Damaged levelized over plant lifetime (mills/kWh)	0.000151	0.000755733	0.00138379	1.4414E-10	0.00035406	0.000207827	0.00011532	2.5369E-05	0	0	0	0
HIGH												
Damage per case valued at time of exposure (1989$)	$8,600,000	$127,000(a)	$4,761,611	$4,761,611	$8,600,000	$127,000(a)	$4,761,611	$4,761,611	$8,600,000	$127,000(a)	$4,761,611	$4,761,611
Damaged levelized over plant lifetime (1989$/yr)	$3,030	$6,171	$27,764	$0	$7,104	$1,697	$2,314	$509	$0	$0	$0	$0
Damaged levelized over plant lifetime (mills/kWh)	0.00037102	0.000755733	0.00340016	3.5418E-10	0.00086999	0.000207827	0.00028335	6.2336E-05	0	0	0	0

[a] Value taken from Martinello and Meng 1992, for major injuries.

Table 6-26. Annual health damages from normal operations for the southwest reactor site

Startpoint	Airborne radionuclide emissions	Waterborne radionuclide emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6-33				
Section No.	6.7.3		6.7.2	6.7-4	
Specific endpoint	Latent cancer fatalities			Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	3.00E-06	3.50E-06	0.12	0.08	7.7
LOW					
Damage per case valued at time of exposure (1989$)	$885,881	$885,881	$885,881	$1,600,000	$8,000
Damaged levelized over plant lifetime (1989$/yr)	$3	$3	$106,306	$128,000	$61,600
Damaged levelized over plant lifetime (mills/kWh)	3.2547E-07	3.7972E-07	0.01301884	0.01567565	0.007544
MEDIUM					
Damage per case valued at time of exposure (1989$)	$1,937,865	$1,937,865	$1,937,865	$3,500,000	$10,300
Damaged levelized over plant lifetime (1989$/yr)	$6	$7	$232,544	$280,000	$79,310
Damaged levelized over plant lifetime (mills/kWh)	7.1197E-07	8.3063E-07	0.02847872	0.3429049	0.009713
HIGH					
Damage per case valued at time of exposure (1989$)	$4,761,611	$4,761,611	$4,761,611	$8,600,000	$34,000
Damaged levelized over plant lifetime (1989$/yr)	$14	$17	$571,393	$688,000	$261,800
Damaged levelized over plant lifetime (mills/kWh)	1.7494E-06	2.041E-06	0.06997628	0.08425664	0.032062

Table 6-27. Annual health damages from decommissioning for the southwest reactor site

Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
Table No.	6-19											
Section No.	6.5.1											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
LOW												
Damage per case valued at time of exposure (1989$)	$1,600,000	$127,000(a)	$885,881	$885,881	$1,600,000	$127,000(a)	$885,881	$885,881	$1,600,000	$127,000(a)	$885,881	$885,881
Damaged levelized over plant lifetime (1989$/yr)	$564	$6,171	$5,165	$0	$1,322	$1,697	$430	$95	$0	$0	$0	$0
Damaged levelized over plant lifetime (mills/kWh)	6.9028E-05	0.000755733	0.00063259	6.5895E-11	0.00016186	0.000207827	5.2716E-05	1.1597E-05	0	0	0	0
MEDIUM												
Damage per case valued at time of exposure (1989$)	$3,500,000	$127,000(a)	$1,937,865	$1,937,865	$3,500,000	$127,000(a)	$1,937,865	$1,937,865	3,500,000	127,000(a)	$1,937,865	$1,937,865
Damaged levelized over plant lifetime (1989$/yr)	$1,233	$6,171	$11,299	$0	$2,891	$1,697	$942	$207	$0	$0	$0	$0
Damaged levelized over plant lifetime (mills/kWh)	0.000151	0.000755733	0.00138379	1.4414E-10	0.00035406	0.000207827	0.00011532	2.5369E-05	0	0	0	0
HIGH												
Damage per case valued at time of exposure (1989$)	$8,600,000	$127,000(a)	$4,761,611	$4,761,611	$8,600,000	$127,000(a)	$4,761,611	$4,761,611	$8,600,000	$127,000(a)	$4,761,611	$4,761,611
Damaged levelized over plant lifetime (1989$/yr)	$3,030	$6,171	$27,764	$0	$7,104	$1,697	$2,314	$509	$0	$0	$0	$0
Damaged levelized over plant lifetime (mills/kWh)	0.00037102	0.000755733	0.00340016	3.5418E-10	0.00086999	0.000207827	0.00028335	6.2336E-05	0	0	0	0

[a] Value taken from Martinello and Meng 1992, for major injuries.

6.7.1.1 Due to Atmospheric Releases

Characterization of radiation doses to people due to routine releases of radionuclides from the power plants to the atmosphere (Sect. 6.4.1) was accomplished by calculating the collective 50-year committed effective dose equivalent (CEDE) to the population residing within 80 km of the plants. The calculations were performed using the CAP-88 suite of computer codes (Beres 1990), which is described in Appendix C. Because of the low order of magnitude of even the most persistent atmospheric radionuclides (such as Krypton-85, a few hundred curies/yr) it is felt unnecessary to go beyond 80 km from the plant for dose calculations.

The CAP-88 package uses a steady-state Gaussian plume atmospheric dispersion model to calculate annual-average concentrations of released radionuclides in ground-level air and the annual quantity of radionuclides deposited on the ground surface via wet and dry deposition processes. Regulatory Guide 1.109 (NRC 1977) food chain models and parameter values are used to calculate radionuclide concentrations in foodstuffs (vegetables, milk, and meat) and subsequent intakes of radionuclides by the population. Dose factors, based on ICRP 26 (ICRP 1977) and 30 (ICRP 1978) recommendations, are used to convert the radionuclide intakes to CEDEs. The dose factors do not account for age dependence.

Meteorological data input to the codes must be in the form of an annual joint frequency (STAR) distribution of wind direction, wind speed, and atmospheric stability category. For the CRBR site, the joint frequency distribution was derived from data collected during 1989 at the 60-m station on the DOE Oak Ridge Site meteorological tower (located about two miles north of the CRBR site). For the Farmington site, two joint frequency distributions were used: a composite of data collected during 1954-59 at the Farmington, New Mexico, weather station and data collected during 1989 at the Gallup, New Mexico, weather station. These two joint frequency distributions are quite different.

Site-specific population distributions, based on 1990 Census data, were used in collective dose calculations. The distributions about the two plants consist of the number of persons residing in each sector segment of a circular grid drawn about the source. For this study, the circular grid was defined by the intersection of sixteen 22.5°-wide sectors and fifteen circular bands. A sector was centered on each of the primary compass directions (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, and NNW). The fifteen circular bands extended 0-515, 515-1207, 1207-1609, 1609-3218, 3218-4827, 4827-8045, 8045-11263, 11263-16090, 16090-20917, 20917-25744, 25744-32180, 32180-40225, 40225-48270, 48270-64360, and 64360-80450 m from the center of the grid.

The total number of persons residing within 80.45 km of the CRBR site was 866,406. The population within 80.45 km of the New Mexico site was 98,168 persons.

For the CRBR site, the annual CEDE was estimated to be about 0.1 person-rem (Table 6-28). The annual effective dose equivalent to the average individual in the population was estimated to be 0.0001 mrem. The predominant exposure pathway was immersion in contaminated air, which accounted for about 58% of the dose. Exposure to contaminated ground surface accounted for about 19% of the CEDE; ingestion of contaminated foodstuffs accounted for about 4% of the CEDE; and inhalation of contaminated air accounted for about 19% of the CEDE. Radionuclides contributing more than ten percent of the CEDE were ^{133}Xe, 32%; ^{3}H, 16%; ^{41}Ar, 15%; and ^{60}Co, 12%.

For the New Mexico site under Gallup weather conditions, the annual CEDE was estimated to be about 0.006 person-rem (Table 6-29). The annual effective dose equivalent to the average individual in the population was estimated to be 0.00006 mrem. The predominant exposure pathway was immersion in contaminated air, which accounted for about 52% of the dose. Ingestion of contaminated foodstuffs accounted for about 33% of the CEDE; exposure to contaminated ground surface accounted for about 9% of the CEDE; and inhalation of contaminated air accounted for about 6% of the CEDE. Radionuclides contributing more than ten percent of the CEDE were ^{133}Xe, 35% and ^{3}H, 30%.

For the New Mexico site under Farmington weather conditions, the annual CEDE was estimated to be about 0.004 person-rem (Table 6-30). The annual effective dose equivalent to the average individual in the population was estimated to be 0.00004 mrem. The predominant exposure pathway was ingestion of contaminated foodstuffs, which accounted for about 46% of the dose. Immersion in contaminated air accounted for about 42% of the CEDE; exposure to contaminated ground surface accounted for about 8% of the CEDE; and inhalation of contaminated air accounted for about 5% of the CEDE. Radionuclides contributing more than ten percent of the CEDE were ^{3}H, 41%, and ^{133}Xe, 27%.

6.7.1.2 Due to Liquid Releases

Characterization of radiation doses to the population due to routine liquid releases of radionuclides from the power plants (Sect. 6.4.2) was accomplished by calculating the CEDE to the population residing within 80 km of the plants. Two distinct situations had to be considered. Releases at the CRBR site were assumed to flow into the Clinch River and, subsequently, into the Tennessee River system.

Table 6-28. Dose by pathway and nuclide (person-rem/yr) for CRBR Site *

Nuclide	Ingestion	Inhalation	Immersion	Surface	Total
H-3	1.14×10^{-02}	5.47×10^{-03}	0	0	1.69×10^{-02}
Ar-41	0	1.28×10^{-05}	1.51×10^{-02}	0	1.51×10^{-02}
Cr-51	1.56×10^{-06}	9.38×10^{-07}	5.34×10^{-08}	1.12×10^{-05}	1.38×10^{-05}
Mn-54	5.90×10^{-07}	2.66×10^{-07}	2.13×10^{-08}	4.39×10^{-05}	4.48×10^{-05}
Co-57	1.74×10^{-07}	6.77×10^{-08}	5.71×10^{-10}	1.20×10^{-06}	1.44×10^{-06}
Co-58	4.94×10^{-07}	1.04×10^{-07}	5.94×10^{-09}	2.87×10^{-06}	3.47×10^{-06}
Co-60	2.79×10^{-04}	1.56×10^{-04}	1.15×10^{-06}	1.18×10^{-02}	1.22×10^{-02}
Kr-85	0	9.03×10^{-05}	1.85×10^{-04}	0	2.75×10^{-04}
Kr-85m	0	2.00×10^{-06}	2.85×10^{-04}	0	2.87×10^{-04}
Kr-87	0	1.11×10^{-06}	2.04×10^{-04}	0	2.05×10^{-04}
Rb-88	1.96×10^{-59}	6.20×10^{-08}	2.35×10^{-07}	1.47×10^{-08}	3.12×10^{-07}
Kr-88	0	2.45×10^{-05}	5.19×10^{-03}	0	5.21×10^{-03}
Sr-89	1.84×10^{-07}	3.33×10^{-08}	4.54×10^{-13}	5.20×10^{-10}	2.18×10^{-07}
Sr-90	4.52×10^{-07}	4.62×10^{-07}	0	0	9.14×10^{-07}
Nb-95	3.19×10^{-07}	9.21×10^{-09}	7.65×10^{-10}	1.83×10^{-07}	5.12×10^{-07}
Zr-95	1.08×10^{-07}	5.81×10^{-08}	1.90×10^{-09}	8.34×10^{-07}	1.00×10^{-06}
Tc-99m	5.72×10^{-16}	4.69×10^{-12}	1.01×10^{-11}	2.01×10^{-11}	3.49×10^{-11}
Ag-110m	7.43×10^{-09}	3.73×10^{-09}	8.19×10^{-11}	1.33×10^{-07}	1.44×10^{-07}
I-131	2.26×10^{-04}	1.53×10^{-05}	1.09×10^{-07}	4.84×10^{-05}	2.90×10^{-04}
Xe-131m	0	7.25×10^{-06}	5.62×10^{-05}	0	6.35×10^{-05}
I-132	1.15×10^{-15}	2.16×10^{-08}	8.02×10^{-08}	3.73×10^{-07}	4.75×10^{-07}
Xe-133	0	1.02×10^{-03}	3.21×10^{-02}	0	3.31×10^{-02}
I-133	4.00×10^{-04}	2.37×10^{-03}	1.52×10^{-04}	6.87×10^{-03}	9.79×10^{-03}
Xe-133m	0	8.02×10^{-05}	1.75×10^{-03}	0	1.83×10^{-03}
Cs-134	3.74×10^{-04}	6.33×10^{-06}	1.39×10^{-07}	6.83×10^{-04}	1.06×10^{-03}
I-134	3.27×10^{-26}	2.44×10^{-08}	2.79×10^{-07}	4.71×10^{-07}	7.74×10^{-07}
Xe-135	0	4.52×10^{-05}	5.71×10^{-03}	0	5.76×10^{-03}
I-135	5.01×10^{-11}	2.68×10^{-08}	2.03×10^{-08}	2.49×10^{-07}	2.96×10^{-07}
Xe-135m	0	5.85×10^{-09}	5.48×10^{-06}	0	5.49×10^{-06}
Cs-137	2.31×10^{-03}	3.28×10^{-05}	4.00×10^{-07}	4.97×10^{-09}	2.34×10^{-03}
Xe-138m	0	0	0	0	0
Total	1.50×10^{-02}	9.34×10^{-03}	6.07×10^{-02}	1.95×10^{-02}	1.05×10^{-01}

* Using 1989 meteorological data for 60 m tower at K-25.

Table 6-29. Dose by pathway and nuclide (person-rem/yr) for New Mexico Site *

Nuclide	Ingestion	Inhalation	Immersion	Surface	Total
H-3	1.62×10^{-03}	1.73×10^{-04}	0	0	1.79×10^{-03}
Ar-41	0	3.95×10^{-07}	4.66×10^{-04}	0	4.66×10^{-04}
Cr-51	1.88×10^{-07}	7.00×10^{-08}	3.98×10^{-09}	3.47×10^{-07}	6.09×10^{-07}
Mn-54	8.46×10^{-08}	2.00×10^{-08}	1.59×10^{-09}	1.37×10^{-06}	1.48×10^{-06}
Co-57	1.06×10^{-08}	5.07×10^{-09}	4.28×10^{-11}	3.75×10^{-08}	5.32×10^{-08}
Co-58	3.42×10^{-08}	7.83×10^{-09}	4.45×10^{-10}	8.96×10^{-08}	1.32×10^{-07}
Co-60	1.64×10^{-05}	1.17×10^{-05}	8.61×10^{-08}	3.69×10^{-04}	3.97×10^{-04}
Kr-85	0	5.79×10^{-06}	1.19×10^{-05}	0	1.77×10^{-05}
Kr-85m	0	8.63×10^{-08}	1.23×10^{-05}	0	1.24×10^{-05}
Kr-87	0	2.83×10^{-08}	5.21×10^{-06}	0	5.24×10^{-06}
Rb-88	1.96×10^{-60}	6.70×10^{-10}	2.63×10^{-09}	7.19×10^{-11}	3.37×10^{-09}
Kr-88	0	9.11×10^{-07}	1.93×10^{-04}	0	1.94×10^{-04}
Sr-89	2.80×10^{-08}	2.50×10^{-09}	3.40×10^{-14}	4.74×10^{-12}	3.05×10^{-08}
Sr-90	6.65×10^{-08}	3.46×10^{-08}	0	0	1.01×10^{-07}
Nb-95	1.57×10^{-08}	6.87×10^{-10}	5.71×10^{-11}	5.70×10^{-09}	2.21×10^{-08}
Zr-95	1.09×10^{-08}	4.35×10^{-09}	1.43×10^{-10}	2.60×10^{-08}	4.14×10^{-08}
Tc-99m	9.25×10^{-17}	2.31×10^{-13}	4.97×10^{-13}	3.97×10^{-13}	1.13×10^{-12}
Ag-110m	1.07×10^{-09}	2.80×10^{-10}	6.14×10^{-12}	4.15×10^{-09}	5.51×10^{-09}
I-131	4.90×10^{-05}	5.21×10^{-07}	3.72×10^{-09}	1.43×10^{-06}	5.10×10^{-05}
Xe-131m	0	4.61×10^{-07}	3.58×10^{-06}	0	4.04×10^{-06}
I-132	2.59×10^{-16}	3.43×10^{-10}	1.27×10^{-09}	5.27×10^{-09}	6.88×10^{-09}
Xe-133	0	6.42×10^{-05}	2.02×10^{-03}	0	2.08×10^{-03}
I-133	1.15×10^{-04}	6.78×10^{-05}	4.35×10^{-06}	1.71×10^{-04}	3.58×10^{-04}
Xe-133m	0	4.93×10^{-06}	1.07×10^{-04}	0	1.12×10^{-04}
Cs-134	2.46×10^{-05}	4.74×10^{-07}	1.04×10^{-08}	2.13×10^{-05}	4.64×10^{-05}
I-134	6.81×10^{-27}	3.23×10^{-10}	3.69×10^{-09}	5.62×10^{-09}	9.63×10^{-09}
Xe-135	0	2.32×10^{-06}	2.94×10^{-04}	0	2.96×10^{-04}
I-135	1.28×10^{-11}	5.71×10^{-10}	4.32×10^{-10}	4.67×10^{-09}	5.69×10^{-09}
Xe-135m	0	6.17×10^{-11}	5.77×10^{-08}	0	5.78×10^{-08}
Cs-137	1.52×10^{-04}	2.46×10^{-06}	3.00×10^{-08}	1.55×10^{-10}	1.54×10^{-04}
Xe-138m	0	0	0	0	0
Total	1.98×10^{-03}	3.35×10^{-04}	3.12×10^{-03}	5.65×10^{-04}	5.99×10^{-03}

* Using Gallup, New Mexico meteorological data for 1989

Table 6-30. Dose by pathway and nuclide (person-rem/yr) for New Mexico Site *

Nuclide	Ingestion	Inhalation	Immersion	Surface	Total
H-3	1.68×10^{-03}	1.15×10^{-04}	0	0	1.80×10^{-03}
Ar-41	0	2.65×10^{-07}	3.13×10^{-04}	0	3.13×10^{-04}
Cr-51	1.42×10^{-07}	3.59×10^{-08}	2.05×10^{-09}	1.80×10^{-07}	3.60×10^{-07}
Mn-54	6.26×10^{-08}	1.03×10^{-08}	8.18×10^{-10}	7.09×10^{-07}	7.83×10^{-07}
Co-57	8.83×10^{-09}	2.60×10^{-09}	2.20×10^{-11}	1.94×10^{-08}	3.09×10^{-08}
Co-58	2.78×10^{-08}	4.02×10^{-09}	2.29×10^{-10}	4.64×10^{-08}	7.84×10^{-08}
Co-60	1.37×10^{-05}	6.01×10^{-06}	4.42×10^{-08}	1.91×10^{-04}	2.11×10^{-04}
Kr-85	0	3.31×10^{-06}	6.80×10^{-06}	0	1.01×10^{-05}
Kr-85m	0	4.84×10^{-08}	6.91×10^{-06}	0	6.96×10^{-06}
Kr-87	0	2.14×10^{-08}	3.94×10^{-06}	0	3.96×10^{-06}
Rb-88	2.41×10^{-60}	8.78×10^{-10}	3.33×10^{-09}	8.89×10^{-11}	4.30×10^{-09}
Kr-88	0	5.46×10^{-07}	1.15×10^{-04}	0	1.16×10^{-04}
Sr-89	2.08×10^{-08}	1.28×10^{-09}	1.75×10^{-14}	2.45×10^{-12}	2.21×10^{-08}
Sr-90	5.09×10^{-08}	1.78×10^{-08}	0	0	6.87×10^{-08}
Nb-95	1.37×10^{-08}	3.53×10^{-10}	2.93×10^{-11}	9.50×10^{-09}	2.36×10^{-08}
Zr-95	8.28×10^{-09}	2.23×10^{-09}	7.33×10^{-11}	1.35×10^{-08}	2.41×10^{-08}
Tc-99m	9.16×10^{-17}	1.30×10^{-13}	2.80×10^{-13}	2.34×10^{-13}	6.44×10^{-13}
Ag-110m	9.02×10^{-10}	1.44×10^{-10}	3.15×10^{-12}	2.15×10^{-09}	3.20×10^{-09}
I-131	4.37×10^{-05}	3.41×10^{-07}	2.43×10^{-09}	9.38×10^{-07}	4.50×10^{-05}
Xe-131m	0	2.63×10^{-07}	2.04×10^{-06}	0	2.30×10^{-06}
I-132	3.07×10^{-16}	3.98×10^{-10}	1.48×10^{-09}	6.09×10^{-09}	7.97×10^{-09}
Xe-133	0	3.65×10^{-05}	1.15×10^{-03}	0	1.19×10^{-03}
I-133	1.08×10^{-04}	5.05×10^{-05}	3.24×10^{-06}	1.28×10^{-04}	2.90×10^{-04}
Xe-133m	0	2.79×10^{-06}	6.06×10^{-05}	0	6.34×10^{-05}
Cs-134	2.08×10^{-05}	2.44×10^{-07}	5.35×10^{-09}	1.10×10^{-05}	3.20×10^{-05}
I-134	8.43×10^{-27}	4.04×10^{-10}	4.62×10^{-09}	7.01×10^{-09}	1.20×10^{-08}
Xe-135	0	1.28×10^{-06}	1.61×10^{-04}	0	1.62×10^{-04}
I-135	1.35×10^{-11}	5.35×10^{-10}	4.04×10^{-10}	4.34×10^{-09}	5.29×10^{-09}
Xe-135m	0	7.88×10^{-11}	7.38×10^{-08}	0	7.39×10^{-08}
Cs-137	1.28×10^{-04}	1.26×10^{-06}	1.54×10^{-08}	8.03×10^{-11}	1.29×10^{-04}
Xe-138	0	0	0	0	0
Total	1.99×10^{-03}	2.18×10^{-04}	1.82×10^{-03}	3.32×10^{-04}	4.37×10^{-03}

* Using Farmington, New Mexico meteorological data for 1954-59

Dose calculations for this site were performed using a modified version of LADTAP XL (Hamby 1991), which is described in Appendix C. No river is available at the New Mexico site. Therefore, we assumed no liquid discharge to off-site surface waters. Liquid discharges were assumed to be held in holding ponds and ultimately disposed of, after drying, as low-level solid waste. Escape of noble gases and tritium from the ponds was treated as an atmospheric emission.

The LADTAP XL transport model estimates annual-average concentrations of radionuclides in river segments by dividing total quantities of radionuclides discharged to the river by the appropriate river-segment volume. The only depletion mechanism considered is radioactive decay. Credit is not taken for sedimentation, but a simple shoreline deposition model is used to conservatively predict shoreline concentrations of radionuclides. This model simply assumes a constant radionuclide deposition rate (100 times the water concentration) that is adjusted for radioactive decay over a period of 50 years.

Exposure pathways considered include ingestion of untreated water and fish from the river, swimming and boating in the river, and use of the shoreline. This code performs these calculations using the models and parameter values recommended in Regulatory Guide 1.109 (NRC 1977). Calculations were performed in three parts: activities in the Clinch River and drinking water from the Kingston treatment plant, activities and drinking water from Watts Bar Lake, and activities and drinking water from Chicamauga Lake.

For the CRBR site, the annual CEDE was estimated to be about 0.2 person-rem (Table 6-28). The annual effective dose equivalent to the average individual in the population was estimated to be 0.00003 mrem. The predominant exposure pathway was eating contaminated fish, which accounted for about 58% of the dose. Using contaminated shoreline accounted for about 25% of the CEDE; drinking contaminated water accounted for about 15% of the CEDE; and swimming and boating accounted for about 0.1% of the CEDE. Radionuclides contributing more than ten percent of the CEDE were ^{137}Cs, ^{134}Cs, and ^{60}Co.

The New Mexico site did not have any on-site specific meteorological data. The nearest locations were Gallup, New Mexico, 50 miles to the SW, and Farmington, New Mexico, 40 miles to the north.

For the New Mexico site under Gallup weather conditions and the assumption that half the tritium and all the noble gases in the liquid source term evaporated, the annual CEDE was estimated to be about 0.006 person-rem. The predominant exposure pathway was ingestion of foodstuffs contaminated with ^{3}H.

For the New Mexico site under Farmington weather conditions, the annual CEDE was estimated to be about 0.004 person-rem. Ingestion of foodstuffs contaminated with ^{3}H remained the predominant exposure pathway.

6.7.2 Occupational Radiation Exposure

Plant workers conducting activities involving radioactively contaminated systems or working in radiation areas can be exposed to radiation. Most of the occupational radiation dose to nuclear plant workers results from external radiation exposure rather than from internal exposure from inhaled or ingested radioactive materials. Experience has shown that the dose to nuclear plant workers varies from year to year. This experience will be used to gauge the radiation doses for the reference PWR facility. Table 6-31 shows the occupational dose history for PWRs operated in the United States. Average collective occupational dose information, as well as average annual individual worker doses, are presented for those plants operating between 1974 and 1989. The year 1974 was chosen as a starting date because the dose data for years before 1974 are primarily from reactors with average rated capacities below 500 MW(e). Since the early 1980s, when the majority of (post Three Mile Island) plant modifications were completed, there has been a decreasing trend in the average collective occupational dose. The average collective doses, however, are based on widely varying yearly doses. For example, between 1974 and 1989, annual collective doses for operating PWRs have ranged from 18 to 3223 person-rem. A decreasing trend in the highest annual collective dose is somewhat apparent, but less so than for the average collective dose. In addition to decreases in collective dose, the average annual dose per nuclear plant worker has been reduced during this period from around 0.7 rem to almost 0.3 rem for PWRs. A breakdown of the number of individual workers receiving doses in different ranges for 1989 is provided in Table 6-32. These data demonstrate that 90% of plant radiation workers received less than 1 rem, and no worker received more than 5 rem. Overall data presented in Tables 6-31 and 6-32 provide evidence that doses to radiation workers are far below the worker dose limit established by 10 CFR Part 20 and that the continuing efforts to maintain doses at as low as reasonably achievable (ALARA) levels have been successful. Notwithstanding, consistent with the reasoning used in the other fuel cycle reports, having emissions or doses within regulated standards does **not** necessarily mean that there are no environmental or health damages. The rationale is based on the economic welfare paradigm used throughout our study.

Table 6-31. Annual average occupational dose for U.S. licensed PWRs

Reported collective occupational dose (person-rem)				Annual average whole-body dose (rem)
Year	Low	Average	High	PWR
1974	18	331	1225	0.68
1975	21	318	1142	0.76
1976	58	460	1583	0.79
1977	87	396	1153	0.65
1978	48	429	1621	0.65
1979	30	516	1792	0.56
1980	154	578	2387	0.52
1981	58	652	3223	0.61
1982	101	578	1426	0.53
1983	68	592	1881	0.56
1984	49	552	2880	0.49
1985	36	416	1581	0.41
1986	23	390	1567	0.37
1987	47	371	1217	0.38
1988	27	336	917	0.36
1989	18	296	1436	0.33

Source: NUREG-0713; Barfield (1990); Hinson and Cougel (1990).

Table 6-32. Number of PWR workers receiving whole-body doses within specified ranges during 1989

Dose range (rem)	PWR workers	All LWR workers
< 0.1 (measurable)	29,912	49,255
0.1-0.25	11,688	19,567
0.25-0.5	9,404	15,727
0.5-0.75	5,112	8,865
0.75-1.00	3,042	5,586
1.00-2.00	4,883	8,845
2.00-3.00	775	1,290
3.00-4.00	88	21
4.00-5.00	11	11
5.00-6.00	0	0
6.00-7.00	0	0
7.00-12.00	0	0
>12.00	0	
Totals	64,907	109,267

Source: Hinson and Cougel (1990).

The wide range of annual collective doses experienced at LWRs in the United States results from a number of factors such as the reactor design, the amount of required maintenance, and the amount of reactor operations and in-plant surveillance. Because these factors have been observed to vary widely and unpredictably, it is impossible to predict in advance a specific year-to-year annual occupational radiation dose for a future plant throughout its operating lifetime. On occasion, there may be a need for relatively high collective occupational doses compared with the average annual collective dose, even at plants with radiation protection programs designed to ensure that occupational doses will be kept to ALARA levels.

Plants such as the reference PWR would be designed in light of the operating history of 100 plus power reactors operating in the United States, plus lessons learned from the international community. Therefore, it is reasonable to expect the reference plant to operate at least as well as the currently operating average plant. Such operation would result in a cumulative dose ~300 person-rem annually to the work force. Because of the data presented in Table 6-32, it is clear that all individuals receive relatively small total doses, and it is appropriate to use the fatal cancer risk factor recommended by the ICRP (1991) for occupational exposures. Based on that factor approximately 0.12 fatal cancers per year of operation are anticipated.

6.7.3 Latent Cancer Fatality Estimate

Radiation doses to the public can be converted to estimates of LCFs using the upper limit risk coefficient suggested by national and international review panels (ICRP 1991, NAS 1990). The ICRP report provides summary estimates for cancer occur risk for a continuous lifetime exposure of 0.1 rem/year. For the general public, the risk factor is 5.0×10^{-4} LCFs per person-rem. For occupational radiation doses, the ICRP report recommends a risk factor of 4.0×10^{-4} LCFs per person-rem.

Multiplying the cumulative doses by the appropriate conversion factors we calculate the health effects as shown in Table 6-33.

6.7.4 Nonradiological Health Effect

Per the data kept by the Institute of Nuclear Power Operation (INPO) and recently published by the U.S. Council on Energy Awareness (USCEA 1993), the industrial safety accident rate for all U.S. nuclear plants was 0.77 accidents per 200,000 man-hours worked. For our reference reactor year (2×10^6 man-hours for an employment of 1,000 per plant) this translates to eight nonradiological accidents per reactor year.

Table 6-33. Latent cancer fatalities for normal reactor operation

Site	Exposure pathways	Expected LCFs (per reactor year)
Southeast	Airborne	5×10^{-5}
	Liquid	1×10^{-4}
	Occupational	0.12
Southwest	Airborne	3×10^{-6}
	Liquid	3.5×10^{-6}
	Occupational	0.12

No data on which of these were fatalities were given; however, for most industrial facilities less than 1% of the accidents result in death. If the 1% figure is used, the result is 0.08 deaths per reactor year.

6.8 ECOLOGICAL EFFECTS

6.8.1 Land Commitment

The Southeast Reference site consists of over 200 acres and is on the undeveloped part of the Oak Ridge Reservation (ORR). (The ORR is not an Indian Reservation, but rather a group of U.S. DOE-owned production and research facilities for defense and civilian atomic energy programs.) Use of this site for a PWR will not disturb any ongoing U.S. DOE operations or research projects. Creation of a reactor exclusion/security area may remove part of the ORR that is now available for controlled deer hunting in the fall season.

The NMGS site will require several hundred acres and lies in a largely unpopulated rural area. The closest designated land use is for the Navajo Indian Reservation. Location of a PWR on this site should cause minimal disturbance to any agricultural activities in this area.

6.8.2 Water Quantity and Quality

Operation of the cooling towers at the Southeast Reference site will require the withdrawal of 39,500 gpm (2.5 m^3/s) makeup water from the Clinch River. This represents only 1.7 percent of the 150 m^3/s average annual flow of the Clinch River near the site (Blasing et al. 1992), and would not have a significant impact on water use in the area.

Concentration of dissolved salts which results from evaporative water loss in the cooling tower requires discharge of a certain percentage of the mineral-rich stream (blowdown) and its replacement with fresh water (makeup). The quantities of blowdown from a closed-cycle condenser cooling system are relatively small compared to the discharges from open-cycle systems, typically on the order of 10 percent. Water quality impacts to surface waters receiving blowdown could occur from the relatively high temperatures of the blowdown or from high concentrations of minerals in the makeup water and chemicals added to the recirculating cooling water (to prevent corrosion and biofouling, regulate pH, etc.). A unit of water may reside in the cooling circuit for 3 to 20 cycles before being lost to evaporation or released in the blowdown stream (Coutant 1981). The concentration of total dissolved solids in the cooling tower blowdown averages 400 percent of that in the makeup water, a concentration factor which can be tolerated by most freshwater biota (Parkhurst and McLain 1978). dilution of the low-volume blowdown by the receiving water also reduces water quality impacts of heat and contaminants discharged from closed-cycle cooling systems.

In the case of the Southeast Reference site, 28,160 gpm (1.78 m^3/s) of blowdown water would be discharged to the Clinch River. This represents 1.1 percent of the average annual discharge of the Clinch River in the vicinity of the reference site, and 1.3 percent of the average summer discharge (Blasing et al. 1992). Heated water, contaminants, and concentrated minerals in the blowdown would be quickly diluted by the high flows of the Clinch River. Further, because of strict regulation of chemical discharges from steam-electric power plants, water treatment systems for cooling tower blowdown have been developed. Many of these systems recapture chemical additives for recycling in the cooling system (Coutant 1981). Routine discharges of blowdown rarely have significant water quality impacts, especially where large volumes of dilution water are available (U.S. NRC 1991b).

The Southwest reference site will transport all blowdown water to evaporation ponds; there would be no discharges to surface waters. Accumulated mineral salts and LLW would be shipped to a permitted disposal site. There would be no nonradiological water quality impacts from operation of the cooling system at the New Mexico site.

6.8.3 Aquatic Ecology

The greatest potential non-radiological impacts to aquatic biota result from operation of the condenser cooling and service water systems. Large amounts of water are withdrawn by condenser cooling systems, passed through the condenser tubes, and discharged back to the waterbody with an added load of heat and chemical contaminants.

Water that is withdrawn for power plant cooling carries with it a variety of aquatic organisms as well. Those organisms that are small enough to pass through the debris screens in the intake pass through the entire cooling system and be destroyed by heat, mechanical and pressure stresses, and possibly biocides. This process, called entrainment, may affect phytoplankton, zooplankton, and fish eggs and larvae (ichthyoplankton). Most nuclear power plants are required to monitor for entrainment effects during the initial years of operation, and this monitoring focuses on the early life stages of fish.

Aquatic organisms that are drawn into the intake with the cooling water and that are too large to pass through the debris screen may be impinged against the screens. Impingement mortality is high at many plants because impinged organisms are eventually suffocated by being held against the screen mesh, or develop a fatal infection from abrasions or other injuries. Impingement can affect large numbers of fish, but because most adult fish are strong swimmers and can avoid the intake screens, most impinged fish are juveniles of weakly swimming species, e.g., gizzard and treadfin shad. Juvenile shad are extremely abundant in the Clinch River near the Southeast Reference site, and often experience natural die-offs in the winter from cold water temperatures.

The heated effluents of steam-electric power plants can cause heat shock mortalities among fish and other aquatic organisms. Temperatures high enough to kill aquatic organisms may be found the near-field area of thermal discharge plumes. Besides direct mortality from heated water, there are mechanisms by which heated effluents can impact aquatic communities. These mechanims include cold shock (from sudden cessation of thermal discharges in the winter), altered growth and production rates, altered solubility of dissolved gases, and increased susceptibility of fish to predation, diseases, or parasites.

Studies relating to condenser cooling system intake and discharge effects at nuclear power plants are reviewed in U.S. NRC (1991). While intake and discharge effects have been of considerable concern at some steam-electric power plants with open-cycle cooling systems, the relatively small volumes of makeup and blowdown water needed for closed-cycle cooling systems result in concomitantly low entrainment, impingement, and discharge effects. Cooling towers have been suggested as mitigative measures to reduce known or predicted entrainment and impingement losses (see, for example, Barnthouse et al. 1988). Studies of intake and discharge effects of closed-cycle cooling systems have generally judged the impacts to be insignificant (Hickey 1980; El-Shamy et al. 1981). Existing nuclear power plants near the Southeast Reference sites (e.g., Sequoyah Nuclear Generating Station) periodically use "helper" cooling towers to reduce the temperature of cooling system discharges. Although there have been concerns about adverse impacts to aquatic biota and dissolved oxygen

concentrations when the Sequoyah station is operating in an open-cycle mode during the summer, there have not been any problems when the cooling towers were brought on line (U.S. NRC 1991b). Use of cooling towers at the Southeast Reference site should preclude significant impacts to the water quality and biota of the Clinch River. Similarly, the relatively low volumes of makeup water withdrawn from the San Juan Reservoir for the Southwest Reference site would not be expected to result in significant entrainment and impingement concerns. Because all blowdown from the New Mexico site would be routed to evaporation ponds, there would be no discharge effects on aquatic biota.

6.8.4 Agricultural Crops and Vegetation

Salt in drift emissions from cooling towers have the potential to damage vegetation, including native plants and agricultural crops. Monitoring data relating to the effects of cooling tower drift on terrestrial vegetation have been extensively reviewed in U.S. NRC (1991). In one case, trees near mechanical-draft cooling towers experienced severe damage during a period of unique meteorological conditions when the towers were not operating properly. After corrective actions were taken, such impacts no longer occurred (Blasing et al. 1992). At several other nuclear plant sites, minor damage was noted to nearby vegetation that had been placed near the towers as an experiment. Overall, cooling tower operations have not had significant impacts on native vegetation or agricultural crops near nuclear power plants.

6.8.5 Terrestrial Ecology

Terrestrial habitats would be destroyed by construction of the nuclear power plants, and associated animals would be destroyed or displaced. These effects would be no greater than those resulting from the clearing and development of other comparably sized industrial or commercial developments in the area. Construction and maintenance of transmission lines could also alter terrestrial habitats, especially near the Southeast Reference site. Numerous transmission line corridors already exist near the site, such that additional clearing would be needed only for relatively small areas to tie the power plant in to existing lines.

The primary concern about effects of power plant operation on terrestrial organisms has been the possibility of bird collisions with cooling towers. Natural draft cooling towers, which are tall structures, are known to cause some bird mortality. The research literature and monitoring data related to this issue were reviewed in U.S. NRC (1991). These studies indicated that cooling towers cause only a small fraction of the total bird collision mortality in the United States. Waterfowl and other birds that commonly occur as permanent or summer residents around nuclear plants do not frequently collide with the towers. Instead, a very

high percentage of the collision mortalities occur during the spring and fall bird migration periods and involve primarily birds migrating at night. Local bird populations are apparently not significantly affected by collisions with cooling towers (U.S. NRC 1991b).

6.8.6 Priority Ecological Impacts

This section lists the priority impact-pathways for ecological impacts associated with electricity generation under normal nuclear fuel cycle operations (Table 6-34, see also Appendix H).

6.9 OTHER EFFECTS

6.9.1 Employment

Compared to other electricity generation technologies, nuclear has a very high full-time-equivalent (FTE) per MW(e) staffing requirement during normal operations. This is a result of the technical and regulatory environment under which these plants must operate. Unlike most fossil power plants, a nuclear facility must maintain a significant on-site engineering staff which can respond to NRC mandates and information requests. There are also many complex engineered systems which require maintenance and surveillance. Many large utilities have large off-site centralized staffs which also deal solely with their nuclear plants. These persons are not counted here, since this is a site-specific study. Table 6-35 lists 1991 employment levels at 37 different W-PWR units (UDI 1991). The average for all of the listed units is 649. Note, however, that most sites have more than one large unit, hence they can share personnel, thus reducing the employment requirement per unit. If only single unit sites are counted the average is 960 FTEs. These are all employees of the utility. If consultants and non-utility contract workers are added, employment increases up to 1000 FTEs at the site. During refuelings, the on-site FTEs may increase by 100 or more FTEs.

Chapter 10 presents analysis of the net benefits of employment for the whole nuclear fuel cycle.

Table 6-34. Primary emissions or activities, pathways and ecological impacts linked to the nuclear fuel cycle from electricity generation

Emissions/activities	Environmental pathway	Impact	Impact evaluation
Air emissions:			
Radionuclides	Deposition on land surface	None to biota due to low concentrations	Qualitative evaluation
Water quality:			
Radionuclides	Discharge to surface water or impoundments	Contamination/ damage to aquatic biota, wildlife or domestic animals, crops	Qualitative evaluation; minimal impacts due to low concentrations
Other factors:			
Low-level radioactive waste	Operations	Land use change; loss of biotic habitat	Quantified
Water use change	Operations	Ground water and surface water depletion	Quantified
Land use change	Development of roads, buildings, and exclusion area	Changes in biodiversity; loss of biotic habitat, loss of grazing land, crops, and forests	Quantified

Table 6-35. On-site employment levels at 37 W-PWR plants for which data are not available

W-PWR plant	On-site employment (FTEs)
1 Braidwood 1	407
2 Braidwood 2	407
3 Byron 1	405
4 Byron 2	405
5 Callaway 1	857
6 Catawba 1	696
7 Catawba 2	696
8 Comanche Peak	1200
9 Cook 1	342
10 Cook 2	342
11 Diablo Canyon 1	981
12 Diablo Canyon 2	981
13 Farley 1	451
14 Farley 2	451
15 Indian Point 2	562
16 Indian Point 3	644
17 McGuire 1	617
18 McGuire 2	617
19 Millstone 3	273
20 North Anna 1	333
21 North Anna 2	333
22 Salem 1	854
23 Salem 2	584
24 Seabrook	1003
25 Sequoyah 1	1459
26 Sequoyah 2	1459

Table 6-35. On-site employment levels at 37 W-PWR plants for which data are not available (continued)

W-PWR plant	On-site employment (FTEs)
27 South Texas 1	839
28 South Texas 2	839
29 Summer 1	761
30 Surry 1	333
31 Surry 2	333
32 Trojan	928
33 Vogtle 1	523
34 Vogtle 2	523
35 Wolf Creek 1	1013
36 Zion 1	410
37 Zion 2	410
Average for all units	649
Average per site	1091
Average for single unit sites	960
Average per unit for multi-unit sites	575

7. SEVERE REACTOR ACCIDENTS - TECHNICAL EVALUATION

7.1 INTRODUCTION

7.1.1 Background

In the most generic sense, a severe accident can be defined as any incident which results in unacceptable impacts on (1) plant investment and operations, (2) employee or public health, (3) environmental quality, or (4) public relations and institutional acceptance. In nuclear power plants, severe accidents are generally considered to be those incidents involving large-scale damage to the plant [e.g., Three Mile Island (TMI)] and/or significant health consequences to the general public (e.g. Chernobyl). Such consequences result from significant damage to the nuclear fuel contained in the reactor's core, coupled with failure of the reactor coolant and containment systems. Should containment failure occur, radioactive material could be released into the environment.

The purpose of this chapter is to present a methodology for estimating risk-based expected damages (health, economic, and ecological consequences) from severe accidents in nuclear power plants, and to demonstrate the methodology via a simplified application to the reference nuclear technology [a Westinghouse pressurized-water reactor (PWR) with a large dry containment—a reactor similar to the Zion nuclear power plant].

This technology is representative of those currently in operation. Certainly, one would expect that any new light-water reactors, advanced boiling water reactors, and other advanced designs will have lower probabilities of severe core damage and containment failure than those used in this study. Thus, the numerical results in this chapter should not be extrapolated as applying to those advanced designs. The general *methodology* in our analysis, however, is equally applicable.

7.1.2 Nuclear Reactor Risk Assessment Methodology

Risk can be defined as the sum over all possible scenarios of the product of the probability of the scenario (P_i) and the consequence of the scenario (C_i), or,

$$Risk = \Sigma P_i C_i \quad . \tag{1}$$

The Reactor Safety Study, WASH-1400, [Nuclear Regulatory Commission (NRC) 1975] was the first comprehensive analysis of the risk of nuclear power plant operation. Prior to the WASH-1400 study, it was believed that the probability of severe accidents in nuclear power plants was extremely small (expected frequency of occurrence less than one per million operating years), but that the public health consequences of such an event would be extremely large. In contrast to this belief, WASH-1400 concluded that the probability of a severe accident was significantly higher, but that the public health consequences of such an accident would be much lower than previously predicted.

Since 1975, a large amount of work has been completed in all areas of nuclear power plant risk analysis, and major improvements in risk assessment technology have occurred. The most definitive study of nuclear power plant risk is the NRC's recently-completed NUREG-1150 effort (NRC 1990), which consists of a state-of-the-art probabilistic risk assessment (PRA) for five domestic commercial nuclear power plants. One of the main conclusions of NUREG-1150 is that the risk to the public from operation of the five plants studied is, in general, lower than the WASH-1400 estimates for the two plants studied in 1975. Among the five plants studied, the two boiling-water reactors (BWRs) present less risk than the three PWRs

There are two basic categories of initiating events that could lead to a severe accident. Internal events encompass the full spectrum of operator errors and equipment failures that could result in a severe accident. Internal events and their subsequent contribution to the frequency of an accident have been extensively analyzed. External events include accidents caused by fires, seismic events, and a broad range of events such as lightning, aircraft impact, tornadoes, etc. There is significant uncertainty regarding the importance of external events due to the infrequency with which these events may occur and the impact of plant-specific considerations. An example of this can be found in the NUREG-1150 analysis for the Surry power plant (located in Virginia). Seismic events and fires were the only external events that were found to be potentially major contributors to the risk profile. At other plant sites, this may not be the case. A second major conclusion of the NUREG-1150 study noted above is that individual early fatality and limited containment failure (LCF) risks from internally-initiated events for the five plants studied are well below the NRC safety goals.

A large array of site- and plant-specific issues must be considered in the evaluation of plant risk. There are many methodologies and computer codes that are used in a full-scope PRA. A PRA assessment starts with a determination of

the initiating events. It identifies the plant-specific scenarios and the probabilities associated with failures that ultimately lead to a fission product release from the containment. (The time history of fission product releases to the environment constitute complete descriptions of the "source term".) Depending on the PRA methodology used, *hundreds* of different source terms may be calculated in a PRA. Prior to the calculations associated with the off-site consequences, the radiological source terms are partitioned. This partitioning is a reduction and grouping of source terms according to the timing of the release, the potential for early health impacts, and the potential for latent cancers. This enables the analyst to perform a consequence analysis with a reasonable (50 or so) number of source terms. (In previous PRAs, partitioning is usually done with an emphasis on health impacts, not economic consequences.) The final step involves using the source terms and the site-specific input to determine the degree of health and environmental damage.

In nuclear reactor PRAs, risk is generally not quoted in the form of a single value. Instead, risk is generally represented with a risk distribution curve that presents the probability of exceeding a consequence value as a function of the consequence value (number of fatalities, for example). In fact, NUREG-1150 cautions against the use of single point values (such as the mean or median) as indicators of risk, especially in seismic analysis where the uncertainty band is high.

7.1.3 Damage Estimation Methodology

In a traditional PRA, the consequences of interest are those related to public health (early and latent fatalities, cancers, etc.). In this study, however, the desire is to include additional consequences such as the cost of replacement power, lost farm production, land decontamination, sequestering, and interdiction, etc. In this regard, the optimal approach would be to individually evaluate the probability and consequences of a complete spectrum of accidents (from normal operational transients to total core melt accidents in which the containment fails) at the reference site. This approach would necessitate a full-scope PRA with additional economic costing exercises to obtain credible estimates for the total fuel cycle damages associated with severe accidents. Our whole approach in fuel cycle study is site specific. Such a massive undertaking was not practical in terms of time or funding for this study.

We used a simpler approach, employing the source terms from the PRA source term bins and performing the last step of the consequence analysis using the source term bins in combination with site-specific data. The last step would only involve running a consequence code such as MELCOR Accident Consequence Code System (MACCS) (Chanin et al. 1990). In the case of the

Zion plant, the NUREG-1150 PRA produced 36 distinct source term bins along with their associated probabilities for internal events. Performing and interpreting the output of these MACCS cases would provide a reasonable health and economic risk profile for a prospective site. This approach is generally acceptable and quite valid for internal events, or any sequence of events that is nonsite-specific. One problem with this approach is that the site-specific characterization of the emergency response plan would not be incorporated up-front in the partitioning of the source terms. It would also have been advantageous to partition (group into the source term categories) the source terms with some emphasis placed on the potential of certain source terms to cause widespread economic damage. Partitioning of the Zion source terms in NUREG-1150 was primarily done on the basis of health impacts.

7.1.4 Assumptions and Limitations of This Study

As previously discussed, the decision was made to evaluate current-generation PWR technology at two sites—the Southeast site in East Tennessee and the Southwest site near Farmington, N.M. A number of simplifying assumptions were made in order to reduce the scope of the consequence analyses to practical levels. A priority of future studies should be to estimate the possible accuracy that is sacrificed with these assumptions.

The first major limitation of this analysis is that the risk of externally-initiated events (those events arising from floods, earthquakes, etc.) was not covered in this study. This limitation is imposed by the absence of risk assessment results for externally-initiated events for the subject plant technology (Zion), coupled with the fact that the risk from externally-initiated events has been found to be very plant- and site-specific. It would be inappropriate to apply such data from another plant or facility to the subject plant. However, it can be said that the overall methodology to determine the risk from "externally-initiated" events could be handled in a somewhat similar approach that is described in the paragraph preceding this section.

The most important assumption employed in this analysis is that the complete spectrum of internally-initiated severe or "core melt" accidents can be reasonably represented by only two scenarios. The first type of accident is a case in which the containment fails (the Massive Containment Failure or "MCF" case) followed by a major release of fission products. Such an accident would have significant health and economic consequences for the surrounding area. The initiating events and the scenarios that could lead to this situation are varied. However, the end state of the accident is one in which there is a significant breach of the containment. (While the actual size of the breach is highly uncertain, in practice. the failure size is assumed to be large enough to completely depressurize

the containment to atmospheric conditions.) For the purposes of this assessment, it is assumed that the probability of the MCF scenario is 0.26, given that a severe accident occurs. However, the source term release fractions actually employed for analysis of the MCF scenario are those associated with an "early" containment failure event which is believed to occur in only 1% of severe accidents (see Section 7.3). The other type of accident that was analyzed was a scenario in which a complete core meltdown occurs, but the containment does not catastrophically fail. In this second scenario, it is assumed the containment leaks at an accelerated rate (above the design basis leak rate). This case is termed the "Limited Containment Failure" or "LCF" case. In such cases, the noble gases would leak out along with relatively minor amounts of the other classes of fission products. It is assumed that the probability of this scenario is 0.74 (even though it is believed that the probability of the containment leaking in excess of the design basis leakage rate is actually only 0.26.)

A third major assumption of this study is related to the manner in which the accident probabilities are derived and applied to develop "expected values" for damages. In essence, the accident probabilities are applied in a way which assumes that all accidents in which the reactor core becomes uncovered with no immediate prospect of reestablishing cooling, result in a complete core meltdown and reactor vessel failure. In addition, the probabilities are applied (in the MCF case) in a way which assumes that all containment failures are massive containment failures. Thus, the expected value (probability times damage) of the damages is judged to be conservatively high.

The impact of uncertainties in the source term is not explicitly included in the analysis of accident consequences, while the impact of uncertainties and variability of weather patterns is considered.

Inputs to the economic models that simulate the consequences associated with large-scale nuclear accidents involve judgmental decisions. The economic values associated with the loss of businesses and regional wealth were done on a best estimate basis using values from the literature. This was done so as to demonstrate the current methodology for performing this analysis.

The primary goal of this effort is to identify and demonstrate a technically sound method for estimation of the expected damages of severe accidents in a nuclear power plant. Some of these damages are internalized in the market, and thus, are not external costs. It is readily apparent that the assumptions employed in this study will result in a simplified characterization of plant risk, compared to that resulting from a full scope PRA. *Therefore, the results presented here may not represent a realistic view of the true social damage due to hypothetical severe*

accidents at any specific domestic nuclear power plant. While this limitation is undesirable, this approach is practical and economical.

7.2 ACCIDENT SCENARIOS

7.2.1 Background

Domestic commercial nuclear power plants employ a "multi-barrier containment" design philosophy for protection from accidental releases of fission products to the environment. This approach relies on three sequential barriers that provide containment of radioactivity. The radioactive "fission products" produced during reactor operation originate in the reactor fuel. The first barrier to the release of these fission products is the metallic Zircaloy *fuel cladding* which surrounds the fuel pins. This cladding is designed to retain its integrity and prevent the escape of fission products during normal operation and during a wide variety of "design basis" accidents. Nevertheless, should the temperature of this cladding exceed ~1200°C, fission products could escape the fuel and be released into the *reactor coolant system.*

The *reactor coolant system* represents the second barrier to fission product release. As long as the vessels and piping that comprise this system are intact, there can be no significant release of radioactivity to the environment. The final barrier to fission product release is the reactor *containment building* which surrounds and encloses the reactor coolant system. These buildings are designed to prevent the release of radioactivity to the environment for accidents involving a rupture of the *reactor coolant system.* These containment buildings (sometimes comprised of a *primary containment* surrounded by a *secondary containment* structure) typically employ pressure control systems and high-capacity filtration, holdup, and exhaust systems to ensure that radioactivity does not reach the environment in an uncontrolled manner.

One scenario for severe accidents assumes the complete failure of all normal and emergency core-cooling systems—a very unlikely event. The failure of these systems, coupled with the continued boiloff of water in the reactor, would gradually reduce the reactor's water inventory and eventually expose the hot nuclear fuel. Once uncovered, the fuel temperature would increase significantly, leading to melting of the reactor core and subsequent breach of the reactor vessel. After reactor vessel failure, the hot core debris would fall onto the concrete floor of the primary containment, causing complex chemical reactions that release a mixture of combustible gases (hydrogen and carbon monoxide), aerosols, and fission products. These reaction products would heat and pressurize the primary containment, which could ultimately fail, releasing fission products, aerosols,

steam, and combustible gases into the secondary containment or the surrounding reactor site.

Based on recent analyses for the Surry, Sequoyah, and Zion PWRs (Table 7-1), it is believed that most PWR core-damage accidents do not result in containment failure. However, if the containment does fail, fission products would be released into the on-site environment, and the radioactive material would be available for transport to the off-site environment via normal meteorological processes.

Table 7-1. Mean PWR conditional containment failure probabilities from NUREG 1150 (NRC 1990)[1]

Containment failure mode	Surry	Sequoyah	Zion
None	81%	66%	74%
Late	6%	21%	24%
Early	1%	7%	1%
Bypass	12%	6%	1%

[1]Assuming that a severe accident occurs.

The containment pressure history and mode of containment failure are also very important because both of these parameters affect the source term magnitude, timing, and energy. In some instances, containment overpressurization could result in cracking and shearing of the containment boundary. This mode of containment failure might, in turn, lead to a very low leak rate of fission products persisting for a long period of time. On the other hand, overpressurization and some other energetic phenomena could result in a very large failure (hole) in the containment boundary—leading to rapid containment depressurization and a source term characterized by very large release rates over shorter periods of time. The interaction between source term timing and emergency response actions plays a major role in determining the early consequences of an accident.

The on-site consequences of a severe accident include radiological decontamination and decommissioning costs, replacement power costs, and the loss of plant capital investment. Many, if not most, of these damages would be insured and thus internalized. The off-site consequences may include significant adverse human health effects and environmental damage. The protective actions

taken by authorities after the accident will greatly impact the magnitude of the off-site consequences of the accident. These measures could include evacuation, sheltering, land decontamination, interdiction (temporary condemnation), and the permanent condemnation of public and private property.

7.2.2 Post-Release Accident Scenario

The specifics of the site characterization, in tandem with the accident scenario, become very important in determining the accident consequences. Once the accident releases radioactive fission products and gases from the containment, the meteorology at the time of the accident governs the directional extent of the accident. For instance, if the wind is blowing the plume of fission products toward a highly populated area, the health and economic damages could be large. The damage would be even larger if it coincidentally rained at the time the plume was over the populated area. This is because the rain would tend to wash radioactive aerosol particles out of the air and deposit them on the ground. In contrast, the wind may carry fission products over uninhabited areas causing only limited damage. The removal mechanisms are presented in Figure 7-1 (Till and Meyer 1983). The analyses performed for this report attempt to take into account the variation of the different weather and site characteristics. The MACCS code is well suited for this purpose. The model associated with the actions taken following the release of the source term is presented below.

The scenario that is modeled with the MACCS code divides the accident into three distinct chronological periods. The first phase of the accident is known as the *early phase*. This phase is assumed to last seven days after the start of the source term release. The exposure pathways that are modeled during this period include (1) the dose resulting from direct exposure to the cloud or plume (cloudshine), (2) cloud inhalation, (3) exposure to material on the ground (groundshine), (4) inhalation of resuspended radioactive aerosols, and (5) skin dose from radioactive aerosols deposited on the skin. During this phase, an evacuation plan would be implemented to protect the health and safety of the public. This plan would call for the evacuation of people downwind within the 16.09 km emergency planning zone that surrounds the reactor. It was assumed that 95% of the people would be evacuated and that 5% of the people either did not heed the warning, or chose not to evacuate. This number of 5% is 10 times larger than the number used in standard U.S. NRC analyses, as documented in NUREG-1150, in which a 99.5%/0.5% evacuation efficiency was assumed. Based on judgement, we have assumed a less complete evacuation.

The evacuation group is assumed to move radially outwards to a point at which they receive no further exposure. At this time in the accident, the first costs associated with the emergency response are tabulated. Another protective action

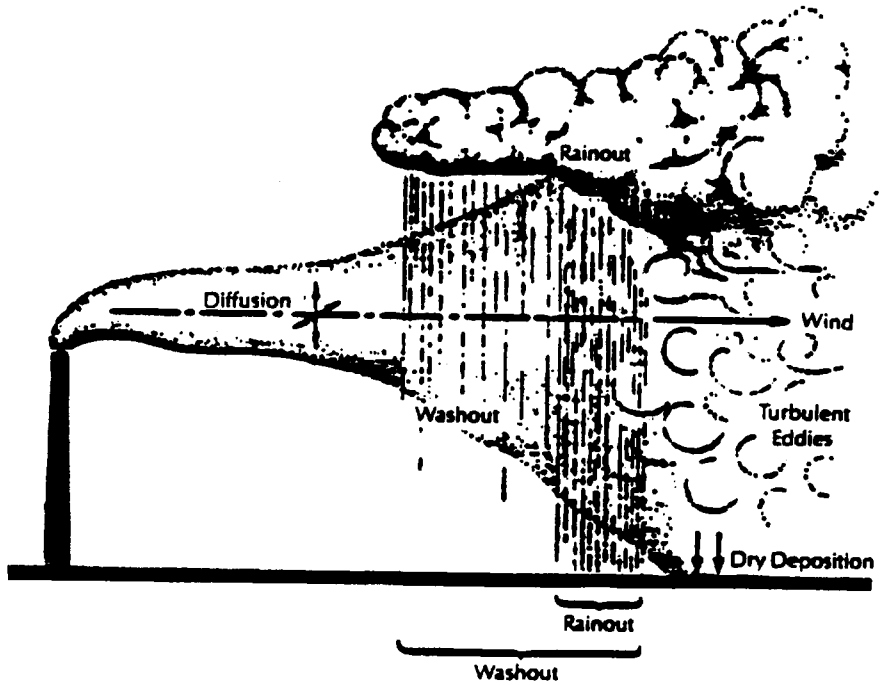

Figure 7-1. Atmospheric Dispersion and Removal Processes (from Till 1983)

that is taken during this phase is known as hot spot relocation. The philosophy here is that if a person outside of the emergency planning zone has the potential to exceed a certain dose (0.5 Sv, for example), then the authorities would be called upon to temporarily relocate these people. The cost (based on a per-diem and the number of people moved) associated with this protective action is summed along with the evacuation cost.

The next phase of the accident is known as the *intermediate phase*. This phase was assumed to last 60 days. During this phase, the only protective action that is taken is hot spot relocation (similar to the philosophy described in the emergency phase above). The pathways modeled during this time period are groundshine and resuspension inhalation. This period could be thought of as the time in which officials determine which long-term strategies and actions might take place. Following this period, it was assumed that there was a decontamination period of 60 days. During the decontamination period, it is assumed that cleanup workers will be able to decontaminate the land such that the groundshine dose is reduced by a factor of three. The costs associated with this protective action are tabulated. The radioactive decay and subsequent decrease in the quantity of radioactive isotopes that have been deposited on the ground are accounted for. Up to this point, a decay period of 127 days has been used.

At this point in the accident, the long-term phase is entered. During the long-term period, radioactive decay and weathering serve to reduce the contamination level. The MACCS model now performs an analysis of the dose levels of the spatial elements. If the dose level in a certain spatial element exceeds what is known as the "long-term dose habitation criterion", then more protective actions will be undertaken. This criterion is the first criterion that is utilized for both farm and non-farm properties. This important criterion could be varied to observe its impact on the health and economic consequences. If a spatial element exceeds this dose rate, the MACCS model enters into a decision making process to determine whether to interdict (a temporary condemnation) the land or permanently condemn the land. If a spatial element does not exceed the dose habitation criterion, then the land will be put back in service and people will be resettled.

Land usage is modeled with two different categories: farmland properties (with costs figured in $/hectare) and non-farm properties (with costs figured on a per capita basis ($/per resident). In the case of farmland costs, the land will not be interdicted longer than eight years. If the land is not habitable after eight years, the property is condemned, and its cost is tallied. If it is habitable within eight years, then a decision is made as to whether that land can be put back into agricultural service according to a set of protective action guidelines for the food chain. Non-farm properties can be interdicted up to a period of 30 years, if it is

cost-effective to do so. The costs associated with the loss of income producing assets for non-farm properties is accounted for during the period of interdiction. If the costs of interdiction and decontamination exceed the non-farm property cost, then the property is condemned and its costs are tallied according to the number of people residing in that element and the input for the per capita value.

7.2.3 Risks From External Initiating Events

The contributions of external initiating risk (principally fire and seismic events) can be significant contributors to the risk profile of a nuclear power plant. Please note that the use of the term "external" in this paragraph refers to a type of initiating event (as described in the introduction) and not to the concept of external costs that is the subject of this project. These initiating events increase the number of accident sequences that must be considered in a risk analysis. In NUREG-1150, the PRA for the Zion plant did not include an analysis for fire or seismic events. As stated before, the probabilities associated with external risks (such as seismic and fire) involve a very high degree of uncertainty with respect to the probability distribution. In addition, these risks are very site-specific. In the case of seismic issues, for example, it becomes necessary to establish an anticipated seismic hazard curve for the site. This is difficult given that the frequency and magnitude of earthquakes can not currently be predicted with great accuracy. To complicate matters, it must be noted that any earthquake severe enough to cause a nuclear power plant accident would probably also cause structural damage to other buildings, roads, and bridges in the region. Any estimate of plant risk from a seismic event would have to include an incremental impact above and beyond the earthquake consequences. Due to the lack of resources in tandem with the lack of available information for the two sites, this aspect of plant risk is not covered by this report.

In NUREG-1150, the risk associated with fires is presented and analyzed for the Surry power plant. It was found that these events do produce a noticeable increase in risk when compared to internal events (though this increase is generally less than that observed when seismic events are included). However, it can be said that the risk associated with fires is probably quite small as compared to the uncertainties associated with a determination of the core damage frequency due to internal events.

7.2.4 Selection of Accident Sequences

It is difficult to choose a "representative" accident scenario because of the large variety of potential accident sequences that lead to a release. In order to proceed with the analysis under the resource constraints of this study, two different accident scenarios were selected for analysis. These are:

MCF Case—a case in which a full-scale reactor core meltdown occurs, coupled with a massive failure of the reactor containment; and

LCF Case—a case in which a full-scale reactor core meltdown occurs, but the containment is assumed only to "leak" at some limited level above the design leakage rate. This event represents a crack in the containment or a leak around the seals of the penetrations in the containment.

A more complete description of these two scenarios and the source terms resulting from these scenarios will be discussed in Section 7.3.

7.3 ACCIDENT SOURCE TERMS AND PROBABILITIES

7.3.1 Introduction

A complete characterization of the fission product source term for a sequence includes estimates of (a) the total core inventory of fission products in the reactor, (b) the total fraction of each fission product or fission product group released over the entire duration of the accident, (c) the time-dependent nature of the fission product release, and (d) the time-dependent energy of the released material. The product of the core inventory of a fission product and the fission product release fraction for that isotope represents the total quantity of that fission product released to the environment. However, the time history of this release is very important, since mitigative actions such as evacuation and sheltering can have significant impacts on the health consequences of the accident. A specific quantity of fission products (such as radioiodine, for instance) can have much greater health impacts if the material is released over two hours rather than two days. Finally, the energy of the material as it enters the atmosphere is important because the height of the radioactive plume and (consequently) the distance which the plume is transported is a function of the energy of the release. This in turn could affect the consequences.

7.3.2 Fission Product Inventory

The inventory of radionuclides present at the start of an accident is a fundamental parameter necessary for accident consequence analysis. The consequence code (MACCS) that will ultimately utilize this inventory is capable of handling 60 radioactive isotopes which have the potential to cause health, environmental, and economic damage. This list of isotopes is traditionally used to evaluate off-site consequences for commercial light-water reactors (LWRs). The inventory of these isotopes will be utilized in combination with the release fractions to define source terms for the accident scenarios.

The nuclear plant technology that utilizes the fuel has been described in Chapter 6. The reference nuclear reactor core inventory is calculated using the ORIGEN2 computer code (Croff 1980). The fuel cycle under consideration is that of an extended-burnup PWR, undergoing refueling on 18-month cycles. The reference case is calculated assuming the accident occurs at the end of an equilibrium cycle when 1/3 of the core inventory has reached the design burnup, which has been assumed to be 51,700 Mwd/MT. At that time, 1/3 of the fuel assemblies have been in core for 3 cycles, 1/3 for 2 cycles, and 1/3 for a single cycle. The use of these assumptions essentially defines the maximum possible core inventory for radioactive releases in an accident. The overestimate, as compared to an average inventory present in the reactor core, is about 20% for long-lived radionuclides such as Cs and Sr and <1% for short-lived nuclides such as Xe and most isotopes of the iodine.

For this assessment, an initial fuel enrichment of 4.7% ^{235}U has been assumed. The reactor contains a total of 88.128 MT of fuel (~191 fuel assemblies), and operates on an 18-month refueling cycle at a capacity factor of 81%. The ORIGEN2 calculations used the reactor model and cross section library developed for an extended-burnup PWR fuel cycle (Ludwig 1989). Table 7-2 lists the total core inventory for these 60 isotopes, as calculated by ORIGEN2.

7.3.3 Source Term Characterization—MCF Case

It is important to realize that, in the strictest sense, the entire concept of an "average" or "representative" source term is ill-defined. While the average release fraction of a fission product class can be defined, a representative time history and energy of the release becomes increasingly difficult to define as the number of source terms used to represent the actual accident spectrum decreases. This is of particular concern when a very small number of source terms are employed (as is the case here).

As previously stated, source terms are desired for two accident scenarios—one in which a massive containment failure occurs and one in which the containment fails in a limited manner. NUREG-1150 discusses the types of accidents that might happen at each plant, and each accident class's contribution to the overall core damage frequency. Source term fractional release distributions are presented for a broad spectrum of accidents, and characterized as 95th percentile, mean, median, and 5th percentile values. These release fraction distributions are available for the Zion nuclear reactor for "early containment failure", and "no containment failure" cases. (See Figs. 7-5 and 7-6 of NRC 1975). Early containment failures are defined to be those containment failures which occur "before or within a few minutes of reactor vessel breach." However, no detailed fission product release *histories* are presented. Thus, the detail needed

Table 7-2. Total core inventory at the time of the accident (Becquerels)[a]

Co-58[b]	1.835E+16	Rh-105	2.955E+18	La-140	5.995E+18
Co-60[b]	2.416E+16	Sb-127	3.392E+17	Ce-141	5.630E+18
Kr-85	3.334E+16	Sb-129	1.029E+18	Ce-143	5.180E+18
Kr-85m	9.153E+17	Te-127	3.349E+17	Ce-144	3.946E+18
Kr-87	1.769E+18	Te-127m	4.358E+16	Pr-143	5.150E+18
Kr-88	2.492E+18	Te-129	1.014E+18	Nd-147	2.200E+18
Rb-86	7.202E+15	Te-129m	1.523E+17	Np-239	6.227E+19
Sr-89	3.440E+18	Te-131m	4.668E+17	Pu-238	1.036E+16
Sr-90	2.645E+17	Te-132	4.647E+18	Pu-239	1.136E+15
Sr-91	4.172E+18	I-131	3.264E+18	Pu-240	1.482E+15
Y-90	2.760E+17	I-132	4.716E+18	Pu-241	3.482E+17
Y-91	4.398E+18	I-133	6.730E+18	Am-241	3.611E+14
Zr-95[c]	5.931E+18	I-134	7.401E+18	Cm-242	1.050E+17
Zr-97[c]	5.837E+18	I-135	6.281E+18	Cm-244	8.723E+15
Nb-95[c]	5.979E+18	Xe-133	6.735E+18	Sr-92	4.481E+18
Mo-99[c]	6.222E+18	Xe-135	1.873E+18	Y-92	4.499E+18
Tc-99m	5.431E+18	Cs-134	5.575E+17	Y-93	5.145E+18
Ru-103	4.906E+18	Cs-136	1.910E+17	Ba-139	6.052E+18
Ru-105	3.188E+18	Cs-137	3.504E+17	La-141	5.527E+18
Ru-106	1.445E+18	Ba-140	5.827E+18	La-142	5.361E+18

[a]Inventory based on ORIGEN2 calculation of extended-burnup PWR; 51,700 MWd/MT burnup; 4.7% enriched; 18-month cycle; 81% capacity factor; 88.128 MT core inventory; with accident at end of equilibrium cycle.

[b]Co-58 and Co-60 inventory result of activation of cobalt impurities in fuel assembly components.

[c]Inventory for these isotopes is the sum of fission product and activation product inventories. Fission product inventory accounts for greater than 95% of the total.

for source term characterization is not available solely from NUREG-1150. Since the resource limits of this effort did not allow plant-specific accident sequence source term analyses, it was necessary to develop a credible source term estimate from available literature.

An approach was developed which utilized the Zion-specific, mean source term *release fractions* for the "early" containment failure mode from NUREG-1150, and the source term timing information available from NUREG/CR-4624 (NRC 1986b). (Figure 7-2 summarizes the range of fission product release fractions predicted for the accident sequences analyzed in NUREG-1150.)

Tables 7-3 and 7-4 present a summary of the actual source term estimates (fission product group release fractions as a function of time) employed for the MCF scenario. Containment failure was predicted to occur 2.2 hr after the start of the accident. Source term releases are assumed to cease after 20 hours. (Although the containment would continue to leak at a very low rate for a longer period of time, available evidence indicates that this additional leakage has no significant impact on the risk of plant operation.)

The energy of the escaping fission products is also required to complete the input for the radioactive plume dispersion calculations. In reality, the total energy of the plume is time-, sequence-, and plant-dependent. The best value for use in these calculations is, therefore, subject to much uncertainty. The source term energy profile employed for the MCF scenario is presented in Table 7-5.

Although the energy of the released material is subject to rather large uncertainties, the values in Table 7-5 were employed as a "baseline" estimate for this study.

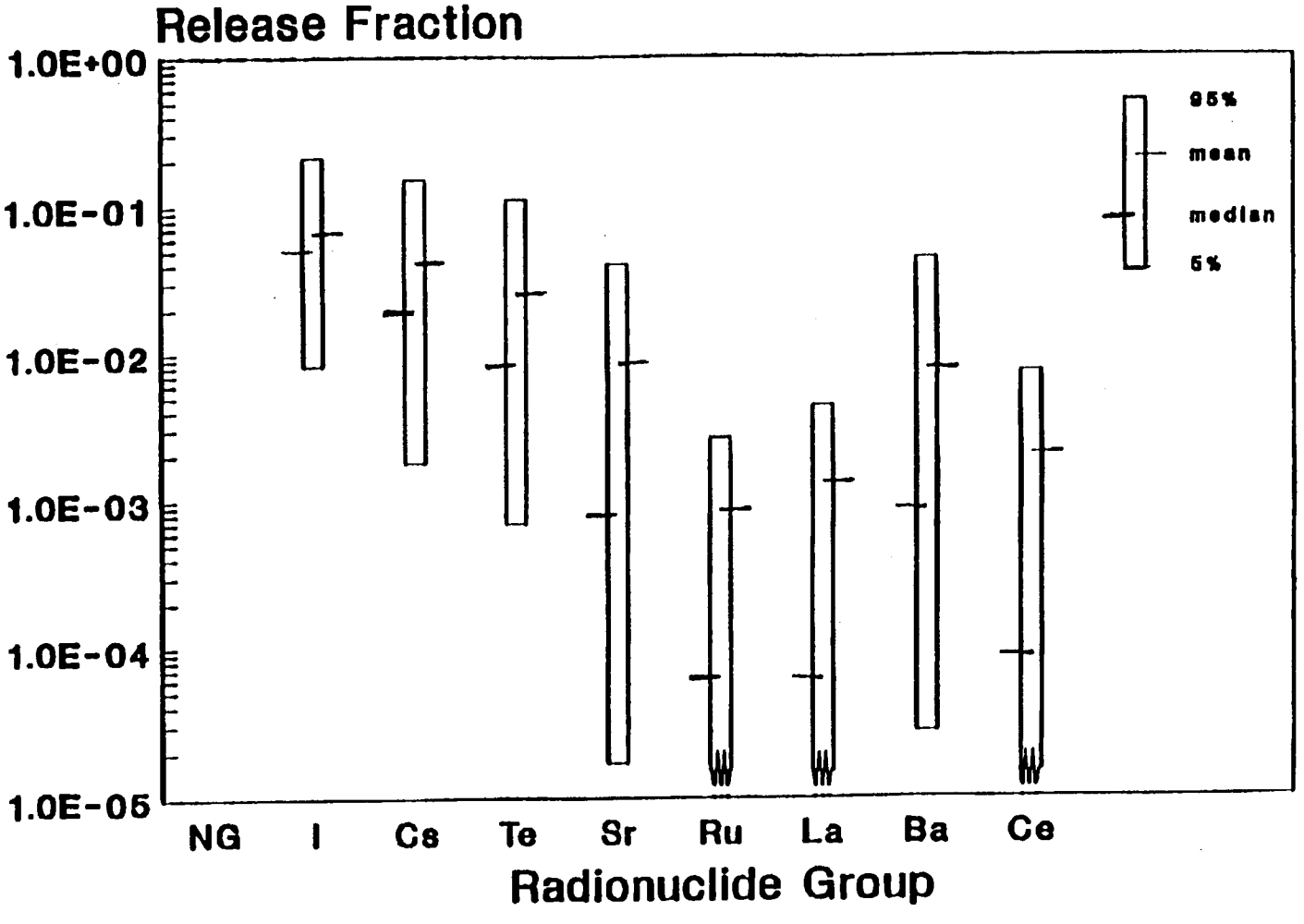

Figure 7-2. Source term release fraction ranges from NUREG-1150.

Table 7-3. Time-dependent radionuclide class release fractions for MCF sequence

Time (h)	Noble Gas (1)	I (2)	Cs (3)	Te (4)	Sr (5)	Ru (6)	La (7)	Ce (8)	Ba (9)
2.2	0.	1.20E-6	7.11E-7	1.61E-7	3.98E-10	1.11E-11	1.39E-13	0	8.64E-9
2.7	0.8283	0.0574	0.0343	0.0109	2.52E-5	6.23E-7	6.99E-9	0	5.79E-4
3.5	0.8788	0.0634	0.0379	0.0121	3.68E-5	6.88E-7	1.24E-8	1.02E-7	6.42E-4
4.5	0.9495	0.0665	0.0399	0.0142	3.76E-3	7.75E-7	5.14E-4	7.39E-4	3.31E-3
5.5	0.9657	0.0681	0.0407	0.0165	6.50E-3	1.11E-6	8.57E-4	1.29E-3	5.28E-3
7	0.9697	0.0691	0.0413	0.0184	8.17E-3	2.75E-6	1.07E-3	1.63E-3	6.50E-3
9	0.9798	0.0694	0.0416	0.0197	8.84E-3	5.64E-6	1.16E-3	1.77E-3	7.02E-3
11	0.9798	0.0697	0.0416	0.0211	9.33E-3	1.13E-5	1.21E-3	1.86E-3	7.39E-3
15	0.9899	0.0697	0.0418	0.0236	9.81E-3	4.05E-4	1.27E-3	1.96E-3	7.73E-3
20	1.0	0.070	0.0420	0.0250	0.0100	0.0009	1.30E-3	2.00E-3	7.90E-3

Table 7-4. Source term fission product groups

Group	Elements
1	Xe, Kr
2	I, Br
3	Cs, Rb
4	Te, Sb, Se
5	Sr
6	Ru, Rh, Pd, Mo, Tc
7	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y
8	Ce, Pu, Np

Table 7-5. Energy associated with source term for the MCF sequence

Time (h)	Source term energy for MCF case (joules)
2.2	0
2.7	5.44E+10
3.5	5.69E+10
4.5	6.05E+10
5.5	6.20E+10
7	6.27E+10
9	6.35E+10
11	6.43E+10
15	6.43E+10
20	6.43E+10

7.3.4 Source Term Characterization - LCF Sequence

NUREG-1150 presented estimates for the range of source terms for severe accidents at Zion in which the containment does not fail. The mean fission product release fractions for the noble gas and iodine groups was estimated to be ~4.0×10^{-3}, and 4.0×10^{-5}, respectively. The estimated release fractions for all other radionuclide groups were below 1.0×10^{-5}.

As previously discussed, NUREG/CR-4624 presents fission product release fractions for scenarios in which the containment fails. Information is provided on the assumed containment leak rate (via containment penetration, hatches, etc.) throughout the entire duration of the accident. Based on this information, source terms were developed for the LCF case by assuming the containment leaks at a rate larger (roughly ten times higher) than the design-basis leak rate, but much smaller than the rate believed to occur in the case of a massive containment failure. The estimated LCF source terms are presented in Tables 7-6 and 7-7. Here again, source term releases are assumed to cease after 20 hours.

7.3.5 Comparison of Assumed Accidental Releases to TMI Source Term

The source term resulting from an accident is a unique function of the type of reactor and containment employed in the plant, the accident sequence assumed, and the timing and mode of both reactor coolant system failure and containment failure. As previously discussed, it is extremely difficult to define a source term (total release fraction, time history of release, and energy of release) which is representative of more than a relatively small class of accidents. The MCF sequence used here is intended to represent the entire class of core damage accidents in which the reactor containment fails (i.e. leaks at a rate greater than the design basis leak rate).

It is important to recall that, according to NUREG-1150, 74% of all accidents which lead to core damage *do not* result in containment failure. Thus, the LCF case is intended to present a *conservative* representation of this class of accidents, in that the containment leak rate actually assumed in this case is roughly <u>ten times larger</u> than the design basis leakage rate.

Since other recent studies of external costs of nuclear power production (Ottinger et al. 1991) have employed Chernobyl-like assumptions regarding the accident sequence and source term, it would be useful to compare the MCF and LCF source terms employed here with those believed to have resulted from the TMI-2 and Chernobyl accidents. Unfortunately, there is substantial uncertainty regarding the actual magnitude of the Chernobyl source term. The official source

Table 7-6. Fission product group release fractions for the LCF case

Time (h)	Noble gas (1)	I (2)	Cs (3)	Te (4)	Sr (5)	Ru (6)	La (7)	Ce (8)	Ba (9)
2.2	0.0	1.20E-6	7.11E-7	1.61E-7	3.98E-10	1.11E-11	1.39E-13	0.0	8.64E-9
2.7	4.14E-5	2.87E-6	1.71E-6	5.45E-7	1.26E-9	3.11E-11	3.49E-13	0.0	2.89E-8
3.5	1.14E-4	8.24E-6	4.93E-6	1.57E-6	4.78E-9	8.94E-11	1.61E-12	1.33E-11	8.35E-8
4.5	2.18E-4	1.53E-5	9.18E-6	3.27E-6	8.65E-7	1.78E-10	1.18E-7	1.70E-7	7.61E-7
5.5	3.19E-4	2.25E-5	1.34E-5	5.44E-6	2.14E-6	3.66E-10	2.83E-7	4.26E-7	1.74E-6
7	4.65E-4	3.32E-5	1.98E-5	8.83E-6	3.92E-6	1.32E-9	5.14E-7	7.82E-7	3.12E-6
9	6.66E-4	4.72E-5	2.83E-5	1.34E-5	6.01E-6	3.84E-9	7.89E-7	1.20E-6	4.77E-6
11	8.62E-4	6.13E-5	3.66E-5	1.86E-5	8.21E-6	9.94E-9	1.06E-6	1.64E-6	6.50E-6
15	1.27E-3	8.92E-5	5.35E-5	3.02E-5	1.26E-5	5.18E-7	1.63E-6	2.51E-6	9.89E-6
20	1.78E-3	1.25E-4	7.48E-5	4.45E-5	1.78E-5	1.60E-6	2.31E-6	3.56E-6	1.41E-5

Table 7-7. Source-term energies for the LCF case

Time (h)	Source term energy for LCF case (joules)
2.2	0.0
2.7	2.74E+06.
3.5	7.28E+06
4.5	1.38E+07.
5.5	2.03E+07
7	2.97E+07
9	4.34E+07
11	5.67E+07
15	5.67E+07
20	5.67E+07

term estimates from the U.S.S.R. State Committee on Utilization of Atomic Energy (Powers et al. 1987) are now believed by many western experts to be unreliable. For this reason, detailed comparisons of the LCF, MCF, and Chernobyl source terms will not be presented. Tables 7-8 and 7-9 do present a comparison of the LCF, MCF, and TMI-2 source terms.

A comparison of the LCF source term to that of TMI-2 indicates that the LCF noble gas release (Table 7-9) is approximately one order of magnitude *lower* than that of TMI-2. The iodine release of the LCF case is ~7000 times *larger* than that of TMI-2. The MCF scenario employed here represents a much more severe accident than the LCF scenario. The MCF *release fractions* are significantly higher in all categories than those from TMI-2.

Table 7-8. Comparison of LCF, MCF, and TMI fission product release fractions

Group	LCF release faction	MCF release fraction	TMI release fraction* (Ref. 7.8-7.9)
Noble gas	1.78E-3	1.0	0.1
Iodine	1.25E-4	7.0E-2	2.0E-7
Cesium	7.48E-5	4.2E-2	0.
Tellurium	4.45E-4	2.5E-2	0.
Strontium	1.78E-5	1.0E-2	0.
Ruthenium	1.60E-6	9.0E-3	0.
Lanthanum	2.31E-6	1.3E-3	0.
Cerium	3.56E-6	2.0E-2	0.
Barium	1.41E-5	7.9E-3	0.

*References are Pigford (1051) and TMI (1980).

Table 7-9. Comparison of total noble gas and iodine source terms for LCF, MCF, and TMI

Scenario	Kr-85 (Ci)	Xe-135 (Ci)	I-131 (Ci)	Cs-137 (Ci)	Sr-90 (Ci)	Ba-140 (Ci)
LCF	45,600	323,700	11,000	700	100	2,200
MCF	25,613,300	181,845,000	6,169,000	397,400	71,400	1,242,900
TMI-2	9,600	14,000,000	10-20	0	0	0

7.3.6 Severity of LCF and MCF Source Terms

The International Atomic Energy Agency (IAEA) has recently instituted an International Nuclear Event Scale (INES), which is a standardized method of classifying and reporting nuclear events worldwide. The system is currently in use in 26 countries around the world. INES employs three safety attributes (on-site impact, off-site impact, and defense-in-depth degradation) and seven severity levels to classify the severity of nuclear accidents. These seven levels are briefly summarized in Table 7-10. As noted in Table 7-10, Chernobyl rates as a Category 7 (Major Accident) on INES, and TMI-2 rates as a Category 5 (Accident with Off-Site Risk) event, based on the destruction of the facility. According to the INES classification guidelines, the MCF case would be characterized as a Category 7 event (Major Accident), and the LCF scenario defined here would be characterized as a Category 5 (Accident With Offsite Risk). Thus, according to the INES protocol, the two accidents employed for this analysis are roughly comparable to the TMI-2 and Chernobyl events.

7.3.7 Severe Accident Probabilities (Internal Initiating Events)

Severe nuclear power plant accidents are considered to be low probability — high consequence events. Even if one considers the probabilities, no one can say when, or if, an accident will occur during the plant's lifetime. The accident could happen the day that the plant goes on-line, but it is far more likely to not happen at all. Since we do not know when (or if) the accident will occur during the plant's lifetime, we simply have amortized the risk (probability times consequences) over the course of a year of operation.

As previously stated, risk can be defined as the sum over all possible scenarios of the product of the probability of the scenario (P_i) and the consequence of the scenario (C_i), or,

$$Risk = \Sigma P_i C_i \quad . \tag{2}$$

In this study, this relationship for risk is approximated as,

$$Risk = P_{LCF}\Sigma C_{LCF} + P_{MCF}\Sigma C_{MCF} \, , \tag{3}$$

Table 7-10. International nuclear event scale

Severity level	Descriptor	Description
7	Major accident	External release of a large fraction of radioactive material in a large facility (quantities equivalent to more than tens of thousands of terabecquerels of iodine-131.) Example: Chernobyl
6	Serious accident	External release of radioactive material in quantities of thousands to tens of thousands of terabecquerels of iodine-131. Example: Kyshtym Reprocessing Plant, Russia, 1957
5	Accident with off-site risk	External release of radioactive material in quantities equivalent to hundreds to thousands of terabecquerels of iodine-131 OR, severe damage to a nuclear facility. Example: TMI-2
4	Accident without significant off-site risk	External release of radioactivity resulting in a dose to the most exposed individual off-site of a few milliSiverts OR significant damage to a nuclear facility OR irradiation of one or more workers which results in an overexposure with a high probability of early death. Example: St. Laurent Nuclear Power Plant, 1980
3	Serious Incident	An external release of radioactivity above authorized limits, resulting in a dose to the most exposed individual off the site of the order of tenths of a milliSievert OR on-site events resulting in doses to workers sufficient to cause acute health effects and/or a severe spread of contamination, OR incidents in which a further failure of safety systems could lead to accident conditions.
2	Incident	Incidents with significant failure in safety provisions but with sufficient defense in depth remaining to cope with additional failures, OR an event resulting in a dose to a worker exceeding a statutory annual dose limit OR an events which leads to the presence of significant quantities of radioactivity in the installation in areas which require corrective action.
1	Anomaly	An event beyond the authorized operating regime.

where,

P_{LCF} = the probability of the LCF sequence;

ΣC_{LCF} = the sum of all economic and health consequences of the LCF scenario;

P_{MCF} = the probability of the MCF sequence; and

ΣC_{MCF} = the sum of all economic and health consequences of the MCF scenario.

The use of only two accident sequences and source terms to represent the complete spectrum of potential accident scenarios in the subject PWR is a major simplification of the methodology associated with a complete risk assessment. Unfortunately, the use of only two accident scenarios presents a challenge in the determination of the probability that should be assigned for these source terms. The "average" source terms that are described here in Section 7.3 are not produced from a first principles analysis. This clouds the determination of an appropriate probability to apply for these source terms and the respective scenarios. Nevertheless, utilization of the Zion plant information presented in NUREG-1150 allows probability estimates to be made. These probability estimates were obtained for internal initiating events for the MCF and LCF cases.

One of the fundamental parameters derived in NUREG-1150 for the Zion plant was the core damage frequency. This parameter (expressed in frequency per year) represents the total probability (summed across all accident sequences) that internal initiating events will ultimately result in <u>significant</u> damage to the fuel. (Actually, NUREG-1150 defines the "core damage" state as one in which the reactor core becomes uncovered, with no imminent prospect of core reflooding. Thus, the extent of core and reactor vessel damage is not actually estimated.) NUREG-1150 estimated that Zion's core damage frequency was 6.2×10^{-5}/year. Again, this is the estimated frequency of all core damage events combined. Only a subset of these events would lead to complete core meltdown and reactor vessel failure. Some of these events will terminate with the reactor vessel left intact (TMI, for example). The manner in which the probability is employed here assumes that these accidents <u>always</u> result in complete core melting, accompanied by reactor vessel failure and escaped of the radioactive material into the containment.

The second major probabilistic parameter derived from NUREG-1150 is the "conditional containment failure probability" (see Table. 7-8). This parameter represents the total probability (summed across all accident sequences in which core damage has occurred) that the containment will fail <u>via any mode</u>, *given that the core has been damaged.* The value assigned to this parameter is 0.26.

The probabilities (P_{LCF} and P_{MCF}) employed for this costing exercise are derived by multiplying the core damage frequency by either the conditional containment failure probability (for the MCF case) or by one minus the conditional containment failure probability (for the LCF case). Thus,

$$Risk = (6.2 \times 10^{-5})(1.0 - 0.26)\Sigma C_{LCF} + (6.2 \times 10^{-5})(0.26)\Sigma C_{MCF} \quad , \tag{4}$$

per reactor-year of operation. This equation reduces to,

$$Risk = (4.6 \times 10^{-5})\Sigma C_{LCF} + (1.6 \times 10^{-5})\Sigma C_{MCF} \quad . \tag{5}$$

It is critical that the limitations and implications of this costing approach be understood. In the LCF case, the containment leak rate (and therefore, the source term) used is significantly larger than the containment leak rate employed in the "no containment" failure cases in NUREG-1150. Nevertheless, it is assumed that the total probability of all such sequences is (1.0–0.26)—the probability that the containment will remain intact (i.e. not fail). Thus, the probability of the LCF scenario was estimated to be 4.6×10^{-5}. The conditional containment failure probability associated with the MCF scenario (0.26) includes all "late", "early", and "bypass" modes of containment failure mentioned in Table 7-1. Therefore, the probability of the MCF scenario was estimated to be 1.6×10^{-5}. However, the actual containment failure mode assumed for the generation of the MCF source term is a large, early containment failure mode. Thus, the approach employed here would tend to bias the results in the direction of higher costs and consequences than are actually expected for the "mean" or average scenario.

7.4 SITE CHARACTERIZATIONS

Accident consequences are very dependent on site-specific characteristics such as the surrounding population, land uses (agricultural vs. residential), and the weather. These major features, in combination with the strength of the source term, ultimately characterize the accident consequences. Descriptions of the general aspects of the Southeast and Southwest site have been given previously in Section 6.2 and that information is not repeated here. However, specific aspects of the site characterizations that are utilized in the MACCS models are covered in this section.

7.4.1 General Modelling Assumptions and Features

There are a number of common (to both the Southeast and Southwest site) assumptions and modelling techniques that were used to describe the features of both sites. Many of these techniques are implicit in the MACCS computer models that were used to represent site specific features. A list of the major features and modelling techniques that are common to both sites is described in the following items.

(1) Modeling Grid. The grid that was used for accident modelling for both sites consisted of 16 different wind directions in tandem with 27 radial rings that extend out to 1609 km. Under normal operations, the doses due to radionuclides at 80.5 km is very small, making it unnecessary to extend that model any further. With respect to accidents, however, the quantities of nuclides that are released are many orders of magnitude greater than those released during normal operation. It is therefore reasonable to follow the accident source term to greater distances. Aerosols, in addition to gases, are assumed to be released during an accident. In the case of accidents, the ring between 805 and 1610 km constitutes a boundary condition. If aerosols make it to this ring, they are assumed to be slowly deposited on the ground. This assures that the *entire aerosol source term will be deposited* on to the computational grid.

(2) Weather Modeling. One year of hourly weather data was analyzed and sampled. This data included hourly readings of wind speed, direction, atmospheric stability, and precipitation for each site.

(3) Population Features. The 1990 population census was used to provide resident populations around the plant out to a distance of 1609 km. These populations are shown in Table 7-11.

Table 7-11. Site population characterization

Site	EPZ (0-16.1 km)	Local area (16.1 km - 80.5 km)	Regional area (80.5 km - 1609 km)	Total (0 - 1609 km)
Southeast	52,970	813,436	191,619,539	192,485,945
Southwest	222	97,946	88,472,461	88,570,629

(4) Economic Characterization. A number of local and regional economic inputs to the model were used. These inputs describe the farm sales, the value of farm land, and the rate of return on capital investments in the area. In addition, the total value of non-farm (which includes business and residential) wealth is input on a per capita basis. The values for these characteristics (for all 50 states, Canada, and Mexico) were extracted from the NUREG-1150 analysis and are in 1989 dollars. County data was used to describe the economics of the local area (0–80.5 km) for both the Southwest and Southeast sites.

(5) Land and Water Fractions. The fractions of land and water on the grid were input for both sites. This information is ultimately used for assessing the consequences due to food and water ingestion doses.

(6) Breakdown of Grid in to Regions. For both sites it was assumed that the plant is surrounded by an exclusion area with a radius of 0.8 km. This area is owned and controlled by the operating utility. Inside a radius of 16.1 km is the Emergency Planning Zone (EPZ). Inside this zone, the public is subject to evacuation should a severe accident occur. The population in this zone runs the highest risk of an early fatality or early injury in the event of a very serious accident. The zone from 16.1 km to 80.5 km will be referred to as the "local" area. The "regional" area is defined as the area from 80.5 km to 1609 km and therefore constitutes a large amount of land and population.

7.4.2 Southeast Site Description

A map showing the location of the plant site is shown in Figure 7-3. The Southeast site is somewhat unique in that the plant site is at the west end of a government reservation known as the Oak Ridge Reservation. A number of small and medium size cities surround the site, the largest of which is Knoxville.

As will be discussed later, a separate MACCS model was constructed for the Oak Ridge Reservation. This facility, which might be thought of as an example of a "high value" property, is inside the EPZ. The Oak Ridge Reservation contains three major plant sites as shown in Figure 7-4. These sites are commonly known as X-10, Y-12, and K-25. Over 15,000 people work at these sites. All three of these sites are within a 16.09 km radius (thus inside of the EPZ) of the Southeast site. The K-25 site (which is the name for the former Oak Ridge Gaseous Diffusion Plant) is approximately two miles north-northwest of the plant site. The Y-12 site starts at about eight miles northeast of the site. The X-10 site is ~5 miles to the east-northeast of the Southeast site. If an accident happened at the Southeast site, both the health and economic impacts

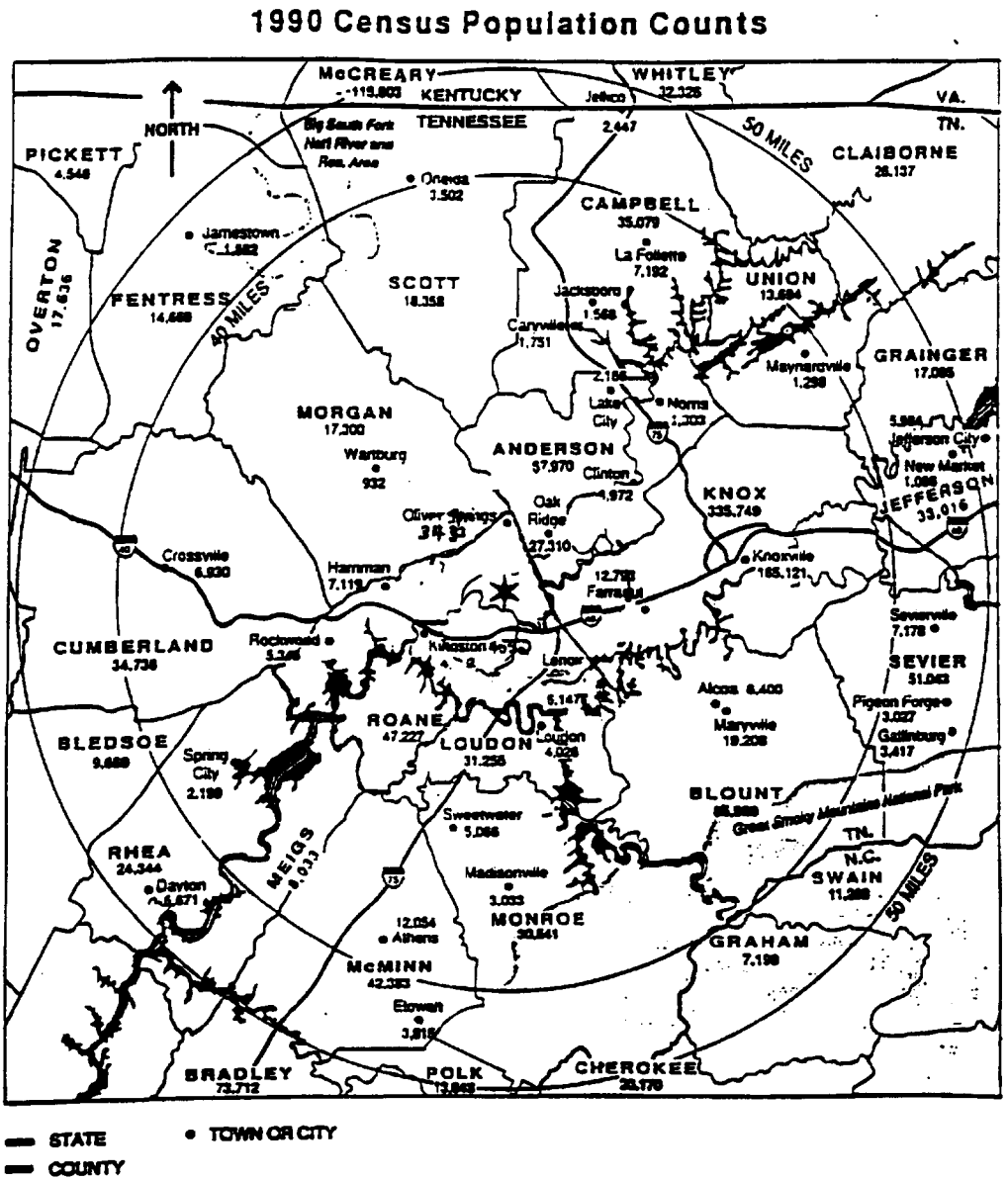

Figure 7-3. The Southeast Plant site

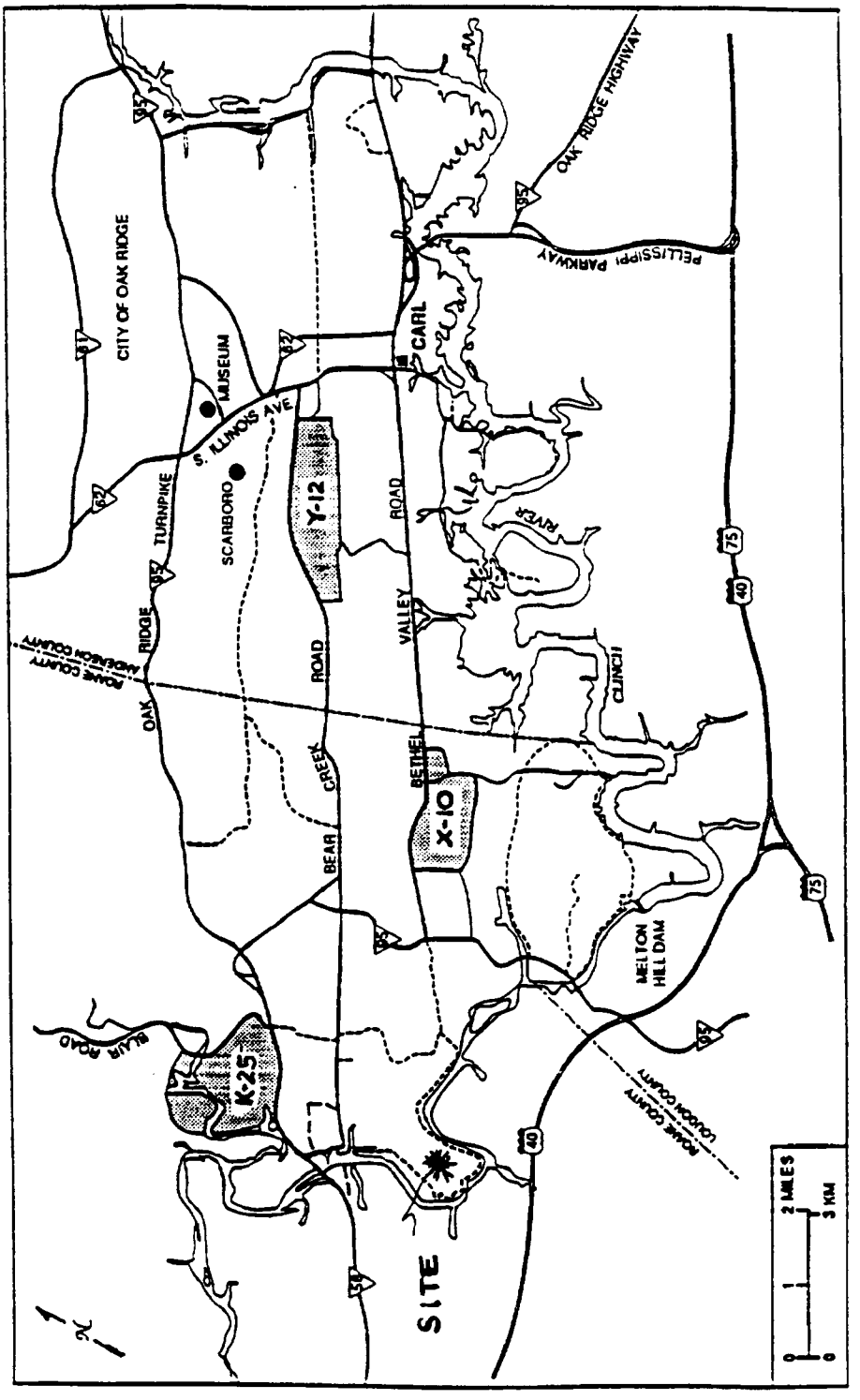

Figure 7-4. The Oak Ridge Reservation and plant site.

associated with these sites could be significant. A recent DOE report (DOE 1991c) states that the work force population consists of: 5,300 at X-10, 6,600 at Y-12, and 3,200 at K-25. The populations at these sites were time weighted according to a 40 hour work week and the assumption of a 50 week work year was used. Thus, the total time-weighted population for the various plants was assumed to be X-10: 1,219, Y-12: 1,518, K-25: 736. The reduction in the permanent population in the regions surrounding the Oak Ridge Reservation due to the influx of workers was not taken into account. Thus, in essence, the worker population was accounted for twice. This assumption results in a small overestimation of the health consequences.

7.4.3 Southwest Site Description

The Southwest site is significantly different than the Southeast site in almost every respect. The population, which is significantly less, is shown in Table 7-11. Since the area surrounding the plant site is relatively barren, it is expected that the accident consequences in almost every respect will be less than those of the Southeast site. The average crop season and share information for New Mexico was found to be significantly less than the Southeast site. (The appropriate agricultural descriptions were used in the respective models for both sites.) A map showing the location of the plant is shown in Figure 7-5.

7.5 PRIORITY IMPACT PATHWAYS

Here we note the priority impact pathways associated with a severe accident that leads to a significant off-site release of radioactive material (Table 7-12).

7.6 HEALTH EFFECTS

The information contained in this section covers the estimated health impacts to the general public for an accident attributed to internal initiating events. These costs are incurred outside the exclusion area and the health effects cited herein do not include any on-site effects. The exclusion area is owned by the operating utility. At the exclusion area boundary, members of the public may reside. The costs and damages directly impacting the public start here. In this section, results are presented for the emergency planning zone (also known as EPZ, 0–16.1 km). The term "local costs" refers to a radius extending from 16.1 km to 80.5 km radius around the plant. The term "regional" refers to those effects that occur between 80.5 km and 1609 km.

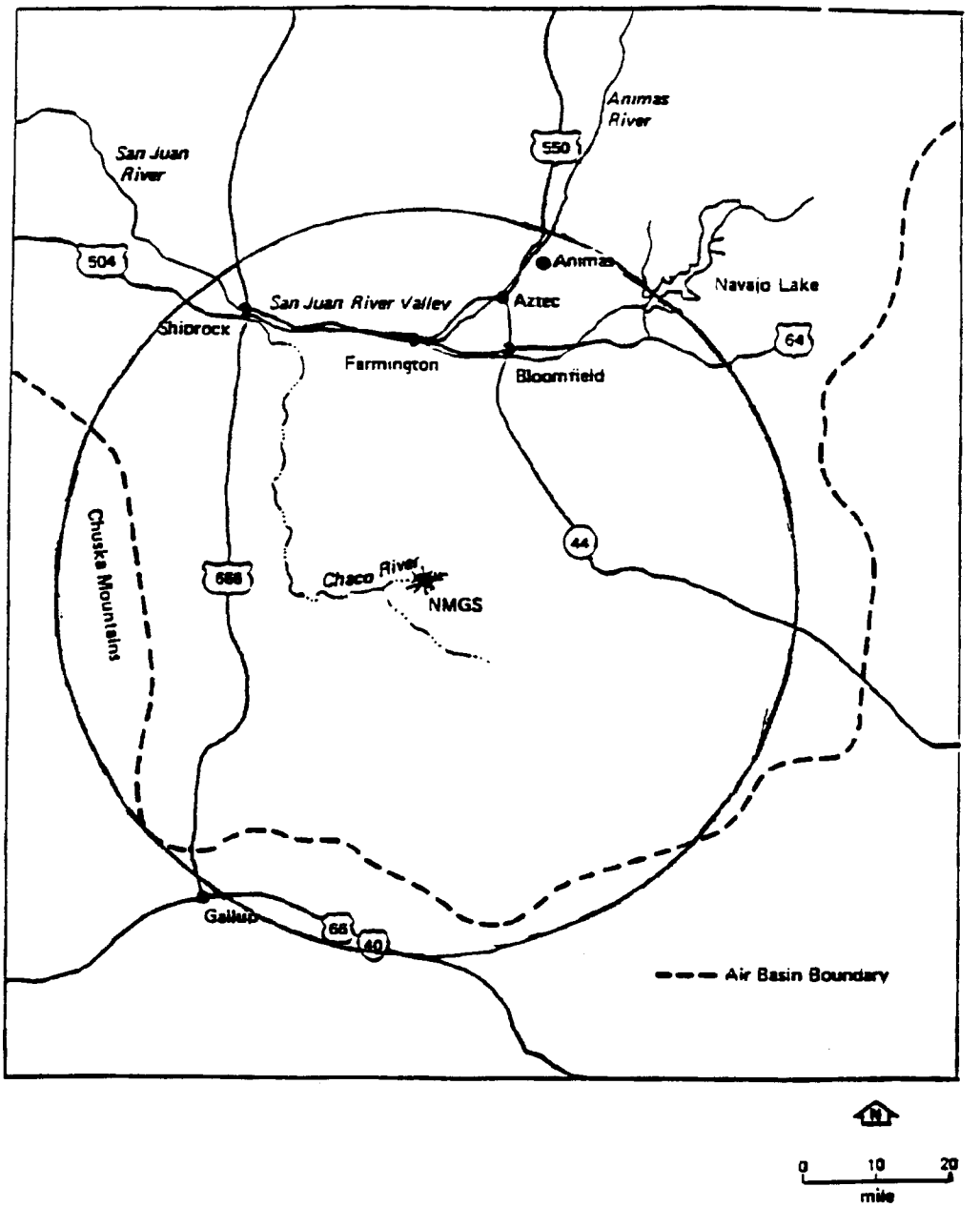

Figure 7-5. The Southwest plant site.

Table 7-12. List of Major Impact-Pathways

Emissions/Activity	Environmental Pathway	Impact	Impact Evaluation
Radionuclides	Exposure to plant/utility workers and law enforcement personnel to execute evacuation/relocation	Human health/Social disruption	Not quantified
Radionuclides	Atmospheric dispersion/deposition (cloud shine, ground shine, inhalation, skin contamination)	Human health (radiological)	Quantified
Radionuclides	Atmospheric dispersion/deposition on land and fresh surface water (food chain and water ingestion dose)	Human health (radiological)	Quantified
Radionuclides	Atmospheric dispersion/deposition Ecology, oceans, recreation	Human health/ Economic	Not quantified
Radionuclides	Ingestion or inhalation of aerosols	Human health/ Chemical toxicity	Not quantified
Radionuclides	Any exposure to radionuclides	Medical costs	Quantified
Radionuclides	A wide array of organic and inorganic waste compacted in to nuclear waste burial ground, much of which will be off-site. This waste comes from decontamination efforts both on and off the plant site	Primarily economic impact to cover off-site cleanup	Quantified
Socioeconomic Effects	Indirect effect	Changes in employment, devaluation of off-site property	Not quantified
Nuclear Industry Impact	Direct effect	Industry phaseout, backfits, regulations, etc.	Not quantified
Evacuation/ Temporary Relocation	Direct effect	Living expenses	Quantified

Table 7-12. List of Major Impact-Pathways (continued)

Emissions/Activity	Environmental Pathway	Impact	Impact Evaluation
Decontamination Period	Direct effect	Decontamination worker exposure (health effects), and expense	Quantified
Interdiction Period	Direct effect	Financial losses of affected businesses, farms: residential relocation, crop losses	Quantified
Condemnation Period	Direct effect	Moving costs, permanent loss of previous land/water utilization	Quantified
Interdiction/ condemnation	Direct effect	Alternative land/water utilization	Not quantified
Loss of Electrical Production Facility and Decommissioning	Direct effect	Costs of on-site decommissioning cleanup, replacement power	Quantified

It is important to keep the MACCS model, its calculations of damage, and its role in modeling an entire accident scenario in perspective. If a major core-melt accident occurred (particularly one with significant off-site consequences), many difficult social and political decisions would have to be made. These decisions would no doubt require that health impacts be balanced against the costs of protective measures. The arrangements associated with decontamination, interdiction, and condemnation would likely be specific to the affected land and take into account the land/water usage, the contamination level, and the individual landowner's wishes. MACCS is not capable of modelling this level of detail and regionally-averaged values are used for many parameters.

One important MACCS code input that impacts the decision as to whether decontamination, interdiction, or condemnation will be undertaken for a given piece of property is the long term habitation dose criterion. This criterion is input as a description of the dose in sieverts (usually as a whole body equivalent) from the pathways of groundshine and resuspension inhalation. Exposures above this

level would trigger the protective actions of decontamination, interdiction, and condemnation. MACCS could be used in an optimization study, whereby the long-term dose habitation criterion is varied to obtain an idea of the sensitivity of health impacts and economic impacts to the initiation of long-term protective actions (decontamination, interdiction, and condemnation). It must be remembered that this criterion mostly affects the pathways of groundshine and resuspension inhalation. These exposure pathways are known as "direct" exposure pathways with respect to the long-term phase of the accident. This criterion has a major health and economic impact within a couple of hundred kilometers from the site and controls chronic exposures to the population that live on the grid of the model. In addition, the model also accounts for the dose that decontamination workers would get during the decontamination phase. The health impacts of this dose are included in the mortality and morbidity tables.

It is difficult to estimate the habitation dose criterion authorities would select in the event of an accident with major off-site consequences. *Individual states may choose to set limits below the current federal guidelines in the event of an accident.* In the MACCS cases that are presented here, a dose criterion of 0.01 Sv over a five year period was chosen as the reference case. This equates to the average reception of 0.002 Sv per year for an individual. This dose rate is approximately equal to that portion of background radiation solely attributable to radon that a person would receive while living in Oak Ridge, Tennessee. Radon gas (and its respective radioactive daughter products) is naturally occurring and can be significant source of background radiation to an individual, depending on where they reside. In Oak Ridge, Tennessee, the annual total background radiation to an individual is ~0.0036 Sv.

The ingestion doses associated with the consumption of contaminated food and water represent important pathways. Protective Action Guides (put out by the Food and Drug Administration) will be used merely as guidelines by the individual states. These guides specify limits on the dose from the ingestion of contaminated food and provide a means of controlling exposure to the population. The MACCS model controls the treatment of farmland by setting limits on the allowable ground concentration of specific radioactive nuclides to meet the Protective Action Guides. As was the case with direct groundshine and inhalation, sensitivity studies and cost benefit analyses can be conducted with the model. It is important to note that the food and water pathways represent a *societal* exposure and the cancers that result from this pathway occur in a very large population over the course of many years and generations. The food and water pathways are known as the "indirect" exposure pathway. It must b e noted that in the ecological section of this report, there may be mention of other "indirect" pathways (consumption of contaminated wildlife, for instance). The MACCS code does not model these other pathways.

7.6.1 General Public Mortality and Morbidity

A number of different types of injuries and cancers are calculated by the MACCS code. The major categories of health effects are: early fatalities, early injuries, cancer fatalities, and cancer injuries. "Early" is used to describe those health effects that would be dealt with in less than one year following the accident. These health effects result from exposures obtained during the first seven days of the accident. For the accident scenarios that were considered here, most of the early health effects result from an exposure to the non-evacuated public (5% of the population inside the EPZ) from the plume.

In all of the summary tables presented in this section, the totals for early fatalities, all LCFs, and cancer injuries are given. In the case of early injuries, however, only the number of cases of skin erythema (burn) is given. These injuries constitute the overwhelming majority of injuries for the source therm that was used in this analysis. If a larger source term was used, a larger array of injuries would have resulted.

The cancer fatalities and injuries occur over many years following the accident. Some of these cancers result from initial exposures obtained during the early phases of the accident. However, many of these cancers also result from the long-term exposure from both direct and indirect pathways. The tables presented in this section present the sum of the different types of injuries and fatalities that were calculated by the MACCS model. In the case of early injuries, the model has the capability to calculate seven different types of injuries such as thyroid gland injuries, skin injuries, and lung injuries. Seven different types of cancers were modelled for the cancer injuries. For a complete listing of the individual health effects that were calculated for each site, please see Appendix D.6. These health effects were used in the assessment of the economic damages of health effects found in Section 7.6.2.

The MACCS code was designed to incorporate either cancer risk factors developed for use in reactor accidents (referred to by the NRC as LMF-132) or cancer risk factors from ICRP 60 (ICRP 1991). Cancer risk factors incorporated in LMF-132 can result in slightly different results in comparison with the cancer risk models specified in ICRP 60. The current version of MACCS could be run incorporating the ICRP 60 methods but the code lacks the capability to calculate the new effective dose measure defined in ICRP 60. Therefore, in the interest of presenting consequences in as much detail as possible, factors from LMF-132 were used. The major difference between the two methods comes from the calculation of risk to persons close to the accident site (0-16.1 km) where inhalation is the dominant source of total dose. In this case, MACCS using the LMF-132 methodology, calculates dose and risk to 7 organs, whereas only a single dose measure would have been possible with current ICRP 60 capability. With typical

source terms from a reactor accident, one would expect about a factor of two difference between the two methods for the close-in situation. Beyond 16.1 km where the dominant dose is due to ground shine and all internal organs receive essentially the same doses, both methodologies result in the same calculation of risk.

The MACCS code models consequence variability that is attributable solely to the weather and has the ability to produce a resultant risk distribution curve. The code also calculates a mean or expected value for the health impacts and those values are provided in this section. The mean value (which is averaged only over the variability in weather) and the 95% confidence intervals for the total fatalities and injuries are given in the summary tables presented in this section. The 95% confidence intervals throughout this report represent *only* the variability due to the weather at the site.

7.6.1.1 The Southeast Site and the Oak Ridge Reservation

The total health effects presented in this section are spread over two different populations. The permanent population, which are members of the general public, are assumed to be at their residence at the time of the accident. The population at risk in this instance is the population as described in Section 7.4. The incremental health effects associated with a possible accident on the Oak Ridge Reservation are also covered at the end of this section.

Table 7-13 presents a summary table for the health impacts for the Southeast site for a massive containment failure accident. These health effects are for the direct exposure pathways such as groundshine and inhalation, as previously discussed. Similarly, Table 7-14 presents the health impacts for a limited containment failure case from the direct pathways. The population at risk for these two tables is the permanent population as described in Section 7.4. This population lives on the grid that is described by the MACCS model.

Tables 7-15 and 7-16 summarize the total (direct plus indirect pathways) health effects for the MCF and the LCF cases, respectively. The number of cancers attributed to the total society (that ingests food or water) from the food and water pathways is therefore the difference between these two tables. An analysis of this table and the MACCS cases that were run shows that most of the mortality and morbidity for the MCF case is due to the food chain ingestion dose. If it was assumed that all of the food and water that is on the grid is consumed by people living on the grid, then these tables represent the total health effects.

Tables in Appendix D present a breakdown on the incidence of cancer by affected organ.

A separate MACCS model was used to evaluate the health effects associated with the large working population that is inside the EPZ zone of the Southeast site. The population at risk here is described in Section 7.4. The time weighted average number of workers was used for this model and this number describes the population at risk. A reduction in the permanent population due to the influx of workers was not taken into account. Thus, the worker population was accounted for twice because the workers were also counted in the permanent population. This assumption results in a small overestimation of the health and economic consequences. Since the code samples the weather data and utilizes wind directional probabilities, estimates of the *incremental* health consequence effects for the Oak Ridge Reservation for a massive containment failure case were made. The results of this run are shown in Table 7-17. This table reflects the *incremental* health consequences associated with an MCF accident at the Southeast site. The tables for the LCF case were not presented due to the low values of the health effects. The resulting early injuries and health effects for this case result primarily from the fact that it was assumed that 5% of the workers did not evacuate. In addition, no credit was taken for shielding that would be provided by the buildings at the work site locations.

Table 7-13. Health effects of direct pathways, Southeast site (MCF case)

Health effect	EPZ zone (0–16.1 km)	Local area (16.1–80.5 km)	Regional area (80.5–1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.00317	0.0	0.0	.00317	.000589
Early skin injury	33.3	4.28	0.0	37.6	166.0
Latent cancer fatalities	14.3	231.0	1500.0	1740.0	3380.0
Latent cancer injuries	34.5	450.0	2830.0	3320.0	6890.0

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

Table 7-14. Health effects of direct pathways, Southeast site (LCF case)

Health effect	EPZ zone (0–16.1 km)	Local area (16.1–80.5 km)	Regional area (80.5–1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.0	0.0	0.0	0.0	0.0
Early skin injury	0.0	0.0	0.0	0.0	0.0
Latent cancer fatalities	1.10	2.50	3.38	6.98	11.6
Latent cancer injuries	2.09	4.74	6.38	13.2	22.8

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

Table 7-15. Total health effects (indirect plus direct pathways), Southeast site (MCF case)

Health effect	EPZ zone (0–16.1 km)	Local area (16.1–80.5 km)	Regional area (80.5–1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.00317	0.0	0.0	0.00317	0.000589
Early skin injury	33.3	4.28	0.0	37.6	166.0
Latent cancer fatalities	20.2	293.0	5020.0	5330.0	14600.0
Latent cancer injuries	44.4	560.0	9290.0	9890.0	30100.0

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

Table 7-16. Total health effects (indirect plus direct pathways), Southeast site (LCF case)

Health effect	EPZ zone (0–16.1 km)	Local area (16.1–80.5 km)	Regional area (80.5–1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.0	0.0	0.0	0.0	0.0
Early skin injury	0.0	0.0	0.0	0.0	0.0
Latent cancer fatalities	2.77	5.82	17.8	26.4	58.3
Latent cancer injuries	5.17	11.1	34.1	50.4	108.0

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

Table 7-17. Health effects for Oak Ridge Reservation workers (direct pathways, Southeast site, MCF case)

Health effect	EPZ zone (0-16.1 km) mean	EPZ zone (0-16.1 km) 95% confidence level*
Early fatalities	0.0000896	0.0
Early skin injury	14.7	24.1
Latent cancer fatalities	1.88	7.51
Latent cancer injuries	5.06	25.0

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

7.6.1.2 The Southwest Site

A similar analysis for the Southwest site was performed to determine the public mortality and morbidity. Table 7-18 presents a summary table for the health impacts for the Southwestern site for a massive containment failure accident. These health effects are for the direct exposure pathway as previously described. Similarly, Table 7-19 presents the health impacts for a limited containment failure case associated with the direct pathways. The population at risk for these two tables is the permanent population as described in Section 7.4 and is much less than the Southeast site.

Table 7-18. Health effects of direct pathways, Southwest site (MCF case)

Health effect	EPZ zone (0-16.1 km)	Local area (16.1-80.5 km)	Regional area (80.5-1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.00001	0.0	0.0	0.00001	0.0
Early skin injury	0.989	0.213	0.0	1.20	4.33
Latent cancer fatalities	0.105	42.8	243.0	286.0	840.0
Latent cancer injuries	0.249	89.7	464.00	553.0	1400.0

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

Table 7-19. Health effects of direct pathways, Southwest site (LCF case)

Health effect	EPZ zone (0-16.1 km)	Local area (16.1-80.5 km)	Regional area (80.5-1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.0	0.0	0.0	0.0	0.0
Early skin injury	0.0	0.0	0.0	0.0	0.0
Latent cancer fatalities	0.0089	0.337	0.369	0.715	1.43
Latent cancer injuries	0.0169	0.639	0.697	1.35	3.07

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

Table 7-20 and Table 7-21 summarize the total (direct and indirect pathways) health effects for the MCF and the LCF cases, respectively. The number of cancers attributed to the total society from the food and water pathways is therefore the difference between these two tables. Tables in Appendix D provide additional information on the incidence of types of cancers estimated to occur.

Table 7-20. Total health effects (indirect plus direct pathways), Southwest site (MCF case)

Health effect	EPZ zone (0-16.1 km)	Local area (16.1-80.5 km)	Regional area (80.5-1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.00001	0.0	0.0	0.00001	0.0
Early skin injury	0.989	0.213	0.0	1.20	4.33
Latent cancer fatalities	2.01	46.4	503.0	552.0	1210.0
Latent cancer injuries	3.0	95.8	944.0	1040.0	2560.0

*The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

Table 7-21. Total health effects (indirect plus direct pathways), Southwest site (LCF case)

Health effect	EPZ zone (0-16.1 km)	Local area (16.1-80.5 km)	Regional area (80.5-1609 km)	Total mean impact	Total 95% confidence level*
Early fatalities	0.0	0.0	0.0	0.0	0.0
Early skin injury	0.0	0.0	0.0	0.0	0.0
Latent cancer fatalities	0.126	0.758	0.976	1.86	4.00
Latent cancer injuries	0.229	1.41	1.82	3.46	7.34

* The 95% confidence level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

7.6.2 Health Damages from Severe Power Plant Accidents

Expected impacts. This section describes the approach used to value the estimates of fatalities, injuries, and non-fatal cancer cases associated with severe accidents presented in the preceding section and the resulting estimates of damage. The estimates of damage are based on the presumption that the public believes the expert assessment of the risks of various types of accidents and the consequences associated with accidents, should one occur, as embodied in the MACCS model. The damage estimates are made from an "expert expected damage" perspective rather than an expected utility perspective, meaning that we are monetizing expected health consequences rather than seeking estimates of the WTP to avoid small increases in the risks of a nuclear accident. The latter measures are more appropriate from the perspective of modern welfare economics, as they would incorporate risk aversion, lay rather than expert risk assessment, and an ex ante rather than an ex post perspective. Future analyses will take up these issues.

The first step in valuation is to convert the health impact estimates presented in Tables 7-15 through 7-19 to expected impacts. Valuation of impacts can then be appropriately based on the "expected" impacts, accounting for the likelihood of an accident occurring, not on the impacts conditional on an accident occurring. The "expected" impacts are obtained by multiplying the impacts by the probabilities of an MCF and an LCF. Summing across the MCF and LCF expected impacts yields estimates of the expected impacts from the range of possible accidents:

$$E = \rho_{MCF} * I_{MCF} + \rho_{LCF} * I_{LCF} \quad , \qquad (6)$$

where E are the expected annual impacts, I are impacts if an accident occurs, and ρ is the probability of an annual LCF or MCF. These probabilities are 4.6×10^{-5} and 1.6×10^{-5}, respectively. Because the MACCS model provides estimates of impacts for a full range of meteorological outcomes, Table 7-38 also presents impacts for 95th percentile weather conditions. We convert both the mean and 95th percentile weather impacts to expected impacts.

Tables 7-22 and 7-23 summarize all of the relevant impact information to be used in the valuation exercise for the Southeast and Southwest reference environments, respectively. Unlike Tables 7-15 through 7-19, no distinction is made between direct and indirect impacts. This distinction is only relevant to highlight the large indirect health effects associated with the foodchain pathway. The expected impacts are distinguished by type of impacts, by zone, and by total mean and the 95th percentile impacts. The table also contains the estimates of conditional impacts (i.e., conditional or an accident occurring)

Table 7-22. Expected impacts of a nuclear power plant accident: Southeast site

	Evacuation zone (0-16.1 km)			Local area (16.1-80.5 km)			Regional area (80.5-1609 km)			Total impacts					
	Mean	LCF mean	MCF mean	Mean	LCF mean	MCF mean	Mean	LCF mean	MCF mean	Mean	95th% tile	LCF		MCF	
												Mean	95th% tile	Mean	95th% tile
Early fatalities	5.25E-08	0	3.26E-03	0	0	0	0	0	0	5.11E-08	9.49E-09	0	0	3.17E-03	5.89E-04
Cancer fatalities	4.83E-04	2.77E+00	2.21E+01	4.99E-03	5.82E+00	2.93E+02	8.17E-02	1.78E+01	5.02E+03	8.71E-02	2.38E-01	2.64E+01	5.83E+01	5.33E+03	1.46E+04
Nonfatal cancer cases	1.03E-03	5.17E+00	4.95E+01	9.54E-03	1.11E+01	5.60E+02	1.51E-01	3.41E+01	9.29E+03	1.62E-01	4.90E-01	5.04E+01	1.08E+02	9.89E+03	3.01E+04
population	52970	52970	52970	813436	813436	813436	1.9E+08	1.9E+08	1.92E+08	1.9E+08	1.9E+08	1.9E+08	1.9E+08	1.9E+08	1.9E+08
Risk per 100,000	0.000912	5.22938	41.684	0.00061	0.71548	36.02	4.3E-05	0.00929	2.619775	4.5E-05	0.00012	0.01372	0.03029	2.76946	7.58615

Table 7-23. Expected impacts of a nuclear power plant accident: Southwest site

	Evacuation zone (0-16.1 km)			Local area (16.1-80.5 km)			Regional area (80.5-1609 km)			Total impacts					
	Mean	LCF mean	MCF mean	Mean	LCF mean	MCF mean	Mean	LCF mean	MCF mean	Mean	95th% tile	LCF		MCF	
												Mean	95th% tile	Mean	95th% tile
Early fatalities	1.64E-10	0	1.02E-05	0	0	0	0	0	0	1.64E-10	0	0	0	1.02E-05	0
Cancer fatalities	3.82E-05	1.26E+01	2.01E+00	7.83E-04	7.58E+01	4.64E+01	8.15E-03	9.76E+01	5.03E+02	8.98E-03	1.97E-02	1.86E+00	4.00E+00	5.52E+02	1.21E+03
Nonfatal cancer cases	5.89E-05	2.29E+01	3.00E+00	1.61E-03	1.41E+00	9.58E+01	1.53E-02	1.82E+00	9.44E+02	1.69E-02	4.16E-02	3.46E+00	7.34E+00	1.04E+03	2.56E+03
population	222	222	222	97946	97946	97946	8.8E+07	8.8E+07	88472461	8.9E+07	8.9E+07	8.9E+07	8.9E+07	8.9E+07	8.9E+07
Risk per 100,000	0.017199	56.7568	905.405	0.0008	0.7739	47.373	9.2E-06	0.0011	0.568538	1E-05	2.2E-05	0.0021	0.00452	0.62323	1.36614

to use later in an uncertainty analysis. Impact estimates to the local work force adjusted for the time they would be on the job, are incorporated in all estimates involving the 0-16 km ring around the site.

Referring to the mean results for the Southeast, expected early fatalities are trivial compared to cancer cases, with less than 1 non-fatal cancer expected (0.162) and a much smaller risk of fatal cancers (0.087). The expected impacts are highest in the outer, regional area ring, because of the larger number of people exposed (191.5 million vs 0.8 million and 53,000 in the local and evacuation zones, respectively). However, people originally living in the evacuation zone face the highest individual risk (defined as expected impacts/population).

The total expected impacts given 95th percentile weather conditions are also shown. The impacts are about two to three times as large as the expected impacts for the expected weather conditions.

Referring to the Southwest results, with fewer people exposed to the radiation from the accident than in the Southeast area, expected impacts are much lower.

Unit Values. There are four types of expected impacts to value: (1) early fatalities, (2) early injuries, (3) latent cancer fatalities, and (4) latent non-fatal cancer cases. Wherever possible, we use unit values that were used in our other fuel cycle studies. To value fatalities, we have previously used two approaches.

One is to multiply estimates of the number of expected fatalities by the average value of a statistical life (which we take from the literature review by Fisher 1989). This study considered primarily wage compensation studies analyzing the premium paid to workers in relatively risky jobs for the excess accidental death risks they bear. It also considers contingent valuation studies of the WTP to avoid automobile death risks. Low, mid, and high values are $1.6 million, $3.5 million, and $8.6 million, respectively.

The other approach is to use the Mitchell and Carson contingent valuation study of the willingness to pay for reductions in risks of premature cancer death from ingesting cancer-causing substances in drinking water. This study produced a nonlinear function relating the size of the change in premature death risks to the WTP to avoid that change. WTP increases at a decreasing rate with the size of the risk change. Dividing the WTP for a particular risk change by the risk change yields a value of a statistical life (VSL) associated with the particular risk change. For risk changes in the range of those of the hedonic wage studies—1 in 10,000 to 1 in 100,000—the Mitchell and Carson study yields estimates for a VSL of $123,000 and $526,000, respectively, in 1989 $.

For the value of early fatalities (experienced within seven days of the accident), we use the Fisher VSL estimates. Being taken from studies involving accidental and immediate deaths (although in the workplace rather than in the general public), these estimates are reasonably appropriate.

For the value of cancer fatalities, an ideal measure would capture the individual WTP to avoid premature death risks from various types of cancer contingent on the age of the person at exposure and the latency of the cancer. As effects can be intergenerational, measures of the WTP to reduce risks to future generations would also be needed. As noted above, measures available in the literature are risk-based, in that the estimated WTP is for reduction in risks of premature death, but the measures do not distinguish age effects well and only the Mitchell and Carson study takes latency at least implicitly into account. There is a study that begins to look at WTP to avoid intergenerational effects (Cropper, Aydede, and Portney 1992) but this work is in its infancy. In any event, we make a number of assumptions about the impacts that reduce the need for these details from WTP studies. Tables in Appendix D.6 distinguish among types of cancer fatalities, but not by age group or generation. We are assuming that (1) all age groups are equally at risk of a cancer fatality and (2) all fatalities are experienced by the current generation. The latter assumption is clearly a major simplification, tending to result in an overestimate of present discounted damages, although probably a small overestimate as most fatalities would be experienced by the current generation. To handle latency of cancer in the current generation, it would be preferable to use the Mitchell and Carson function, since this study sought VSLs for cancer and implicitly captures the latency effects. Unfortunately, this study does not investigate the WTP to avoid mortality risks that are as small as those estimated by the MACCS model, which are all smaller than 10^{-6}. Using their function yields VSL's exceeding $50 million. But, we have no confidence in these estimates.

Our approach is to discount the Fisher estimates of a VSL according to the average latency of a cancer fatality in the current generation, from exposure to death. We assume that the time from the accident to death averages 20 years for all cancers except leukemia, for which we assume a latency of 13 years.[1]

The discount factor used throughout our study is 3%, which is based primarily on estimates of the subjective rate of time preference. This rate reflects individuals' willingness to trade off current for future consumption. Although this rate may bear little resemblance to their willingness to tradeoff current for future illness or death risks (Cropper and Portney 1992), the idea of using a lower VSL for valuing latent deaths relative to valuing immediate deaths makes intuitive sense

[1]In future work, we may use latency factors appropriate to each type of cancer.

and accords well with the findings of the Mitchell and Carson study compared to the literature on immediate death risks reflected by Fisher.

The two main differences between the VSL from Mitchell and Carson and that of Fisher is that the former address latent risks involuntarily foisted on the public, while the latter address immediate death risks borne more or less voluntarily by workers. Latency should reduce WTP to avoid risks, since the consequences will not be experienced in the present, while we would expect WTP to be higher for avoidance of involuntary risks. In fact, for comparable risks, Mitchell and Carson find the latency effect dominating, with VSLs far lower than those reported by Fisher. Thus, we conjecture that the VSL for latent death risks involuntarily undertaken will be lower than for immediate death risks voluntarily undertaken. Applying a discount rate to the Fisher VSLs is an approach to implementing this conjecture.[2]

For the valuation of non-fatal cancer cases, which are also assumed to occur in the current generation, the ideal measure is the willingness to pay for reductions in the risk of developing a non-fatal cancer with a given latency period, an expected set of symptoms, medical costs, and income consequences, perhaps varying by age, income, and other variables. Such a measure does not exist. Rather, one set of estimates is available from Hartunian, et al. (1980) for the direct (primarily medical) costs and indirect costs (principally wage losses associated with hospitalization, temporary and permanent impairment, and work loss from premature death) associated with the lifecycle of seven types of cancers by age and sex. Oster et al. (1984) and by Baker et al. (1991) also provide lifecycle cost estimates, but only for lung cancer medical costs. Abt (1992) closely analyzes these studies, preferring Baker to Oster for a variety of reasons. Because the Baker and Hartunian estimates of direct medical costs of lung cancer are close to one another [$21,402 (as adjusted by Abt) and $20,271, respectively in 1988 dollars]), we use the more recent Baker estimate. For the indirect costs of lung

[2]It may be appropriate to add morbidity costs associated with cancer to the VSL. However, to remain consistent with our earlier fuel cycle studies, we did not do this here. In the earlier fuel cycle analyses, deaths associated with cancer were not an issue for the general public because exposure to carcinogenic substances from these fuel cycles was much less likely and not designated a priority pathway. Mortality effects in these cycles were primarily restricted to deaths by heart attacks from exposure to lead, which we assumed take place without long periods of illness, and to deaths from exposure to particulates. Little is known about why people die from particulate exposures or the health status of such people. Thus, we could not add morbidity costs to the VSL estimates. For deaths associated with cancer, there would surely be a significant period of morbidity before death, which implies that morbidity costs should be added to estimates of the willingness to pay to avoid risks of premature death. In future work, we may add morbidity costs associated with fatal cancers to the VSL estimates.

cancer and for the direct and indirect costs of all other cancer types, we rely on the Hartunian et al. estimates (with all estimates inflated to 1989 dollars).

The Hartunian et al. estimates of costs may underestimate or overestimate the willingness to pay to avoid a non-fatal cancer. While they do not cover values for avoiding pain and suffering and omit other cost categories, they include costs for both non-fatal and fatal cancers. The latter have lower morbidity costs than the former because those who die of cancer usually do so within five years of diagnosis, while the survivors keep incurring medical costs. However, the latter also have higher indirect costs because of the inclusion of lost earnings from premature death.[3] The relationship of this measure to the ideal measure, which would account for latency, risk aversion, and other factors is also unclear.[4]

Table 7-24 presents discounted values of average lifecycle medical and indirect costs by cancer type (which Hartunian et al. developed using a 6% rate of discount;[5] inflated to 1989 dollars using the medical Consumer Price Index). These costs are the result of aggregating across age categories using weights based on the fraction of the total cancer population of a given type in each particular age group. This aggregation is appropriate under the assumption that all age groups are equally at risk from developing non-fatal cancers after exposure to radiation from a nuclear accident. The table shows that direct costs are a relatively small percentage of total costs, with the indirect costs (primarily lost wages) being the major cost.

These costs for each cancer type are then multiplied by the expected non-fatal cancers of each type shown in Table 7-22. These products are then discounted to adjust for latency from the accident to onset of illness, which we assume averages 15 years for all cancers except leukemia, for which we assume

[3]At this time, we do not know whether the Hartunian estimates can be disaggregated into costs for non-fatal and fatal cancers.

[4]One further qualification is that the Hartunian et al estimates are based on the age and sex distribution of various types of cancers in the population. This age distribution of cancers caused by a nuclear accident would likely be much different, being less skewed to the elderly. Ignoring this effect, as we do, results in an underestimate of indirect effects and unknown bias in the estimate of medical costs.

[5]There is an inconsistency in using a 3% discount rate in most of the rest of this report while the discounted lifecycle costs (which are estimated in Hartunian et al) use a 6% rate to discount the time stream of medical and indirect costs. At this time, we do not know whether these estimates can be disentangled and a 3% rate applied.

Table 7-24. Present value of total average cost per cancer patient assuming same risk across age groups (1989 $)

	Digestive	Respiratory	Buccal Cavity	Reproductive	Urinary	Nervous	Leukemias	Lymphomas	Cancers of other sites
Direct(a)	$29,445	$23,054(c)	$47,311	$44,735	$34,238	$48,831	$29,668	$46,821	$34,983
Indirect(b)	$287,741	$345,372	$205,239	$188,903	$218,780	$295,877	$359,497	$291,536	$152,199
Total	$317,18	$366,774	$252,550	$233,638	$253,018	$344,708	$389,165	$338,357	$187,181

Source: Hartunian et al., 1980. Adjusted using medical CPI

(a) Includes hospital, physician, nursing home, drugs, special equipment and prosthetics, and other categories discounted at 6%.

(b) Includes foregone earnings discounted at 6%.

(c) This value taken from Baker et al., (1991), all others from Hartunian et al.

disease onset is 8 years,[6] using the standard 3% subjective rate of time preference. Assuming this discount rate is not too large,[7] we feel confident that these cost estimates would underestimate ideal damage measures. No range is given for the unit cost estimates. Finally, we have no information for valuing early injuries, and leave this impact category unvalued. The effects are quite small, in any event.

Damage Estimates. In this section we present estimates of the health damage associated with a set of severe accidents. These estimates are presented by type of effect, by region, and for the average and 95th percentile weather pattern. Where the unit values have a judgmental probability distribution, we follow the simplistic convention followed in the other fuel cycle studies of multiplying Mid impact estimates by Mid unit values and High impact estimates by High unit values. There are no Low impact estimates; LOW damage estimates are obtained by multiplying Mid impacts by Low unit values.

The damages estimated for the Southeast and Southwest reference environments are provided in Tables 7-25 and 7-26. Referring to the Southeast results, total expected damages are $203,000 per year, but with bad luck on the weather (the 95th percentile conditions) they could rise to over $558,000. Using a higher or lower value for a statistical life has a somewhat less than proportional effect on total damages, since the non-fatal cancer damages are not affected by changing the VSL. Corresponding damages for the Southwest site are an order of magnitude smaller, due largely to the smaller population exposed.

Health damages vary from 0.0132 to 0.056 mills per kWh for the Southeastern site, with a Mid estimate of 0.025 mills/kWh. With unfortunate weather patterns, our HIGH estimate is 0.153 mills/kWh. As noted, damages at the Southwest site are far smaller.

Uncertainty Analysis. There are several important sources of uncertainty in the estimation of several accident impacts and damages including:

— uncertainty in accident probability
— uncertainty in release fractions and timing of releases
— uncertainty in weather
— uncertainty in dose response functions
— uncertainty in the nature and efficiency of counter measures
— uncertainty in unit values assigned to impacts.

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[6]In future work, we may apply latency factors to each type of cancer.

[7]Cropper and Portney suggest that discount rates on saving lives in public programs are much, much higher. However, the decision here involves individual, not public, risks.

Table 7-25. Annual health damages from nuclear power plant accidents: Southeast site (1989 $)

	Mean weather			95th %tile weather		
	Low	Mid	High	Low	Mid	High
Early fatalities	$0	$0	$0	$0	$0	$0
Cancer fatalities	$79,867	$174,709	$429,284	$217,857	$476,563	$1,170,984
Nonfatal cancer cases	$28,340	$28,340	$28,340	$81,232	$81,232	$81,232
Total (1989 $)	$108,207	$203,049	$457,625	$299,089	$557,795	$1,252,215
Total (mills/kWh)	0.01326072	0.02488351	0.05608154	0.03665306	0.0683572	0.1534577

Table 7-26. Annual health damages from nuclear power plant accidents: Southwest site (1989$)

	Mean weather			95th %tile weather		
	Low	Mid	High	Low	Mid	High
Early fatalities	$0	$0	$0	$0	$0	$0
Cancer fatalities	$8,161	$17,853	$43,867	$17,932	$39,227	$96,385
Nonfatal cancer cases	$2,917	$2,917	$2,917	$7,295	$7,295	$7,295
Total (1989 $)	$11,078	$20,770	$46,784	$25,227	$46,522	$103,680
Total (mills/kWh)	0.00135763	0.00254532	0.00573332	0.00309156	0.0057012	0.0127059

So far, we have separately addressed the uncertainties in weather and in unit values of impacts. A more complete analysis is needed to address each of the above sources of uncertainty.

7.7 ECOLOGICAL EFFECTS

This section lists the priority impact-pathways for ecological impacts associated with a severe reactor accident for the nuclear fuel cycle (Table 7-27, see also Appendix F).

Table 7-27. Primary emissions or activities, pathways, and ecological impacts linked to a severe reactor accident

Emissions/activities	Environmental pathway	Impact	Impact Evaluation
Air emissions:			
Radionuclides	Atmospheric dispersal; deposition on land surface and water	Immediate death; reduced population; bioaccumulation	Quantified (deer only)
Water quality:			
Radionuclides	Water releases; deposition on water	Immediate death; reduced population; bioaccumulation	Qualitative evaluation
Other factors:			
Radionuclides	Land use change	Loss of land resource for crops, fishing, and recreation	Affected and use is quantified, though not the impacts.

7.8 ENGINEERING ECONOMIC ESTIMATES OF OTHER CONSEQUENCES

This section briefly describes the underlying models used to estimate non-health-related impacts and damages from a severe reactor accident at each reference site. The on-site costs associated with loss of the facility from impacts within the "exclusion area" owned by the facility can be considered to be internalized by insurance and operation procedures; hence, these will not be considered further. The principle non-health, public consequences of an accident are related to the purchase of alternative power by the utility and any evacuation, attempts at mitigation, and subsequent adjustments to normal living and business

operations associated with the temporary or permanent condemnation of property as a result of radioactive contamination. Evaluation costs are particularly interesting because evacuations could be ordered as a result of relatively minor accidents. Because such accidents have a relatively high probability, expected damages could be relatively large even if the consequences of a minor accident were small in contrast to the consequences of a major accident.

Considering the issue of the purchase of alternative power, NUREG-1150 found these on-site damages to present 95% of total damages (Harding 1990). Even so, NUREG-1150 ignored multiple power plant effects, e.g., shutting down co-located but undamaged reactors and reactors with the same design as the reactor involved in the accident (in the limit, involving shutting down all U.S. nuclear plants). Burke et al. (1986), who contributed to the MAACS code, argues that such shutdowns are a cost of "societal overreaction, not attributable to the accident itself." We disagree. Society's reactions are what they are, imposing real costs on the economy and on individuals. One may wish to moderate society's reactions, but this is a separate issue. Here, we take society's reactions and perceptions as given.

The economic model used is embedded in the MACCS code used to estimate the health consequences. This model may be termed an "engineering-economic" model because it treats the consequences of the accident deterministically and deals with the probabilistic nature of these consequences in an expected value sense. The alternative model, that may be termed a behavioral-economic model, assumes that the probabilistic nature of the event is completely integrated into the individuals' ex ante decisions regarding their willingness to accept a nuclear power plant with some probability of a severe nuclear accident, using the concept of expected utility.

While we feel that the latter model captures the essence of the decision problem far better than the former model, data to exercise the latter model are hard to come by. In addition, the MACCS model is a standard in the nuclear industry. Therefore, in this section, we take the engineering-economic model on its own grounds, briefly presenting its underlying assumptions and valuation approach, the parameters used to calculate damage, and the expected damage estimates.

One minor problem with the model is that it assumes that there are no risks associated with massive evacuations. However, under emergency evacuation orders, transportation accident risks and other types of risks, as a result of deviating form one's normal routine, may be elevated. Witzig and Shillonn (1987) estimate that there would be 2 expected fatalities and 18 expected injuries from the evacuation itself, which is characterized by 30,000 people, driving in 15,000

vehicles, taking a 200 mile night time round trip, on wet, rural, two-lane roads. Given the extreme nature of these assumptions and the low resultant health impact (as compared to the radiological impacts of the accident), this impact-pathway was not designated as a priority for analysis.

The information contained in this section covers the estimated costs for an accident attributed to internal initiating events. The costs associated with the loss of the electricity production facility include site cleanup, replacement power, and the loss of investment. These costs are incurred inside the exclusion area which would be owned by the operating utility so that some of these costs would be internalized. The costs associated with all of the protective actions and counter-measures mentioned in previous sections are incurred outside the exclusion area. This includes evacuation and relocation, interdiction, decontamination, and condemnation costs.

These costs would be internalized to the extent of utility liability. The decontamination, interdiction, and condemnation costs are divided into two major categories according to whether the property is used for farming or nonfarming (business, residential). Farm condemnation and decontamination costs as expressed here refer solely to land costs based on utilization of the land. Once the model identifies the number of hectares affected by the condemnation or decontamination activity, it multiplies that number times the appropriate unit per hectare and sums that cost. Nonfarm values, which include all business and residential wealth are calculated in proportion to the number of people affected. In this case, the model takes the number of people on a grid element and multiplies that number times the per capita value of wealth that was input to obtain this cost. In the case of interdiction, which is a temporary condemnation of the land, the loss of the rate of return on investment is calculated for both farm and nonfarm properties.

Crop losses are also estimated based on protective action guidelines (that limit societal doses) that are input to the code. In addition, separate incremental costs associated with the possible damage (capital losses) to the facilities on the Oak Ridge Reservation are also calculated. Lost wages for the Oak Ridge facilities for the long-term phase were not accounted for directly. An aggregate per capita cost for the permanent population was used to account for this. Many of the costs described above could be covered by insurance and would be internalized. All costs quoted in this section are in 1989 dollars and the results presented constitute the total damage for the mean case.

As was the case with the health effects analysis presented in Section 7.6, the long-term dose habitation criterion also has a significant effect on the cost of an accident. The tighter this criterion, the more land that is decontaminated,

interdicted, or condemned. This results in higher costs. In addition, there are a number of other inputs to the analysis that significantly alter the costs. The assumed farm and nonfarm land values significantly influence the cost estimates, especially for condemnation and interdiction. Site population characteristics used for this analysis were discussed in Section 7.4 and are mentioned in the sections that follow. As was the case with the health impacts, the arrangements associated with decontamination, interdiction, and condemnation would likely be highly site-specific and take into account the land/water usage, the contamination level, and the individual owners' wishes. The economic aspects of these choices would be complicated. A series of parametric studies could identify the sensitivity of these parameters.

Finding accurate information on the two past major reactor accidents, TMI-2 and Chernobyl, is difficult. Some data are available in the literature, and are based on court settlements, estimates by economists, and insurance settlements. Some claims are still outstanding, which clouds the issue further. According to a recent special insert in NRC 1994, Chernobyl damages are estimated at over $30 billion. The TMI-2 accident, which did not even warrant US NRC classification as "an extraordinary nuclear occurence" worthy of Price-Anderson compensation, had damages estimated at around $4 billion; i.e. mostly loss of the plant and replacement power costs.

7.8.1 Loss of Electricity Production Facility

The following is a description of the losses associated with the reactor site (inside the 0.8 km) exclusion area. It is assumed that the site cleanup and loss of electrical production costs are the same, regardless of whether it is an MCF or LCF scenario. This is because both of these accident scenarios include an implicit assumption that the plant damage would be extensive.

In addition to off-site damages, there are sizeable costs to the PWR plant owner and the ratepayers from the loss of the electricity production facility. Among these are loss of the utility's capital asset, the need for replacement power, site cleanup, and the immediate need to begin plant decommissioning. The projected costs for these items are described in the paragraphs below.

7.8.1.1 Loss of Utility Assets and Site Cleanup Costs

A severe accident, such as that which took place at TMI-2, can mean a significant financial loss to the utility. This loss is, in turn, transferred over the years to the ratepayers, stockholders, and taxpayers both within and outside the region. The remaining or "book" value of the plant depends on the number of years of the plant's 40-year life left. For this study we will assume that the

accident occurs at year 20, or halfway through the reactor's life. Using Zion I as an example, which is 20 years old this year, ~66% of its original cost (including escalation and interest) constitutes the "book" value. This may seem high for a twenty-year-old plant; however, as with most nuclear plants, there are many retrofits, capital additions, and equipment purchases which are capitalized. In essence, nearly all of today's nuclear plants bear a string of "second mortgages" which keep the debt load high for many years. Using the new plant cost of $4.1 billion from Section 6.3.1.7 (a better experience PWR plant number from the Energy Economic Data Base (EEDB 1987) and the 66% number above, an asset loss of $2.7 billion could be charged to the utility. This cost does not include the $2.2 billion which would be needed to clean-up the utility's site and buildings before decommissioning could proceed. (This number is escalated from the $1.9 billion in 1986 $ which appears in NUREG/CR-4551, Vol 1 (NRC 1986a). This latter number seems reasonable in light of the billions spent to clean up the TMI-2 plant. The cost of the decommissioning is estimated at $400 million and was discussed in Chapter 6. Some of these costs may be partially covered by insurance which the utility purchases; hence, these covered costs should be internalized. (See 7.8.1.3 below.)

The total damage for this category at either of the two sites is $5.3 billion. For the massive containment failure case, with its probability of 0.0000159, the expected (probability-adjusted) damage is $84,270. Distributed over the 8.16 billion kWh generated in a reactor-year, the unit damage is 0.0103 mills/kWh. For the limited failure case and its probability of 0.00004607, the expected damage is $244,171 or 0.0299 mills/kWh. Note that the damage to the site is the same for both accidents. This is not the case for the damage outside the site.

7.8.1.2 Need for Replacement Power

During short-term (less than one year) outages of nuclear plants, utilities normally utilize power from other production assets within their own system or purchase power from other utilities via pooling agreements. All utilities are, in essence, linked by their membership in the North American Electric Reliability Council (NERC). The nation is divided into nine NERC regions which, in turn, have their own "power pools". It is within the local power pool that the utility will most often have an agreement for nearly instantaneous replacement power. Researchers at Argonne National Laboratory (VanKuiken 1992) have compiled the experienced and projected average replacement power unit cost (in 1991 mills per kilowatt-hour) for all U.S. nuclear plants. The replacement power cost is defined as the power purchase cost minus the nuclear plant variable operations & maintenance and variable fuel costs normally attributable to the downed facility. (Variable costs are those costs incurred only when the plant is operating.)

For the Southeast reference site the local power pool (Southeastern Electric Reliability Council or SERC) consists only of the huge Tennessee Valley Authority (TVA) utility. The replacement cost used here for this site is taken as the average for TVA's three presently operating reactors (see Table 7-28). In the event of a severe accident where the plant is so badly damaged that it can not be brought back on line, the utility is probably faced with five years of purchasing power before they can bring another baseload asset on line, such as a natural gas-fired station. For the first year, the utility would pay the short-term replacement rate derived from the document above. In years 2–5 the utility could probably optimize their own system or optimize outside purchases to realize a one-third reduction in the first year rate. The total power replacement constant-dollar cost at the Clinch River site for 5 years would be $415 million dollars (1989 $). (Assuming the need to replace 8.16 billion kWh per year.)

A power plant at the Southwest reference site would serve and draw from two power pools within the Western States Reliability Council or WSRC, the Arizona/New Mexico one and the California/Nevada one. This is because California buys a large portion of their power from out-of-state. In order to calculate the New Mexico replacement unit charge, seven units were used: three in Arizona and four in California. (Table 7-28 shows the calculation.) For the five years of replacement power needed for this site's utility, the cost would be a total of $734 million. Again, 8.16 billion kWh per year are assumed replaced.

The total damage for this category is $415 million for the Southeast site and $734 million for the Southwest site. This damage would be the same for either containment failure scenario. For the massive containment failure case at the Southeast and Southwest sites, with its probability of 0.0000159, the expected (probability-adjusted) damages are $6599 and $11670, respectively. Distributed over the 8.16 billion kWh generated in a reactor-year, the unit damages are .00081 mills/kWh and .00143 mills/kWh, respectively. For the limited failure case and its probability of .00004607, the expected damages at the Southeast and Southwest sites are $19,119 or .00234 mills/kWh and $33,815 or .00414 mills/kWh, respectively. Note that the financial loss at a given site is the same for both accidents; however, the market price of power causes the damage to be different at each site.

Table 7-28. Historical replacement power costs at reference sites in same power pools as reference sites

Reactors in SERC power pool #18 (Tennessee Valley Authority)		Reactors in WSRC power pools #26 (AZ-NM) & #27 (CA-NV)	
Reactor	Mills/KWH (1982$)	Reactor	Mills/KWH (1992$)
Brown's Ferry 2	14.3	Palo Verde 1	20.7
Sequoyah 1	16.1	Palo Verde 2	20.7
Sequoyah 2	16.1	Palo Verde 3	20.7
		Diablo Canyon 1	34.4
		Diablo Canyon 1	34.4
		San Onofre 1	30.6
		San Onofre 1	30.6
Average	15.5	Average	27.4
First year's worth of power, ($8.16 billion kWh replaced/yr)	126,480,000		223,584,000
Year 2-5 unit cost for replacement power (mills/kWh)	10.3		18.3
Year 2-5 cost of power (sum)	337,200,000		597,097,000
	---		---
Year 1-5 power cost (1992$)	463,680,000		820,681,000
Year 1-5 power cost (1989$)	414,741,000		734,062,000

7.8.1.3 Insurance Coverage

Most utilities purchase public liability and plant property damage insurance from a commercial source. For an annual cost of around $20 million/yr (2.5 mills/kWh) they will typically obtain $200 million in public liability and $1.1 billion in plant property damage coverage (Delene 1992). These insurance costs are internalized. Utility operated nuclear plants are also covered under the U.S. Government's Price-Anderson coverage. The utilities do not pay premiums for this insurance and the U.S. Government does not maintain a sinking fund for it. The $7.5 billion value of this insurance is to cover public liability beyond commercial insurance in the event of a severe accident. This insurance cost is not internalized and would become a liability to the U.S. taxpayer should its use be required.

7.8.2 Evacuation and Temporary Relocation Costs

This classification of costs for the reference scenario includes those costs that would be incurred in the first 127 days of the accident. The evacuation costs are primarily incurred within the 16.09 km emergency planning zone and take place in the first seven days of the accident. For the purposes of this analysis, it was assumed that all but 95% of the people inside the 16.09 km radius were evacuated. The assumption was made that $70 was lost per workday (used as an approximation of the average daily wage in Tennessee and New Mexico) and that five workdays were lost during the early phase of the accident. Based on standard MACCS code methodology, it was also assumed that there was one worker for every four permanent residents. Living expenses of $27 per day were assessed for every person that was evacuated. Utilizing this approach, evacuation costs were estimated and are presented in Tables 7-29 and 7-30. It was assumed that the same evacuation plan was used for both the MCF case and the LCF case.

Relocation costs are generally incurred within several hundred kilometers of the site. Relocation is a counter-measure that can take place either in the early or intermediate phase of the accident (within the first 127 days of the accident). It results from an action taken by authorities to limit public exposure to a plume that has been deposited. In this case, people are removed from their homes and are assumed to be temporarily relocated and cannot work. The total costs result from a per diem of $27 in combination with the lost wages ($70/day for 1 of every 4 persons) who are affected for each weather trial. The MACCS code was used to calculate the relocation cost in Tables 7-29 and 7-30 for the mean weather. The costs associated with the evacuation of workers and their associated lost income from the Oak Ridge Reservation workers were not calculated.

Table 7-29. Evacuation and relocation costs: Southeast site

Plant scenario	Total mean costs (0-1609 km) $(millions)
MCF evacuation	14.15
MCF relocation	1,420.0
LCF evacuation	14.15
LCF relocation	0.30

Table 7-30. Evacuation and relocation costs: Southwest site

Plant scenario	Total mean costs (0-1609 km) $(millions)
MCF evacuation	0.06
MCF relocation	0.130
LCF evacuation	0.06
LCF relocation	0.01

7.8.3 Decontamination, Interdiction, and Condemnation Costs

During the long-term phase of the accident scenario, many extensive costs will be incurred, especially in the MCF scenario. The costs associated with the decontamination of land, the interdiction of property, and the permanent condemnation of land have been calculated for the Southeast site and the Southwest site. During the interdiction period, the depreciation of capital assets and a lost rate of return are tallied in the costs for this period. In the case of permanent condemnation of farmland, the cost of the farmland is used. For nonfarm property (which includes residential and business wealth), the per capita costs are used in combination with the population distribution to determine the total cost. It must be remembered that the MACCS code determines the cost-effective treatment of land.

The methodology that is used in MACCS to determine the cost effectiveness of long-term countermeasures is outlined in the WASH-1400 study. This methodology determines whether property will be decontaminated, interdicted, or condemned. Farmland must be habitable to be farmable. In the case of farmland, ingestion dose restrictions on the ground concentration in tandem with a prediction on the reduction in contamination that occurs with radioactive decay enter into the decision. For each parcel of land in the spatial grid, a cost effectiveness test is conducted for the farm property to determine the degree of countermeasures that must be taken to meet the FDA dose guidelines. If interdiction is necessary, then the cost to restore the farmland is the cost of decontamination (a decontamination factor of 3 is used based on standard MACCS code methodology) plus the compensation resulting from the loss of usage of the property during the interdiction period. This loss includes the depreciation of the farm property improvements which is calculated as an exponential (e^{-} dpr × time) decay over the interdiction time. For this analysis, a depreciation rate of 20% per year is used. It also includes loss of profits, based on a 12% rate of return on investments. These values are used by MACCS to make decisions on whether to interdict or condemn the farmland and to calculate the interdiction costs associated with farm costs.

In the case of nonfarm property, the cost effective decisions that are made are similar to the treatment of farmland. However, these costs are calculated on a per-capita basis. First, decontamination is attempted to see if the habitation dose criterion can be met. In this analysis, a single decontamination factor of 3 is used. If this is not sufficient, decontamination may be used with a supplemental interdiction period. As was the case with farmland, the post-interdiction value of wealth due to property improvements is calculated using an exponential decay for both depreciation and the loss of the return on the investment. This value plus the property cost is used to make the decision as to whether the property should be condemned. Interdiction period costs are calculated taking into account the depreciation and loss of return on investment if the land is deemed to be put back in service at the end of the interdiction period. These assumptions are built into the MACCS code methodology; the reader is referred to Chanin et al. (1990) for more information.

The decontamination costs presented here only include the labor cost of decontamination. Low specific activity waste disposal costs are not handled by MACCS; however, they are addressed as a separate issue in Chapter 7, Section 7.8.5. Those costs are for the disposal of the large amount of contaminated waste that would be generated from the cleanup of land around the reactor site. According to one study (Nordic 1992) the cleanup of the area within the vicinity of Chernobyl produced an estimated four million cubic meters of this type of waste. This waste was buried at nearly 800 interim sites near Chernobyl. It is not

known how much of this came from the plant site and how much came from areas off of the site.

The MACCS economic model for nonfarm costs utilizes an important per capita value that drives the major costs associated with decontamination, interdiction, and condemnation. The long-term dose habitation criteria has a major impact in that it directly effects the decision and extent of the protective actions. The limit for this criteria was discussed in Section 7.6. Another major cost issue concerns the inputs to the model for the values of nonfarm costs and farmland costs. For the purposes of this analysis, a value of $66,000 per capita was used for the local (inside 80.5 km) population at the Southeast site. A value of $63,000 was used for the Southwest site. These numbers were derived based on per capita values for reproducible, tangible wealth (from the U.S. Statistical Abstracts) less the amount of farm wealth in the U.S. (from NUREG-1150). This number was then scaled according to the state (Canada and Mexico included) per capita income. Farmland cost averages ($/hectare) for the states were used. All of these parameters were obtained from U.S. NRC (USNRC 1990) and are in 1989 dollars. In the future, it would be desirable to develop a better methodology for the determination of these important parameters.

The other important cost factor concerns the federal protective action guidelines that govern whether food can be grown and consumed on the farmland that surrounds the sites. *It is possible that local authorities would set tighter limits, causing the costs to go up.* The protective action guidelines for the various crop categories as defined in NUREG-1150 were utilized in this study. These guidelines directly affect the number of cancers from the food chain and thereby control the cost-benefit ratio of protective actions for farmland.

7.8.3.1 Southeast Site Economic Consequences

The costs for the MCF and LCF scenarios are presented in Table 7-31 and Table 7-32 for the reference case. These costs represent those incurred around the site, excluding any damage to the Oak Ridge facilities. The costs outlined in these tables are incurred during the time period ranging from 60 days to many years after the accident.

The cases (mean values) that were run show that for the MCF scenario, farmland was interdicted to a distance of 244 km and condemned to a distance of 136 km. Non farm property was interdicted to a distance of 183 km and condemned to a distance of 41 km. For the LCF scenario, the results show that farmland was interdicted to a distance of 5.6 km and condemned to a distance of 3 km. Nonfarm property was interdicted to a distance of 3.3 km and condemned to a distance which is inside the exclusion area.

Table 7-31. Southeast site (MCF case) costs

Type of cost	Total mean impact (0-1609 km) $(millions)
Non-farm decontamination cost	1,140.0
Farm decontamination cost	135.0
Non-farm interdiction cost	6,300.0
Farm interdiction cost	394.0
Non-farm condemnation cost	1,900.0
Farm condemnation cost	394.0
TOTAL	10,263.0

These costs co not include low specific waste disposal.

Table 7-32. Southeast site (LCF case) costs

Type of cost	Total mean impact (0-1609 km) $(millions)
Non-farm decontamination cost	0.248
Farm decontamination cost	0.037
Non-farm interdiction cost	1.130
Farm interdiction cost	0.130
Non-farm condemnation cost	0.0483
Farm condemnation cost	0.191
TOTAL	.779

These costs do not include low specific activity waste disposal.

Since the Oak Ridge Reservation and its plants surround the site, a facility-specific MACCS economics model was put together to model the incremental economic impact that could occur. To perform this analysis, a key assumption was made that the property value of three plants totalled $2.5 billion. The assumed breakdown was as follows: Y-12: 1.130 billion, X-10: 0.909 billion, and K-25: 0.461 billion. A per capita property value for each of these plants was calculated on the basis of the time weighted average number of workers for each facility (see Section 7.4). This resulted in a per capita property value of nearly three quarters of a million dollars for the Y-12 and X-10 facilities, and about 630,000 dollars per capita for the K-25 plant. Table 7-33 presents the incremental cost estimate associated with the risk of the loss of the facilities on the Oak Ridge Reservation due to an MCF scenario.

7.8.3.2 Southwest Site Economic Consequences

The costs for the MCF and LCF scenarios are presented in Tables 7-34 and 7-35 for the reference case. These costs represent those incurred around the site. The costs presented here cover the time period in the accident from 60 days and on out to many years after the accident. The cases that were run show, that for the MCF scenario, farmland was interdicted to a distance of 232 km and condemned to a distance of 145 km. Non farm property was interdicted to a distance of 177 km and condemned to a distance of 47 km. For the LCF scenario, the results show that farmland was interdicted to a distance of 9 km and condemned to a distance of 6.6 km. Non-farm property was interdicted to a distance of 2 km and condemned inside the exclusion area.

7.8.4 Other MACCS-Calculated Costs

There are some other miscellaneous costs that are calculated by the MACCS models. These costs are incurred as a result of the indirect pathways. If an accident occurred, there would be protective actions taken to limit exposure through the food chain. The costs associated with taking farmland out of service during the years subsequent to the first year of the accident were previously discussed. However, the costs associated with the purchase of contaminated milk and crops were not addressed. This cost category covers the relatively minor costs of crop and milk purchase, should the accident occur only during the growing season of the first year of the accident. The disposal is contingent upon exceeding certain FDA protective action guidelines. The costs are presented for both sites in Table 7-36. In the case of the Southeast site (mean case), it was found that crops were purchased out to a distance of 180 kms and that milk was purchased out to a distance of 240 kms. For the southwest site, it was found that crops were purchased of out to a distance of 239 kms and that milk was disposed of out to a distance of 310 kms.

Table 7-33. Southeast site (MCF case) costs Oak Ridge Reservation facility damage

Type of cost	Total mean impact (0-1609 km) $(millions)
Non-farm decontamination cost	1.7
Non-farm interdiction cost	177.0
Non-farm condemnation cost	340.0
TOTAL	518.73

These costs do not include low specific activity waste disposal.

Table 7-34. Southwest site (MCF case) costs

Type of cost	Total mean impact (0-1609 km) $(millions)
Non-farm decontamination cost	111.0
Farm decontamination cost	69.2
Non-farm interdiction cost	782.0
Farm interdiction cost	91.4
Non-farm condemnation cost	477.0
Farm condemnation cost	201.0
TOTAL	1,731.6

These costs do not include low specific waste disposal.

Table 7-35. Southwest site (LCF case) costs

Type of cost	Total mean impact (0-1609 km) $(millions)
Non-farm decontamination cost	0.009
Farm decontamination cost	0.049
Non-farm interdiction cost	0.038
Farm interdiction cost	0.139
Non-farm condemnation cost	0.0
Farm condemnation cost	0.552
TOTAL	0.787

These costs do not include low specific activity waste disposal.

Table 7-36. Sum of milk and crop purchase costs

Site/scenario	Total mean impact (0-1609 km) $(millions)
Southeast/MCF	320.4
Southeast/LCF	0.042
Southwest/MCF	127.6
Southwest/LCF	0.1

These costs do not include disposal costs for this low specific activity waste.

7.8.5 Costs for Disposal of Low-Specific Activity Wastes Resulting from Decontamination Activities

Our review of waste disposal costs associated with off-site decontamination activities after a severe reactor accident revealed that the MACCS code does not include a cost for this activity. For this reason, we have investigated a methodology to calculate these costs that use the MACCS-calculated numbers for the extent of off-site decontamination, as well as unit costs (expressed as dollars per hectare of decontaminated land for farm areas and dollars per person for suburban areas).

Post-accident decontamination activities taking place outside the reactor site would produce large quantities of low-specific activity materials such as contaminated topsoil, destroyed crops, grass, leaves, roofing shingles, etc., which would pose a large disposal problem (most of the activity in this material would be from long-lived isotopes such as Cs-137 and Sr-90). In the U.S., there are no designated facilities for handling the billions of cubic feet of such materials that might result from a Massive Containment failure class of reactor accident. Low-specific activity waste produced from reactor accidents appears to most closely match uranium mill tailings materials in its specific radioactivity, its hazard level and the nature of the material to be handled (soils and organic materials), and disposal of accident wastes at mill tailings impoundments might be an option. Low-level wastes tend to be of higher specific radioactivity than is expected of accident decontamination wastes and of lower volume and more diverse chemical and physical forms.

A survey of the literature has uncovered very little data on the methods or costs for ultimate disposal of these contaminated materials. The absence of data is probably for the following reasons:

- The U.S. NRC has directed most of its accident analyses on understanding reactor accident probabilities (PRAs) and understanding reactor accident progression sequences. Modeling of physical/engineering phenomena has received much more attention than modeling costs and other socioeconomic consequences of a severe accident. For example, the economic modules in MAACS are not nearly as advanced in their development as are the plume deposition modules.

- The 1979 accident at TMI-2 did not cause any off-site contamination, hence no massive decontamination effort was mounted.

- Data from the 1986 Chernobyl accident in the former Soviet Union on the extent of decontamination and its ultimate costs has not been made available. It is unclear whether the disposal methods used after Chernobyl would be suitable in the U.S; for example, much of the contaminated dirt and crops were merely pushed into large mounds in the immediate area and were stabilized. In the U.S., the public would probably require that such materials be disposed of at a distant unpopulated area (Nordic Council of Ministers 1992).

- Ongoing activity in the disposal of low-level wastes (LLW) from normal reactor operations provides little guidance since the contaminated materials are different, the quantities much smaller, and the physical and chemical forms of the waste streams are quite different. The $30 to $400 per cubic foot fees charged by LLW repositories are for specialized packaging and burial procedures. Bulk materials such as low-specific activity soils are more analogous to mill tailings wastes and handling procedures involving heavy mechanized equipment are probably most applicable.

As a cost basis for decontamination costs, we elected to use cost data that is used in the RADTRAN IV model for evaluating transportation accidents involving nuclear shipments. This code, which is discussed in Chapter 8, does a more rigorous and complete job of determination of decontamination costs than the MACCS code. For the sake of consistency in methodology, we find it appealing to use the same unit costs in calculating decontamination waste disposal for both types of nuclear accidents (reactor and transportation.)

Table 7-37 shows the areas affected by the four severe accident scenarios. Using cost data from the RADTRAN IV Code (see Chapter 8), the dollars required to dispose of crops, farm soil, and non-farm contaminated materials have been estimated. RADTRAN IV's 1982 $ value of $1 million per square km for extensive tilled land (soil) cleanup translates to $12,900 per hectare in 1989 $. For crop disposal, RADTRAN did not give a value; however, the lower density and weight of crop materials suggest a per hectare value about one-fifth that for soil disposal or $2,580 per hectare. For single family households, RADTRAN provides a "high" value of $1172 per person in 1982 $ for decontamination. Much of this value would be for disposal of contaminated grass, leaves, tree limbs, roof shingles, and contaminated household articles. In 1989 $ the per household (4 persons) value is $6048.

Table 7-37. Costs and units affected for disposal of low specific activity materials resulting from post accident decontamination activities

Category	SE/MCF	SE/LCF	SW/MCF	SW/LCF
Crop disposal area (Hectares)	727000	183	892000	1320
Contaminated crop disposal cost ($M)[a]	**1875.7**	**0.5**	**2301.4**	**3.4**
Farmland decontamination area (Hectares)	241000	65.1	123000	86.9
Low activity soil disposal cost ($M)[b]	**3108.9**	**0.8**	**1586.7**	**1.1**
Non-farm households affected (#)	94750	21	9250	1
Non-farm household low specific activity material disposal cost (garden & other cont. outdoor waste) ($M)[c]	573.2	0.128	56.0	.008
Total low specific activity material disposal cost ($M)	**5557.8**	**1.4**	**3944.2**	**4.5**

[a]Contaminated crop disposal costs 2580 $/hectare
[b]Low activity soil disposal costs 12,900 $/hectare (From RADTRAN IV).
[c]One southeast non-farm household assumed to occupy .25 acre or 0.1 hectare and to have 4 persons. Using RADTRAN's $1512 per person this would translate to $24192 per acre or $60,000 per Hectare or $6048 per household. (All values in 1989 $.)

It can be seen that for the MCF case the total disposal cost is very large, i.e in the billions of dollars. There is considerable uncertainty in these cost figures due to the lack of decontamination experience and the lack of data on how today's disposal regulations would affect costs. (DOE's ongoing remediation efforts for the 1943-1993 Weapons Production Complex are not to the point that useful cost data is yet available. Once the contaminated soil at the Hanford Reservation is treated and disposed, better cost numbers should be available.)

As a reality check, the low activity waste disposal cost can be considered on a volumetric basis. If a 5 cm depth of contaminated topsoil were removed for each square foot of land, the $12900 per hectare cost would translate to $0.75/ft^3. One can compare this to an estimated cost for disposing of mine tailings. For the ore described in Chapter 5, 795 lb of tailings are produced for every pound of U_3O_8 produced. If $4 out of every $20 to produce a pound of U_3O_8 is used for tailings disposal, a cost on the order of $0.6/ft^3 of tailings results (tailings specific gravity of 4 assumed). This value is in the same order of magnitude as the assumed volumetric soil disposal cost.

The topic and methodology for calculation of costs attributable to contaminated waste disposal from an MCF severe accident is in need of much more study from a technical, economic, and institutional standpoint. The uncertainties are so large that this impact-pathway may, in reality, have associated with some of the highest monetized damages associated with severe accident consequences.

7.8.6 Summary of Engineering Economic Accident Costs for Southeast and Southwest Sites

The results for the two sites show that overall, there is a considerably higher offsite impact for a severe accident at the Southeast site. This holds true for both the MCF and LCF Southeast plant site. The assumed value for nonfarm value for each site was similar. However, due to the numbers of people involved and the nonfarm costs, more economic damage was estimated at the Southeast site. In addition, since farmland at the Southeast site was assumed to be worth considerably more (by a factor of 3-5) than at the Southwest site, higher costs for the interdiction and condemnation of farmland were incurred for the Southeast site. The results (for offsite costs) show a very large discrepancy between the MCF and LCF cases. This is due to the wide disparity of the two source term strengths that were chosen as representative source terms.

The costs that were presented in previous sections have been summarized for each site and scenario in Table 7-38. The summary has been done on the basis of the type of countermeasure (offsite) or plant related (onsite) expense incurred as a result of the accident. For this study, it was assumed that the incremental mean costs for the Oak Ridge Reservation are simply added to the Southeast site economic damage for the categories listed. Thus, the totals in this table represent a best estimate of the economic damage (0-1609 km) of the different accident types for the mean weather case.

Table 7-38. Summary of accident costs for Southeast and Southwest sites

Type of cost	Southeast MCF $ (millions)	Southeast LCF $ (millions)	Southwest MCF $ (millions)	Southwest LCF $ (millions)
Evacuation	14.15	14.15	0.06	0.06
Relocation	1,420.0	0.30	0.13	0.01
Decontamination (farm plus nonfarm)	1,276.7	0.29	180.2	0.06
Interdiction (farm plus nonfarm)	6,871.0	1.26	873.4	0.18
Low-specific activity waste disposal (off activity site)	5557.8	1.43	3944.1	4.5
Condemnation (farm plus nonfarm)	2,634.0	0.23	678.0	0.55
Crop and milk losses	320.4	0.04	127.6	0.10
Replacement power	415.0	415.0	734.0	734.0
Loss of utility assets	2,700.0	2,700.0	2,700.0	2,700.0
Decommissioning	400.0	400.0	400.0	400.0
Utility site cleanup	2,200.0	2,200.0	2,200.0	2,200.0
Total	23,809.05	5,732.70	11,837.49	6,039.46

Table 7-39 presents the accident costs from Table 7-38 that have been appropriately weighted according to the accident probability. A comparison of the total cost (mills/kwh) reveals that the Southeastern and Southwestern sites are not largely different even though Table 7-38 shows that much high costs are incurred for many of the cost categories. This is due to the fact that the LCF cost is similar (actually slightly higher at the Southwest site due to the loss of the plant) at both sites and that the probability associated with this accident places a higher weighing factor on the LCF consequence in the totals. This results in totals that cause the Southeast and Southwest sites to be more similar than one would expect.

In the analysis that has been performed for both sites, a deliberate attempt was made to utilize as many NUREG-1150 parameters as practical. This philosophy necessitated the use of the FDA guidelines for the food chain model. A review of NUREG-1150 (NRC 1992) made the point that levels much lower than the Protective Action Guides are sometimes determined by political decisions and the market acceptance of the food. The review goes on to state that the result of these decisions is to increase economic impacts while reducing health impacts. This criticism applies equally to the methodology that has been presented here.

7.8.7 Variability in Cost Estimates Due to Weather

As was the case with the health effects, the MACCS models also provide a 95th percentile level associated with the variability in weather at the plant site. This variability does *not* include the spatial variation of weather across the computational grid (i.e. out to 1609 km). Table 7-40 provides an overall summary of the total accident costs for the 95th percentile (not including on-site costs nor health effects costs). These costs can be compared with previous results to obtain an understanding of the effects of weather variability on the total cost of the accident.

Table 7-39. Total economic risk due to severe accidents

Site/case	Probability/ reactor-yr	Economic risk $/reactor-yr	Economic risk mills/kwh
SE/MCF	0.000016	380,945	.046
SE/LCF	0.000046	263,704	.032
SE TOTAL	**0.000062**	**644,649**	**.078**
SW/MCF	0.000016	189,400	.023
SW/LCF	0.000046	277,815	.033
SW TOTAL	**0.000062**	**467,215**	**.056**

Table 7-40. Total accident costs 95th percentile weather variability

Case	95th percentile level* total accident costs $ (millions)
MCF/southeast site	26,614.2
LCF/southeast site	7.6
MCF/Oak Ridge reservation	2,020.0
MCF/southwest site	4,340.1
LCF/southwest site	1.8

*The 95th percentile level refers solely to uncertainties associated with weather conditions at the plant site over the course of a single year.

7.8.8 Conclusions

As previously stated, no comparisons between the MCF source term and the estimated Chernobyl source term were performed due to the lack of reliable estimates. The source term for the LCF was, however, compared to the TMI-2 accident. Despite the various differences in source terms, it is interesting to take note of recent cost estimates for the Chernobyl and TMI-2 accidents. According to NRC (1994), recent assessments of accident costs for Chernobyl are in the range of 30 billion dollars. No detailed comparisons between the hypothetical MCF accident mentioned in this chapter and the Chernobyl accident were performed due to the difficulties inherent in such an evaluation. As for TMI-2, NRC (1994) estimates the total costs to be approximately 4 billion dollars.

Even though the variability in consequences due to weather is addressed in Section 7.8.7, this is but one of many uncertainties that ultimately dictate the cost of an accident. This uncertainty component is probably less important than uncertainties in other parameters (such as source term release fractions). As was stated previously, estimating the costs associated with widespread societal countermeasures (decontamination, interdiction, etc.) is difficult. The MACCS code techniques for estimating accident costs (which are decades old) are in need of re-assessment. If better techniques and methods for analyzing accident costs are developed, then an uncertainty analysis on various parameters would provide more confidence in the estimates of the social cost of reactor accidents. Additional studies could also focus on the broader picture of industry viability, given a severe accident. This important aspect was not quantified in this study.

7.9 LEGAL LIABILITY, INSURANCE COVERAGE, AND THE CALCULATION OF EXTERNAL COST

This section provides an estimate of the portion of expected damages from severe reactor accidents that are reflected already in the private financial cost of the nuclear fuel cycle under the provisions of the 1988 amendments to the Price-Anderson Act.

The Price-Anderson Act specifies the strict and limited legal liability of individual nuclear operators for damages to third parties resulting from an "extraordinary nuclear occurrence (ENO) associated with the operation of a commercial or government nuclear facility. An ENO is defined as an event causing substantial radiation levels and substantial damages to third parties or

property off-site as determined by the Nuclear Regulatory Commission.[8] In the event of an ENO, individuals can file claims for monetary loss stemming from personal injury or damage. The LCF and MCF events in our study are both ENOs.

The Price-Anderson Act was originally passed in 1957 and amended most recently in 1988 to serve the dual purpose of promoting the nuclear industry while providing an explicit "no-fault" mechanism for compensating third parties in the case of a nuclear accident. To provide for compensation, the Act specifies a legal standard of strict liability for claims up to explicit limits, and requires that firms carry private insurance to guarantee the rapid availability of funds for compensation.[9] To hasten the introduction of nuclear power the Act exempts operators from all liability for damages in excess of a specified limit.[10]

Under some circumstances, the imposition of strict liability for third party damages can effectively provide incentives for a firm to exercise an efficient level of care in its activities and for the firm and its customers to consider fully the value of potential damages to third parties. To accomplish this, the liability system must overcome problems of detection, monitoring of damages, enforcement of liability and the potential insolvency of the liable party. If such problems can be overcome, one would expect the firm to anticipate its potential liability by charging a price *ex ante* that is adequate to reimburse expected damages.

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[8] 42 U.S.C. § 2014(j) (1982). The scope of coverage is "omnibus" in nature, extending to utility licensees and to any other persons who may be legally liable. The scope includes any accidents, including those that may come about because of theft or sabotage, in transportation of nuclear fuel and waste materials related to the operation of a nuclear reactor.

[9] To expedite the provision of compensation for accident victims in the event of an ENO the Act waives legal defenses of contributory and comparative negligence, waives defenses of charitable and governmental immunities (which applies only to nuclear research facilities), and relaxes the statute of limitations defense. If the NRC does not declare a particular accident an ENO, nuclear plant operators are not required to waive these defenses. Victims would then have to litigate their claims in court; however, the industry's liability would still be limited (Rosenthal 1990, p. 124, 126).

[10] "Under the Act, the victims of a nuclear power accident would have a relatively assured receipt of some compensation as a trade for a potentially larger, though possibly not collectable, traditional tort remedy" (Reitze and Rowe 1987, p.10186). The Presidential Commission on Catastrophic Nuclear Accidents (1990) concluded that the imposition of strict liability is essential to the delivery of compensation. "(C)ommon law principles of tort in traditional methods of litigation would result in the outright denial of recovery to many deserving claimants and would make recovery for others a difficult and protracted process," (p.3).

Detection, enforcement and monitoring of short run damages appear to be surmountable issues in the heavily regulated nuclear power industry. However, monitoring of long run damages such as cancers that may be latent for many years encounters the difficulty of establishing causation that has plagued radiation tort litigation.[11] Abstracting from the compensation issue and focusing on the issue of estimating marginal damages, we assume the information provided in this report accurately forecasts cancers that are likely to occur.

The remaining issue concerns the solvency of the firm in the face of potentially large damage liabilities. One way to guarantee solvency is to require the firm to bond itself against eventualities through the purchase of private insurance. Further, insurance premiums must be paid *ex ante*, guaranteeing that the expected damage is reflected in the private financial costs of the economic activity. Hence, in a stylized situation of strict and unlimited liability absent monitoring and enforcement problems, and with a requirement that a firm fully insure against third party damages, there does not exist an externality that is relevant from the perspective of economic efficiency. There would remain a probability that damages to third parties might occur, but those parties could be fully compensated in such an event and the firm would internalize the expected damages in its activities. In this case one could witness third party effects, or a positive probability of third party effects, without there being an external cost.

Before the Price-Anderson Act was adopted, the prevailing legal mechanism for potentially damaged third parties to obtain compensation was the tort system embodied in common law. Generally speaking, the tort system imposed a legal standard that required a finding of negligence on the part of a firm before liability for damages could be assigned. The Price-Anderson Act stipulated an alternative standard of strict liability for third party damages on the nuclear industry, while at the same time limiting that liability.

There are two levels of coverage for liability assigned under the 1988 amendments to the Act for damages that might result from an ENO. The first level is a requirement that individual nuclear operators carry $200 million in private liability insurance against damages to third parties. The second level is achieved for damages in excess of $200 million through a pooling of liability shared equally among all nuclear operators. Every operator is potentially liable for up to a maximum of $63 million that can be assessed at a maximum of $10

[11] The Act relies upon state tort law for rules of causation (Berkovitz 1989, 4).

million per year.[12] The approximately 110 operating nuclear facilities make the total liability of the industry about $7 billion. For all damages to the public beyond this amount, the Price-Anderson Act provides an explicit exemption from liability for individual operators, the plant owner, builders and parts suppliers and for the industry as a whole.

7.9.1 Incentives for Efficiency

These two levels of coverage differ in two important respects. Insurance premiums for the operator's requisite $200 million in private insurance for damages to third parties is experience rated, providing an incentive to operate facilities safely. (In addition, operators typically carry insurance that is also experience rated for damages to operator owned property.) However, the $7 billion industry pool for extended damages to third parties masks accountability for damages. The individual operator has a limited incentive—exposure of up to $63 million—to avoid damages that may total up to $7 billion or greater. Of course, there are a variety of important public relations and regulatory costs that would accrue in the event of an ENO that provide incentives in addition to financial liability.

The second respect in which the two levels of coverage differ is in the accounting for potential damages in the price of electricity. To the extent that the price of electricity does not reflect potential damages, the price is an underestimate of the social opportunity cost of resources allocated to the production of electricity. The requirement to carry private insurance for up to $200 million in damages guarantees that the expected value of damages that may occur in the future up to this amount are reflected in the price of electricity produced with the nuclear fuel cycle. (The same applies to insurance against damages to operator owned property.) The second layer of coverage stemming from the industry-pooled liability does not require a financial contribution prior to the occurrence of an ENO, and the current price of electricity does not reflect the expected value of damages in this range. Hence, damages above $200 million are not presently accounted for in the price of electricity.

This type of potential inefficiency has caused confusion with regard to the issue about whether an externality is present. If individuals can expect to press claims successfully for damages up to more than $7 billion through the mechanism

[12] Potential insolvency or illiquidity is not an important problem for responsibilities stemming from the industry's pooled liability. An NRC report determined that nearly all licensees in all years from 1978 to 1983 could have met a $10 million assessment within three months from internal cash flow. [U.S. Nuclear Regulatory Commission, "Additional Information on Retrospective Nuclear Liability Insurance Proposed by NRC 5" (April 1985) reprinted in the 1985 House Interior Committee Hearings, (p. 201).]

of the industry pool, and if the pool consists entirely of assessments on the industry, then absent any of the other problems we have discussed concerning the performance of a liability standard, one could expect the price for nuclear power to accurately reflect its environmental costs. However, to our knowledge there is no public service commission or nuclear operator that sets aside money in advance to cover the potential $63 million liability in the unlikely event of a catastrophic accident at any nuclear facility. Therefore, it is likely that present period financial costs borne by a nuclear operator do not reflect this potential retroactive liability.

In summary, two different concepts of efficiency are evident. When an inefficient amount of environmental damage occurs, nuclear power is not produced at the least social cost and "productive efficiency" is not obtained. On the other hand, if safety regulators successfully enforce prudent operation of facilities, then the outcome would be productively efficient.[13]

However, if the resulting damage that is expected to occur is not reflected in prices, even if this is an efficient level of damage, the result is not "allocatively efficient." That is, even if there is an efficient level of care taken *given* the amount of nuclear power that is produced, there may be too much produced if its price does not reflect expected damages.

7.9.2 Estimate of Externality

One previous estimate of the subsidy to nuclear operators implicit in the Price-Anderson Act limit on liability was developed by Dubin and Rothwell (1990), who assumed the distribution of damages resulting from an ENO to be between $1 million and $10 billion. The upper limit was the worst case scenario described by the Nuclear Regulatory Commission and excludes estimates of health effects.[14] The authors use two sources of estimated probabilities for damages within various parts of these ranges. For damages greater than or equal to $10 billion the authors use probabilities provided by the NRC. For damages less than $200 million—the amount for which nuclear operators must hold private insurance—the authors infer probabilities from premiums charged by private insurers. The authors use these two probabilities to establish endpoints of a logistic probability density function over all damages between $1 million and $10

[13] Rosenthal (1990, 137-138) suggests moral hazard could be evident in other decisions such as the location of facilities. Nuclear power is highly concentrated along the East coast and near population centers where energy demand is large, rather than in remote regions.

[14] U.S. Nuclear Regulatory Commission, "Statement of the U.S. Nuclear Regulatory Commission Concerning Price-Anderson," Hearings Before the Subcommittee on Nuclear Regulation of the Committee on Environment and Public Works, U.S. Senate, Reauthorization of the Price-Anderson Act, 99th Congress, October 22-23, 1985, 255-310.

billion. Dubin and Rothwell assume that the subsidy to the industry includes only damages in excess of the industry-pooled liability limit of $7 billion. They estimate the subsidy to be $21.72 million per year for each facility in 1985 dollars.[15]

Our methodology differs from Dubin and Rothwell because we use probabilities and damages associated with accidents that are calculated in this study. In the case of an ENO at either the Southwest or Southeast facilities, approximately $5.3 billion is expected in damage to utility assets, decommissioning costs, and costs incurred for utility site cleanup. Mechanisms to internalize these costs include private insurance, and shareholder behavior toward uninsured potential liabilities. These costs represent the lion's share of costs in the case of an LCF.

In addition, it is likely that present period financial costs borne by a nuclear operator do not reflect potential retroactive liability associated with the industry pool. In this case one should consider all damages expected in the case of an ENO above $200 million. For comparison, we consider the $7 billion and $200 million figures.

In the event of an ENO, the noninternalized portion of damages is the sum of nonhealth and health damages, less the liability limit. Data for nonhealth damages excluding damage to utility property is found in Table 7-38. For health damages, we use our aggregated results. From Tables 7-15, 7-16, 7-20, and 7-21, we estimate the ratio of latent cancer injuries to latent cancer fatalities for an MCF and LCF at each reference site. (We ignore early injuries and fatalities, as there are very few of them.) This ratio is 0.005 at the Southeast site and 0.003 at the Southwest site. We use this information to disaggregate the injuries in the event of an MCF and LCF at each site, using the expected probability formula on page 7-43 and the expected mean total damages in Table 7-25. The resulting estimates for nonhealth (excluding damage to the utility's own property) and health damages and their sum in the event of an ENO are reproduced in Table 7-41.

[15] The authors assume a real rate of inflation of 5%.

Table 7-41. Externalities of severe reactor accidents

	Damages if event occurs			$7 billion liability limit		$200 million liability limit	
	Health damage ($)	Nonhealth damage ($)	Sum ($)	Expected annual externality ($)	Externality (mills/kWh)	Expected annual externality ($)	Externality (mills/kWh)
SE							
MCF	1.2511E+10	1.8509E+10	3.102E+10	384,315	0.047	493,115	0.060
LCF	62,553,604	432,000,000	494,553,604	0	0	13,549	0.002
Sum				384,315	0.047	506,664	0.062
SW							
MCF	1,285,741,700	6,537,000,000	7,822,741,700	13,163	0.002	121,963	0.015
LCF	4,307,235	739,000,000	743,307,235	0	0	24,992	0.003
Sum				13,163	0.002	146,955	0.018

The expected damages are the product of damages in the event of an ENO times the probability of an ENO, and the externality is the portion of expected damages that are not internalized through the liability limit. In Table 7-41, the expected externalities that correspond to the risk of each type of ENO are summed for each liability limit. These estimates appear shaded. The externality in the Southeast Reference environment if the $7 billion liability limit binds is 0.047 mills/kWh, and if the $200 million binds it is 0.062 mills/kWh. In the Southwest Reference environment, if the $7 billion liability limit binds the externality is 0.002 mills/kWh, and if the $200 million binds it is 0.018 mills/kWh.

8. TRANSPORTATION SHIPMENTS

This chapter addresses the methodology for estimating the impacts and damages associated with the transportation stages of the nuclear fuel cycle at a southeast reference reactor site (former Clinch River Breeder Reactor near Oak Ridge, Tennessee) or a southwest reference reactor site (Four Corners, located west of Farmington, New Mexico). The steps of the U.S. nuclear fuel cycle involve uranium mining and milling, conversion of the uranium oxide (U_3O_8, called "yellowcake") to uranium hexafluoride (UF_6), enrichment in a gaseous diffusion plant, manufacturing the enriched uranium oxide (UO_2) into fuel, "burning" the fuel in nuclear reactors, and ultimately, disposal of the radioactive spent fuel in a geologic repository. Interconnecting each fuel cycle step is a transportation step that involves materials that are radioactively and/or chemically hazardous, and thus, has some impact on society. Impacts may be categorized as either "normal" or "accidental". Normal impacts are those associated with day-to-day transport operations, and include both non-radiological (e.g., injuries and deaths from accidents) and radiological (e.g., radiation from shielded shipping containers) factors. Radiological and chemical accident impacts are those consequences of potential low-probability accidents severe enough to release radioactive and hazardous materials from the shipping container. Radioactive materials released from the shipping container may be modeled to determine how these materials are dispersed in the environment, and to estimate the exposure (contact, inhalation, ingestion) and dose received by the population due to an accident.

Operation of the nuclear fuel cycle associated with nuclear reactor power plants involves transporting a number of radioactive and hazardous materials between various fuel cycle facilities. This chapter presents a description of current transportation technologies and estimates the health effects associated with using these technologies in a reference nuclear fuel cycle. The analysis considers both the radiological effects and chemical toxicity effects associated with the transport of radioactive materials to support the operation of a nuclear reactor power plant. This includes transportation of radioactive and hazardous materials associated with the once-through nuclear fuel cycle.

There are five major transportation steps in the representative U.S. nuclear fuel cycle: (1) U_3O_8 shipments between a uranium mine/mill and a conversion plant, (2) UF_6 shipments from a conversion plant to an enrichment plant, (3) enriched UF_6 shipments between the enrichment plant and the fuel fabrication facility, (4) shipments of newly-assembled fuel (fresh fuel) from the fuel

fabrication facility to the nuclear reactor plant, and (5) radioactive spent fuel shipments from the nuclear reactor plant to a spent fuel storage facility. Additional steps are possible if there is reprocessing, plutonium recycle, or if the fuel fabrication procedure involves multiple steps at separate assembly plants. The mining procedure, by which uranium ore is removed from the host geology, and the milling procedure, where the ore is processed to extract U_3O_8, are assumed to occur at the same geographic location and, thus, there are no associated transportation risks to the general public. As described in Chapter 5, uranium mining and milling operations are frequently located in the same area. All five of the major transportation steps in the representative nuclear fuel cycle are analyzed. Two separate scenarios were used to analyze spent fuel transportation to account for shipments from either the southeast or the southwest reference reactor sites to the repository.

8.1 TECHNOLOGY

Transportation shipments are necessary links in the U.S. nuclear fuel cycle. The transportation of radioactive materials is regulated by the U.S. Department of Transportation (DOT) and the U.S. Nuclear Regulatory Commission (NRC). Their regulations delineate packaging requirements, allowable radiation dose rates, and handling procedures such that shipments of radioactive materials are conducted to reduce the risks to the public and workers. Radioactive material shipping packages are designed to transport material within a framework of criteria set forth in DOT and NRC regulations. An excellent reference on nuclear fuel cycle risk assessment (Schneider 1982) has been used extensively in the description of transportation technology.

Selection of transportation technologies for the steps of the nuclear fuel cycle are dependent on the materials being handled. Uranium ore is commonly transported between a uranium mine and mill in large trucks with payloads of 25 tons or more, just like coal, iron ore, and other minerals. Yellowcake, from uranium mills, is shipped to conversion plants in 55-gal drums. The conversion plant changes the chemical form of yellowcake (a powder) into UF_6 (a solid form when stored at room temperature). Uranium hexafluoride is shipped to and from the enrichment plant in cylindrical shipping containers. The enriched UF_6 is then converted to UO_2 pellets and manufactured into fuel assemblies at a fuel fabrication facility. Fresh fuel is shipped on trucks and requires only modest packaging (e.g., wooden shipping crates), since it is only mildly radioactive from decay of the long-lived uranium isotopes. Only after the uranium fuel is "burned" in a nuclear reactor must it be shipped in massive, shielded spent-fuel casks. Spent fuel casks are designed to withstand extreme accidents intact, protecting the general public from radiation exposure.

Each transportation step of the nuclear fuel cycle involves conditions and assumptions about material quantities, form, distances, shipment method, and route. In order to compare nuclear fuel cycle risks, we have selected a unit of net electricity production (i.e., a reactor year) as a common basis. The following paragraphs describe the transportation technologies associated with each link in the nuclear fuel cycle transportation system.

Transportation technologies and shipment quantities

Uranium ore is shipped to the ore stockpiles adjacent to uranium mills in 25-ton (22.73 MT) truckloads. Standard dump trucks or hopper trucks are used, although the ore is usually covered to minimize losses during transport. Shipment distances between the mine facility and the uranium mill are generally short (<50 km). Transport of raw ore generally takes place on private haulage roads, rather than public highways. Uranium ore is designated as "low specific activity" (LSA) material by DOT regulations, and requires no special packaging when transported in an exclusive-use vehicle. Based on previous assumptions about ore grade and fuel cycle needs, it is estimated that about 12,800 truckloads (at 25 tons/load) of uranium ore would be required annually to support the production of a reactor year of electricity. Since shipments generally occur on private roads, and in many cases, mines and mills are located in close-proximity, and the fact uranium ore has low radioactivity, we have excluded it from our risk analysis. In addition, potential transportation accidents involving impacts or collisions pose the only viable mechanism for accidental release since uranium ore is not flammable and does not react energetically with water.

Yellowcake shipments. The product of uranium milling (or in situ leaching) is uranium ore concentrate, commonly called yellowcake. Yellowcake contains from 90 to 96% U_3O_8 and is packaged in 55-gal drums for shipment to the uranium conversion plant. Each drum weighs between 300 to 400 kg (650 to 950 lb), depending on the product density. Shipment of yellowcake consists of 50 DOT specification 17H steel drums carried in a van-type trailer. Each drum has a removable head consisting of a lid and bolt locking ring closure, as shown in Figure 8-1. In shipment configuration, 50 drums, each containing ~350 kg of yellowcake are loaded, standing on end, into a conventional van-type trailer. Drums are arranged in two groups of 25 drums each to concentrate the weight over the trailer axles. Wood supports are nailed to the floor of the trailer to prevent shifting of the drums during transport. To support production of a reactor year of electricity, 21 annual shipments of yellowcake would be required. Uranium ore concentrate presents both a radiological and a chemical health hazard if inhaled. The radiological effects result from exposure to the radioactive isotopes in the natural uranium. The chemical hazard of the material are due to

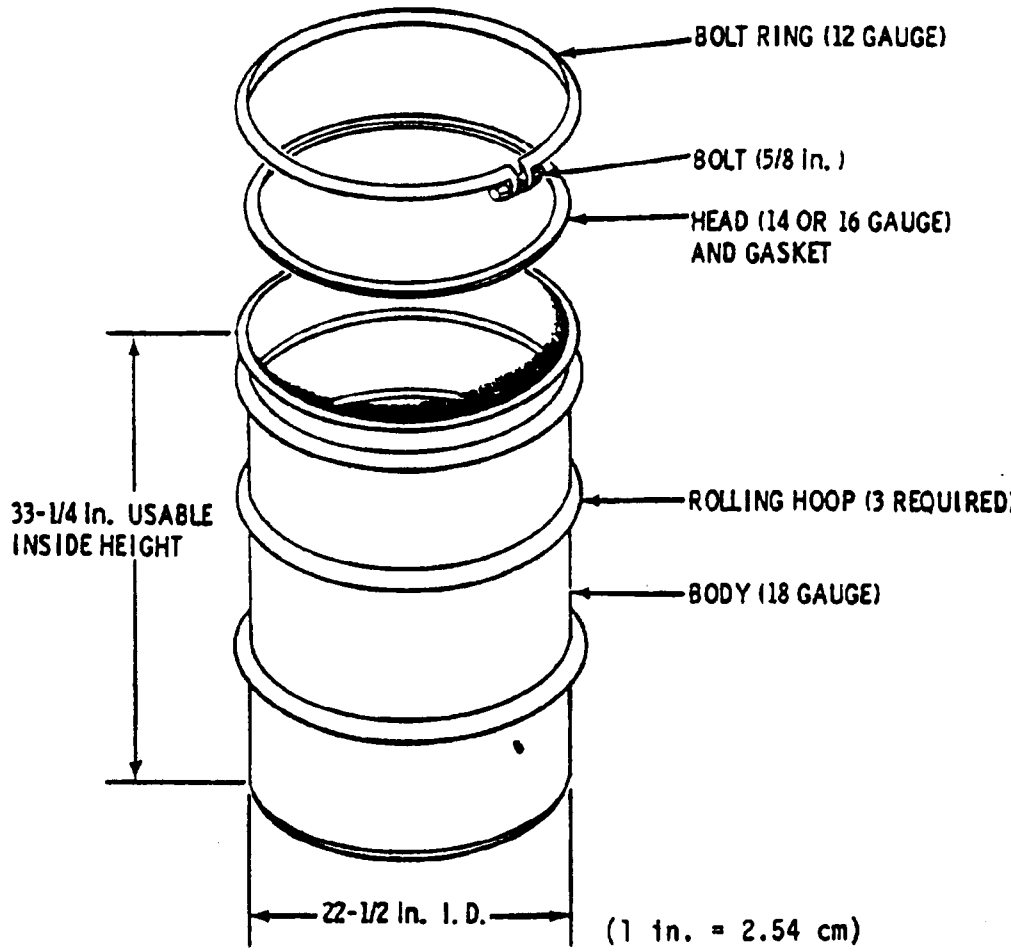

Figure 8-1. Steel drum for transporting yellow cake

the toxicity of the heavy metal, uranium. The extent of health effects experienced by inhalation of yellowcake are a function of the solubility of the material. As an insoluble compound, uranium is slow to be eliminated from the body and its major effect is associated with its radiological hazard from continued exposure. As a soluble compound, the chemical toxicity of uranium can result in damage to the kidneys and other organs.

Uranium hexafluoride shipments. At the conversion plant, yellowcake is purified during conversion to UF_6. This material is called natural UF_6, where the term natural refers to the abundance of the ^{235}U isotope found in nature (0.711 wt% ^{235}U). Natural UF_6 is transported to the enrichment plant where it is enriched to the desired enrichment (assumed to be 4.7 wt% in this study). Enriched UF_6 is then shipped to the fuel fabrication facility.

Natural UF_6 qualifies as LSA material. Packaging standards are, thus, set by the chemical hazard of the material rather than by its radioactive properties. Natural UF_6 is shipped in 9 or 12.7 MT capacity steel cylinders. Cylinders may be transported by truck or rail; however, most shipments are by truck. Two 9 MT or one 12.7 MT cylinder can be transported on a standard truck trailer. For this study, we have assumed that the 12.7 MT cylinders are used. Each cylinder is 48 inches (122 cm) in diameter and 150 inches (381 cm) long, with a gross weight of about 33,000 lb. Each cylinder has a volume of 142.7 ft^3. To support a reactor year of electricity production, it is assumed that 25 shipments of 12.7 MT UF_6 cylinders are required annually.

Enriched UF_6, unlike natural UF_6, is not exempt from classification as fissile material. Therefore, it cannot be shipped as LSA material. Instead, enriched UF_6 shipments constitute a Type B quantity of radioactive material under NRC regulations. Protective overpacks are used for either the 2.3 MT or 9 MT cylinders to satisfy transportation accident test criteria set forth in 10CFR71. Enriched UF_6 is generally shipped by truck, with each truck capable of carrying five 2.3 MT or one 9 MT cylinders protected by overpacks. For this analysis, we have assumed that 9 MT cylinders are utilized. Each 9 MT cylinder is 48 inches (122 cm) in diameter and 121 inches (307 cm) long, with a gross weight of 26,000 lb. Each cylinder has a volume of 109 ft^3 UF_6. To support a reactor year of electricity production, it is estimated that 3 shipments of 9 MT UF_6 cylinders are required annually.

Uranium hexafluoride is a highly reactive material which reacts chemically with water, ether, and alcohol to form soluble reaction products. It reacts with moist organic compounds and with many metals; however, its reactivity with fluorocarbons is low. Uranium hexafluoride does not react with oxygen, nitrogen, or dry air, and it is sufficiently inert to aluminum, copper, nickel, and

aluminum-bronze. When released to the atmosphere, UF_6 combines chemically with the moisture present in the air to form hydrogen fluoride (HF) gas and uranium oxyfluoride (UO_2F_2), a particulate. All products of UF_6 release represent a health hazard when inhaled. HF gas presents a danger that is only chemical, while UO_2F_2 is both a chemical and radiological hazard. For all enrichments of ^{235}U, the chemical toxicity is generally considered to be far greater than the radiotoxicity. Hydrogen fluoride gas causes severe irritation of the eyes and respiratory system. If sufficient quantities are inhaled, death from pulmonary edema can occur. HF damage is a function of both the concentration inhaled and the duration of exposure. The chemical effects of UO_2F_2 involve toxicity to both fluoride and uranium.

Fresh (unirradiated) fuel shipments. The fuel fabrication plant converts the UF_6 to UO_2, forms the UO_2 into pellets that are assembled into fuel pins, and bundled together as fresh fuel assemblies. The term "fresh" refers to the fact that the fuel has not been irradiated in a nuclear reactor. Fresh fuel assemblies (for a PWR) generally weigh about 650 kg (1430 lb). Each assembly is roughly 14 feet long, and about 22 by 22 cm (9 by 9 inches) square. Fresh fuel assemblies are commonly packaged in wooden shipping crates that are placed within protective outer packages designed to prevent damage to the fuel elements in transit. Generally, two PWR fuel assemblies are placed within a protective overpack, and about six overpack containers are shipped per truck trailer. To support the generation of a reactor year of electricity, the reactor would require 49 fresh fuel assemblies annually, which translates to roughly 4 shipments per year. It is important to note that the reactor operates on an 18-month refueling cycle, and most plants maintain a full-core reload supply of fresh fuel at the reactor.

Spent (irradiated) fuel shipments. Fresh fuel is burned (irradiated) in the nuclear reactor to produce heat that, in turn, is used to generate electricity. Each fuel assembly remains in the reactor for 4.5 years. When it is discharged from the reactor core, the fuel assembly is kept at the reactor in an underwater storage pool to allow some of the intense radiation to decay. After at least 10 years of storage, it is planned that spent fuel would be shipped to a final disposal site, a deep geologic repository. Shipment of spent fuel involves loading (underwater) of a massive spent fuel cask. Truck casks generally weigh 40 tons, and casks shipped by rail may weigh 100 tons or more. Spent fuel casks are licensed by the U.S. NRC and must undergo rigorous testing to assure that each cask can withstand severe accidents without releasing the highly radioactive materials contained within.

A representative truck spent fuel cask is shown in Figure 8-2. The shipping system consists primarily of the cask and a truck trailer. The cask has

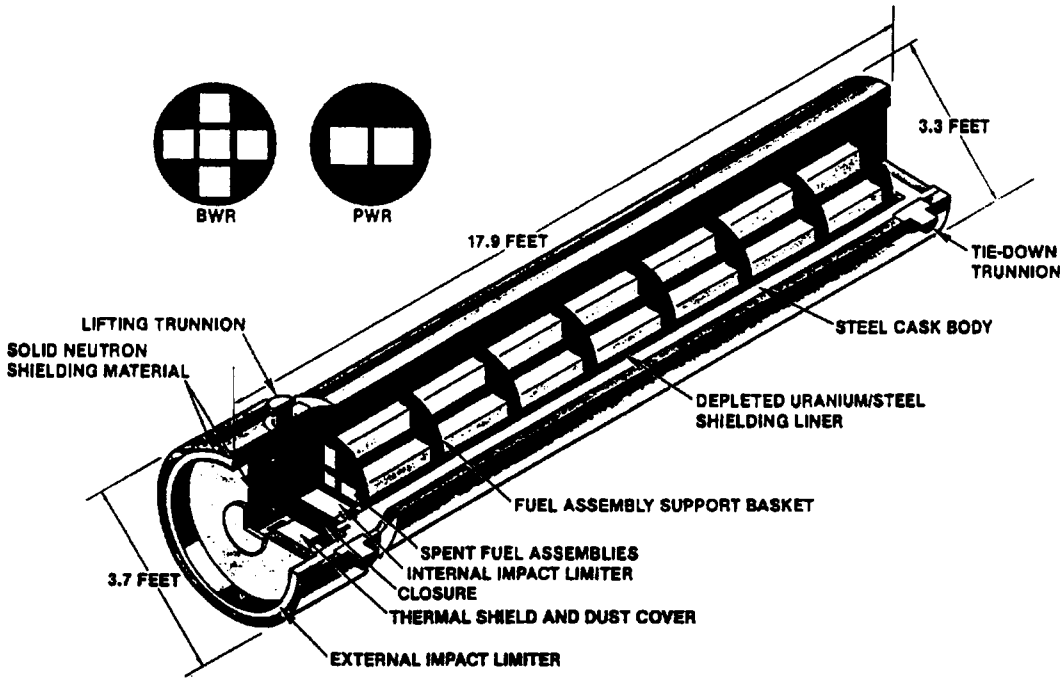

Figure 8-2. Truck spent fuel cask

an overall length of 215 inches (5.44 m) and a diameter of 39 inches (1 m). Dimensions of the internal cask cavity are 178 inches (4.52 m) in length and 22.7 inches (0.57 m) in diameter. Interchangeable fuel baskets support the spent fuel assemblies inside the inner cavity. Each cask has about 3.0 inches of neutron shielding material composed of a solid, organic material, and gamma shielding of about 9 to 10 inches thickness (steel equivalent). Gamma shielding materials used include steel, lead, or depleted uranium. To support the generation of a reactor year of electricity, it is assumed that 49 assemblies must be shipped annually, which translates to 13 spent fuel cask shipments (4 PWR assemblies/cask) per year. It is important to note that spent fuel will be stored in underwater pools at the reactor for at least 10 years before shipment. In addition, all spent fuel discharges from the reactor are presently stored on-site in underwater storage pools, since current U.S. high-level waste disposal plans call for the repository to begin spent fuel acceptance in the year 2010.

8.2 SITE CHARACTERIZATION

The analysis of nuclear fuel cycle transportation impacts involves specifying the locations of various fuel cycle facilities, selecting the most likely transport routes, and then calculating the risks of transporting nuclear materials along those routes. This study does not consider a fixed exposure or accident site along the routes but, instead, models moving line- and point-sources along the entire route with accident rates expressed per unit distance traveled. The accident analysis considers the probability and consequences of accidents occurring in three different population zones on two different road types.

Six transportation scenarios are considered: (1) U_3O_8 shipments from the mining/milling facilities near Grants, New Mexico, to the conversion plant at Metropolis, Illinois; (2) natural UF_6 shipments from the conversion plant at Metropolis, Illinois, to the enrichment plant at Portsmouth, Ohio; (3) enriched UF_6 shipments from the Portsmouth enrichment plant to the fuel fabrication plant at Richland, Washington; (4) fresh fuel shipments from the fuel fabrication plant at Richland, Washington, to the southeastern reference reactor site; (5) spent fuel shipments from the Southeastern reference reactor site to the proposed Yucca Mountain Federal Repository; and (6) spent fuel shipments from the Southwestern reference reactor site in Farmington, New Mexico, to Yucca Mountain.

The fresh fuel shipments from Richland, Washington to the southwest reference reactor site were not explicitly modeled because of the short distances and trivial impacts involved; the fresh fuel shipments for the southwest site are simplistically assumed to have the same (nearly trivial) impacts as the analogous shipments to the southeast site (designated above as scenario 4).

The HIGHWAY computer code model (Joy 1983) was used to select routes and analyze each transportation scenario. The HIGHWAY model is designed to simulate routes on the highway system in the U.S. The data base includes all interstates; most U.S. highways; and many roadways with state, county, or local classifications. It represents ~240,000 miles of roadway. Several different routing options are available in the highway program, including probable commercial routes, routes on the interstate system, and routes that bypass major urbanized areas. Additional detailed routing analysis can be performed by blocking individual or sets of highway segments or intersections contained in the data base. The selection of preferred routes assumes that each shipment consists of highway route controlled quantities of radioactive materials. Travel time is optimized based on maximum utilization of the interstate highway system with preference given to bypasses around major cities, except where alternate routes have been designated by state or local officials.

An analysis of the transportation scenarios was performed using the RADTRAN 4 risk assessment code (Neuhauser 1992) to determine the radiological impacts associated with the transport of radioactive materials in a once-through nuclear fuel cycle. The HIGHWAY model provides the total travel distance and the fraction of travel in each population density zone which are needed inputs to the RADTRAN 4 program and are given in Table 8-1. The routing data from the HIGHWAY model, which makes use of 12 population density zones, has been collapsed into 3 zones for use in RADTRAN. The 3 zones (i.e., rural, suburban, and urban) are further divided into freeway (interstate) or non-freeway road types. Non-freeway designates a U.S., state, or local road. Factors such as population density, accident rates, and vehicle velocity can be varied for different zones. Each population zone, along with an associated road type, make up a RADTRAN 4 transportation link. The mileage for each link in the route is shown in Table 8-1.

8.3 ACCIDENT SCENARIOS AND RELEASES

An analysis of the transportation scenarios was performed using the RADTRAN 4 risk assessment code (Neuhauser 1992) to determine the radiological impacts associated with the transport of radioactive materials in a once-through nuclear fuel cycle. The radiological impacts considered were health effects associated with both normal transport (incident-free) and with low-probability accidents severe enough to release some or all of the radioactive material. Incident-free risk results from exposure of the surrounding population to radiation emitted by the waste packages during normal transport.

Table 8-1. Transportation route analysis from HIGHWAY model[1]

Population density zone	Population density mean (people/km^2)	Total travel distance for each HIGHWAY routing scenario (kilometers)					
		Grants, NM to Metropolis, IL	Metropolis, IL to Portsmouth, OH	Portsmouth, OH to Richland, WA	Richland, WA to SE reactor site	SE reactor site to Yucca Mt. Site	SW reactor site to Yucca Mt. Site
Rural	0-139	1,723.5	648.1	3,186.2	3,294.1	2,965.0	1,389.7
Suburban	139-3,326	320.2	161.1	662.9	646.1	538.4	78.5
Urban	3,326-10,000+	35.3	13.1	18.1	23.8	38.7	10.8
	Total:	2,079.0	822.3	3,867.2	3,964.0	3,542.1	1,479.0
RADTRAN 4 transportation link							
Rural freeway		1,723.5	587.1	3,112.2	3,279.6	2,856.0	1,165.7
Rural non-freeway		0.0	61.0	74.0	14.5	109.0	224.0
Suburban freeway		320.2	161.1	662.9	646.1	538.4	78.5
Urban freeway		35.3	13.1	18.1	23.8	38.7	10.8
	Total:	2,079.0	822.3	3,867.2	3,964.0	3,542.1	1,479.0

[1] Reference Joy, 1983. All distances are given in kilometers.

Accident impacts considered both acute fatalities and latent cancer fatalities (LCFs) (chronic) to both the present and future generations due to accidents. The accident risk (expected value of dose from accidents) is the combination of the products of estimated dose for each accident-severity category and the associated probability of occurrence for the category.

One method to establish accident-severity categories is to assign a severity category based upon the duration and temperature of fire occurring during an accident and the crush force exerted on the package. For this study, eight accident-severity categories were considered, with category 1 used to represent the regulatory conditions of Type A packages; category 2 used to represent regulatory conditions for Type B packages; and higher categories defined for situations that exceed regulatory limits. This is a common method for defining accident-severity categories as described in an earlier RADTRAN guide (Madsen 1986). No other categorization schemes currently in use were identified.

The probability of truck accidents was defined for each of the eight accident-severity categories and each of the three population zones for a total of 24 accident probabilities. In addition, the fraction of contents released was defined for 5 physical/chemical groups, each with 8 accident-severity categories, for a total of 40 release fractions. The accident probabilities and release fractions are given in Appendix E for each of the transportation scenarios. The release fractions for UF_6 were used to calculate both the radiological and chemical health effects.

RADTRAN 4 models both the incident-free radiological exposure and the consequences of radiological releases due to severe accidents. The incident-free risks are dependent on the radiation dose rate from the shipment, number of shipments, package dimensions, route distance, vehicle velocity, and population densities along the travel routes. The accident risks are dependent on the radiological inventory, accident severity, probability of occurrence for each accident category, amount of inventory released, and the dispersibility of the waste form (amount aerosolized, respirable, and inhaled). The primary RADTRAN assumptions used for the transportation risk assessment are shown in Table 8-2.

Incident-free radiological exposure was determined by calculating a total body dose for the transport crew and the general population from the radiation dose rate at 1 m from the package surface. Both point-source and line-source approximations were used based upon the distance between the exposed individuals and the radiation source. Each shipment was modeled as a single "effective" package with a homogeneous distribution of the radiological inventory throughout the package. The package size, or characteristic dimension, is the largest linear dimension of the configuration and is used in the line-source

Table 8-2. RADTRAN 4 assumptions for the nuclear fuel cycle externalities study transportation risk assessment

Scenario	Route description	Primary isotopes[1]	Total inventory (Ci/shipment)	Dispersion category[2]	Package size[3] (m)	Radiation dose rate[4] (mrem/hr)	Shipments per reactor-yr	Packages per shipment
1	NM mine/mill to IL conversion plant	U-235 U-238	0.14 5.75	5	7.92	0.1	21	1
2	IL conversion plant to OH enrichment plant	U-235 U-238	0.2 4.2	7	3.07	0.1	25	1
3	OH enrichment plant to WA fuel fab. plant	U-235 U-238	0.88 2.89	7	3.07	0.1	3	1
4	WA fuel fab. plant to SE reactor site[5]	U-235 U-238	0.03 3.5×10^{-4}	3	4.00	0.001	4	1
5	SE reactor site to Yucca Mountain site	21 isotopes (see Table E-1)	6.898×10^{5}	varied	5.94	5	13	1
6	SW reactor site to Yucca Mountain site	21 isotopes (see Table E-1)	6.898×10^{5}	varied	5.94	5	13	1

[1] Radionuclide data was obtained from the ORIGEN2 computer code (Croff, 1980).

[2] The dispersion category, used to classify the relative dispersibility of the radiological inventory, is used to determine the amount of material that is aerosolized and respirable. Dispersion category 7 is for volatile solids such as UF_6 and category 5 is for small powder such as yellowcake. The dispersion category for the spent fuel varied by isotope (category 10, gas, for Kr-85; category 7 for Cs-134; category 3, solid loose chunks, for actinides; etc.). Isotope by isotope categorization is given in Table E-1 of Appendix E.

[3] The package size, or characteristic dimension, is the largest linear dimension of the configuration. This value is used in determining the incident-free risk from exposure to radiation emitted from the package.

[4] Radiation dose rate at 1 meter from the package surface. The use of an "exclusive-use vehicle" is required by 49 CFR 173 if the dose rate at 1 meter exceeds 10 mrem/hr.

[5] WA fuel fab. plant to the SW reactor site was not explicitly modeled because of its very low impacts, and the analogous shipment to the SE site is used as a surrogate.

approximation to calculate total dose. The source term was conservatively assumed to consist entirely of gamma radiation for calculation of incident-free health effects. In fact, it consists of beta and alpha radiation which is less dangerous to health because of its very low capacity to penetrate matter.

The dispersion category is used to characterize the relative dispersibility of the radiological inventory based upon the chemical and physical properties of the material. RADTRAN uses the dispersion category to determine the fractions of the total inventory that are aerosolized and respirable. RADTRAN contains default values for aerosolized and respirable fractions of the total inventory based on the assignment of dispersion category. The user assigns a dispersion category to each material and chooses release fractions as a function of accident severity based on the type of transportation package.

8.4 PRIORITY IMPACT-PATHWAYS

This section discusses the priority impact-pathways associated with the transportation of radioactive and hazardous materials within the nuclear fuel cycle. Table 8-3 lists the primary emissions or activities, their associated environmental pathways and impacts, and lists the evaluation status of each impact.

Operation of the nuclear fuel cycle involves the transport of a number of radioactive and hazardous materials. These materials include yellowcake from the uranium mill to the UF_6 conversion plant, UF_6 to and from the gaseous diffusion plant, fresh fuel from the fuel fabrication plant to the reactor, and spent fuel from the reactor to the repository.

The radiological impacts of all these materials have been evaluated, both during normal transport and resulting from infrequent accidents. The chemical hazards associated with UF_6 have also been quantified.

Costs associated with accidents, included the costs of evacuation, decontamination, condemnation, and loss of income have been quantified.

8.5 HEALTH EFFECTS

The radiological impacts considered were health effects associated with both normal transport (incident-free) and with low-probability accidents severe enough to release some or all of the radioactive material. Incident-free risk results

Table 8-3. Primary emissions or activities, pathways and ecological impacts linked to the nuclear fuel cycle from transportation of radioactive or hazardous materials

Emissions/ activities	Environmental pathway	Impact	Impact evaluation
Radiation exposure	Direct exposure to radiation from shipments	Human health	Quantified
Radionuclides	Dispersion, inhalation, and ingestion of radionuclide potentially released during accidents	Human health	Quantified
Chemical hazards	Exposure to UF_6 released, dispersed, and inhaled during accidents	Human health	Quantified
Evacuation	Direct cost from accidents	Cost of responding to accidents by public agencies	Quantified
Decontamination	Direct cost from accidents	Cleanup costs, temporary removal of land from use	Quantified
Condemnation	Direct cost of accidents	Permanent loss of land use	Quantified
Road usage	Direct cost	Apportioned share of road maintenance due to shipments	Quantified
Income loss	Direct cost from accidents	Loss of income from displaced business, loss of agriculture	Quantified

from exposure of the surrounding population to radiation emitted by the waste packages during normal transport. Accident impacts considered both acute fatalities and LCFs (chronic) to both the present and future generations due to accidents.

The greatest radiological risk will be associated with shipments of spent nuclear fuel, which contain a larger inventory of high-curie radionuclides relative to the fresh fuel, yellowcake, and UF_6 shipments. However, the release of natural or enriched UF_6 following a transportation accident would primarily pose a toxic chemical hazard rather than a radiological hazard (McGuire 1991). This is because the uranium in these shipments is only weakly radioactive and the UF_6 forms hazardous chemical compounds that are readily soluble in the human body.

In the solid state, UF_6 is a nearly white to pale yellow, dense crystalline solid. It has a sharp, penetrating odor. Solid particles of UF_6 will be irregularly shaped grains similar to rock salt if formed by freezing from the liquid phase.

Alternately, the solid may be a formless mass if formed by desubliming from the vapor phase (DOE 1991).

When UF_6 is released in air, it reacts rapidly with water vapor and forms UO_2F_2 and HF:

$$UF_6(g) + 2H_2O(g) \rightarrow UO_2F_2(g) + 2HF(g) + \text{heat.}$$

The chemicals formed by this reaction produce three toxic effects in humans: (1) the uranium in the uranyl complex acts as a heavy-metal poison that can affect the kidneys; (2) the HF is an acid that can cause acid burns on the skin or lungs if it is concentrated; and (3) the fluorides (UO_2F_2 and HF) can cause fluoride poisoning if intakes are large (McGuire 1991). Each of these toxic effects will be considered in the analysis.

8.5.1 General Public Mortality and Morbidity

Radiological health effects. Table 8-4 lists the risk of LCFs per shipment expected to result from radiation exposure during incident-free transportation and during accidents. Radiation doses to the population were converted to estimates of LCFs using the upper limit risk coefficient suggested by the National Academy of Sciences (NAS) (ICRP 1991, NAS 1990). The NAS report, commonly called the BEIR V report, gives statistics on the number of cancer deaths expected to occur from a continuous lifetime exposure of 0.1 rem/year which results in a risk factor of 5.0×10^{-4} LCFs per person-rem that is generally applied to exposures of the general public.

This assessment indicates that the radiological risks of shipping UF_6 and spent nuclear fuel are low. The number of LCFs statistically expected to occur from the calculated exposures would not exceed 2.10×10^{-3} LCFs for members of the public exposed during incident-free transportation. The results of the analysis indicate that there would be no fatalities from acute radiation exposure as a result of the release of radioactive material from any hypothetical accident. The largest number of LCFs for the general public associated with any of the hypothetical accidents for the spent fuel shipments would be 2.19×10^{-2}.

The radiological transportation risk has been separated into two components; the probability of an accident occurring and the consequences of the accident. The associated probabilities and consequences for each of the six transportation scenarios are shown in Part 2 of Appendix E. The data shown in Appendix E is for all eight accident categories in three population density zones. A summary of the weighted-average probabilities and consequences for each scenario is also shown in Table 8-4.

Table 8-4. Radiological risk per reactor year to the general population[1]

Scenario	Description	Incident-free risk: Latent cancer fatalities	Accident probabilities: number of expected accidents	Accident consequences: Latent cancer fatalities per accident	Accident risk: Latent cancer fatalities
1	NM mine/mill to IL conversion plant	1.18E-4	1.80E-5	5.53E-1	9.95E-6
2	IL conversion plant to OH enrichment plant	9.69E-6	1.01E-5	3.85E+1	3.89E-4
3	OH enrichment plant to WA fuel fab. plant	5.45E-6	4.22E-6	3.43E+1	1.45E-4
4	WA fuel fab. plant to SE reactor site	1.27E-7	1.70E-6	7.99E-10	1.36E-15
5	SE reactor site to Yucca Mountain site	2.10E-3	1.44E-4	1.52E+2	2.19E-2
6	SW reactor site to Yucca Mountain site	8.77E-4	2.13E-5	1.48E+2	3.15E-3

[1] Transportation risks were calculated using RADTRAN version 4.0.13 dated October 27, 1992. Access to RADTRAN 4 was furnished on the TRANSNET MicroVAX computer by the Department of Energy's Transportation Technology Center at Sandia National Laboratories.

Toxic chemical health effects.

Radioactive materials may be in a form that can pose chemical exposure risks in addition to risks associated with the radioactivity of the material. For the transportation scenarios described in this chapter, the radiological risks have been calculated for both normal (incident-free) transport and due to releases of radioactive material in accidents. In the case of the highly radioactive spent fuel, the radiological risk associated with exposure to the radioactive materials that may potentially be released from the shipping cask far outweighs the chemical hazard associated with what fraction of the release might be inhaled or ingested. Fresh (unirradiated) fuel assemblies, on the other hand, contain only a small amount of radioactivity because the long half-life isotopes of uranium in the fresh fuel require such a long time to decay. In addition, fresh fuel does not pose a significant chemical hazard due to the fact that the assembly composition is not chemically reactive; each assembly is composed of structural metal components (Zircaloy cladding, stainless steel, and inconel) and uranium dioxide (UO_2) fuel pellets.

Uranium hexafluoride, either natural or enriched, also presents a relatively small radiological risk as a result of the low radioactivity in the long-lived uranium isotopes. However, UF_6 is a highly reactive chemical and forms two highly toxic chemicals: HF and UO_2F_2. Under accident conditions severe enough to breach the UF_6 cylinder, some amount of UF_6 could be released. When UF_6 comes in contact with water vapor in the air, HF and UO_2F_2 are formed. These chemicals would then be released to and dispersed in the environment. The primary exposure pathway for these chemicals is by inhalation.

Uranium hexafluoride is transported in cylindrical shipping containers to maintain UF_6 in solid form. Natural UF_6 is transported in 14 ton (12.7 MT) cylinders, with a single cylinder per truck. Transportation regulations allow natural UF_6 (<1.0% enriched) to be transported without an overpack. For UF_6 with enrichments >1% ^{235}U, regulations require that the cylinder be transported in an overpack that meets 10 CFR Part 71, Type B packaging criteria. Type B packages must be capable of withstanding (1) a 30-foot drop onto an unyielding surface, followed by (2) a 40-inch drop onto a 6-inch spike, followed by (3) a 30-minute fire at 1475°F without releasing any of the package contents.

The radiological risks of transportation previously discussed were based on a probabilistic assessment of accident severity probabilities multiplied by the consequences of an accident in each of eight severity categories. Each severity category is a function of impact force and/or duration of exposure to fire. One unique aspect of UF_6 is that, while in solid form during transport, it sublimates (similar to how dry ice is transformed directly from solid to vapor, without a

liquid phase) to gas when its temperature reaches 56°C (at 1 atmosphere). For accidents that do not involve a heat source (fire), it is reasonable to assume that only a small fraction of the contained UF_6 would be released from the package. In these cases, the rate at which UF_6 is released becomes a function of the size of the package breach and the rate at which moisture (water vapor) reacts with the UF_6 to form its gaseous byproducts. Mitigating the amount of material released could simply involve covering up the breach.

It is also reasonable to assume that the enriched UF_6 shipments that, by law, are contained within Type B overpacks, could withstand a fairly intense, 30-minute fire without releasing the package contents. Unfortunately, the accident probability data (as it relates to the concept of severity category) does not provide a breakdown of accidents involving fire to total accidents. Therefore, we have assumed that transportation accidents involving a severe fire will release 100% of the UF_6 and that this occurs 5% of the time. The remainder of the accidents involve either no fire or a fire of small duration that will not damage a Type B package. Impact damage is assumed to release 10% of the UF_6 in each package. Furthermore, it is assumed that reasonable measures will be taken to warn the affected population to further mitigate the potential for injuries and death.

The probability of an accident (that results in total release of UF_6) was determined by summing the probabilities of all accidents that exceed Type B requirements, excluding the accident probabilities of less severe accidents. This assumption is based on the judgement that minor (fender bender-type) accidents would likely not damage the package, and that only a small fraction of all accidents involve fire. Therefore, the bounding risk of UF_6 transport as calculated in this study is a function of the accident probability times the consequence resulting from the expected UF_6 release from the package.

The consequences of inhalation of UF_6 byproducts (HF and UO_2F_2) are a function of the concentration and uptake (inhalation) factors applied to the average population located downwind. Using methods developed to analyze the effects of postulated UF_6 releases from an accident at a gaseous diffusion plant, we have determined the health effects from transporting UF_6 by calculating the average population located at various distances downwind from an accidental release, using the average population density along each transport route.

Based on dispersion, the concentration of HF and UO_2F_2 in the air generally decreases downwind from the accident site. For populations located very close to the release, the major health effect will result from exposure to HF gas, which, if exposure levels are sufficient, can result in death. As the distance from the accident increases the risk of death decreases. A secondary health effect is the exposure to the UO_2F_2, which results in permanent injury to the renal system from

the heavy metal (uranium). As one moves further from the accident location, exposure results in only temporary injury to the renal system. Finally, at sufficient distance, when the exposure concentration has dissipated, no additional health effects are attributable to the accidental release.

The most important health effect from intake of soluble uranium is tissue damage in the kidneys with subsequent functional loss as indicated by failure to resorb urinary protein, glucose, catalase, phosphate, citrate, and creatinine. The heavy metal poison will damage capillary membranes, increase blood pressure, and decrease clotting ability. It is also known to damage the liver, muscle tissue, and affect the nervous system similar to other heavy metal poisons. The health effects from intake of soluble uranium are summarized in Table 8-5 (McGuire 1991). The transient renal injury value is the amount of uranium intake at which health effects are first observable, but the effects are temporary with the chemical components of the urine returning to normal levels. The permanent renal damage value is the intake required before permanent kidney damage is possible.

Inhalation of moderate amounts of HF gas will cause smarting of the skin, respiratory irritation, irritation of the mucous membrane lining the eyelids, and a pronounced taste. Continued exposure can cause progressive destruction of the bronchial mucous membrane and swelling of lung tissue, which can be fatal. Unlike many other toxic chemicals, there are no permanent, serious injuries that occur from sublethal exposures to HF gas. If fatality from suffocation caused by edema (swelling) in the lungs does not occur, the swelling will subside and recovery should be complete. Thus, acute sublethal inhalation of HF gas is not expected to have long-term health effects. Experimental data on the effects of inhaling HF gas on animals is shown in Table 8-6 (McGuire 1991).

Table 8-5. Health effects from intake of soluble uranium

Health effect	Uranium per kg body weight (mg-U/kg)	Uranium content in 70 kg person (mg)
50% lethality	1.63	114
Threshold for permanent renal damage	0.3	21
Threshold for transient renal injury or effect	0.058	4.06
No effect	0.03	2.1

Table 8-6. Effects of inhalation of HF on animals

HF concentration (mg/m^3)	Effect on animals
1,500	Some animals died from a 5-minute exposure.
1,000	No animals died from exposures of 30 minutes or less, but there was damage to tissue.
500	All animals exposed for 15 minutes or more showed signs of weakness and ill health.
100	Could be tolerated for 5 hours without causing death, but was a severe irritant.
50	Rabbits and guinea pigs showed signs of mild irritation, such as coughing and sneezing, which appeared to lessen after 5 to 15 minutes.
24	Was tolerated for a total of 41 hours without a fatality, although animals subsequently lost weight.

McGuire 1991.

The final effect, fluoride toxicity from the fluoride ion (F^-), is the least important toxic effect. This is due to the fact that a UF_6 release will result in lethal doses of both uranium metal and HF gas long before lethal levels of fluoride is reached. Fluoride ions will penetrate the skin, destroy tissue under the skin, and cause inhibition of vital enzymes and dangerous disturbances in calcium and carbohydrate balance. Death will eventually occur from cardiac or respiratory failure. A lethal dose from acute fluoride poisoning is estimated to be an absorption of 32 to 64 mg of fluoride per kilogram of body weight (EPA 1988). A safe or no-effect absorption is considered to be 8 to 16 mg/kg of body weight (560 to 1,120 mg in a 70 kg person).

Table 8-7 shows the toxic chemical impacts from natural and enriched UF_6 shipments per reactor year. Only fatal and permanent injuries are considered. Reversible injuries, such as temporary renal injury, will occur, but have not been quantified in this study.

Table 8-7. Toxic chemical risk per reactor year to the general population[1]

	Natural UF_6 shipments	Enriched UF_6 shipments
Accident probability	0.00412	0.00202
Accident consequences		
Fatalities, near[2]	0.58	0.35
Fatalities, far[3]	0.37	0.22
Permanent renal injury[4]	38.8	23.4
Accident risk		
Fatalities, near	0.00239	0.00071
Fatalities, far	0.00152	0.00044
Permanent renal injury	0.15986	0.04727

[1] To support a reactor year of electricity production, it is assumed that 25 shipments of 12.7 MT natural UF_6 and 3 shipments of 9 MT enriched UF_6 will be required.

[2] The near fatalities represent the consequences inside the LD50 boundary surrounding the accident site. The dominant cause of death is from inhalation of HF and UO_2F_4 (uranium lethality).

[3] The far fatalities represent the consequences inside the LD10 boundary surrounding the accident site. The dominant cause of death is from inhalation of UO_2F_4 (uranium lethality).

[4] The renal injuries represent the consequences inside the effected boundary where permanent kidney damage is likely to occur.

8.5.2 Occupational Health Effects

Table 8-8 lists the risk of occupational LCFs per shipment expected to result from radiation exposure during incident-free transportation and accidents. Radiation doses to the truck crews were converted to estimates of LCFs using the upper limit risk coefficient suggested by the NAS (ICRP 1991, NAS 1990). The NAS report, commonly called the BEIR V report, gives statistics on the number of cancer deaths expected to occur from a continuous exposure of 1 rem/year from

Table 8-8. Incident-free radiological risk to occupational workers[1]

Scenario	Description	Radiological latent cancer fatalities per reactor year for occupational workers[2]
1	NM mine/mill to IL conversion plant	8.00E-6
2	IL conversion plant to OH enrichment plant	1.21E-6
3	OH enrichment plant to WA fuel fab. plant	6.84E-7
4	WA fuel fab. plant to SE reactor site	1.58E-8
5	SE reactor site to Yucca Mountain site	2.64E-4
6	SW reactor site to Yucca Mountain site	1.10E-4

[1] Transportation risks were calculated using RADTRAN Version 4.0.13 dated October 27, 1992. Access to RADTRAN 4 was furnished on the TRANSNET MicroVAX computer by the Department of Energy's Transportation Technology Center at Sandia National Laboratories.

[2] The number of radiological LCFs statistically expected to occur from the calculated exposures was estimated using a conversion factor of 4.0E-04 LCFs per person-rem for the crew (NAS 1990, UNSCEAR 1988). The number of LCFs presented here should be compared to the national average lifetime risk of cancer from all causes, which is ~2.5E-01 (about 1 in 4). The crew size was assumed to be 2 persons.

age 18 until age 65. This value results in a risk factor of 4.0×10^{-4} LCFs per person-rem that is most applicable to occupational exposures. The number of LCFs statistically expected to occur from the calculated exposures would not exceed 2.64×10^{-4} LCFs for the truck drivers (2 crew members) exposed during incident-free transportation.

8.5.3 Health Damages from Fuel Transportation

There are several different uranium fuel transportation stages treated together in this chapter. Workers and the public are at risk of dying from cancer from radiation exposure even in the absence of an accident, although risks of cancer fatalities is higher for accidents, even when the low probability of such an accident is considered. The public is also at risk from toxic, non-radiological exposures, both of immediate death and of permanent kidney (renal) injury.

Unit values for mortality. (See Chapter 7 for a fuller explanation). The damages associated with immediate deaths to the public from a release of toxic materials (no estimates are provided of immediate occupational deaths associated with the transportation stage) are based on the average value of a statistical life (Fisher 1989). This study considered primarily wage compensation studies analyzing the premiums paid to workers in relatively risky jobs for the excess accidental death risks they bear. It also considers contingent valuation studies of the WTP to avoid automobile death risks. Low, Mid, and High values of statistical lives are $1.6 million, $3.5 million, and $8.6 million, respectively. Being taken from studies involving accidental and immediate deaths (although in the workplace rather than for the general public), these estimates are acceptable.

Cancer deaths are valued following the approach discussed in Section 5.6.4, which involves correcting the above VSL estimates for latency. To address latency, we use an estimate of the average latency period for cancer (20 years) to date the onset of cancer and discount the accidental death WTP estimates from the date of onset to the present. Multiplying the discounted WTP estimate by the annual expected deaths from cancer gives the annual expected damage for the annual exposure.

Unit values for Morbidity. The only morbidity effects estimated are those for permanent renal injuries. No studies exist that attempt to estimate the WTP to avoid increased risks of permanent renal injury, which, in this case, is caused by metal poisoning from exposure to uranium hexaflouride. However, Rossman, Miller, and Douglass (1991) have estimated the medical costs and productivity losses associated with injuries caused by metal poisoning. Specifically, they

estimate medical costs, lost work days, and lost household productivity totals.[1] Their estimates omit pain and suffering and therefore, are underestimates of the WTP to avoid a case of metal poisoning. They indicate that a case of metal poisoning costs, on average, $9,359 in 1989 dollars.

Mortality Damage Calculations. As shown on Table 8-9 for the southeast reference reactor site, cancer fatalities to the public, based on radiation released in an accident and immediate death from toxic chemical releases, result in midpoint risks of 0.024 and 0.005 per year, respectively. The VSL applied to cancer deaths is discounted to account for the 20 year latency period.

Because of this discounting, damages for these two effects are similar—0.006 mills/kWh for cancer deaths and 0.002 mills/kWh for immediate deaths from toxic releases. In the non-accidental radiation release categories, damages are trivial, while no estimate of worker risks from radiation released in an accident is given. Table 8-10 provides the analogous information for the southwest reference reactor site.

Morbidity Damage Calculations. For the southeast reference reactor site (Table 8-9), the damages associated with permanent renal injuries are $2,080 annually, or 2.5×10^{-4} mills/kWh. Table 8-10 provides the analogous information for the southwest reference reactor site.

Uncertainties. Tables 8-9 and 8-10 also present judgmental LOW and HIGH estimates of damage based entirely on ranges of unit values for the VSL's and VSI's, as discussed above. For this stage for the southeast reference reactor site, total damages range from 0.004 mills/kWh to 0.022 mills/kWh with a midpoint estimate of 0.009 mills/kWh. For the southwest reference reactor site, total damages range from 0.006 mills/kWh to 0.010 mills/kWh with a midpoint estimate of 0.007 mills/kWh. The damages associated with the southwestern site are smaller than those for the southeastern site because the fuel is transported through less populated regions.

[1]They also report estimates of the administrative costs of processing injury claims. While these are not a component of a person's WTP to avoid an injury they could be an externality from society's point of view, if such costs are borne by the government rather than the utility injury. Nevertheless, these costs, which are about $900 per case, are omitted in the estimate in the text.

Table 8-9. Annual health damages from transportation for the southeast reactor site

Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill	
Exposure	Public	Worker	Public	Worker	Public	
General endpoint	Mortality				Mortality	
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury
Yr of first exposure to risk	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0
Expected cases resulting from each annual exposure	0.00333899	0.00029405	0.02409442	#N/A	0.00545322	0.22223116
LOW						
Damage per case valued at time of exposure (1989$)	$885,881	$885,881	$885,881	$885,881	$1,600,000	$9,359
Damage levelized over plant lifetime (1989$/yr)	$2,958	$260	$21,345	#N/A	$8,725	$2,080
Damage levelized over plant lifetime (mills/kWh)	0.00036225	3.1902E-05	0.00261401	#N/A	0.00106853	0.00025471
MEDIUM						
Damaged per case valued at time of exposure (1989$)	$1,937,865	$1,937,865	$1,937,865	$1,937,865	$3,500,000	$9,359
Damage levelized over plant lifetime (1989$/yr)	$6,471	$570	$46,692	#N/A	$19,086	$2,080
Damage levelized over plant lifetime (mills/kWh)	0.00079242	6.9785E-05	0.00571815	#N/A	0.00233742	0.00025471
HIGH						
Damage per case valued at time of exposure (1989$)	$4,761,611	$4,761,611	$4,761,611	$6,761,611	$8,600,000	$9,359
Damage levelized over plant lifetime (1989$/yr)	$15,899	$1,400	$144,728	#N/A	$46,897	$2,080
Damage levelized over plant lifetime (mills/kWh)	0.00194708	0.00017147	0.01405032	#N/A	0.00574337	0.00025471

Table 8-10. Annual health damages from transportation for the southwest reactor site

Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill	
Exposure	Public	Worker	Public	Worker	Public	
General endpoint	Mortality				Mortality	
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury
Yr of first exposure to risk	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0
Expected cases resulting from each annual exposure	0.00333899	0.00012873	0.00396559	#N/A	0.00545322	0.22223116
LOW						
Damage per case valued at time of exposure (1989$)	$885,881	$885,881	$885,881	$885,881	$1,600,000	$9,359
Damage levelized over plant lifetime (1989$/yr)	$2,958	$114	$3,513	#N/A	$8,725	$2,080
Damage levelized over plant lifetime (mills/kWh)	0.00036225	1.3966E-05	0.0043023	#N/A	0.00106853	0.00025471
MEDIUM						
Damaged per case valued at time of exposure (1989$)	$1,937,865	$1,937,865	$1,937,865	$1,937,865	$3,500,000	$9,359
Damage levelized over plant lifetime (1989$/yr)	$6,471	$249	$7,685	#N/A	$19,086	$2,080
Damage levelized over plant lifetime (mills/kWh)	0.00079242	3.055E-05	0.00094113	#N/A	0.00233742	0.00025471
HIGH						
Damage per case valued at time of exposure (1989$)	$4,761,611	$4,761,611	$4,761,611	$4,761,611	$8,600,000	$9,359
Damage levelized over plant lifetime (1989$/yr)	$15,899	$613	$18,883	#N/A	$46,897	$2,080
Damage levelized over plant lifetime (mills/kWh)	0.00194708	7.5066E-05	0.00231248	#N/A	0.00574337	0.00025471

8.5.4 Ecological Effects of Accidental HF Releases

Accidental releases of HF could have serious effects on terrestrial biota, especially vegetation. For example, exposure to atmospheric concentrations of HF as low as 0.25 mg/m^3 for 1 hour can cause damage to vegetation (U.S. NRC 1985). The effects of HF concentrations on vegetation depends primarily on the quantity of fluoride absorbed into the leaf tissue. If an accidental release occurs during the growing season, both gaseous and particulate fluorides would accumulate on leaf surfaces. Initial, short-term exposure would be manifested as visible areas of dead tissue between the leaf veins; continued high levels of exposure would be seen as chlorotic (yellowed) leaf margins and tips and eventually death (U.S. NRC 1986c). Accumulation of atmospheric fluorides can also result in changes in plant metabolism, growth, development, and yield.

Plant species differ greatly in their tolerance to fluorides absorbed into their tissues. NAS (1971) presented extensive lists of plants species and judgements about their susceptibility to fluorides. Several important coniferous trees are highly susceptible, whereas other conifers, and most broad-leaved plants, are of intermediate susceptibility or relatively tolerant. Common vegetable crops and field crops are tolerant or only moderately susceptible, whereas practically all important fruits and berries are at least moderately susceptible.

The amount of damage to agricultural crops and native vegetation from an accidental release of HF would depend on a number of factors, including the amount of material released, meteorological conditions (e.g., humidity and wind speed), the distance of plants from the source of fluoride, and the age of the leaf tissues (immature leaves are most susceptible to damage). Most injured plants would probably recover quickly from brief exposures to fluorides (U.S. NRC 1986c). In the absence of continued exposure to airborne HF, new foliage would develop that would be essentially unaffected. Fluoride in the soil would not be taken up in sufficient quantities to affect new foliage.

Livestock and wildlife would also be exposed to accidental fluoride (HF) releases from the air (inhalation) or ingested from water or forage. Inhalation generally contributes only a negligible amount to the total fluoride intake of animals. Long-term ingestion of feedstocks with fluoride concentrations of greater than 40 ppm can produce a significant incidence of symptoms (lameness, changes in growth, bone lesions) in dairy cattle, considered to be the most sensitive domestic animals (NAS 1971). The average fluoride exposure considered likely to cause adverse effects in cattle (e.g. 40 ppm in fresh forage for 30 days) would also cause visible foliar necrosis in sensitive plant species. In general, plants are

more sensitive to fluoride than animals, and as a result, biotic effects of accidental HF releases are more likely to be seen at greater distances in vegetation than among livestock and wildlife.

8.6 ENGINEERING-ECONOMIC ESTIMATES OF OTHER CONSEQUENCES

This section summarizes the economic risks of transportation accidents and describes the costs computed by the RADTRAN 4 computer code. The economic costs considered in the model include accident site surveillance, cleanup, evacuation, and long-term land-use denial. Additional information on the economic cost methodology can be found in the RADTRAN III User's Guide (Madsen 1986) and the RADTRAN 4 User's Guide (Neuhauser 1992).

For the purposes of modelling, the economic costs are divided into two categories: basic emergency response costs and radioactive decontamination and restoration costs. The basic emergency response costs are independent of the type or quantity of material released and include such costs as law enforcement, fire prevention, health services personnel, and other equipment and personnel costs associated with a typical accident response effort.

The radioactive decontamination and restoration costs used by the RADTRAN 4 code consider the cost of restoring a given area of given population density using one of several potential cleanup scenarios. A large number of decontamination cost values are reported to have been considered using data from actual accidents and from cost estimates supplied by major contractors who have provided accident cleanup services.

It should be noted that less quantifiable, though potentially significant (even dominant), costs were not included, such as litigation, government actions, indirect corporate losses (business loss due to fear, etc.), and political or social repercussions. These undetermined costs could potentially be greater than the costs calculated by RADTRAN 4.

8.6.1 Emergency Response Costs

The basic emergency response costs are independent of the type or quantity of material released and include such costs as law enforcement, fire prevention, health services personnel, and other equipment and personnel costs associated with a typical accident response effort. These costs are assumed to be greater for more severe accidents and are given for eight accident severity categories as shown in Table 8-11.

Table 8-11. Emergency response costs per accident*

Accident severity category	Response cost (dollars)
1 (least severe)	26
2	518
3	648
4	777
5	1943
6	2202
7	2720
8 (most severe)	3238

* Values are shown in 1989 dollars.

8.6.2 Decontamination and Property Condemnation Costs

The radioactive decontamination and restoration costs used in RADTRAN 4 consider the cost of restoring a given area of given population density using one of several potential cleanup scenarios. Most of these cost values are shown in Table 8-12. These cost values are used to determine average restoration costs per accident for 12 different material dispersibility categories and 4 ranges of material release fractions as shown in Table 8-13. For this study, the nuclear fuel is categorized as large, nondispersible material, and the UF_6 is categorized as volatile sublimer/solution. In addition, it is assumed that 50% of the land is under cultivation and that the regulatory cleanup level for land decontamination is 0.2 $\mu Ci/m^2$.

8.6.3 Lost Productivity Costs, etc.

Lost productivity costs used in RADTRAN 4 include the loss of personal and corporate income due to the disruption created by the transportation accident and the subsequent mitigation efforts. These are direct personal and business income losses and do not include such things as indirect business income loss due to public fear. In addition, the cost to relocate government agencies is considered. The values of lost productivity costs used in this study are shown in Table 8-14.

Table 8-12. Decontamination and property condemnation costs for economic analysis using RADTRAN 4 (all values in 1989 dollars)

Category	Cost ($)
Survey cost	$\$1.3 \times 10^5$ per km^2
Purchase crops	$\$4.5 \times 10^4$ per km^2
Security	\$181 per km^2 per day
Evacuation	\$23 per person per day
Deep plowing	$\$1.4 \times 10^5$ per km^2
Scrape and bury—low	$\$2.8 \times 10^5$ per km^2
Scrape and bury—high	$\$6.5 \times 10^5$ per km^2
Dwelling cleanup—rural—low	\$2332 per person
Dwelling cleanup—rural—high	\$2979 per person
Permanent relocation—rural/suburban	\$5018 per person
Permanent relocation—urban	\$50180 per person
Land value—rural	$\$2.2 \times 10^5$ per km^2
—suburban	$\$3.0 \times 10^4$ per person
—urban	$\$3.0 \times 10^5$ per person
Extensive tilled land cleanup	$\$1.3 \times 10^6$ per km^2
Raze and rebuild—rural	$\$3.8 \times 10^7$ per km^2
—suburban	$\$9.2 \times 10^7$ per km^2
—urban	$\$4.7 \times 10^9$ per km^2
Single family unit cleanup—low	\$474 per person
Single family unit cleanup—high	\$1518 per person
Multifamily unit cleanup—low	\$52 per person
Multifamily unit cleanup—high	\$484 per person
High density building cleanup (>6 story)—low	\$26 per person
High density building cleanup (>6 story)—high	\$242 per person
Public area cleanup—low—suburban	\$69 per person
Public area cleanup—low—urban	\$687 per person
Public area cleanup—high—suburban	\$725 per person

Table 8-12. Decontamination and property condemnation costs for economic analysis using RADTRAN 4 (all values in 1989 dollars) (continued)

Category	Cost ($)
Public area cleanup—high—urban	$7250 per person
Park and cemetery—low—suburban	$51 per person
Park and cemetery—low—urban	$505 per person
Park and cemetery—high—suburban	$66 per person
Park and cemetery—high—urban	$660 per person
Commercial areas—low—suburban	$36 per person
Commercial areas—low—urban	$360 per person
Commercial areas—high—suburban	$1841 per person
Commercial areas—high—urban	$18410 per person

Table 8-13. Decontamination and property condemnation cost* for each dispersibility category

RADTRAN material dispersibility category	Fraction of contents releases from package			
	0	>0 but <0.01	>0.01 but <0.1	>0.1 but <1.0
1. nondispersible—small	325	1620	1620	3240
1A. nondispersible—large	12950	12950	12950	12950
2. immobilized	325	12950	12950	12950
3. sintered, loose chunks	325	2270	2270	4530
4. loose powder—large	325	12950	32400	64800
5. loose powder—small	325	3110	3110	6500
6. particulate—spent fuel	325	3110	3110	6500
7. volatile sublimer or solution	325	2270	2270	64800
8. large liquid shipments	325	12950	32400	64800
9. small liquid shipments	325	3110	3110	6500
10. gases	325	1300	1300	2600
11. flammable	325	12950	32400	64800

* Values are shown in 1989 dollars.

Table 8-14. Lost productivity costs for economic analysis using RADTRAN (all values in 1989 dollars).

Category	Cost ($)
Personal income loss—suburban and rural	$21 per person per day
Personal income loss—urban	$207 per person per day
Business income loss—suburban	$9 per person per day
Business income loss—urban	$91 per person per day
Relocate government agencies	$868 per person

8.6.4 Impacts and Damages from Truck Traffic

This section presents an analysis of the damage to roadway surfaces that would occur due to the operation of nuclear power plants in the Southeast and Southwest reference reactor sites. For an introduction to the theory that is presented in this section, see (ORNL/RFF 1994a, Coal Fuel Cycle).

Unlike the road damage analyses presented in the coal and oil fuel cycle documents, this analysis considers the transportation of the waste product, in this case, the spent fuel. However, the analysis does not include the road damage due to the transportation of the empty heavy steel cylinders used to contain the fuel during shipping. In addition, the trucks, once unloaded, do not make the return trip empty, but are employed in some other economic use unrelated to the nuclear fuel cycle.

8.6.4.1 Burden

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.

Table 8-15 shows the haul distances, the size of the loads, and the number of shipments for each fuel processing step for the southeast and southwest reference reactor sites. The haul distances were calculated using the Highway computer code model (for further discussion, see Section 8.2).

8.6.4.2 Impacts

To determine the impacts that result from this burden, we estimate the injury to roadway surfaces that occur due to each passage of a fully loaded truck on each link. This impact is calculated in terms of the effect of each passage on the life of a road surface.

Table 8-15. Transportation requirements

Fuel Step	Origin	Destination	Haul distance (km)	Trips/yr	Weight of loaded truck (10^3 pounds)
Yellowcake	Grants, NM	Metropolis, IL	2079	21	107
Natural UF_6	Metropolis, IL	Portsmouth, OH	822	25	91
Enriched UF_6 shipments	Portsmouth, OH	Richland, WA	3867	3	76
Fresh (unirradi-ated) fuel	Richland, WA	SE Reactor site SW Reactor site	3964 1826	4	80
Spent (irradi-ated) fuel shipments	SE Reactor site SW Reactor site	Yucca Mtn.	3542 1479	13	110

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]

$$N_j = (A0(D + 1)^{A1} (L_2)^{A3})/[(L_1 + L_2)^{A2}]$$

where:

L_1 = thousands of pounds of load on axle j,

L_2 = the type of axle weight. L_2=1 for single axles and L_2=2 for tandem axles (two axles close together),

[2]However, many state laws penalize trucks with a greater number of axles. Fuel taxes punish trucks with a greater number of axles 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, pg. 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.

D = the road's durability. [For rigid pavements, D = 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)], and

Aj = 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,

A0 $=e^{13.505}$ or 733,073
A1 =5.041
A2 =3.241
A3 =2.270

For flexible pavements,

A0 $=e^{12.062}$ or 173,165
A1 =7.761
A2 =3.652
A3 =3.238[5]

Due to limited resources, pavement designs could not be collected for the numerous road segments over which the transportation of the fresh and spent fuel occurs. Instead, typical pavement designs for various classes of roads in the States of New Mexico and Tennessee are assumed to be representative of the road classes for which we have a breakdown of haul distances. The roads that are traveled are broken down into four categories: rural freeway, rural non-freeway, suburban freeway, and urban freeway. A typical New Mexico design for Interstate I40 is applied to the rural freeway, suburban freeway, and urban freeway road classes. For the rural non-freeway road class, we assume a design comparable to that of Tennessee state roads when transporting fresh fuel and a typical state road design

[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.

used in New Mexico when shipping spent fuel. In general, state roads in New Mexico are designed to be more durable than Tennessee state roads.

We assume that the trucks used to transport the fresh and spent fuel weigh 30,000 pounds when empty. When fully loaded, the weight of the truck is distributed unevenly among the axles. For example, on a fully loaded truck weighing 80,000 pounds, 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 truck passages that the roadway will withstand before resurfacing is needed. In the nuclear fuel cycle, fully loaded trucks often weigh in excess of 80,000 pounds. This analysis assumes that the majority of the excess weight is distributed evenly over the tandem axles and that very little of this burden is borne by the steering axle.

8.6.4.3 Economic Valuation

Roadways have to be resurfaced regularly with or without the impacts of heavy trucks. In this analysis, the roadways are assumed to be resurfaced regularly 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 nuclear truck traffic, minus the present discounted value of resurfacing costs, absent the nuclear trucks. Finally, this difference in present discounted value should be levelized over the 40-year operation of the nuclear facility.

To illustrate the methodology we employ, consider one stretch of road affected by new truck traffic, the damage of which we want to assess. Suppose this road would withstand about 1,000,000 passages of fully loaded (80,000 lb) trucks until resurfacing would be required, if this was the only traffic on the road. If present traffic conditions require a ten year resurfacing schedule, then present conditions would be equivalent to the passage of about 100,000 trucks annually. Suppose the proposed facility would add 10,000 truck passages to that figure. Hence, with the addition of the new truck traffic, this stretch of roadway would need to be resurfaced according to a 9.09 year (1,000,000 passages/110,000 passages/yr) 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.

Typically, 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 new truck traffic, the lane bearing the additional traffic would be determinant for the resurfacing schedule. The cost of resurfacing a typical two-lane highway with flexible pavement and a durability equal to 3.33 inches, in Tennessee, amounts to about $80,000 per road mile. The corresponding resurfacing costs for the more expensive and more durable state road design (durability = 3.76 inches) in New Mexico per road mile (both lanes) is $485,000.[7] For a divided four-lane highway, such as an interstate, each side may be resurfaced at different times. The cost of resurfacing one side of a divided four-lane highway (durability = 5 inches) in New Mexico is $400,000 per road mile.

We estimated the damage for each link between fuel processing sites for each different road class in a manner similar to the example above, and summed these to obtain an estimate for the entire route. The difference between the present discounted value of future resurfacing needs, absent the new truck traffic, and with the new truck traffic is ~$222,000 for the Southeast reference reactor site and $176,000 for the Southwest reference reactor site. These values are the net present discounted costs of the new nuclear truck traffic for the two reference reactor sites.

These estimates are not abatement cost measures of damage, but true damage measures 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 the fuel on public roads.

The total levelized cost for the damage that results is $12,959 and $10,244 per year for the Southeast and Southwest reference reactor sites, respectively.

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[6]In practice it is possible that roadway engineers 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, these estimates of road damage are equal to 0.00155 mills/kWh for the Southeast reference reactor site and 0.00123 mills/kWh for the Southwest reference reactor site. These are the midpoint estimates of roadway damages.

Our estimate of a 95% confidence interval for the Southeast reference reactor site ranges from 0.00044 mills/kWh as a low estimate to 0.00545 mills/kWh as a high estimate. For the Southwest reference reactor site, the corresponding range is 0.000348 to 0.00431 mills/kWh. 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.

These damage estimates do no reflect the degree to which damages are internalized in the financial costs of producing electricity in this fuel cycle. Fuel taxes and road fees offset some of these damages.

8.6.5 Summary of Engineering-Economic Risk

Engineering-economic risks are those direct, quantifiable risks associated with the immediate chemical and radiological consequences of a transportation accident such as the emergency response costs, decontamination and property condemnation costs, lost productivity costs, and other direct costs associated with the engineering and technical mitigation of the accident consequences. A summary of the calculated engineering-economic risks for all six transportation scenarios is shown in Table 8-16.

Note that spent fuel shipments pose the dominant source of transportation impacts. This is due to the fact that spent fuel has about eight orders of magnitude more radioactivity than the uranium involved in other shipments and because a fraction of the radioactive fission products in spent fuel are volatile and dispersable in air, thus increasing their capacity to cause radiation doses to the public.

Engineering-economic risks do not include the less quantifiable costs of the litigation, political, and social repercussions that occur over an extended period of time following an accident. These less quantifiable costs are distinct and independent from the engineering technology of transportation and were not considered in this study.

Table 8-16. Engineering-economic risk per reactor year

Scenario	Description	Accident probabilities: number of expected accidents	Accident consequences: Cost per accident (million dollars)	Economic accident risk: Total cost (dollars)
1	NM mine/mill to IL conversion plant	2.53E-5	1.05	27
2	IL conversion plant to OH enrichment plant	5.20E-6	10.0	52
3	OH enrichment plant to WA fuel fab. plant	3.62E-6	6.29	22
4	WA fuel fab. plant to SE reactor site	1.16E-4	.0505	6
5	SE reactor site to Yucca Mountain site	5.24E-5	8,603	450,228
6	SW reactor site to Yucca Mountain site	1.18E-5	8,674	102,731

[1] Economic risks from transportation were calculated using RADTRAN version 4.0.13 dated October 27, 1992. Access to RADTRAN 4 was furnished on the TRANSNET MicroVAX computer by the Department of Energy's Transportation Technology Center at Sandia National Laboratories. Values are shown in 1989 dollars.

9. SPENT FUEL DISPOSAL

The term spent fuel refers to reactor fuel that has been "consumed" to a degree that it is discharged from the reactor and replaced with fresh fuel. Spent fuel differs from fresh fuel in several important ways. Other chemical elements and isotopes are present, having been created during the fissioning and irradiation processes within the reactor. Plutonium and other radioactive transuranic elements are present at a concentration of about 1.5%, and radioactive fission products are present at a concentration of about 3%. These fission products include radioactive isotopes of about 50 chemical elements, some of which have high mobility in air and/or water. Spent fuel is considered to have very high radiotoxicity and remains highly radiotoxic for very long periods of time (> 100,000 years). The radioactive elements within spent fuel represent a very significant health hazard if they are released to the environment, hence the need for extraordinary measures to dispose of spent fuel.

This chapter examines the impacts associated with the final disposition of spent fuel from the reference reactor technology. At the present time, spent fuel is stored at the reactor site pending the construction of a more permanent storage (or disposal) facility. The Nuclear Waste Policy Act of 1982, as amended in 1987, authorizes the Department of Energy (DOE) to evaluate and eventually implement a high-level waste (HLW) repository designed to accept spent nuclear fuel from civilian nuclear reactors. This DOE repository program is funded directly from a tax of 1 mill/kWh that is placed upon nuclear energy production by public utilities. This tax is passed along to the rate payer, thus internalizing the actual direct costs of the repository program. However, indirect costs to society associated with potential releases from the repository are not provided for, and are properly considered to be external to the price of electricity.

This study assumes that a HLW repository will be constructed as planned at the candidate Yucca Mountain, Nevada site. Although this facility does not yet exist, it is appropriate to define a HLW repository as part of the "1990 technology case" because all spent fuel from operating reactors during the period 1990-and-later is expected to report to a HLW repository.

In this chapter we address only the health impacts of the Yucca Mountain repository. Health impacts of spent fuel storage at reactor sites are implicitly covered in Chapter 6 discussions of normal reactor operations. Societal impacts of the Yucca Mountain repository, such as public fear and dread and possible disruptions to regional businesses, are an important topic, but are not treated in

this report. Finally, the health impacts of the repository have not yet been monetized and translated into societal damages. The long time delays between electricity generation and repository health impacts, when considered with the 3% discount rate used throughout this report, will mean that the calculated damages associated with the health impacts described herein are likely to be very small.

9.1 REPOSITORY SITE

The spent fuel repository is assumed to be located at the Yucca Mountain site in Nevada. Yucca Mountain is presently considered to be a candidate site for a geologic repository but has not been selected at this time. Rather, it has been designated by the Congress as the only candidate repository site to be characterized. If the candidate site is found to be suitable, the U.S. DOE will be required to demonstrate to the NRC that the repository system, including the site, meets regulations for radiation safety during operations and for long-term isolation.

The Yucca Mountain site is in Nye County, in southern Nevada approximately 100 miles northwest of Las Vegas as shown in Figure 9-1. The site is in an and region with sparse vegetation and few people. The candidate site is at the junction of federal lands managed by three federal agencies as shown in Figure 9-2: public lands managed by the Bureau of Land Management of the Department of the Interior; the Nellis Air Force Range, which has been withdrawn from the public domain by the Air Force; and the Nevada Test Site, which has been withdrawn from the public domain by the DOE. The nearest public habitation is twelve miles distant, and the nearest town, Beatty, Nevada, is 15 miles distant from the repository site. It is assumed that the site will be accessible by both highway and rail (DOE 1991a).

At the Yucca Mountain site it is proposed to construct a repository in the "unsaturated zone" - the rock mass between the surface of the land and the water table. The unsaturated zone is thick enough to allow the construction of a repository from 660 to 1300 feet above the water table. Because the rocks in which the potential repository would be located are unsaturated (i.e., the pores within the rocks are not completely filled with water), the amount of ground water moving through the rocks is expected to be small (but nonzero). This characteristic is important because the flow of ground water is the most likely mechanism for transporting radionuclides from a repository to the accessible environment, should there be any leakage of radionuclides from their containers.

Figure 9-1. Location of the Yucca Mountain site.

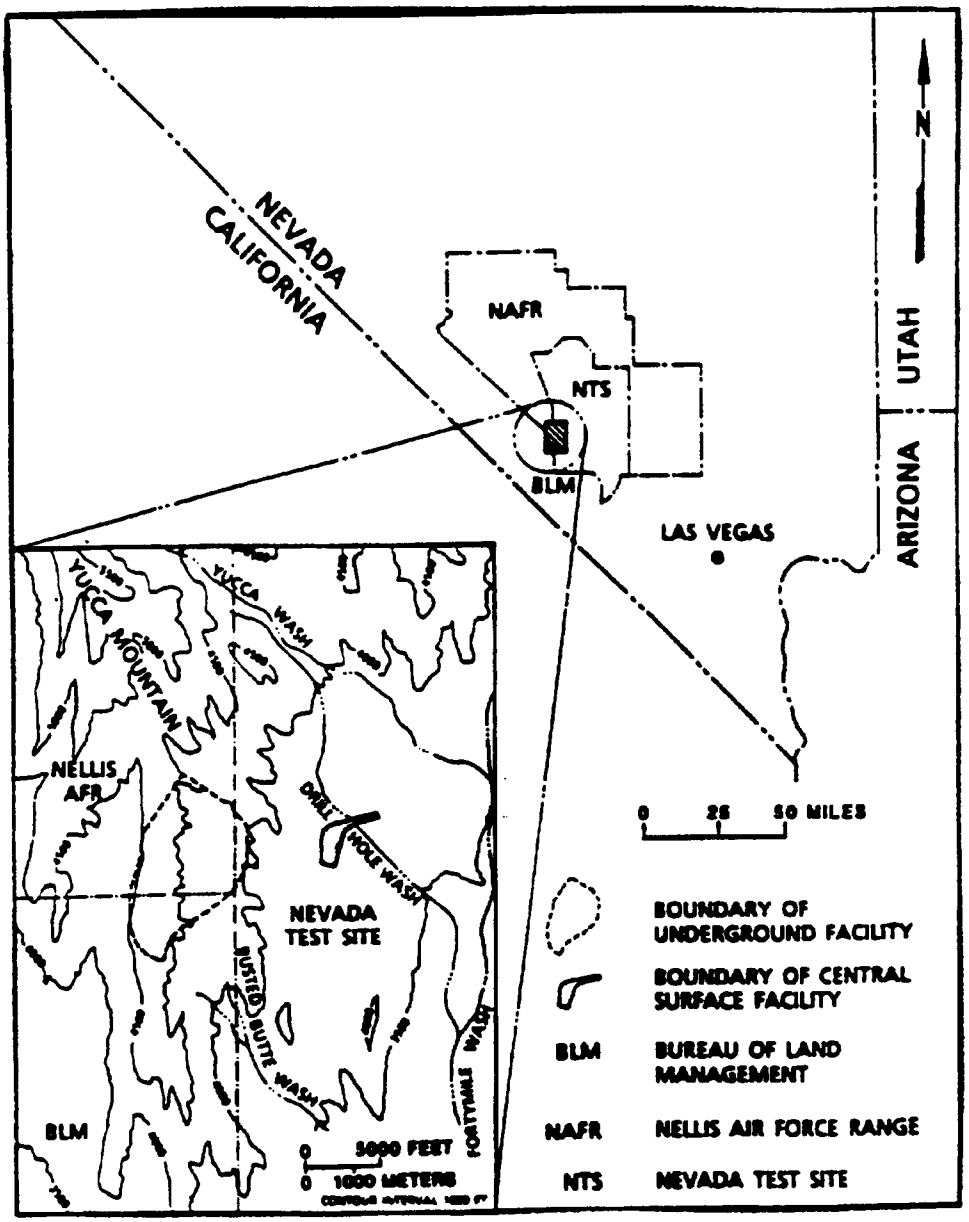

Figure 9-2. Boundaries of the reference Yucca Mountain.

The Yucca Mountain site lies within a region that is both seismically and volcanically active, thus creating the potential for natural phenomena, depending on the nature and magnitude of the event, to disrupt the repository and cause releases of radioactivity to the environment.

Another unusual site characteristic is that the geologic medium, called tuff, in which the repository is sited is chemically oxidizing, rather than chemically reducing (Forsberg 1992). Most soils are chemically reducing and the Yucca Mountain site is the only site ever proposed for a geologic repository that is chemically oxidizing. The oxidizing nature of the soil can be expected to result in the oxidation of several components of emplaced spent fuel with potentially important effects upon radioactive releases. Examples of these effects are:

- The major component of spent fuel is UO_2. In an oxidizing environment, the UO_2 will slowly transform to U_3O_8, causing breakup of the fuel pellets and greatly increasing the surface area of the fuel available to water leaching (Forsberg 1992). Thus, oxidation of the fuel pellets may lead to increased aqueous releases of radionuclides.

- Radioactive ^{14}C produced during irradiation of the fuel may be oxidized to CO or CO_2, both of which are gases at ambient conditions. These gases may then diffuse through cracks and pores in the geologic media and be released to the environment (Wilson 1992, Barnard 1992).

- Other radioactive fission products may be converted to oxides in which form their solubility in water and mobility through the geologic media may be significantly increased. An example of such a concern is the radioisotope ^{79}Se which forms selenium oxide, which is a water-soluble, mobile chemical compound.

These performance considerations deriving from the oxidizing nature of the repository site are unique to Yucca Mountain and are not relevant to the proposed EC repository sites (all of which are chemically reducing) (Forsberg 1992).

9.2 REPOSITORY TECHNOLOGY

The repository technology design is based on a conceptual design that has been proposed by the Yucca Mountain Project (Sandia 1987).[1] As shown in

[1] Recent legislation (the National Energy Policy Act of 1992) requires the Environmental Protection Agency to go to the National Academy of Science for advice on a reasonable standard to protect public health and safety.

Figure 9-3, the repository at Yucca Mountain is assumed to consist of surface facilities, underground facilities, and shafts and ramps connecting the surface facilities to the underground facilities. During the "preclosure operations" period, waste will be received and emplaced in the repository. As part of preparation for the permanent closure of the repository, the shafts, ramps, and exploratory boreholes will be sealed.

Surface Facilities. The purpose of the surface facilities is to receive the waste and prepare it for permanent disposal in the repository. The surface facilities would consist of facilities for waste-handling operations; for providing access portals and ventilation for the repository, and for providing general support, access, and utilities.

Spent fuel is received in the waste handling building and unloaded from shipping cask in which it arrives. The spent fuel is transferred to a packaging station in a "hot cell" - a room that is shielded against radiation and equipped with remotely controlled equipment. In the hot cell, the spent fuel is loaded into disposal containers; the disposal container is transferred to another operating station where it is sealed. Sealed containers are then moved to a surface vault for temporary storage before transfer underground and emplacement in the disposal areas. Containers are placed within transfer casks and moved by use of specially-designed transporters for the transfer and emplacement operations.

Other planned surface facilities include a surface facility for testing the quality of sealed waste packages; a decontamination building used for decontamination of equipment and components that have become radioactively contaminated during hot-cell operations; and the waste-treatment building, which would be used to prepare low-level radioactive wastes produced at the repository for offsite disposal. Other support facilities include laboratories, facilities for security, fire protection, administration, environmental monitoring, and maintenance.

Shafts and Ramps. As currently envisioned, the surface facilities would be connected to the underground area of the potential repository through two ramps and four shafts. One of the ramps would be used to transport waste containers from the surface to the underground area and to provide a fresh-air supply for the waste emplacement area. The second ramp would be used to assist in excavating and constructing the repository and for removing mined rock from underground. This second ramp would also serve as the primary exhaust airway for the underground areas that are being excavated.

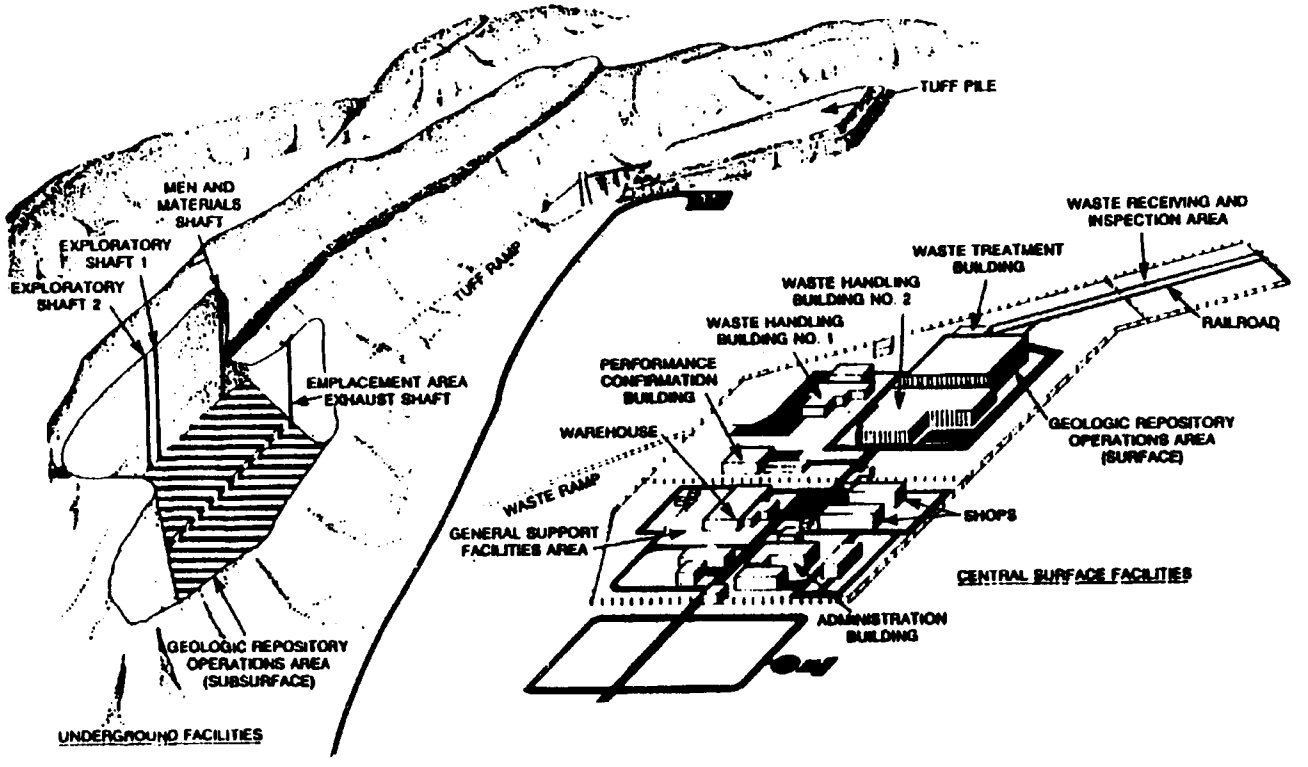

Figure 9-3. Surface and underground facilities at the planned Yucca Mountain repository.

Four shafts are currently planned for the repository to provide additional ventilation to the waste-emplacement and construction areas and to provide access for workers and materials.

Underground facilities. The repository is expected to be constructed at a depth of ~1000 feet below the surface in the unsaturated zone. According to the current conceptual design, the underground repository would have three main horizontal passageways, called "drifts," excavated parallel to one another. Each of these drifts would serve a number of waste emplacement areas, which, in turn, would consist of rooms in which the waste would be emplaced (Figure 9-3). Vertical holes would be bored into the floor of these rooms and the waste containers containing the spent fuel would be inserted into them.

Waste emplacement is envisioned as beginning many years before the excavation of the repository has been completed (DOE 1991a). Waste emplacement is planned to start as soon as two of the waste emplacement areas have been completely excavated and constructed. This operating plan, thus, enables repository usage to begin at a relatively early date, but also results in a significant population of excavation workers being at risk of exposure in the event of a preclosure accident scenario involving radioactive releases. The repository will remain open for a period of ~50 years.

Postclosure seals. The permanent closure of the repository will require the sealing of all shafts, ramps, exploratory boreholes, and other underground openings. The design objectives for seals and backfill is to reduce, to the extent practical, the potential for creating preferential pathways for ground water and radionuclide migration. The ultimate capability of these postclosure seals is uncertain.

Waste package. The principal engineered barrier to radioactive releases at the Yucca Mountain repository is the waste package. The waste packages are required by regulations to permit the spent fuel to be retrieved during the preclosure period and provide nearly complete containment for at least 300 to 1000 years after closure. The waste package consists of the spent fuel itself and the disposal container. The disposal container is currently assumed to be a single-walled, stainless steel cylinder. Tougher, more corrosion-resistant materials for the disposal canister are being considered, but to date the economic disadvantages of constructing more than 70,000 containers out of materials that are more expensive than stainless steel have outweighed the safety advantages of using more durable materials. Recent consideration has been given to the use of a large universal container, suitable for shipping and for ultimate placement in the repository, rather than cylinders.

9.3 SPENT FUEL SOURCE TERM

As documented earlier in this report, the reference quantity of spent fuel reporting to a repository from one gigawatt-year of electricity generation is 49 fuel assemblies. These 49 fuel assemblies, comprised of 9,261 fuel pins and associated structural hardware, correspond to 22.6 MT of heavy metal fuel.

The composition and properties of spent fuel are affected by the initial enrichment of the as-loaded fuel by the extent to which the fuel is "burned-up" within the reactor and by the age, or cooling time, of the fuel. The isotope composition of the spent fuel from the reference Westinghouse PWR has been calculated by the ORIGEN2 model (Croff 1980, see Appendix B) assuming a nominal 10-year cooling time. This isotope composition is shown in Table 9-1 for isotopes that are of significance for geologic disposal.

Table 9-1. Spent fuel source term for repository releases

Isotope	Inventory (curies)*	Isotope	Inventory (curies)
^{3}H	10,550	^{238}U	6.98
^{14}C	0.0041	^{237}Np	16.0
^{79}Se	14.4	^{238}Pu	153,000
^{85}Kr	167,000	^{239}Pu	9,730
^{93}Zr	2,013,000	^{240}Pu	16,800
^{90}Y	2,013,000	^{241}Pu	56.4
^{93}Sr	63.7	^{242}Pu	49,300
^{99}Tc	440	^{241}Am	2,200,000
^{135}Cs	15.9	^{242}Am	1,110
^{137}Cs	2,860,000	^{243}Am	829
^{137}Ba	2,700,000	^{244}Cm	109,000
^{234}U	29.9	^{245}Cm	17.3
^{235}U	0.39		
^{236}U	8.98		

* Assumes 22.6 MT of spent fuel with a 10-year cooling time.

9.4 PRECLOSURE RELEASES

There are no current analyses of preclosure releases that are specific to the reference Yucca Mountain facility. However, preclosure releases have been estimated for a different U.S. spent fuel repository site in a geologic salt formation (Waite 1984; Yook 1984; Harris 1985). Preclosure releases are a function of surface operations, the condition of the received spent fuel, and of generic waste rock properties and, thus, are not expected to be strongly site-dependent. For this reason we use the evaluations performed for the salt repository site as a basis for the preclosure release estimates at the Yucca Mountain repository.

There are two categories of preclosure releases to be characterized: (1) operational releases and (2) accident releases.

9.4.1 Operational Releases

There are two sources of operational releases from a spent fuel repository during the preclosure period as defined by Waite (1984): (1) damaged fuel pins and (2) waste rock.

During the operational phase of the repository, a small percentage of the received spent fuel elements will have been damaged during transport. All fuel elements are planned to be removed from the transportation casks within heavily shielded facilities, commonly called hot-cells, at the surface of the repository complex. Within these hot-cell facilities, radioactive gases from any damaged fuel elements would vent through an engineered off-gas system and then be released to the environment. The engineered off-gas system is comprised of high-efficiency particulate and charcoal filters that are assumed to trap essentially all of the released particulates and 99% of the released iodine. Other gases that will pass through these filters and be released to the environment include ^{14}C, ^{85}Kr, and tritium (^{3}H).

Using the methodology of Waite (Appendix B, p. 139 of Waite 1992), we assume:

- A pin failure fraction during transport of 2 per million. This value is based on experience with transport of several million spent fuel assemblies from DOE-Savannah River site reactors.

- Pin releases, based on tests performed in 1979 (Table 7.4.1 of Battelle 1979) of 0.005 curies of tritium, 0.00004 curies of ^{14}C, 3 curies of ^{85}Kr, and 0.0005 curies of ^{129}I.

The above listed values of pin releases need to be scaled for the higher inventory of radioactive gases present in the reference fuel pins as compared to the inventory of radionuclides in the tested fuel pins. Performing this scaling and taking into account the failure rate of 2 pins per million and the assumption that only 1 percent of the iodine gases are not trapped in the offgas system, estimates of radioactive gas releases for the reference spent fuel have been calculated and are presented in Table 9-2.

Table 9-2. Operational repository releases due to failed spent fuel pins

Isotope	Releases (curies/year)*
^{3}H	0.00008
^{14}C	0.0000006
^{85}Kr	0.048
^{129}I	0.0000008

*Attributable to the reference 22.6 MT/y of spent fuel.

Radiation exposures to the public from tritium, ^{14}C, and ^{129}I gases are ordinarily from inhalation pathways. Radiation exposure from ^{85}Kr is principally by external pathways.

A second source of operational releases to the environment comes from the waste rock that is excavated during construction. All rock contains some quantity of naturally occurring radon gas, which is a short-lived daughter of long-lived natural elements such as thorium and radium. By bringing the rock up to the surface in a high specific-surface area form, increased releases of naturally occurring radon gas will occur. These radon releases will continue at essentially the same level for the entire time period that the waste rock is at the surface. For the reference repository it is assumed that this surface storage time for the waste rock is 50 years.

These releases are identical in nature to the radioactive releases from waste rock in the uranium mining step as evaluated in Chapter 5.4.2 of this report.

Table 9-3 shows the radioactive emissions from the waste rock. In addition to ^{220}Rn and ^{222}Rn, the long-lived decay of radon - ^{210}Pb, ^{212}Pb, and ^{210}Bi - are shown as well. The second column of Table 9-3 shows values reported in

Waite (1984) for emission rates from 35 million tons of salt displaced from repository excavations. In the absence of more site specific values for the Yucca Mountain repository, these values will be used in this report. The third column in this table shows the release rate scaled to a value that is attributable to the reference quantity of spent fuel per unit of electricity production. The final column in this table shows the total value of the releases over the assumed 50-year duration of surface storage.

Table 9-3. Operational repository release from excavated rock stored at the surface

Isotope	Release rate* (curies/sec)	Release rate - reference spent fuel (curies/sec)	Total Releases - reference spent fuel (curies/year)
^{220}Rn	2.9×10^{-11}	1.0×10^{-14}	0.000016
^{222}Rn	4.0×10^{-11}	1.3×10^{-14}	0.000021
^{210}Pb	3.5×10^{-15}	1.2×10^{-18}	2.0×10^{-9}
^{212}Pb	4.4×10^{-14}	1.5×10^{-17}	3.0×10^{-8}
^{214}Pb	4.0×10^{-11}	1.3×10^{-14}	0.000021
$_{210}Bi$	4.0×10^{-11}	1.3×10^{-14}	0.000021

* Release rate values are for 35 million tons of waste rock.

9.4.2 Accident Releases

Harris et al. (1985) have reviewed and defined preclosure accidents for a basalt repository and qualitatively assessed the nature of releases and the occurrence probability of the accident. Because of the fact that surface operations are likely to be similar between dissimilar sites, we assume that the accident scenarios identified by Harris et al. are qualitatively relevant and applicable to the reference Yucca Mountain repository.

In their safety analysis, Harris et al. identify 153 potential initiating events for repository preclosure accidents that may result in either radioactive releases to the public, occupational radiation exposures, or non-radiological occupational injuries. Of these events, a total of 109 possible initiating events are evaluated as potentially causing radioactive releases. Table 9-4 presents category definitions for preclosure repository accidents discriminated by a qualitative description of their frequency and potential severity. These qualitative evaluations are those of

Harris et al. and no quantitative definition of the terms **high**, **medium low**, or **very low** is offered.

Table 9-4. Preclosure repository accident scenarios involving radiation releases to the public

Qualitative ranking of accident scenario probability and severity*	Number of identified accident scenarios*
High frequency, medium severity	2
Medium frequency, medium severity	16
Medium frequency, low severity	14
Low frequency, high severity	8
Low frequency, medium severity	36
Low frequency, low severity	27
Very low frequency, medium severity	4
Very low frequency, low severity	2

* Information is extracted from Harris et al. (1985). Use of the qualitative terms high, medium, low, and very low is per Harris et al.

The two accident scenarios judged by Harris et al. to have high frequency and medium consequences are:

Truck/train collides with stationary structures in the arrival area. Harris et al. state that accidents in rail yards and truck depots often occur. This type of accident possesses the capacity for energetic impact/crushing of the spent fuel cask due to the mass and momentum inherent in switchyard locomotives and diesel truck tractors; thus, the radiological consequences to the public were judged by Harris et al. to be medium. Potential radiological consequences to the occupational work force were judged to be high.

Waste canister struck by retrieval machine-operator error. This scenario deals with the optional retrieval of the spent fuel from the borehole within which it is emplaced. The Yucca Mountain repository will also be designed and operated to maintain the retrievability of the emplaced spent fuel prior to final repository closure. However, waste retrieval operations of this sort are usually not considered to be part of the

reference Yucca Mountain operations plan and, therefore, this scenario probably does not apply.

The eight accident scenarios defined as having low frequency of occurrence but high severity are all initiated by airplane crashes into the site, resulting in major breaches in radioactive contaminant systems. No damage to the subsurface portion of the repository is expected from aircraft crashes.

No quantitative calculation of radioactive releases due to these specific accident scenarios is available. It seems reasonable to assume that the high-frequency accident scenario involving a truck collision with the receiving depot would probably result in releases similar to the severe accidents for spent fuel transportation that are discussed in Chapter 8. The economic and health consequences of a truck collision at the repository receiving depot are likely to be considerably less than the analogous accident consequences on a public highway due to the remoteness of the repository from public habitation.

Yook et al. (1984) have also identified and evaluated potential accident scenarios at a spent fuel repository at a candidate salt site. The majority of these scenarios involve energetic vertical impacts upon spent fuel casks due to handling errors or droppage from mechanical grappling systems. Horizontal impact accidents, usually involving vehicles, are also identified. The evaluations of Yook et al. focused primarily on calculating the incident forces on the cask as a result of the defined impacts. Neither quantitative nor qualitative assessments of accident probability or severity were reported by Yook.

A quantitative assessment of releases and health impacts from two preclosure spent fuel repository accidents was performed by Waite (1984). These two accidents are not described in detail. The first accident scenario is generally described as involving a drop of a spent fuel canister down a shaft resulting in releases to the environment. The second scenario, an unspecified handling accident in the receiving area, involves releases within the shielded facilities. The releases in the latter scenario are smaller because the off-gas system is assumed to trap all airborne particulates and 99% of the radioactive iodine.

Releases reported from Waite for these accident scenarios are shown in Table 9-5.

Table 9-5. Releases resulting from preclosure accidents at a spent fuel repository

Isotope	Releases from shaft drop of spent fuel (curies)	Releases from spent fuel handling accident in receiving area (curies)
^{3}H	9	5.4
^{14}C	0.06	0.036
^{85}Kr	6000	3600
^{90}Sr	0.0002	
^{90}Y	0.0002	
^{129}I	0.009	0.0054
^{137}Cs	0.0002	
Pu	0.00014	
Am, Cm	0.000005	

9.5 POST-CLOSURE RELEASES

The basic objective of a repository is to store radioactive wastes deep underground until the radioactive materials decay to inconsequential levels. Some radioactive materials remain hazardous for thousands of years; thus, very long storage times are required. No surface facility could be expected to survive for such a long time because of erosion, climate change (ice ages), and other factors. In contrast, typical rocks underground exist for millions of years without change.

During the preclosure period, spent fuel is to be placed within engineered barrier systems, and then these engineered systems are emplaced into holes, called vertical boreholes, within large underground chambers that have been excavated at the Yucca Mountain site. The vertical boreholes may be backfilled with material that will enhance the isolation of the spent fuel, but the spent fuel is maintained in a retrievable mode up until final closure of the repository. After final repository closure, the site will be monitored for environmental releases. Ultimately, however, the long-term scenarios for the geologic repository assume a loss of institutional control. Isolation of the extremely hazardous components of spent fuel from the accessible environment relies upon the engineered barrier system and the natural barriers.

In this section we estimate releases from the Yucca Mountain repository attributable to the 22.6 MT of spent fuel associated with one gigawatt-year of electricity production from the reference reactor. The definition of the term releases in the context of repository discussions will refer to the quantities of materials that reach the accessible environment. The accessible environment includes the air, the surface of the land or any surface body of water, any underground aquifer, or groundwater that passes beyond the boundaries of the repository project site.

Since the geologic medium is the primary instrument for isolating the spent fuel from the accessible environment, it follows that any repository performance projections will be very site-specific. The ability of Yucca Mountain to isolate wastes will be quite different than that of a European site repository or the basalt site repositories studied in the United States in the 1980s. Thus, repository performance literature that is specific to the Yucca Mountain site is preferred as a basis for estimates of impacts from postclosure releases.

By its nature, no experimental data on long-term repository performance is available, so projections must be based on computer models. Several total system performance assessments of a Yucca Mountain repository have been published, including the work of Barnard (1992) for the DOE Yucca Mountain Project Office, the work of McGuire (1992) for the Electric Power Research Institute (EPRI), and the work of researchers at DOE's Pacific Northwest Laboratory (Eslinger 1992). We have selected the work of Barnard to be used as a basis for the calculations of releases from the reference reactor spent fuel at a Yucca Mountain repository. Barnard's work is the most thoroughly documented and appears to be the most comprehensive and authoritative analysis. Barnard does not assess volcanic scenarios in which massive expulsion occurs, however, so other sources will be used for those release estimates (see Chapter 9.4.1).

Several important caveats apply to Barnard's work. First, the Yucca Mountain site is incompletely characterized, and there are a number of key geologic uncertainties that affect expected performance. Even though site characterization measurements are planned, it is questionable whether any analysis will ever be definitive due to the inability to characterize the geologic system at the temperatures to which it will rise (60 to 300°C) when spent fuel is emplaced. Secondly, the Barnard study does not look at all of the potentially important scenarios for releases to the environment.

The methodology used by Barnard was a probabilistic calculation of repository releases using simple models that have been abstracted from more detailed, mechanistic models. The overall system model represents the repository as an ensemble of five layers of geographic strata with parameter assumptions

about the hydrogeologic and chemical properties of each stratum. Key parameter assumptions were stochastically varied by Barnard over probability distributions defined to represent the uncertainty in each parameter. The underlying mechanistic models include a number of hydrologic and gas flow models. Specialized models to represent features and processes associated with breaching the engineered barrier systems were also developed and used. The methodology is too detailed to summarize here and the reader is referred to Barnard (1992) for additional information.

There are four categories of release pathways to the accessible environment that affect repository releases. The first two, aqueous releases and gaseous releases, are expected to occur given the normal, undisturbed state of the repository. Two other release modes, human intrusion and volcanic expulsion, are considered to be unplanned disturbances to the repository; the releases in these disturbed performance scenarios are treated somewhat analogously to accident releases in the other fuel cycle steps. Human intrusion scenarios are generally considered to be very probable (probabilities close to 1 of at least some intrusion occurring), whereas volcanic expulsion probabilities are very low (but non-zero). The releases from each of these four modes for the reference quantity of spent fuel will be discussed in the subsections below.

9.5.1 Groundwater Flow and Transport[2]

This release mode refers to the breaching of the waste container followed by the dissolution of radioactive material in the groundwater. At Yucca Mountain, the spent fuel is planned to be emplaced at an elevation that is significantly above the water table (within the so-called "unsaturated zone") which is expected to ameliorate the long-term leaching and transport of radioactive materials significantly. However, the unsaturated zone is not completely dry and groundwater is present that is capable of dissolving containers and transporting radionuclides. The movement of the radioactive material in the groundwater has been modeled in detail, but is subject to major uncertainties in the assumptions about porosity of the geologic media and the role of fractures and cracks.

The radionuclides that are released in the most significant quantities are those that tend to be highly soluble in water and which are not readily reabsorbed back into the geologic media during their flow out of the repository. Long-lived radioactive fission products such as ^{99}Tc and ^{129}I are both highly soluble, highly mobile and, thus tend to dominate aqueous release estimates. Cesium fission

[2] Note that in the 10,000 year timeframe, defined by the U.S. Environmental Protection Agency, significant changes could occur in the groundwater regime, including the possibility of it getting drier.

products are also highly soluble but tend to be highly sorbed by most of the geologic media at Yucca Mountain. Plutonium and uranium are relatively insoluble in water, so they contribute only weakly to aqueous releases. The element neptunium is similar to plutonium in its toxicity, but is more soluble and mobile and, thus tends to contribute to aqueous releases.

Table 9-6 gives the results of Barnard's calculations for aqueous releases from the Yucca mountain repository assuming mean values for all input parameters and giving appropriate credit to the limited groundwater available for aqueous dissolution and transport phenomena. In the source report, Barnard presents the calculated release quantities as "fractions of the EPA limit," where the term "EPA limit" refers to statutory releases limits on each radioisotope within a 10,000-year timeframe as defined by the U.S. Environmental Protection Agency (EPA) (EPA 1985). For the convenience of the reader, the units have been converted to curies, using the EPA limit definitions in Table 1 of Part 191, Subpart B, Appendix A of Title 40 Protection of Environment (EPA 1985).

Table 9-6. Cumulative aqueous releases from the Yucca Mountain repository for a 1,000,000 year time frame

Isotope	Quantity release as reported by Barnard* (curies/MT spent fuel)	Incremental quantity released from 22.6 MT of fuel from a reference reactor (curies)
^{99}Tc	8.9	297
^{129}I	0.020	0.68
^{237}Np	0.0001	0
^{234}U	100,000	0

* Derived from Barnard 1992

Table 9-6 also shows the values of incremental aqueous releases associated with the 22.6 MT quantity of spent fuel that results from one gigawatt-year of electricity production from the reference reactor. The values for Tc and I are derived from the Barnard values for one MT of spent fuel, but have been scaled to reflect the differences in the quantity of spent fuel (a factor of 22.6) and a difference between Barnard's case and the reference case in the specific inventory of Tc and I in spent fuel (a factor of 1-5). This latter factor for specific inventory arises due to the fact that the reference reactor has about a 50% higher burnup of

its spent fuel than that assumed by Barnard, resulting in about 50% more Tc and I radioactivity.

Incremental releases of uranium and neptunium attributable to the reference fuel are assumed to be zero. Both uranium and neptunium are relatively insoluble in water, and the groundwater is assumed to be saturated with uranium and neptunium. Thus, the total quantity of these elements in the groundwater is limited by the total amount of available groundwater and not by the available amount of uranium and neptunium to be dissolved. In this condition, the emplacement of additional uranium and neptunium in the repository will not increase the total aqueous releases for a given timeframe.

The temporal nature of the releases are shown in Figure 9-4 as calculated by Barnard using mean values of the input parameters. None of these releases reach significant levels before 10,000 years, and the total cumulative value of the Tc and I releases are reached in about 100,000 years.

9.5.2 Gas Flow and Transport

At the Yucca Mountain site, the only gaseous effluent identified as being significant is ^{14}C in the form of CO_2. The isotope ^{14}C is formed from the reactions of neutrons in the reactor with low levels of nitrogen in the fuel. Some fraction of the ^{14}C has already formed the chemical CO_2 form and exists on the external surfaces of the fuel as an oxidation layer. Roughly one-third of the remainder of the ^{14}C is either entrained in the fuel matrix or in gaps in the fuel pins and is readily oxidized to CO_2 by the chemical conditions of Yucca Mountain.

The scenario for gaseous releases begins with an eventual breach of the waste container. The ^{14}C, already in the gaseous CO_2 form, is released from the container, escapes into the surrounding rock, and begins the percolation process through the geologic medium. In addition, some of the remaining ^{14}C is gradually oxidized to CO_2 and is released to the surrounding rock. Fractured rock, present due to the stress fields created by the original excavation of the repository, will likely provide paths for the radioactive CO_2 gas. In addition, the backfilled tunnels of the repository will have sufficient porosity that the gas can be expected to move through the backfill as well.

The elevated temperatures of the repository have the effect of driving gas flow to a more rapid rate than would be present with ambient temperatures. Indeed, gas travel times to the accessible environment, as reported by Barnard, appear to vary between 1,000 and 10,000 years dependent upon the detailed temperature assumptions.

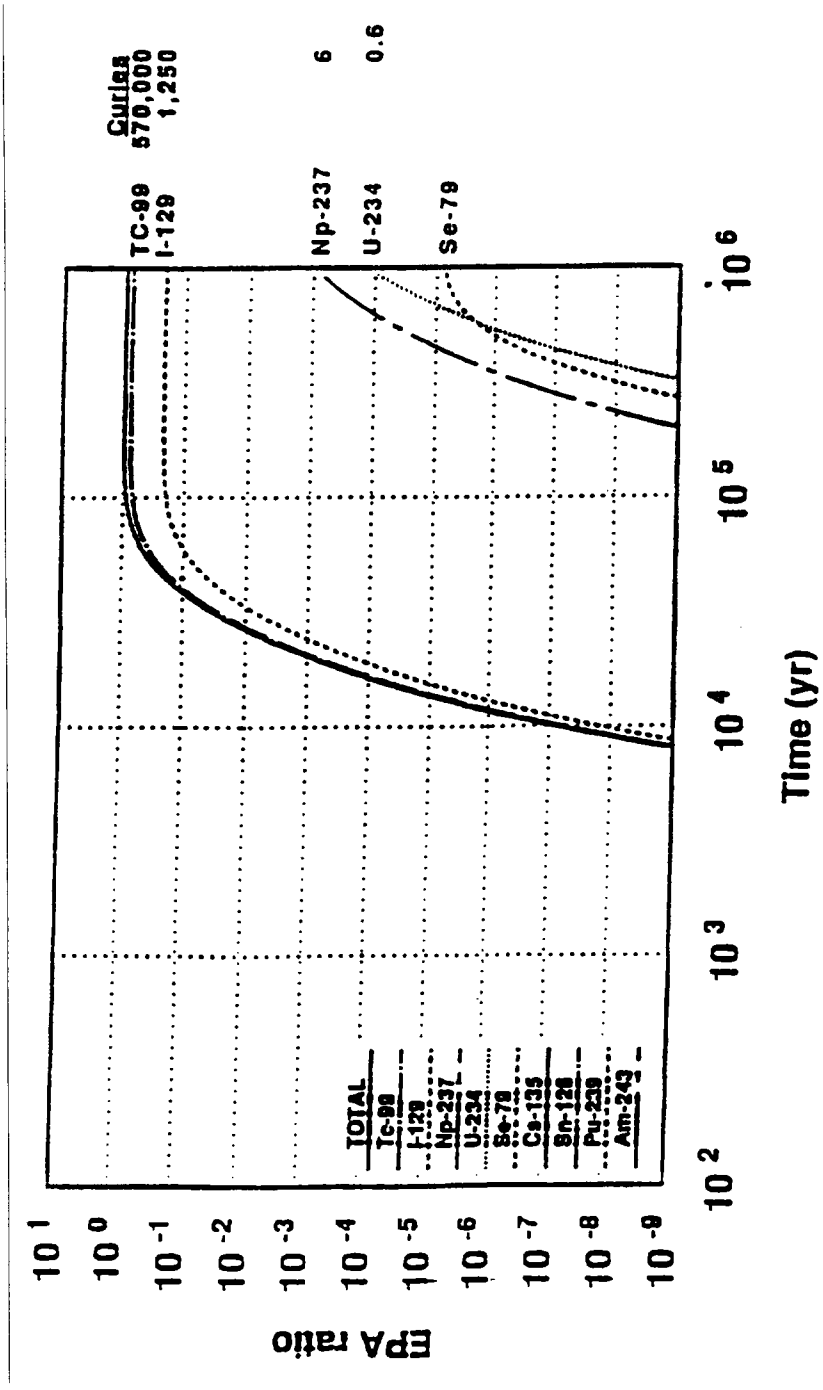

Figure 9-4. Expected temporal nature of repository aqueous releases in curies. Numbers shown refer to the radioactivity of the releases from the entire inventory of spent fuel within the Yucca Mountain. Adapted from Barnard et al. (1992).

For a case that employs mean values for all input parameters, Barnard reports a ^{14}C release of 30 Ci per 1,000 MT of emplaced spent fuel at 10,000 years, and a total release of ^{14}C gas in 20,000 years of about 51 Ci per 1,000 MT. Scaling to 22.6 MT and applying a factor of 1.5 to account for specific inventory differences due to the higher burnup of the reference fuel, the levels of ^{14}C releases are calculated to be:

^{14}C gaseous releases: 2.4 Ci.

This is the value that will be adopted in the calculation of health effects in Section 9.6.

9.5.3 Human Intrusion

The essence of the human intrusion scenario is that the repository is penetrated by the action of humans on the surface. This scenario might result from either inadvertent or deliberate intrusion. Inadvertent human intrusion refers to a scenario in which institutional control over access to the repository has lapsed and humans drill through the repository exploring for resources, e.g., water, petroleum, and natural minerals. In deliberate intrusion scenarios, the intruder is assumed to be aware of the repository contents and is actually seeking them, e.g., noble metals and plutonium (Forsberg 1991).

In either case there can be two deleterious effects on repository performance. The first is to provide a "short circuit" pathway for water to either enter or exit the repository (Channell 1991). The second deleterious effect is that some amount of waste material could be physically disturbed and either brought directly to the surface as drilling residuals or drop back into the drilling borehole and reach the water table below (see Figure 9-5).

Barnard evaluates inadvertent intrusion scenarios and uses rather sophisticated models to determine transport to the surface for whatever fraction of the waste intercepted by the drill bit that drops down to the water table. However, most of the fundamental assumptions on which human intrusion calculations are predicated are necessarily gross, and a high level of sophistication in transport calculations does not seem warranted.

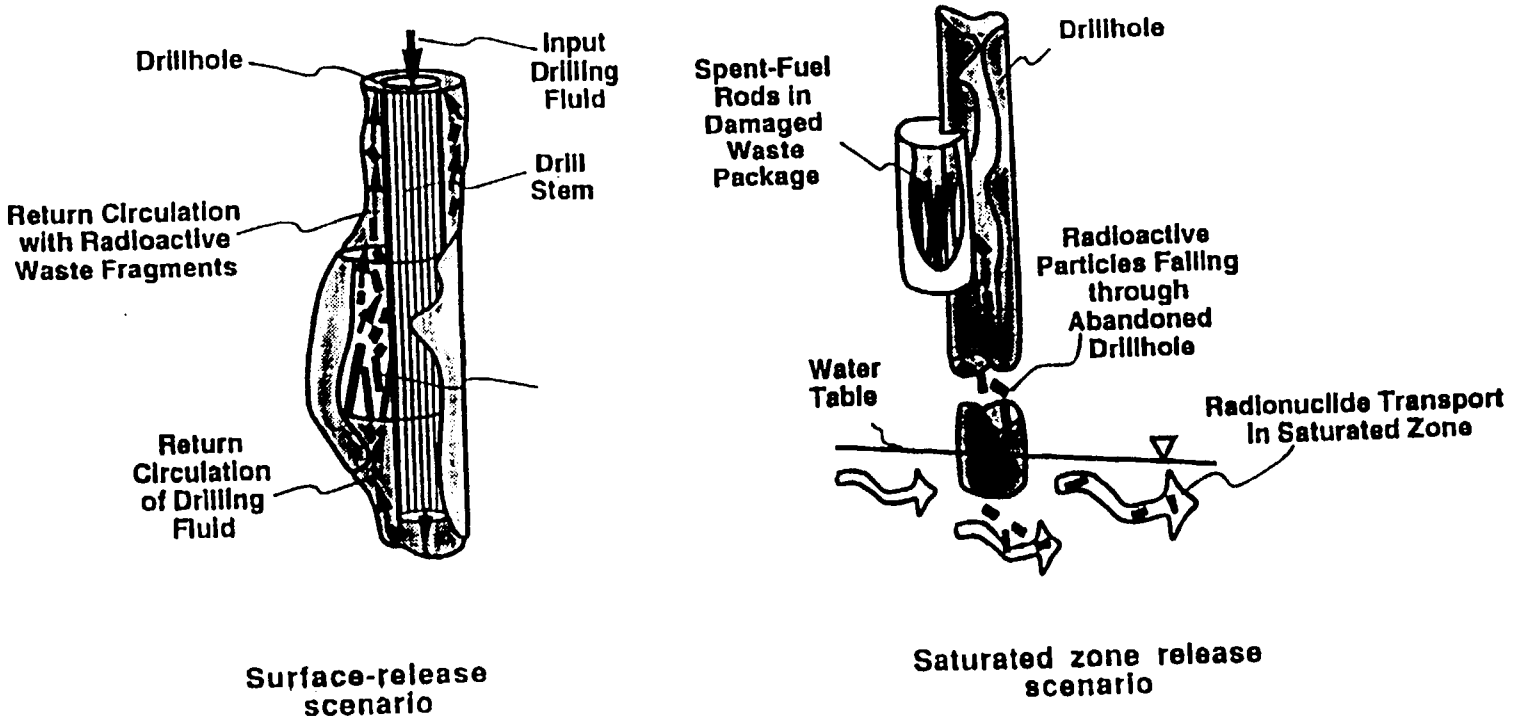

Figure 9-5. Scenarios for releases to the environment as caused by human intrusion. Adapted from Barnard et al. (1992).

Probability of inadvertent intrusion. For this analysis we adopt the following first-order model for the probability of human intrusion disrupting a given waste package:

$$P_{HI} = N_{events} \times P_{geom} \times Q_{waste} / Q_{canister}$$

where P_{HI} = probability of a human intrusion event resulting in a release in a given timeframe,
N_{events} = the number of assumed drilling events in the given timeframe,
P_{geom} = geometric probability of the drill bit intercepting a given waste package,
Q_{waste} = the total quantity of fuel emplaced as waste, MT, and
$Q_{canister}$ = the quantity of spent fuel present in a waste canister, MT.

Barnard assumes that the average value of N_{events} = 17 for a 10,000-year timeframe. This is based upon an EPA requirement (EPA 1991) that human intrusion calculations be based upon three boreholes/km^2 per 10,000 years, and the area of the Yucca Mountain repository, which is 5.4 km^2. There is probably no defensible method for predicting the frequency of human intrusion.

The geometric probability of a drill bit intercepting any of 33,000 waste packages is calculated by Barnard based upon the area of the repository, the area of a waste canister, and the area of a drill bit. Barnard reports a probability of 0.0066; division by 33,000 waste canisters will yield the probability of a drill bit intercepting any given canister, which is 2.0×10^{-7}.

For the reference spent fuel from one gigawatt-year of electricity production, Q_{waste} can be assumed to be 22.6 MT; $Q_{canister}$ for the Yucca Mountain system is about 2.1 MT (reference). Assuming N_{events} = 17 for a 10,000 year timeframe, and $P_{geom} = 2.0 \times 10^{-7}$, we calculate the following:

probability of human intrusion releases (10,000 year timeframe) = 3.6×10^{-5}.

Releases from inadvertent intrusion. There is no reliable basis for estimating the fraction of spent fuel in the waste canister that is lifted to the surface by the drill bit. We will assume an average value of 50%, but this number could range from 0 to 100%. The absolute quantity of radioactive material released will depend upon when the intrusion event occurs because of the nature of radioactive isotopes to decay to stable isotopes over time. Table 9-7 gives the releases to the environment for a human intrusion event for three reference time periods, assuming that a drilling event has occurred and has scored a direct hit on one of the canisters that holds spent fuel from the reference reactor.

Table 9-7. Conditional releases to the accessible environment for a human intrusion event

	Release to the environment (curies)*		
Isotope	at 500 y	at 5,000 y	at 50,000 y
^{14}C	0.0002	0.0001	$4x10^{-7}$
^{93}Zr	2.8	2.8	2.8
^{99}Tc	19.4	19.2	16.5
^{135}Cs	0.70	0.70	0.69
^{226}Ra	0.0012	0.095	1.3
^{230}Th	0.014	0.16	1.3
^{231}Pa	0.0002	0.002	0.016
^{233}Pa	1.3	1.8	1.8
^{234}U	3.7	3.7	3.3
^{235}U	0.02	0.02	0.02
^{236}U	0.41	0.48	0.61
^{238}U	0.31	0.31	0.31
^{237}Np	1.3	1.8	1.8
^{238}Pu	145	0	0
^{239}Pu	425	377	106
^{240}Pu	718	446	3.8
^{242}Pu	2.5	2.5	2.3
^{241}Am	2520	2.4	0.01
^{242}Am	2.6	0	0
^{243}Am	35.0	23.0	0.34
^{245}Cm	0.73	0.51	0.01

* Release assumes that a human intrusion event has occurred, and that 50% of the inventory of waste containing 2.1 MT of the reference spent fuel is transported to the surface.

Deliberate Intrusion Scenarios. Deliberate intrusion scenarios pose methodology issues for both the estimation of probability and consequences. Uncertainties in consequences arise because of the likelihood that the intruders will adopt countermeasures to contain the release of radioactivity. The probability of deliberate intrusion arises for scenarios in which spent fuel repositories represent the best (or only) sources of such commodities as plutonium and rhodium. The possibility of viewing the repository as a plutonium mine is a classic safeguards concern (Forsberg 1991). Given current rhodium consumption rates, the world's resources of rhodium could be exhausted within 200 years (Michaels 1993), causing spent fuel repositories to be the sole reasonable source of rhodium on Earth. Thus, plausible scenarios may exist for deliberate intrusion into the repository, resulting in releases of radioactive material.

No analysis in the literature of deliberate intrusion scenarios was found and the scenarios will not be analyzed in this study.

9.5.4 Volcanic Expulsion

The Yucca Mountain region has been a site of past volcanic activity (see Figure 9-6). The Crater Flat Volcanic Field lies immediately west of the repository site. Basaltic volcanism occurred in two episodes at Crater Flat approximately 3.7 and 1 million years ago, with eruption volumes of 0.65 km^3 (Perry 1992). The Lathrop Wells Volcanic Center lies at the southern end of Yucca Mountain and was active during the past two hundred thousand years (Perry 1992) with an eruption volume of 0.06 km^3. Some 20 to 23 volcanic centers in the Yucca Mountain region have been identified (Crowe 1992). The Yucca Mountain region and the Lunar Crater Volcanic Field to the north form the northern end of the Death Valley-Pancake Range volcanic zone (Foland 1992).

In a recent paper, the U.S. Geological Service reported results of a teleseismic survey of the Yucca Mountain region tectonics. These results (Evans 1992) rule out large mature magma chambers near Yucca Mountain, but did reveal a weak feature below Crater Flats which might have various interpretations, including crustal heating beneath that basin. Another anomaly in the survey might represent a large-volume partial-melt of rock, with its northern end in Crater Flats, just west of Yucca Mountain (Evans 1992). The detection of such possible hot spots is important because, if confirmed, they signal a source of heat that could originate a volcanic event.

Expulsive events, as they relate to repository performance, have not been extensively studied. This is largely so because the probability of a volcanic event is believed to be very small, thus making the resultant risk (probability x consequence) almost negligible. The most likely scenario involves the extrusion of a basaltic dike through the repository mechanically entraining some of the emplaced waste and bringing it to the surface. A lower-probability, higher-consequence scenario is a massive explosive expulsion of a significant fraction of

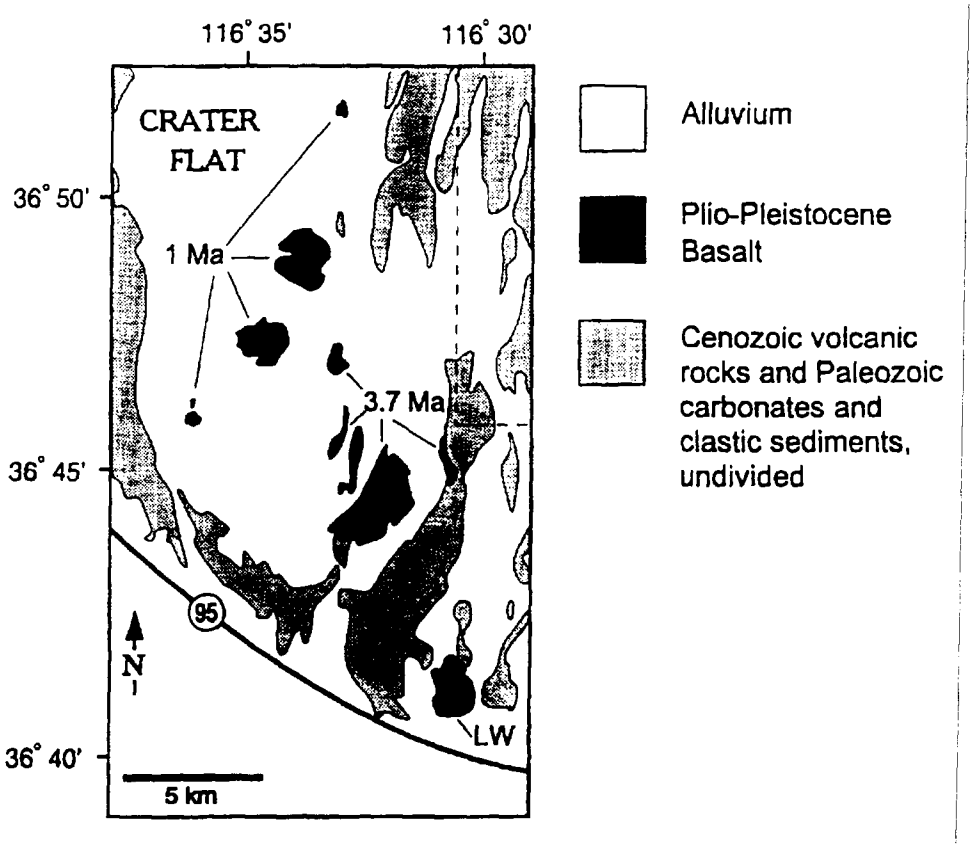

Figure 9-6. Volcanic fields near the Yucca Mountain repository site. The repository site is in dashed rectangle at upper right. Figure is from Perry (1992).

the repository inventory. Both of these scenarios involve transport to the accessible environment of radionuclides in a manner that bypasses the natural geologic barriers of the repository.

Results from past analyses of the effects of volcanic expulsion events on geologic repositories provide a perspective on the problem. Scientific Applications, Inc., (Logan 1980) performed an analysis of a volcanic event in a repository located near Carlsbad, New Mexico. The primary assumptions were that 7.5% of the inventory present at the time of the event was transported to the surface, the time of the event was 1,000,000 years after waste had been emplaced (thus implying significant reductions in radionuclide inventory), and an expulsive release frequency of once every 100 billion years (1×10^{-11}/year). The cancer death rate caused by the accidents in this study was less than 330 LCF per year (probably more than 600 fatalities per year with modern dose conversion factors); but the total fatalities over the next 100,000 years resulting from this incident was calculated to be 13 million (probably equivalent to over 25 million fatalities with modern dose conversion factors).

An EPA report (EPA 1985) evaluates risk and release fractions from a geologic repository. In this more generic EPA assessment, the probability of a volcanic expulsive release was assumed to be 1 in 33 million years. The release fraction was assumed to 0.04% of the existing inventory of radioactive nuclides. Although health effects are not calculated explicitly in the EPA report, Forsberg (1991) has converted the EPA releases into health effects. Forsberg reported an expected number of 0.9 health effects in 10,000 years, which can be expressed as a conditional consequence of about 3,000 fatalities, given a volcanic explosive release. This consequence is about 4,000 times lower than the results of the Logan study, which is only partly explainable by the use of a release fraction that is about 187 times lower (0.01% versus 7.5%).

Most recently, Barnard (1992) has performed an assessment of basaltic dike intrusion through the Yucca Mountain repository. The Barnard analysis assumed a mean probability of a volcanic event disrupting the repository of 2.4×10^{-8}/Year. The parameter for eruption volume was assigned a probability distribution with an average value of about 0.01 km^3 and a peak value of about 0.1 km^3, despite the evidence cited by Perry (1992) that proximate eruption events had a history spanning a range of eruption volumes from 0.06 to 0.65 km^3. The range of release fractions used by Barnard is difficult to derive because of the way his results are reported, but they appear to be very low, certainly below 0.01%.

Crowe (Crowe 1992, Crowe 1990, Crowe et al. 1989) has studied the recurrence rate of volcanism, particularly as applied to the Yucca Mountain site. He concludes (Crowe 1992) that the recurrence rate for volcanism in the Yucca Mountain region is $1\text{-}6 \times 10^{-6}$/y. Crowe further concludes, however, that no consensus exists about which of several existing models for volcanic recurrence is correct, that the number of events at Yucca Mountain is marginal for mathematical analysis, that existing models simplify a very nonlinear highly-coupled complex problem, and that validation of a model on-one volcanic center

does not imply reliability in prediction of recurrence rates at other volcanic centers.

We conclude that the volcanic events are a potentially important source of releases for a repository and can be characterized as a low frequency event with potentially large consequences. More information is needed to support reliable estimates of probabilities and release fractions at the Yucca Mountain site.

Reference definition of a volcanic expulsion scenario. Table 9-8 provides the reference assumptions for probability and conditional releases for a volcanic expulsion event at Yucca Mountain. The reference recurrence rate for the region is assumed to be five events per million years, based on the observation that there have been two multiple volcanic events (several at Lathrop Wells Volcanic Center and one at Crater Flats Volcanic Center) during the last one million years., The conditional probability that this eruption is a basaltic dike that penetrates the repository is taken to be 2.4×10^{-3}, based on the work of Crowe (1991). These values are similar to those selected by Barnard (1992).

The conditional probability that the volcanic even explosive disruption of the repository is taken to be 1×10^{-6} (Bingham 1991). The release quantities for both the dike intrusion and the expulsion cases are shown in Table 9-8.

9.6 PRIORITY IMPACT PATHWAYS

The priority impact-pathways for impacts associated with spent fuel disposal, are as shown in Table 9-9.

9.7 IMPACTS[3]

9.7.1 Health Effects: Mortality and Morbidity

The calculation of expected health impacts due to releases from a repository to the accessible environment poses some methodology issues due to the long timeframes that are involved.

- One issue is that the long-lived radionuclide will decay to other longlived nuclides, which may have different transport mobility in the environment and different somatic effects when introduced to an organism. An example of such an issue is the consideration of ^{234}U releases. Released ^{234}U is relatively immobile but decays, in two steps, to ^{226}Ra. This radium isotope is soluble in

[3] As mentioned previously, we estimate health impacts but do not estimate the externalities in monetary terms. Almost any non-zero discount rate would result in zero present value. This long-term intergenerational issue is a major unresolved issue.

Table 9-8. Reference assumptions for volcanic expulsion scenario

	Basaltic igneous activity	Massive volcanic expulsion
Probability of occurrence in 10,000 years	0.00024	$1x10^{-8}$
Probability that event expels the reference spent fuel	$3.5x10^{-5}$	.001
Total probability of release	$8.4x10^{-9}$	$1x10^{-11}$
Incremental release quantities, curies		
^{14}C	0.0002	0.0023
^{99}Tc	38.4	440
^{135}Cs	1.4	15.9
^{234}U	7.4	83.6
^{236}U	1.0	11.3
^{237}Np	3.6	40.7
^{239}Pu	791	8,980
^{240}Pu	937	10,600
^{242}Pu	5.3	60.1
^{241}Am	5.0	56.8
^{243}Am	48.3	548
^{243}Cm	1.1	12.5

* Incremental releases are those releases attributable to the presence of 22.6 MT of the reference spent fuel in the repository. The volcanic event is assumed to occur at 5,000 years.

Table 9-9. Primary emissions or activities, pathways, and impacts linked to the nuclear fuel cycle from spent fuel disposal

Emissions/activities	Environmental pathway	Impact	Impact evaluation
Preclosure air emissions			
Radionuclides	Atmospheric dispersion, deposition on land surface	Human health	Minimal impacts due to low releases
		Damage to wildlife and biosystems	Modeling request to assess impacts
Post-closure emissions			
^{14}C	Atmospheric dispersion	Human health	Quantified
^{99}Tc, ^{129}I	Leaching to ground water, food chain pathways	Human health	Quantified
Radionuclides from intrusive/expulsive scenarios	Discharge to surface and/or air	Human health	Quantified
Land use change	Development of roads, permanent impoundment	Loss of biotic habitat, loss of natural resources	Qualitative evaluation
Socioeconomic effects	Direct effect	Loss of gaming revenues, real estate devaluation	Not yet evaluated
		Employment benefits	Not yet evaluated

water and, thus, has the potential to move more rapidly away from the repository environs to the population areas. Radium is a bone seeker and, thus, has a higher toxicity upon ingestion than uranium isotopes. Radium itself will decay to radon gas, which is quite mobile and is an ingestion hazard.

- Another difficulty is in making credible assumptions about population density for far-future scenarios.

- The time periods involved in this issue are sufficiently long that regional climate and local weather patterns may have changed dramatically. Climate change in general, and impacts upon local weather in particular, are beyond current capabilities to predict reliably.

- Even basic health assumptions are questionable given the very long time frames involved. It is not clear why all studies assume that medical science will not advance enough in the next several hundred years (or several thousand years) so that cancer will be completely curable and that other radiation-induced damage to humans can be reversed.

- This discount rate/intergenerational equity issue is a major concern that remains unresolved.

These are difficult questions. The EPA has adopted a methodology for converting long-term repository releases into health effects (Smith 1985). This methodology has been used in developing the current EPA regulatory guidelines for release limits from geologic repositories. We will adopt this methodology because it is a straightforward and well-documented approach. Health impacts will be modified (increased) from the values given by Smith, however. The 1985 Smith report assumes BEIR III values for conversion of man-rem to health impacts. For this report we will use simple linear scaling to adjust these values to reflect the more recent BEIR V determinations.

In Chapter 9.4 releases to the accessible environment from postclosure repository scenarios were defined. The EPA/Smith study then calculates the transport of these released radionuclides through the environment and projects the health impacts to the general public. The pathways used in the EPA/Smith study are shown in Table 9-10.

The EPA numbers for fatal cancers per released curie for different release modes from a HLW repository are shown in Table 9-11. The EPA numbers for genetic effects per curie released from a repository for different release modes are shown in Table 9-12.

Using these values, it is straightforward to calculate the health effects due to repository releases by the following formula:

For a given released radionuclide:

Fatal cancers = (released Ci of radionuclide) x
(fatal cancers/Ci released)

where the latter term is provided in Table 9-11. A similar equation applies for the projected number of genetic effects using the conversion factors provided in Table 9-12.

The results for health effects from normal repository operations are given in Table 9-13. The results for health effects from human intrusion and volcanic scenarios in a repository are given in Table 9-14.

9.7.2 Land Commitment

The repository represents a permanent commitment of land of about 6 km^2. Drilling and mining operations will be barred from occurring on the Yucca Mountain site. An environmental assessment of the site (DOE 1986) concluded that no economic minerals are present at Yucca Mountain. Castor et al. (1989) performed geochemical analyses of the site and concluded that the petroleum potential of the site is low and identified no significant mineral resources. However, Younker et al. (1992) reports that a history of claims for gold have been filed for the area and that gold is being extracted from the nearby Bare Mountain area.

Table 9-10. Release modes and environmental pathways used in EPA (Smith 1985) analysis of repository health effects

Release mode	Pathways included in this release mode
Releases to river (aqueous releases)	Drinking water Freshwater fish ingestion Food crops ingestion Milk ingestion Beef ingestion Inhalation of resuspended material External dose-ground contamination External dose-air submersion
Releases directly to land surface (human intrusion)	Food crops ingestion Milk ingestion Beef ingestion Inhalation of resuspended material External dose-ground contamination External dose-air submersion
Releases due to volcano	
Releases directly to land	Food crops ingestion Milk ingestion Beef ingestion Inhalation of resuspended material External dose-ground contamination External dose-air submersion
Releases to air over land	Food crops ingestion Milk ingestion Beef ingestion Inhalation of dispersed and resuspended material External dose-ground contamination External dose-air submersion
Releases to air over ocean	Ocean fish ingestion Ocean shellfish ingestion

Table 9-11. Number of fatal cancers per curie released from a repository

Nuclide	Releases to a river (aqueous mode)	Releases to land surface (human intrusion)	Volcanic releases
^{14}C	0.117	0.117	0.117
^{99}Tc	0.0073	1.1×10^{-7}	0.004
^{129}I	0.161	0.0079	0.111
^{135}Cs	0.0155	0.0012	0.0098
^{234}U	0.0392	0.0013	0.0119
^{235}U	0.0434	0.0004	0.0165
^{236}U	0.0370	0.0017	0.0112
^{238}U	0.0412	0.0014	0.0113
^{237}Np	0.159	0.0002	0.0566
^{239}Pu	0.0994	0.0125	0.0240
^{240}Pu	0.0968	0.0104	0.0230
^{242}Pu	0.0958	0.0127	0.0218
^{241}Am	0.1084	0.0021	0.051
^{243}Am	0.1144	0.0049	0.068
^{245}Cm	0.202	0.016	0.121

Numbers are derived from Smith (1985), adjusted to BEIR V dose factors.

Table 9-12. Number of genetic effects per curie released from a repository

Nuclide	Releases to a river (aqueous mode)	Releases to land surface (human intrusion)	Volcanic releases
^{14}C	0.0606	0.0606	0.0606
^{99}Tc	0.0003	5.2×10^{-8}	0.00002
^{129}I	0.0004	0.00002	0.00026
^{135}Cs	0.006	0.0047	0.0040
^{234}U	0.0033	0.0001	0.00002
^{235}U	0.0041	0.0002	0.0015
^{236}U	0.0031	0.0001	0.00002
^{238}U	0.0036	0.0001	0.0001
^{237}Np	0.0258	0.00004	0.0073
^{239}Pu	0.0161	0.0020	0.0014
^{240}Pu	0.0157	0.0016	0.0014
^{242}Pu	0.0154	0.0020	0.0013
^{241}Am	0.0178	0.0003	0.0061
^{243}Am	0.0189	0.0009	0.0010
^{245}Cm	0.0328	0.0027	0.0151

Numbers are derived from Smith (1985).

Table 9-13. Health effects from the Yucca Mountain repository due to long-term releases from the reference reactor spent fuel

Nuclide	Fatal cancers (deaths/GW(e)-y)	Genetic effects (effects/GW(e)-y)	Approximate delay from repository closure to health effects (years)
Aqueous release			
^{99}Tc	0.109	0.0052	2,000 - 100,000
^{129}I	0.0545	0.00012	20,000 - 100,000
Gaseous release			
^{14}C	0.14	0.073	200 - 20,000

Table 9-14. Incremental long-term health effects from human intrusion and volcanic scenarios at Yucca Mountain repository attributable to 22.6 MT of spent fuel from the reference reactor

Release scenario	Conditional latent cancer fatalities	Expected latent cancer fatalities	Conditional genetic effects	Expected genetic effects
Human intrusion events (probability = 3.6 x 10^{-5} for 10,000 years)				
at 500 years	18.3	6.6×10^{-4}	2.80	1.0×10^{-4}
at 5,000 years	5.79	2.1×10^{-4}	0.93	3.3×10^{-5}
at 50,000 years	0.13	4.7×10^{-6}	0.024	8.6×10^{-7}
Basaltic igneous events (probability = 8.4×10^{-9} for 10,000 years)				
at 5,000 years	44.8	3.8×10^{-7}	2.55	2.1×10^{-8}
Massive volcanic expulsion (probability = 1×10^{-11} for 10,000 years)				
at 5,000 years	508	5.1×10^{-9}	28.9	2.9×10^{-10}

10. NET NEW EMPLOYMENT BENEFITS

In this section we estimate the net new employment benefits that may result from construction and operation of a nuclear facility in Tennessee or New Mexico (the Southeast and Southwest reference environments considered in this study). 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.

Net new employment opportunities are sometimes described as "employment benefits." 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. When properly specified, these benefits are equivalent to the difference between society's opportunity cost (or the shadow price) of labor and the private cost of labor (the market wage).[1]

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.[2]

In a perfectly competitive economy, the wage rate will equal a worker's marginal contribution to the value of what is produced. 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

[1]For an introduction to the theory underlying this section, see the document entitled *Fuel Cycle Externalities: Analytical Methods and Issues* (ORNL/RFF 1994).

[2]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.

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.

Data and Research Approach

Data for the unemployment rate in thirty-seven industrial categories for the nation and for regions of the country were gathered from annual publications of *Employment and Earnings* and *Geographic Profile of Employment and Unemployment* published by the U.S. Bureau of Labor Statistics.[3] Table 10-1 presents numerical references to the data in these documents. Unemployment rates by industrial sector for the United States, for the East South Central region, which includes the State of Tennessee, for the Mountain region, which includes the State of New Mexico, and for the East North Central and Pacific regions, which are affected in mining and fuel processing, for selected years between 1981 and 1991, are presented in Tables 10-2 through 10-6.[4] The averages of these data for each industrial category are presented in the final column of the tables. These averages are taken to represent a forecast of the persistent rates of unemployment over the 40-year life of the facility.

The year 1989 is selected as a modern estimate of a full-employment period with low inflation. The year 1989 has the lowest average unemployment rate (5.3%) for the United States of any year in this period. Inflation for all items less food and energy was 4.5%, the midpoint between 1983 and the present, when inflation ranged from 4% to 5% annually.[5] Unemployment rates observed in this year in each industry are taken to be industry-specific natural rates of unemployment.

Johnson and Layard (1986) survey recent estimates of the natural rate of unemployment ranging from 4.7% to 6.5%, and the average rate for 1989 (5.3%) falls well within this range. As an alternative and more conservative estimate, calculations are presented using the year 1987 as a base. The average unemployment rate for the United States was 6.2% in 1987, near the upper bound suggested by Johnson and Layard, while inflation was 4.0%, the lowest of any year in the decade.

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[3]These publications actually provide data for thirty-seven industries. The mapping from the reported industries to the thirty-seven industries we use, along with an index of the numerical references, are presented in Table 1.

[4]The years 1982 and 1984 were omitted in these series in order to place greater weight on recent observations.

[5]Energy is excluded because prices have been heavily influenced by international markets. Food is excluded because fluctuations are due in large part to weather.

Table 10-1. Matching of the input-output and unemployment table categories

Category in input-output table	Category number for reference to other tables	Category from which the data was taken in the unemployment data
Agricultural products and agricultural, forestry, and fishery services	1	Farming, forestry, and fishing*
Forestry and fishery products	2	Farming, forestry, and fishing*
Coal mining	3	Mining
Crude petroleum and natural gas	4	Mining
Miscellaneous mining	5	Mining
New construction	6	Construction
Maintenance and repair construction	7	Construction
Food, kindred products, and tobacco	8	Food and kindred products
Textile mill products	9	Textile mill products
Apparel	10	Apparel and other textile products
Paper and allied products	11	Paper and allied products
Printing and publishing	12	Printing and publishing
Chemicals and petroleum refining	13	Chemicals and allied products
Rubber and leather products	14	Rubber and miscellaneous plastic products
Lumber, wood products, and furniture	15	Average of lumber, wood products, and furniture
Stone, clay, and glass products	16	Stone, clay, and glass products
Primary metal industries	17	Primary metal industries
Fabricated metal products	18	Fabricated metal products
Machinery, except electrical	19	Machinery, except electrical
Electric and electronic equipment	20	Electrical machinery, equipment, and supplies
Motor vehicles and equipment	21	Motor vehicles and equipment
Transportation equipment, except motor vehicles	22	Transportation equipment, including motor vehicles

Table 10-1. Matching of the input-output and unemployment table categories (continued)

Category in input-output table	Category number for reference to other tables	Category from which the data was taken in the unemployment data
Instruments and related products	23	Professional and photo equipment, watches, etc.
Miscellaneous manufacturing industries	24	Manufacturing average
Transportation	25	Transportation
Communication	26	Communication and other public utilities
Electric, gas, water, and sanitary services	27	Communication and other public utilities
Wholesale trade	28	Wholesale trade
Retail trade	29	Retail trade
Finance	30	Finance, insurance, and real estate
Insurance	31	Finance, insurance, and real estate
Real estate	32	Finance, insurance, and real estate
Hotel, lodging places, and amusements	33	Services, excluding households
Personal services	34	Services, excluding households
Business services	35	Professional services
Eating and drinking places	36	Services, excluding households
Health services	37	Medical services, including hospitals
Miscellaneous services	38	Services, excluding households
Households	39	No corresponding entry

*Farming, forestry, and fishing is an occupational category. All of the other unemployment categories are industrial sectors.

Table 10-2. United States unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990*

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
3	4.8	5.8	7.9	10.0	13.5	9.5	17.0	6.0	9.3
4	4.8	5.8	7.9	10.0	13.5	9.5	17.0	6.0	9.3
5	4.8	5.8	7.9	10.0	13.5	9.5	17.0	6.0	9.3
6	11.1	10.0	10.6	11.6	13.1	13.1	18.4	15.6	12.9
7	11.1	10.0	10.6	11.6	13.1	13.1	18.4	15.6	12.9
8	7.1	7.4	8.3	8.6	9.9	9.8	13.1	8.4	9.1
9	5.9	4.9	5.3	6.7	7.6	9.9	9.6	10.1	7.5
10	9.3	8.4	8.2	9.7	10.7	11.4	12.4	10.6	10.1
11	4.1	3.5	3.2	3.9	4.1	4.5	6.8	11.5	5.2
12	4.2	4.0	4.2	4.4	4.8	5.5	6.7	5.3	4.9
13	3.5	3.1	2.9	4.1	5.1	4.7	7.3	5.4	4.5
14	6.2	6.2	5.6	5.4	7.9	7.6	10.8	5.1	6.9
15	7.6	6.1	7.9	8.0	10.3	11.6	15.0	12.6	9.9
16	5.6	5.3	5.4	6.2	7.8	9.6	11.2	8.6	7.5
17	4.9	4.1	4.5	7.3	10.0	11.3	20.0	8.5	8.8
18	7.0	6.6	5.6	7.0	8.3	8.8	14.4	9.6	8.4
19	4.6	3.6	4.1	5.2	6.3	6.2	12.2	5.9	6.0
20	5.6	4.8	4.9	4.9	6.4	7.8	8.9	6.8	6.3
21	9.0	6.2	6.3	7.9	6.9	7.3	12.6	14.7	8.9
22	6.4	4.8	5.3	5.8	5.2	5.8	10.9	10.4	6.8
23	3.9	3.4	3.3	3.9	4.3	4.4	7.0	5.9	4.5
24	5.8	5.1	5.3	6.0	7.1	7.7	11.2	8.3	7.1
25	5.1	5.0	5.2	5.9	6.7	5.9	8.6	5.2	6.0
26	2.0	2.2	2.1	2.6	3.0	2.5	3.6	6.1	3.0
27	3.8	3.9	3.9	4.5	5.1	5.1	7.4	8.9	5.3
28	4.5	4.0	4.3	4.5	5.3	5.2	7.5	2.3	4.7
29	6.8	6.5	6.7	7.6	8.1	8.2	10.7	8.1	7.8
30	3.0	3.1	3.0	3.1	3.5	3.5	4.5	3.5	3.4
31	3.0	3.1	3.0	3.1	3.5	3.5	4.5	3.5	3.4

Table 10-2. United States unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990* (continued)

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
32	3.0	3.1	3.0	3.1	3.5	3.5	4.5	3.5	3.4
33	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4
34	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4
35	3.2	3.0	3.2	3.6	4.0	4.2	5.5	4.7	3.9
36	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4
37	3.2	3.0	3.2	3.6	4.0	4.2	5.5	4.7	3.9
38	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4

*Unemployment rates taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics, for years shown above.

Table 10-3. East South Central region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990*

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
3	7.6	7.6	8.0	11.5	22.3	11.4	24.2	9.1	12.7
4	7.6	7.6	8.0	11.5	22.3	11.4	24.2	9.1	12.7
5	7.6	7.6	8.0	11.5	22.3	11.4	24.2	9.1	12.7
6	14.8	10.8	13.6	15.5	17.9	18.0	23.7	15.1	16.2
7	14.8	10.8	13.6	15.5	17.9	18.0	23.7	15.1	16.2
8	10.3	7.3	8.6	8.7	11.3	10.8	15.2	10.4	10.3
9	6.5	9.3	6.8	7.1	8.4	12.2	7.5	10.5	8.5
10	7.5	8.7	8.5	13.4	11.8	13.0	12.1	10.5	10.7
11	2.6	3.5	4.7	2.7	2.7	2.1	8.9	5.8	4.1
12	4.3	3.7	4.3	5.2	5.9	6.0	4.5	5.8	5.0
13	2.5	1.3	2.5	3.0	7.2	6.5	7.2	5.0	4.4
14	4.8	3.6	5.5	6.8	6.6	7.3	8.9	6.3	6.2
15	4.8	6.5	9.8	9.1	10.4	12.6	17.4	13.8	10.5
16	8.2	4.3	7.2	7.3	8.7	11.9	14.8	11.6	9.3
17	5.6	5.5	6.6	3.6	10.5	8.5	14.8	10.8	8.2
18	4.0	7.2	4.6	5.8	8.1	10.2	15.1	14.3	8.7
19	7.6	3.7	5.5	6.3	8.1	7.4	11.9	7.0	7.2
20	6.1	5.2	7.8	6.3	9.2	11.3	8.2	11.7	8.2
21	8.1	7.5	7.6	8.9	8.8	7.0	14.7	14.5	9.6
22	8.5	8.8	7.3	8.6	9.0	9.6	17.2	11.2	10.0
23	6.1	6.1	7.2	7.3	9.3	10.4	14.8	11.6	9.1
24	6.2	6.2	7.0	7.7	9.3	10.1	12.7	10.0	8.7
25	4.7	4.3	5.6	7.1	7.8	7.4	9.4	6.7	6.6
26	1.9	2.7	1.9	2.4	3.6	1.7	3.4		2.5
27	1.9	2.7	1.9	2.4	3.6	1.7	3.4		2.5
28	4.7	4.3	4.4	4.6	7.7	4.5	8.7	10.1	6.1
29	7.5	7.8	7.8	8.9	11.3	10.7	14.2	11.3	9.9
30	1.3	3.2	3.0	4.5	4.0	3.0	5.1	4.1	3.5
31	1.3	3.2	3.0	4.5	4.0	3.0	5.1	4.1	3.5

Table 10-3. East South Central region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990* (continued)

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
32	1.3	3.2	3.0	4.5	4.0	3.0	5.1	4.1	3.5
33	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8
34	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8
35	3.4	3.8	4.3	4.1	4.8	4.6	7.5	5.1	4.7
36	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8
37	3.3	3.8	4.6	4.7	4.8	5.4	6.7	6.7	5.0
38	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8

*Unemployment rates are taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics (BLS), for the years presented above. A blank cell indicates either that the value did not meet BLS reliability standards or that the category definition in that year was inconsistent with the rest of the years.

Table 10-4. Mountain Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990*

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
3	5.3	7.8		9.2	11.0	9.2			8.5
4	5.3	7.8		9.2	11.0	9.2			8.5
5	5.3	7.8		9.2	11.0	9.2			8.5
6	10.2	7.8	8.9	10.9	12.3	13.9	19.1	15.5	12.3
7	10.2	7.8	8.9	10.9	12.3	13.9	19.1	15.5	12.3
8	7.6	11.0	11.8	11.1	13.4	14.4	20.0	15.4	13.1
9		9.0	7.8	7.0	7.5	9.4	8.3	13.0	8.9
10	8.2	9.0	7.8	7.0	7.5	9.4	8.3	13.0	8.8
11	2.5	2.5	1.4	3.0	4.3	6.5		5.0	3.6
12	3.7	3.5	5.2	4.4	5.3	6.3	7.2		5.1
13	6.0	4.9	3.2	3.9	6.1	5.2	9.8	5.5	5.6
14	6.0	3.4	5.1	5.0	7.5	13.6	13.1	8.5	7.8
15	9.1	8.1	9.7	5.9	10.2	12.9	16.8	17.1	11.2
16	4.3	6.3	4.7	7.4	5.2	11.3			6.5
17	5.7	4.8	3.3	8.5	12.4	13.2	15.7	11.0	9.3
18	7.5	7.4	5.7	7.8	9.7	10.7	12.5	9.6	8.9
19	4.8	3.7	5.1	5.3	6.5	6.3	9.9	5.6	5.9
20	5.2	4.6	3.1	5.2	6.0	7.1	7.6	5.7	5.6
21	8.7	3.1		5.6	15.2				8.2
22	3.8	2.6	3.5	3.1	3.5	4.3	8.0	5.8	4.3
23	4.4	4.0	3.7	5.3	4.8	4.4	10.6	5.6	5.4
24	5.7	5.4	5.3	5.6	6.9	8.1	11.2	8.3	7.1
25	4.9	5.4	5.5	5.6	6.1	6.2	9.7	7.8	6.4
26	2.3	3.0	2.5	1.9	2.8	3.0	3.8		2.8
27	2.3	3.0	2.5	1.9	2.8	3.0	3.8		2.8
28	4.2	4.4	5.6	4.9	6.0	6.2	9.0		5.8
29	6.3	6.3	6.6	7.2	8.2	8.3	11.0	8.9	7.9
30	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6
31	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6

Table 10-4. Mountain Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990* (continued)

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
32	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6
33	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
34	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
35	3.3	3.3	2.9	3.9	4.3	4.8	6.3	4.6	4.2
36	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
37	3.2	3.3	2.6	3.6	3.8	4.4	6.5		3.9
38	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1

*Unemployment rates are taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics (BLS), for the years presented above. A blank cell indicates either that the value did not meet BLS reliability standards or that the category definition in that year was inconsistent with the rest of the years.

Table 10-5. East North Central Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990*

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
3	6.7	5.6	7.9	8.0	10.4	9.3	26.0	11.3	10.7
4	6.7	5.6	7.9	8.0	10.4	9.3	26.0	11.3	10.7
5	6.7	5.6	7.9	8.0	10.4	9.3	26.0	11.3	10.7
6	12.4	11.5	13.8	13.5	16.5	17.8	24.6	21.7	16.5
7	12.4	11.5	13.8	13.5	16.5	17.8	24.6	21.7	16.5
8	7.4	6.6	8.8	11.6	10.8	9.3	14.8	12.0	10.2
9								13.3	13.3
10	10.6	6.4	10.0	13.4	11.5	15.2	15.9	13.3	12.0
11	4.9	5.4	5.0	4.6	4.4	5.6	8.6	6.7	5.7
12	4.6	4.0	3.8	4.7	5.7	6.5	7.6	6.7	5.5
13	4.2	4.1	3.3	5.1	5.1	5.9	7.2	5.1	5.0
14	7.9	6.7	5.8	5.2	8.2	7.4	10.5	11.8	7.9
15	9.5	6.0	5.5	11.6	11.5	13.2			9.6
16	4.7	7.1	5.9	8.3	9.5	12.3	15.6		9.1
17	4.7	4.1	4.8	8.0	9.6	11.4	19.8	9.6	9.0
18	7.0	6.8	6.0	8.2	8.6	8.8	17.0	11.6	9.3
19	4.8	3.4	4.3	5.5	7.0	7.8	17.2	7.5	7.2
20	5.7	5.2	6.8	6.0	8.8	10.0	13.3	9.3	8.1
21	7.9	6.2	6.3	7.4	6.2	7.6	12.8	15.5	8.7
22	7.6	6.1	6.5	7.4	6.2	7.3	13.0	15.0	8.6
23	5.7	4.3	6.9	7.2	6.0	8.9	12.0	7.5	7.3
24	6.1	5.3	5.7	7.1	7.7	8.5	14.0	10.2	8.1
25	6.3	6.4	7.1	7.5	8.5	10.2	13.5	10.6	8.8
26	2.0	2.3	2.2	3.1	3.4	2.2	5.2		2.9
27	2.0	2.3	2.2	3.1	3.4	2.2	5.2		2.9
28	4.6	3.7	4.1	4.5	5.2	5.9	8.3		5.2
29	7.1	6.8	7.3	8.2	8.8	9.8	12.2	10.3	8.8
30	2.6	2.8	4.1	2.9	3.8	4.3	6.0	5.4	4.0
31	2.6	2.8	4.1	2.9	3.8	4.3	6.0	5.4	4.0

Table 10-5. East North Central Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990* (continued)

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
32	2.6	2.8	4.1	2.9	3.8	4.3	6.0	5.4	4.0
33	5.0	5.0	5.4	6.3	6.6	7.7	9.7	7.0	6.6
34	5.0	5.0	5.4	6.3	6.6	7.7	9.7	7.0	6.6
35	3.1	3.1	3.6	4.2	4.2	5.4	6.4	5.3	4.4
36	5.0	5.0	5.4	6.3	6.6	7.7	9.7	7.0	6.6
37	3.2	3.3	3.6	4.4	4.2	5.8	6.0		4.4
38	5.0	5.0	5.4	6.3	6.6	7.7	9.7	7.0	6.6

*Unemployment rates are taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics (BLS), for the years presented above. A blank cell indicates either that the value did not meet BLS reliability standards or that the category definition in that year was inconsistent with the rest of the years.

Table 10-6. Pacific Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990*

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
3	5.3	7.8		9.2	11.0	9.2			8.5
4	5.3	7.8		9.2	11.0	9.2			8.5
5	5.3	7.8		9.2	11.0	9.2			8.5
6	10.2	7.8	8.9	10.9	12.3	13.9	19.1	15.5	12.3
7	10.2	7.8	8.9	10.9	12.3	13.9	19.1	15.5	12.3
8	7.6	11.0	11.8	11.1	13.4	14.4	20.0	15.4	13.1
9		9.0	7.8	7.0	7.5	9.4	8.3	13.0	8.9
10	8.2	9.0	7.8	7.0	7.5	9.4	8.3	13.0	8.8
11	2.5	2.5	1.4	3.0	4.3	6.5		5.0	3.6
12	3.7	3.5	5.2	4.4	5.3	6.3	7.2		5.1
13	6.0	4.9	3.2	3.9	6.1	5.2	9.8	5.5	5.6
14	6.0	3.4	5.1	5.0	7.5	13.6	13.1	8.5	7.8
15	9.1	8.1	9.7	5.9	10.2	12.9	16.8	17.1	11.2
16	4.3	6.3	4.7	7.4	5.2	11.3			6.5
17	5.7	4.8	3.3	8.5	12.4	13.2	15.7	11.0	9.3
18	7.5	7.4	5.7	7.8	9.7	10.7	12.5	9.6	8.9
19	4.8	3.7	5.1	5.3	6.5	6.3	9.9	5.6	5.9
20	5.2	4.6	3.1	5.2	6.0	7.1	7.6	5.7	5.6
21	8.7	3.1			5.6	15.2			8.2
22	3.8	2.6	3.5	3.1	3.5	4.3	8.0	5.8	4.3
23	4.4	4.0	3.7	5.3	4.8	4.4	10.6	5.6	5.4
24	5.7	5.4	5.3	5.6	6.9	8.1	11.2	8.3	7.1
25	4.9	5.4	5.5	5.6	6.1	6.2	9.7	7.8	6.4
26	2.3	3.0	2.5	1.9	2.8	3.0	3.8		2.8
27	2.3	3.0	2.5	1.9	2.8	3.0	3.8		2.8
28	4.2	4.4	5.6	4.9	6.0	6.2	9.0		5.8
29	6.3	6.3	6.6	7.2	8.2	8.3	11.0	8.9	7.9
30	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6
31	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6

Table 10-6. Pacific Region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990* (continued)

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
32	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6
33	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
34	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
35	3.3	3.3	2.9	3.9	4.3	4.8	6.3	4.6	4.2
36	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
37	3.2	3.3	2.6	3.6	3.8	4.4	6.5		3.9
38	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1

*Unemployment rates are taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics (BLS). for the years presented above. A blank cell indicates either that the value did not meet BLS reliability standards or that the category definition in that year was inconsistent with the rest of the years.

Unemployment rates are based on rates for each affected region as a whole. Although the generation facilities are to be located within Tennessee and New Mexico, respectively, and mining and fuel processing activities occur at other specific locations, the appropriate labor markets include portions of each entire region.

A region may have persistently higher rates of unemployment than the national average in many sectors of the economy. Consequently, employment benefits are likely to occur even when the nation is "fully employed." The high unemployment rate in the region would be dampened inappropriately by using base year (1989 or 1987) levels of unemployment for the region, so we use base year levels for the entire United States.

The unemployment rates that we utilize pertain to the experienced civilian labor force. This will tend to exclude new entrants to the labor market. Also, unemployment numbers are reported by industry rather than by occupation. One occupation may appear in several industries; however, we were not working at a sufficient level of detail to enable us to map from occupation to industry. The existence or direction of a bias in the estimates from this limitation is unclear.

The construction and operation of the facilities in Tennessee and New Mexico will directly stimulate employment in three industries. One is the new construction industry. We assume the construction phase will entail a $3.1 billion "overnight" construction cost for a 1150 MW facility in both reference environments. The concept of overnight construction cost excludes finance costs associated with regulatory policy governing cost recovery and the time profile of construction, and is based on 1989 dollars. To associate construction expenditures (and associated potential employment benefits) with the flow of electricity output from the facility, they must be annualized over all the kilowatt-hours of electricity that are generated by the project. We do so using constant 1989 dollars and a real interest rate of 5%, resulting in an annual expense of $180 million in both reference environments.

Expenditures on the operation and maintenance of the facility have been divided according to their fuel component, including fuel processing, and all other expenditures including waste disposal. Expenditures on the nonfuel items are attributed to the Electricity, Gas, Water, and Sanitary Services industry. We assume this industry will be stimulated with $104.3 million of production annually throughout the 40-year operation of the plant. The fuel expense, including fuel processing, is attributed to the Mining industry, and will entail about $45.4 million per year for each facility.

Expenditures in these three industries constitute direct (or primary) demand for final goods and services. In addition, secondary demand is created in industries that supply inputs to these primary industries. Finally, induced demand is created in all other industries that create goods and services that will be sought by workers in the primary and secondary industries.[6]

Earnings multipliers for the United States in Table 10-7 reflect the increase in the total annual primary, secondary, and induced earnings (wages) that are received by workers in all 38 industries for each dollar of expenditure in the three primary industries. These multipliers are taken from input-output tables provided by the Bureau of Economic Analysis of the U.S. Department of Commerce.[7]

The possible existence of employment benefits—that is, a difference between the opportunity cost of labor and its market wage—depends on the possibility that newly employed workers are drawn from the pool of workers who were previously involuntarily unemployed.[8] This possibility is represented as an S-shaped probability function of the unemployment rate in Fig. 10.1.A-1 presented in the appendix to the coal document. A precise mathematical expression for this S-function for the midpoint estimate, and for a low and high estimate, was used.

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[6]A possibility for error results from the assignment of expenditures in the primary industries. Expenditures for the ongoing operation of the facility have been broken into two parts, a fuel component and an operations and maintenance component, corresponding to two different categories of expenditures. The fuel component is viewed as an expenditure in the crude petroleum and natural gas industry, while the operations and maintenance is viewed as an expenditure in an industry that includes electric, gas, water, and sanitary services. Some part of an expenditure in the latter industry includes expenditures for fuel, although it will be an average of a variety of fuels from a variety of locations.

This double-counting is expected to be minimal because the primary expenditure is not counted twice, but rather how parts of the primary expenditure are spent may be counted twice while other parts are under- counted. On net, it is unclear whether this error will serve to inflate or deflate the estimate of employment benefits.

[7]See Regional Multipliers: A User Handbook for the Regional Input-Output Modeling System (RIMS II), May 1986. Data for unemployment in households are not relevant and they are excluded. More detailed input-output tables disaggregated for 531 industries may be obtained from the Bureau of Economic Analysis.

[8]This may occur directly if an unemployed person fills the vacancy, or indirectly if an unemployed person fills a job vacated by a person leaving to fill the newly created position. The alternative is that some job previously filled is vacated and eliminated from the economy.

Table 10-7. United States input-output coefficients (multipliers) for earnings to industrial sectors

Sector number	Miscellaneous mining	New construction	Electrical services
1	0.0088	0.0108	0.0050
2	0.0002	0.0004	0.0001
3	0.0060	0.0032	0.0278
4	0.0089	0.0069	0.0229
5	0.3046	0.0039	0.0008
6	0.0000	0.3027	0.0000
7	0.0218	0.0164	0.0329
8	0.0103	0.0121	0.0058
9	0.0028	0.0044	0.0016
10	0.0048	0.0058	0.0027
11	0.0046	0.0062	0.0027
12	0.0087	0.0105	0.0052
13	0.0173	0.0167	0.0111
14	0.0073	0.0074	0.0033
15	0.0035	0.0167	0.0021
16	0.0029	0.0179	0.0019
17	0.0108	0.0202	0.0035
18	0.0119	0.0287	0.0054
19	0.0269	0.0148	0.0080
20	0.0087	0.0174	0.0048
21	0.0036	0.0038	0.0021
22	0.0019	0.0019	0.0013
23	0.0019	0.0029	0.0015
24	0.0018	0.0023	0.0010
25	0.0347	0.0399	0.0310

Table 10-7. United States input-output coefficients (multipliers) for earnings to industrial sectors (continued)

Sector number	Miscellaneous mining	New construction	Electrical services
26	0.0116	0.0139	0.0065
27	0.0182	0.0088	0.1117
28	0.0430	0.0559	0.0228
29	0.0435	0.0662	0.0251
30	0.0271	0.0225	0.0155
31	0.0153	0.0172	0.0118
32	0.0043	0.0042	0.0028
33	0.0088	0.0084	0.0039
34	0.0074	0.0084	0.0048
35	0.0545	0.1044	0.0302
36	0.0163	0.0195	0.0093
37	0.0407	0.0479	0.0227
38	0.0242	0.0253	0.0116
39	0.0025	0.0030	0.0014
Total	**0.8322**	**0.9796**	**0.4649**

There actually are a family of functions behind each estimate, one for each industry. The S-function depends on the difference between the average unemployment rate for each industry and the base year 1989 unemployment rate (the natural rate of unemployment).[9]

The value for this function for each industry in the United States and the four affected regions are presented in Table 10-8. In each case, if some percentage of the newly employed workers will 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 the earnings multipliers by the probability that workers are drawn from the pool of previously unemployed workers, and summing for all thirty-seven industries.[10] Finally, this estimate must be adjusted to reflect the opportunity cost of time for unemployed workers. We return to this issue below.

An important feature that differentiates regional earnings multipliers and multipliers for the United States is referred to as the "leakage effect." Some portion of economic activity that is stimulated by the demand for goods and services in a region leaks over that region's borders and stimulates secondary and induced activity in other states. Consequently, multipliers for an individual state will necessarily be smaller than multipliers for a region, which will be smaller, in turn, than for the entire United States.

The preferred analysis should match earnings multipliers with unemployment rates for the relevant geographic labor market to estimate net new employment benefits. Typically, state boundaries do not correspond well with relevant labor markets, which are regional in nature. However, earnings multipliers for specific regions were not available to us given available resources. Therefore, we rely on earnings multipliers for the entire United States. In applications of this methodology to other fuel cycles, we have examined the sensitivity of this assumption by looking also at estimates based on multipliers derived for the state level, and found it to be relatively unimportant.

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[9]When this difference is negative, it is set equal to zero.

[10]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).

Table 10-8. Percent probability that newly employed person was drawn from the pool

Sector	United States			East South Central Region			Pacific Region			East North Central Region			Mountain Region		
Number	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
3	4.1	8.0	28.3	15.6	28.7	53.6	2.4	4.8	21.9	7.8	14.9	38.6	1.4	2.9	16.9
4	4.1	8.0	28.3	15.6	28.7	53.6	2.4	4.8	21.9	7.8	14.9	38.6	1.4	2.9	16.9
5	4.1	8.0	28.3	15.6	28.7	53.6	2.4	4.8	21.9	7.8	14.9	38.6	1.4	2.9	16.9
6	4.7	9.2	30.3	20.2	36.3	60.3	2.9	5.8	24.1	22.1	39.3	62.7	8.9	17.0	41.3
7	4.7	9.2	30.3	20.2	36.3	60.3	2.9	5.8	24.1	22.1	39.3	62.7	8.9	17.0	41.3
8	1.4	2.8	16.8	3.4	6.7	25.8	12.6	23.6	48.6	3.0	6.0	24.4	1.9	3.8	19.5
9	2.2	4.3	20.7	4.0	7.9	28.0	4.7	9.3	30.4	20.8	37.2	61.0	2.7	5.4	23.2
10	1.4	2.9	17.0	2.3	4.6	21.5	0.1	0.1	3.5	5.9	11.4	33.7	0.0	0.0	0.0
11	0.2	0.5	6.8	0.1	0.2	4.6	0.0	0.0	0.7	1.2	2.4	15.6	4.0	7.9	28.0
12	0.2	0.5	6.7	0.3	0.5	7.2	0.3	0.7	8.1	0.6	1.2	10.8	0.3	0.6	7.9
13	0.5	1.0	9.8	0.4	0.9	9.3	1.6	3.1	17.7	0.9	1.8	13.6	4.9	9.6	31.0
14	0.7	1.3	11.5	0.0	0.0	0.2	0.9	1.7	13.1	1.1	2.1	14.5	1.0	2.0	14.2
15	4.9	9.6	31.0	6.7	12.9	35.9	8.9	17.1	41.3	4.1	8.0	28.3	6.2	12.0	34.6
16	1.5	2.9	17.2	4.9	9.6	31.0	0.5	1.0	9.8	4.5	8.7	29.5	0.1	0.3	5.2
17	6.2	12.1	34.8	4.8	9.4	30.6	7.6	14.6	38.3	6.7	13.0	36.0	1.0	2.0	14.0
18	1.2	2.4	15.4	1.5	3.1	17.5	1.9	3.7	19.2	2.5	5.0	22.4	0.0	0.0	0.0
19	1.6	3.1	17.6	3.4	6.8	26.0	1.4	2.8	16.8	3.4	6.8	26.0	0.8	1.7	13.0
20	0.6	1.3	11.3	3.5	6.9	26.3	0.2	0.4	5.9	3.3	6.6	25.7	0.1	0.2	4.2
21	2.5	4.9	22.1	4.1	8.0	28.3	1.3	2.6	16.2	2.2	4.4	21.0	0.0	0.0	0.0

Table 10-8. Percent probability that newly employed person was drawn from the pool (continued)

Sector	United States			East South Central Region			Pacific Region			East North Central Region			Mountain Region		
Number	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
22	0.6	1.3	11.3	8.1	15.6	39.5	0.0	0.0	0.0	4.4	8.6	29.4	0.0	0.0	0.0
23	0.3	0.5	7.4	8.5	16.2	40.3	1.0	2.0	14.1	4.0	7.9	28.1	1.5	3.0	17.3
24	1.2	2.4	15.4	3.9	7.6	27.7	1.2	2.4	15.4	2.7	5.4	23.3	1.0	2.0	14.2
25	0.3	0.7	8.3	0.8	1.6	12.7	0.6	1.2	11.0	4.3	8.5	29.1	0.7	1.5	12.0
26	0.0	0.1	2.3	0.0	0.0	2.2	0.1	0.1	3.8	0.1	0.2	4.9	0.5	1.0	10.0
27	0.0	0.1	2.2	0.0	0.0	2.2	0.1	0.1	3.8	0.1	0.2	4.9	0.3	0.6	7.7
28	0.3	0.6	7.8	1.3	2.5	15.8	0.9	1.7	13.1	0.4	0.8	8.9	0.4	0.8	8.8
29	0.6	1.2	11.0	4.2	8.3	28.8	0.7	1.3	11.4	1.9	3.8	19.5	0.6	1.3	11.2
30	0.0	0.0	2.2	0.0	0.1	3.0	0.1.	0.1	3.9	0.2	0.4	6.4	0.2	0.4	6.5
31	0.0	0.0	2.2	0.0	0.1	3.0	0.1	0.1	3.9	0.2	0.4	6.4	0.2	0.4	6.5
32	0.0	0.0	2.2	0.0	0.1	3.0	0.1	0.1	3.9	0.2	0.4	6.4	0.2	0.4	6.5
33	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	0.2	0.4	6.6	0.7	1.5	12.1	0.4	0.7	8.4	0.5	1.0	10.1	0.3	0.6	7.8
36	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
37	0.2	0.4	6.6	1.0	2.0	14.2	0.2	0.4	6.5	0.5	0.9	9.7	0.4	0.7	8.4
38	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*United States unemployment rates for 1989 were taken to represent the natural unemployment rates for these industries.
L = low, M = middle, and H = high.

The approach we use combines unemployment rates for a region with national multipliers. This will result in an over-estimate of true benefits if the region has higher than average unemployment, because some of the earnings will accrue in other areas where unemployment may be lower, and hence, net employment benefits would be lower. Conversely, this approach will under-estimate true benefits if the region has lower than average unemployment.

The earnings multipliers presented in Table 10-7 are for total earnings and capture the sum of primary, secondary, and induced effects. These multipliers are an overestimate for our purposes because they reflect the induced effects for all the primary earnings that result from this investment. To a significant degree, these "respending" effects would have occurred anyway as a result of activity that would engage many workers in the primary industries in their next best employment opportunity. A proper accounting should only include the induced effects that result from net new earnings in the primary and secondary industries. To correct for this problem, we reduce all earnings that occur outside the three primary industries by the ratio of net new earnings over total new earnings that occur in the primary industries, which represents that portion of induced earnings that are new.[11]

The estimates that are obtained by the model described thus far are preliminary because they do not account for the social opportunity cost of workers previously unemployed. Estimates of the opportunity cost of time for unemployed workers are usually expressed as a fraction of their previous market wage. Unfortunately, existing estimates must be viewed as unreliable for our purposes. Estimates depend on a number of factors, including the possibility of flexible working hours (most jobs have a fixed work schedule), whether the worker can maintain a subsistence lifestyle during periods of unemployment, costs of searching for employment, the activities of the worker during periods of unemployment, and the location of residence. Since a worker typically cannot make marginal adjustments to working hours, the true opportunity cost of the worker's time may include an element of consumer surplus flowing from activities during unemployment.

We examined three alternative estimates of the opportunity cost of an unemployed worker's time in order to illustrate the range of plausible estimates. The most conservative approach is to value time for unemployed workers at after-tax wages. Conversion of before-tax to after-tax rates requires information about the average rates applied to new earnings for each household. Instead, the

[11] This approach underestimates secondary effects. Secondary industries are more closely linked to primary industries and are stimulated by the demand for new output in the primary industries, rather than by just the net new respending effects.

1987 average tax rate on individual income (federal and state income taxes and FICA) of 20.8% was used.[12] This estimate provides an extreme lower bound on employment benefits, which are equivalent to net new contributions to the public treasury. This estimate is unreliable for at least one important reason. Assuming that the market wage, a worker's reservation wage, and the opportunity cost of time are equal is logically inconsistent with observed persistent unemployment and apparent labor market disequilibrium.

The second approach is to value time for unemployed workers at the estimated minimum wage after taxes. We calculate that the 1990 after-tax minimum wage was about $3.42 or about 26% of average hourly earnings across all industries in our model.[13] The third approach is to value the opportunity cost of time at zero. This number is also unreliable, but it serves to provide an upper bound on net employment benefits.

Estimates of employment benefits

Employment benefit estimates are summarized in Table 10-9 for the most persuasive set of assumptions that we identified. These assumptions include using 1989 as a base year index for the natural rate of unemployment, and using unemployment rates for the region in which associated economic activity would occur. For example, the new construction and electric services industries affected by the Southeast facility are located in the East South Central region, while mining and fuel processing occurs in the Mountain, East North Central and Pacific regions, and waste disposal occurs in the Mountain region. The opportunity cost of a person's time who was previously involuntarily unemployed is taken to be the after-tax minimum wage. The significance of these and other assumptions on the estimates that are obtained will be discussed further below.

Each entry in Table 10-9 represents the monetary value of net new employment benefits (primary, secondary, and induced) for the entire United States resulting from expenditures in each primary industry. The first three rows for each reference environment pertain to the three primary industries - new

[12]Calculated from the U.S. Bureau of the Census, 1991, 1991 Statistical Abstract, 111th edition, Washington, DC. The tax rates for 1990 remain virtually unchanged.

[13]Calculated from the U.S. Bureau of the Census, 1991, 1991 Statistical Abstract, 111th edition, Washington, DC. The tax rates for 1990 remain virtually unchanged. One reason a number of this magnitude appears reasonable is that it is similar to the estimate of 30% for the opportunity cost of workers' time in commuting as a function of their hourly earnings that has emerged as focal from a voluminous literature. See for example, Bruzelius 1979. Admittedly, many features vary between the commuting and unemployment contexts, so estimates of the value of a person's time in commuting are poor for direct comparison with unemployment.

Table 10-9. United States employment benefits (mills/kWh)[a]

Sector or output	Low	Mid	High
Southeast facility			
New construction	1.05	1.99	4.11
Mining	0.05	0.10	0.40
Electric services	0.00	0.00	0.04
Total	**1.11**	**2.08**	**4.55**
Southwest facility			
New construction	0.45	0.87	2.50
Mining	0.05	0.10	0.40
Electric services	0.01	0.01	0.15
Total	**0.05**	**0.99**	**3.04**

[a]1989 base year natural rate of unemployment and regional unemployment.

construction, mining, and electric services—and the third row is their sum. Benefits are presented as mills per kilowatt-hour of electricity that would be produced at the proposed facility. Within each row, three numbers are presented. These are the low estimate, mid estimate, and high estimate, which vary according to the three specifications of the S-function [refer to ORNL/RFF (1994a,b)].

The model projects that the mid estimate of benefits across all industries due to all spending associated with the project is the bold numbers in the final row for each reference environment; or 2.08 mills/kWh for the Southeast Reference environment and 0.99 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 compared with that obtained in analyses of other fuel cycles. Two factors help to explain this. One is persistent high unemployment in the new construction industry in the East South Central region relative to other parts of the country. In the Mountain region, which is the site of the Southwest Reference environment, unemployment in new construction is nearly midway between the unemployment rate for the East South Central region and the national average. A second factor

is the high construction costs per megawatt of capacity associated with nuclear, which affects the estimates for both reference environments.

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. This opportunity cost is expressed as a function of the market wage, so the employment benefit is changed in direct proportion to the assumption that is made. The estimates we present are based on an opportunity cost estimate that is 26% of the market wage on average. Instead, if one assumes an opportunity cost equal to the after-tax wage, then the midpoint estimate of net new earnings is reduced to obtain a comparable point estimate of 0.58 mills/kWh in the Southeast and 0.27 mills/kWh in the Southwest Reference environments. If an opportunity cost of zero is assumed, then net new benefits equal net new earnings, or 2.82 mills/kWh in the Southeast and 1.33 mills/kWh in the Southwest Reference environments.

The next most critical assumption is the choice of 1989 as base year for the natural rate of unemployment. The choice of a base year index is important to the estimates that are obtained because the S-function is nonlinear. A small change in the definition of the natural rate of unemployment for each industry has a relatively large effect on the estimate of employment benefits. Using 1987 as an alternative base year, in the Southeast Reference environment, the midpoint estimate of total employment benefits as a result of expenditures summed for all three primary industries is 1.36 mills/kWh, or about two-thirds of that obtained when 1989 is used as a base year. Using 1987 as the base year in the Southwest Reference environment produces a midpoint estimate of 0.41 mills/kWh, about four-tenths of that obtained when 1989 is used as a base year.

The use of unemployment rates for the entire United States produces an estimate of 0.57 mills/kWh in both reference environments, about one-quarter of that obtained with regional unemployment rates for the Southeast reference environment and one-half for the Southwest reference environment. The reason is that higher-than-average unemployment rates in new construction in the East South Central region, and to a lesser degree in the Mountain region, leads to higher benefit estimates from a regional perspective.

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 assumption depends in a complicated way on the nature of the underlying probability distributions. Absent the resources to conduct a sophisticated

uncertainty analysis using Monte Carlo sampling methods, we have to exercise judgment to identify the endpoints for a 90% confidence interval.

In the Southeast, for the upper bound of 90% confidence interval for employment benefits, we select 4.55 mills/kWh, the high point estimate presented in Table 10-10 under the basic set of assumptions. For the lower bound we select 1.09 mills/kWh, the low estimate under the basic set of assumptions. Note that this is lower than the 1.36 mills/kWh obtained as a midpoint estimate when 1987 is used as the base year natural rate of unemployment. In the Southwest, for the upper bound, we select 3.04 mills/kWh, the high point estimate presented under the basic set of assumptions. For the lower bound, we select 0.41 mills/kWh, which is the midpoint estimate when 1987 is used as the base year natural rate of unemployment. We note that this is lower than the 0.50 mills/kWh estimate of a lower bound under the basic set of assumptions. These results are presented in Table 10-10.

Table 10-10. Best estimate and judgmental ninety percent uncertainty range for U.S. employment benefits (mills/kWh)[a]

	Low	Mid	High
Southeast facility			
Total	1.10	2.08	4.55
Southwest facility			
Total	0.41	0.99	3.04

[a]Judgmental ninety percent uncertainty range is based on a combination of assumptions. See text for explanation.

Our reasoning for the selection of our preferred midpoint estimate and the 90% confidence interval is the following. The set of assumptions for this example are the most persuasive in our judgment. These include the use of 1989 unemployment rates by industry as the definition of an index of the natural rate of unemployment because this rate is closer to the midpoint of the range provided in the literature. For almost two-thirds of the industries, the unemployment rate in 1989 across the United States was the lowest observed in the decade, while 1989 was also within a period of low inflationary pressures. The inflation rate in 1989 was the midpoint observed between 1983 and the present. We note that the natural rate of unemployment is not likely to be much less than this index provides. On the other hand, the calculation of projected unemployment rates is fairly conservative. We have truncated the observations that are the basis for this

projection at 1981, leaving out many years of relatively high unemployment in the 1970s, and ignoring the period of relatively high unemployment since 1991. In addition, we have assigned greater weight to observations toward the end of the last decade, a period of unusually stable economic performance.

The possibility that the estimate we obtain is an underestimate is captured by the high value for the S-function under the strongest assumptions we can make about other variables. This bound reflects, in particular, the great uncertainty in this analysis surrounding the actual search process for employment opportunities. It also stands in for the possibility that unemployment could be greater than we have projected, which we think is more likely than for it to be less than we projected.

The possibility that we have obtained an overestimate is captured by the alternative assumption using 1987 as a base year for the natural rate of unemployment. It seems to us that the distribution of true values is somewhat skewed; and although the 1989 index is the expected value, there is considerable probability mass around a greater index (the median of this distribution is greater than the mean, in our minds). This estimate also stands in for the possibility that the true opportunity cost of unemployed labor is greater than the after-tax minimum wage. It is noteworthy that these estimates are close to the low-point estimate provided under the basic set of assumptions in Table 10-8. For the lower bound, we have chosen the smaller of the estimates obtained in the low estimate in the base case, and the mid estimate when 1987 is used as base year.

In the Southeast, the range of the confidence interval from 1.10 to 4.55 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 2.08 mills/kWh, indicate our confidence that employment benefits are significant. Similarly, in the Southwest the 90% confidence interval between 0.41 and 3.04 mills/kWh, and the midpoint estimate of 0.99 mills/kWh indicate that the true value is greater than zero. The midpoint numbers we obtain are high relative to other fuel cycles, particularly for the Southeast Reference environment, due to the relatively high expenditures on new construction per megawatt of capacity in the nuclear fuel cycle, and due to the high projected rate of unemployment for this industry in the East South Central region. The midpoint numbers represent 21% of total (primary, secondary, and induced) earnings generated by this project in the Southeast and less than 10% in the Southwest. They represent 6% of the earnings in just the three primary industries in the Southeast and 3% in the Southwest.

11. SUMMARY OF NUMERICAL RESULTS

11.1 TABULATION OF NUMERICAL RESULTS

The numerical analysis given in this report is illustrative of the type of analysis that is appropriate using the DFA for the nuclear fuel cycle. The numerical results are summarized in Tables 11-1 through 11-6. Tables 11-1 through 11-3 present summaries of the estimated health impacts on the general public and on the occupational workers. Table 11-4 summarizes the total cost of countermeasures, property losses and business disruption associated with severe reactor and transportation accidents. The economic damages associated with these impacts are then summarized in Tables 11-5 and 11-6. For each of these six summary tables we show the results of the impacts and damage estimates that we performed, but these tables should **not** be interpreted to be a complete survey of **all** the impacts, damages, and benefits of the nuclear fuel cycle. Also, except for the discussion of the Price-Anderson Act at the end of Chapter 7, no analysis is done to ascertain the portion of the damages and benefits that are externalities.

The damages in Table 11-4 attributable to limited containment failure reactor accidents are dominated by the loss of the asset value of the power reactor itself, and the replacement cost of electric power.

Table 11-1. Summary of occupational health impacts

	Near-term health impacts		Long-term health impacts
Fuel cycle stage	Deaths[b]	Injuries/ illnesses[b]	Genetic effects[b]
Uranium mining	0.0429	1.793	0.023
Uranium milling	0.0	1.230	a
Reactor operations[c]	0.2	7.7	a
Reactor decommissioning[d]	0.0128	0.1	a
Reactor accidents	a	a	a
Spent fuel disposal	a	a	a
Transportation (southeast site)	0.00029	a	a
Transportation (southwest site)	0.00013	a	a

[a]Not quantitatively estimated.
[b]Health effects are for annual operation of the reference reactor.
[c]Deaths include radiological and nonradiological causes. Injuries/illnesses are for nonradiological only.
[d]Health effects from the five years of decommissioning operations are spread over the 40 years of reactor operations.

Table 11-2. Summary of expected health effects to the general population for the southeast site

	Near-term health effects[c]		Long-term health impacts[c]	
Fuel cycle stage	Deaths	Injuries/illnesses	Deaths	Genetic effects
Uranium mining	0.0455	a	0.002	0.0015
Uranium milling	0.015	a	0.035	0.015
Reactor operations	0.00015	a	b	a
Reactor decommissioning[d]	0.00022	a	b	a
Reactor accidents	0.087	0.162	b	a
Transportation	0.0329	0.2222	b	a
Spent fuel disposal	a	a	0.304	0.0784

[a]Not quantitatively estimated
[b]No significant long-term fatalities are expected to result from this fuel cycle stage
[c]Health effects are for annual operation of the reference reactor
[d]Health effects for five years of decommissioning operations are spread over 40 years of reactor operations.

Table 11-3. Summary of expected health effects to the general population for the southwest site

	Near-term health effects[c]		Long-term health impacts[c]	
Fuel cycle stage	Deaths	Injuries/illnesses	Deaths	Genetic effects
Uranium mining	0.0455	a	0.002	0.0015
Uranium milling	0.015	a	0.035	0.015
Reactor operations	0.000007	a	b	a
Reactor decommissioning[d]	0.00022	a	b	a
Reactor accidents	0.00898	0.0169	b	a
Transportation	0.0128	0.2222	b	a
Spent fuel disposal	a	a	0.304	0.0784

[a]Not quantitatively estimated.
[b]No significant long-term fatalities are expected to result from this fuel cycle stage.
[c]Health effects are for annual operation of the reference reactor.
[d]Health effects for five years of decommissioning operations are spread over 40 years of reactor operations.

Table 11-4. Expected cost of countermeasures and property losses for nuclear fuel cycle accidents

	Number of expected accidents (per reactor year)	Conditional consequences (millions$/ accident)	Expected cost ($/reactor year)
Southeast Site			
Severe reactor accidents			
Limited containment	4.6×10^{-5}	5,733	263,700
failure	1.6×10^{-5}	23,809	380,940
Massive containment failure			
Transportation accidents			
Spent fuel shipments	5.24×10^{-5}	9,630	504,000
All other shipments	1.5×10^{-4}	0.8	120
Southwest site			
Severe reactor accidents			
Limited containment	4.6×10^{-5}	6,039	277,800
failure	1.6×10^{-5}	11,837	189,390
Massive containment failure			
Transportation accidents			
Spent fuel shipments	1.18×10^{-5}	9,710	115,000
All other shipments	1.5×10^{-4}	0.8	120

Note: Most of these costs are calculated using standard models developed by the DOE national laboratories and used by the U.S. NRC, with some "default" values used for some cost parameters.

Table 11-5. Summary of nuclear fuel cycle damages and benefits estimated for the southeast site (1989$)[a]

Impact-pathway	Estimated damage, mills/kWh		
	Low[b]	Mid[b]	High[b,c]
Mining and milling			
Public cancer fatalities (radon)	0.00662	0.0145	0.0356
Occupational cancer fatalities (radiation)	0.00521	0.0114	0.0280
Nonradiological occupational fatalities	0.00393	0.00860	0.0211
Occupational nonfatal accidents	0.00292	0.00767	0.0124
Electricity generation—normal operations			
Public cancer fatalities			
- Airborne radiation emissions	5.42×10^{-6}	0.000012	0.000029
- Waterborne radiation emissions	0.000011	0.000024	0.000058
Occupational exposures: cancer fatalities	0.0130	0.0285	0.0700
Nonradiological occupational fatalities	0.0157	0.0343	0.0843
Nonradiological occupational injuries	0.00754	0.00971	0.0321
Electricity generation-decommissioning			
Public cancer fatalities-emissions	6.6×10^{-11}	1.4×10^{-10}	3.5×10^{-10}
Worker cancer fatalities-radiation exposure	0.000685	0.00150	0.00368
Worker fatalities-nonradiological accidents	0.000231	0.000505	0.00124
Worker morbidity-nonradiological accidents	0.000964	0.000964	0.000964
Public cancer fatalities-waste transportation	0.000012	0.000025	0.000062

Table 11-5. Summary of nuclear fuel cycle damages and benefits estimated for the southeast site (1989$)[a] (continued)

Impact-pathway	Estimated damage, mills/kWh		
	Low[b]	Mid[b]	High[b,c]
Severe reactor accidents			
Public fatalities	0.0098	0.0214	0.1435[c]
Public morbidity	0.0035	0.0035	0.0099[c]
Evacuation and relocation costs		0.0029	
Decontamination costs		0.0025	
Radioactive waste disposal costs		0.0108	
Interdiction costs		0.0135	
Condemnation costs		0.0052	
Crop and milk losses		0.0006	
Replacement power		0.0032	
Loss of utility assets		0.0205	
Decommissioning		0.0030	
Utility site cleanup		0.0167	
Transportation shipments			
Public cancer fatalities			
- Incident-free radiation exposure	0.00036	0.00079	0.00195
- Radioactive emissions: accidents	0.00261	0.00572	0.00141
Worker cancer fatalities (Incident-free radiation exposure)	0.00003	0.00007	0.00017
Public fatalities: accidental UF_6 releases	0.00107	0.00234	0.00574
Public renal injuries: accidental UF_6 releases		0.00025	
Cost of accident countermeasures/property loss		0.0618	
Road wear	0.00044	0.00155	.00545
Employment benefits	1.10	2.08	4.55

[a]This table includes only those damages for which estimates were calculated and does not represent a complete list of damages and benefits.

[b]The range of estimates is based on average estimates of impacts and only reflect uncertainty in economic valuation.

[c]The "high" estimates are based on 95% weather conditions with the use of high economic valuation parameters.

Table 11-6. Summary of nuclear fuel cycle damages and benefits estimated for the southwest site (1989$)[a]

Impact-pathway	Estimated damage, mills/kWh		
	Low[b]	Mid[b]	High[b,c]
Mining and milling			
Public cancer fatalities (radon)	0.00662	0.0145	0.0356
Occupational cancer fatalities (radiation)	0.00521	0.0114	0.0280
Nonradiological occupational fatalities	0.00393	0.00860	0.0211
Occupational nonfatal accidents	0.00292	0.00767	0.0124
Electricity generation—normal operation			
Public cancer fatalities			
- Airborne radiation emissions	3.3×10^{-7}	7.1×10^{-7}	1.7×10^{-6}
- Waterborne radiation emissions	3.8×10^{-7}	8.3×10^{-7}	2.0×10^{-6}
Occupational exposures: cancer fatalities	0.0130	0.0285	0.0700
Nonradiological occupational fatalities	0.0157	0.0343	0.0843
Nonradiological occupational injuries	0.00754	0.00971	0.0321
Electricity generation-decommissioning			
Public cancer fatalities-emissions	6.6×10^{-11}	1.4×10^{-10}	3.5×10^{-10}
Worker cancer fatalities-radiation exposure	0.000685	0.00150	0.00368
Worker fatalities-nonradiological accidents	0.000231	0.000505	0.00124
Worker morbidity-nonradiological accidents	0.000964	0.000964	0.000964
Public cancer fatalities-waste transportation	0.000012	0.000025	0.000062

Table 11-6. Summary of nuclear fuel cycle damages and benefits estimated for the southwest site (1989$)[a] (continued)

Impact-pathway	Estimated damage, mills/kWh		
	Low[b]	Mid[b]	High[b,c]
Severe reactor accidents			
Public fatalities	0.00100	0.00219	0.0118[c]
Public morbidity	0.00036	0.00036	0.0009[c]
Evacuation and relocation costs		0.000000767	
Decontamination costs		0.000354	
Radioactive waste disposal costs		0.00771	
Interdiction costs		0.00171	
Condemnation costs		0.00133	
Crop and milk losses		0.000251	
Replacement power		0.00557	
Loss of utility assets		0.0205	
Decommissioning		0.00304	
Utility site cleanup		0.0167	
Transportation shipments			
Public cancer fatalities			
- Incident-free radiation exposure	0.00036	0.00079	0.00194
- Radioactive emissions: accidents	0.00043	0.00094	0.00231
Worker cancer fatalities (incident-free radiation exposure)	0.00004	0.00003	0.00008
Public fatalities: accidental UF_6 releases	0.00107	0.00234	0.00574
Public renal injuries: accidental UF_6 releases		0.00025	
Cost of accident countermeasures/property loss		0.0141	
Road wear	0.000348	0.00123	0.00431
Employment benefits	0.41	0.99	3.04

[a]This table includes only those damages for which estimates were calculated and does not represent a complete list of damages and benefits.

[b]The range of estimates is based on average estimates of impacts and only reflect uncertainty in economic valuation.

[c]The "high" estimates are based on 95% weather conditions with the use of high economic valuation parameters.

11.2 THE MORE IMPORTANT MARGINAL IMPACTS

11.2.1 Scope of the Study

The main goal of the study is to compile a set of appropriate models and other analytical tools, and to demonstrate their use to estimate nuclear fuel cycle externalities. Thus far, analysis has been limited to estimating damages. The next step is to ascertain to what extent these damages are already internalized through existing market, regulatory, tax, insurance, or other conditions.

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. Fuel cycle impacts are generally site-specific.

It is impossible to analyze every fuel-cycle activity, release of material, and subsequent impacts. Practical implementation of the DFA 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 expected damages or benefits. For the nuclear fuel cycle in particular, another criterion for selecting an impact-pathway is the severity of the impact should an accidental release occur.

11.2.2 Usefulness of the DFA

This study has demonstrated that the DFA is an operational method for estimating many of the damages and benefits of a nuclear fuel cycle. Also, as more studies are done using this approach, it will be easier and less costly to implement. In the future, many of the calculations can be "automated" further and perhaps "reduced-form" equations may be derived after the larger computer models are run many times.

Insofar as many Public Utility Commissions (PUC) in the United States, as well as many other countries, are considering ways of internalizing the external damages of fuel cycles, it seems all the more important to invest in thorough assessments to estimate the magnitude of those externalities. Regulatory burdens imposed on utilities and others are costly. They should be justified by thorough study. By the same token, the external damages to health and the environment should be accounted for and, many people feel that they should be internalized and reflected in energy prices. The DFA approach demonstrated in this study builds on insights gained from previous studies and is a further step in developing sound methodologies for estimating fuel cycle externalities. Thus, in spite of its limitations and gaps in scientific information, results gained from studies using this

approach will add to the base of knowledge to support informed decisions about energy, and specifically about nuclear options.

11.2.3 The More Important Marginal Impacts, Damages, and Benefits

Benefits. The only benefit analyzed was that of employment at the nuclear plant. Because of the large staffing at nuclear plants (about 1,000 persons) and the large construction cost per MW of capacity for nuclear plants, the number of persons employed during the plant's life cycle is relatively large (on a per MW basis) compared to other power generation fuel cycles. For the SE site the benefit for the "mid" case is 2.08 mills/kWh. For the SW site, the benefit is 0.99 mills/kWh. The SE value is higher because of the higher construction unemployment rate in the SE and the fact that the model defines higher benefits to the employment of unemployed individuals. The benefit value calculated includes multiplier effects on the economy.

Damages. Occupational exposures to radiation among reactor staff resulted in estimates of about 0.12 deaths per reactor year and damages of 0.0285 mills/kWh. Radiation exposure levels to the occupational staff are measured and are known unambiguously. Radiation doses to mine workers, primarily from inhalation of radon gas and other airborne particulates are also an important pathway, accounting for an estimated 0.043 deaths per reactor year with an estimated damage of 0.0145 mills/kWh. Both radiological and nonradiological morbidity in the mining and milling work staff are estimated to be important, resulting in an estimated total of about 3.02 occupational injuries and illnesses per reactor year.

Nonradiological fatalities resulted in 0.08 deaths per reactor year and damages of 0.0343 mills/kWh. The safety statistics (injury and fatality rate) for nuclear plants are actually somewhat lower than for a typical industrial facility. The occupational injury rate for nuclear plants is 7.7 accidents per reactor year, assuming a plant staff of 1,000 persons.

Potential severe reactor accidents had the highest estimated health impact upon the public, which was an expected number (probability multiplied by consequence) of 0.087 deaths per year for the southeast site. Our estimates were carried out to distances of 1,000 miles (1,609 km) with complete deposition of all radioactive releases. The majority of accident health effects were calculated to occur far from the reactor (from 50 to 1,000 miles), mostly due to indirect transport through food and water pathways. For example, in the massive containment failure (MCF) accident case for the southeast reactor site, 5,020 out of a total of 5,330 deaths occur at distances from 50 miles (80.5 km) to 1,000

miles (1,609 km). Overall, public cancer fatalities due to reactor accidents are estimated to have a damage of 0.0214 mills/kWh.

The costs of countermeasures and property losses from a severe reactor accident were calculated to be somewhat greater than the damages associated with public health impacts. As an example, the estimated cost of countermeasures and property losses for the MCF accident at the southeast site was $23.8 billion, whereas the economic damages associated with public morbidity and deaths were estimated to be about $12.7 billion. For limited containment failure accident cases, the calculated damages are dominated by the cost of replacement power due to the loss of the reactor itself, and economic damages associated with public health impacts are relatively low.

The loss of the utility assets represents the single largest damage estimate (0.0205 mills/kWh for the southeast site) for the impact pathways that have been evaluated to date. A major reason that this damage is large is that it occurs for both the LCF and MCF scenarios. Utility on-site damages would be internalized, as would some of the damages to the public.

The Price-Anderson Act requires firms to carry $200 million in private insurance to compensate third parties in the event of severe nuclear accidents. As a result, for all impact pathways associated with the possibilities of severe reactor accidents, 0.062 mills/kWh of the 0.104 mills/kWh in damages are externalities for the Southeast Reference case, and 0.018 mills/kWh of the 0.060 mills/kWh for the Southwest Reference case.

Three types of impacts were observed due to transportation accidents involving shipments of uranium hexafluoride, UF_6, to and from uranium enrichment plants. UF_6 reacts with air to form hydrogen fluoride (HF) gas and uranyl fluoride; both reaction products are gaseous and chemically very toxic. The expected impacts of public health effects from potential accidents involving shipments of UF_6 are about 0.0031 deaths from HF inhalation, 0.0020 deaths from inhalation of uranyl fluoride, and 0.2071 permanent renal injuries, also from inhalation of uranyl fluoride. The estimated damage associated with permanent renal injuries is 2.5×10^{-4} mills/kWh.

Emissions of radon from uranium mines are estimated to cause about 0.0455 deaths to the general public per reactor year, resulting in estimated damages of 0.0214 mills/kWh.

The expected value of direct financial consequences of accidents involving spent fuel shipments was estimated, at $504,000 per year or 0.0618 mills/kWh for the southeast site, to be almost as high as the analogous financial consequences

estimate for reactor accidents ($644,600 per year or 0.079 mills/kWh, including low specific activity waste disposal costs). This is a surprising result that may be partially explained by these factors:

- transportation accidents involving spent fuel shipments are estimated to be more probable by about a factor of three than reactor accidents involving major releases to the environment

- a small fraction of transportation accidents has the potential to occur in urban or suburban areas with higher population densities and property values than are found in the areas immediately proximate to the reference reactor sites

- release fractions of radionuclides from breached spent fuel casks are higher than from damaged reactors, presumably due to the lesser containment offered by a shipping cask relative to a reactor system

- there may be inconsistencies or methodological problems with one or both estimates; though based on standard risk assessment models, additional review of the methodology is needed.

Aqueous releases of ^{99}Tc and ^{129}I and gaseous releases of ^{14}C from the repository are estimated to result in long-term health impacts of 0.304 deaths and 0.095 genetic effects to the public per reactor year. The high magnitude of these impacts may not translate into high economic damages, dependent upon whether discounting assumptions are used. This issue warrants further work; no estimates of spent fuel repository damages appear in this draft.

11.2.4 Information Needs

A major conclusion of this study is that while the base of scientific knowledge is reasonably good in some areas, it is certainly lacking in others. An important gap in our study is the lack of methodology for estimating the impacts upon public health and the environment of contaminated groundwater from in-situ leaching processes for uranium mining. This is probably the major environmental and health impact for this method of mining.

Another major need is for more realistic models of atmospheric dispersion over the long distances (1,600 km) relevant to reactor accident calculations. Current models ignore changes in wind direction and speed over the dispersion path, and are instead based upon the local weather at the reactor site at the time of the release. This simplification probably does not bias the result, but may not offer a realistic picture of dispersion transport.

A third need is to understand the effects of seismic events upon both the probability and the releases of severe reactor accidents. This effect, which is very site-dependent, may in fact dominate internally-initiated accident scenarios for some specific sites. No methodology is available to make estimates on this issue.

In economics, a major issue in this area of research is the accuracy and precision of estimates of individuals' WTP to avoid certain health risks or ecological impacts. Estimates of the value of a statistical life and of the monetary value of morbidity vary by several factors.

The economic estimates of reactor and transportation accident costs due to countermeasures are based on scenario and parameter assumptions that require review to determine whether they are outdated. As an example, our review of the imbedded cost assumptions revealed that the cost of disposal of contaminated soil, crops, sod, and other low specific activity decontamination wastes was omitted from the reactor-accident computer code. Our rough estimate of these costs is $5.56 billion, for the SE-MCF scenario and $3.94 billion for the SW-MCF scenario. The cost values reported in this draft report now include these disposal cost estimates.

The crucial gap in the existence of reliable quantitative information is on the subjective or perceived risks of severe reactor accidents. Public perception of the risks of nuclear technology is pivotal to its eventual acceptance or demise. The issue of WTP to avoid the perceived risk of accidents is a special topic that is to be studies further.

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 releases.
- Limitations in the knowledge base are likely to preclude quantitative estimates of subjective risk.
- The analyses are project- and site-specific.
- Except for severe reactor accidents, there are as of yet no estimates of externalities, since no account has been made yet of regulations, insurance, taxes or other conditions that internalize some or all of the damages.

- 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.

Notwithstanding the above caveats, this study has demonstrated the application of the DFA to estimate the damages and benefits of nuclear fuel cycles. The study has identified important limitations in the quality of scientific information and in the feasibility of doing certain calculations, which preclude the possibility of quantifying all of the damages and benefits. Finally, the study has developed a range of estimates of many of the important impacts of a new nuclear reactor plant at two reference sites in the United States. These estimates form the basis for future study to distinguish more fully the external portions of these costs and benefits.

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APPENDIX A:

ADDITIONAL ECONOMIC DAMAGE ESTIMATES EMPLOYING A 5% DISCOUNT RATE

1. INTRODUCTION

The purpose of this appendix is to present additional economic damage estimates using a 5% discount rate instead of the 3% rate used in this study. Previous fuel cycle studies for other fuel cycles have used a 5% discount rate for the purposes of levelizing the cumulative damages or damages distributed in ways other than annually for the lifetime of the power plants. This appendix provides the damage estimates using the 5% discount rate to facilitate comparison with other fuel cycle reports.

Tables A-1, A-2, and A-3 are for the Southeast site at 5% discount rate, for low, mid, and high cost estimates, respectively. Tables A-4, A-5, and A-6 are for the Southwest site at 5% discount rate, for low, mid, and high cost estimates, respectively.

Table A-1. Damage estimates with 5% discount, Southeast site, low estimate

Annual damages from the nuclear fuel cycle (1989$), Southeast site: low estimates, 5% discount rate

Cycle step	Uranium mining and milling										
Substep											
Startpoint	Radon emissions						Nonradiological occupational risk				
Exposure	Public				Miners		Miners and Millers				
General endpoint	Mortality		Morbidity		Mortality	Morbidity	Mortality	Morbidity			
Table No.	5.6-1				5.6-3		5.6-2				
Section No.	5.6.1				5.6.3		5.6.2				
Specific endpoint	Cancer fatalities during plant lifetime	Cancer fatalities during 1st hundred yrs after shutdown (a)	Genetic defects during plant lifetime	Genetic defects during 1st hundred yrs after shutdown (a)	Cancer fatalities	Genetic defects	Fatalities	NFDL accidents	NDL accidents	Illnesses	Lost work days (LWD)
Yr of first exposure to risk	1	40	1	40	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	1	40	1	40	40	40	40	40	40	40
Latency period (yrs)	20	20	#N/A	#N/A	20	#N/A	0	0	0	0	0
Expected cases resulting from each annual exposure	0.0605	0.039045	0.0535	0.039045	0.048	0.023	0.02007515	2.9812131	1.798175	0.12034	80.687
Damage per case valued at time of exposure (1989$)	$603,023	$603,023	#N/A	#N/A	$603,023	#N/A	$1,600,000	$8,000	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (1989$ / yr) (e)	$36,483	$195	#N/A	#N/A	$28,945	#N/A	$32,120	$23,850	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.00446792	2.38698E-05	#N/A	#N/A	0.00354479	#N/A	0.00393364	0.0029208	#N/A	#N/A	#N/A

Table A-1. Damage estimates with 5% discount, Southeast site, low estimate (continued)

Annual damages from tl

Cycle step	**Electricity generation-normal operations**				
Substep	**General operation**				
Startpoint	Airborne radon emissions	Waterborne radon emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6.7-6			?	
Section No.	6.7.3		6.7.2	?	
Specific endpoint	Latent cancer fatalities	Latent cancer fatalities	Latent cancer fatalities	Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	5.00E-05	1.00E-04	0.12	0.08	7.7
Damage per case valued at time of exposure (1989$)	$603,023	$603,023	$603,023	$1,600,000	$8,000
Damage levelized over plant lifetime (1989$ / yr) (e)	$30	$60	$72,363	$128,000	$61,600
Damage levelized over plant lifetime (mills/kWh)	3.6925E-06	7.385E-06	0.00886198	0.01567565	0.007544

Table A-1. Damage estimates with 5% discount, Southeast site, low estimate (continued)

Annual damages from tl

Cycle step	Decommissioning											
Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
General endpoint	Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality	
Table No.	6.5-2											
Section No.	6.6.2											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
Damage per case valued at time of exposure (1989$)	$1,600,000	$127,000 (b)	$603,023	$603,023	$1,600,000	$127,000 (b)	$603,023	$603,023	$1,600,000	$127,000 (b)	$603,023	$603,023
Damage levelized over plant lifetime (1989$ / yr) (e)	$333	$3,641	$2,075	$0	$780	$1,001	$173	$38	$0	$0	$0	$0
Damage levelized over plant lifetime (mills/kWh)	4.0732E-05	0.000445942	0.00025409	2.6468E-11	9.5509E-05	0.000122634	2.1174E-05	4.6583E-06	0	0	0	0

Table A-1. Damage estimates with 5% discount, Southeast site, low estimate (continued)

Annual damages from tl

Cycle step	Transportation shipments during plant lifetime						Severe reactor accidents		
Substep									
Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill		Severe reactor accident risk		
Exposure	Public	Worker	Public	Worker	Public		Public		
General endpoint	Mortality				Mortality		Morbidity	Mortality	
Table No.	8.5.1-1	8.5.2-1	8.5.1-1	#N/A	8.5.1-4		7.6.2-1		
Section No.	8.5.1	8.5.2	8.5.1	#N/A	8.5.1		7.6.1		
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury	Nonfatal cancer cases	Early fatalities	Cancer fatalities
Yr of first exposure to risk	1	1	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0	(c)	0	(c)
Expected cases resulting from each annual exposure	0.00333899	0.00029405	0.02409442	#N/A	0.00796457	29.62963	0.161739 (e)	5.1E-08 (e)	0.087 (e)
Damage per case valued at time of exposure (1989$)	$603,023	$603,023	$603,023	$603,023	$1,600,000	$9,359	(c)		(c)
Damage levelized over plant lifetime (1989$ / yr) (e)	$2,013	$177	$14,529	#N/A	$12,743	$277,304	$28,340	$0.18	$174,709
Damage levelized over plant lifetime (mills/kWh)	0.00024658	2.1716E-05	0.00177937	#N/A	0.00156062	0.0339603	0.003470748	2.19E-08	0.021396

Table A-1. Damage estimates with 5% discount, Southeast site, low estimate (continued)

Annual damages from tl

Cycle step	
Substep	
Startpoint	
Exposure	
General endpoint	
Table No.	
Section No.	
Specific endpoint	
Yr of first exposure to risk	
Total consecutive yrs of exposure to risk	
Latency period (yrs)	
Expected cases resulting from each annual exposure	

Annual damages from the nuclear fuel cycle (1989$), Southeast site: low estimates, 5% discount rate

Damage per case valued at time of exposure (1989$)	All	Public	Occupational	Mining and milling	Electricity generation-normal operations	Transportation shipments during plant lifetime	Severe reactor accidents
Damage levelized over plant lifetime (1989$ / yr) (e)	$901,504	$546,446	$355,058	$121,593	$270,094	$306,767	$203,049
Damage levelized over plant lifetime (mills/kWh)	0.110403599	0.066921	0.043482553	0.014890997	0.033077363	0.037568579	0.024866661

Table A-1. Damage estimates with 5% discount, Southeast site, low estimate (continued)

(a) Assumes all the exposure occurs in the first yr after shutdown
(b) Value taken from Martinello and Meng, 1992, for major injuries
(c) Varied with cancer type. For more detail, see Section 7.6.2
(d) Based on annual probabilities of three possible outcomes:
P(massive containment failure)= 0.000046
P(limited containment failure)= 0.000016
P(no failure)= 1 - 0.000046 - 0.000016 = 0.999938
(e) Example calculation:
Occupational latent cancer fatalities from radiation exposure during decommissioning operations at site
1) Find Damage per case valued at time of exposure
= Present value(Damage per case valued at time of ocurrence= $1,600,000, discount rate = 5%,
number of yrs in the future = latency period=20)
= $603,023
2) Calculate Damages resulting from each annual exposure
= Damage per case valued at time of exposure* Expected number of cases resulting from each annual exposure
= $603,023 * 0.0960 = $57,890
3) Calculate Total damages from all years of exposure valued at start of exposure
=Present value(stream of damages resulting from each annual exposure = $57,890,
number of years =Total consecutive yrs of exposure to risk = 5, discount rate = 5%)
= $263,166
4) Calculate Present value of total damages resulting from all years of exposure to risk
= Present value(Total damages from all years of exposure valued at start of exposure= $263,166,
number of yrs in the future = First year of exposure to risk = 41, discount rate = 5%)
= $35,602
5) Calculate Damage levelized over plant lifetime (1989$ / yr)
=Annuity(Present value of total damages resulting from all yrs of exposure to risk= $35,602,
number of yrs in the future = plant lifetime = 40, discount rate = 5%)
= $2,075
6) Calculate Damage levelized over plant lifetime in mills/kWh
= Damage levelized over plant lifetime (1989$ / yr) / kWh per yr *(1000 mills/ $)
= 0.00025 mills / kWh

Table A-2. Damage estimates with 5% discount, Southeast site, mid estimate

Annual damages from the nuclear fuel cycle (1989$), Southeast site: mid estimates, 5% discount rate

Cycle step	Uranium mining and milling										
Substep											
Startpoint	Radon emissions						Nonradiological occupational risk				
Exposure	Public				Miners		Miners and Millers				
General endpoint	Mortality		Morbidity		Mortality	Morbidity	Mortality	Morbidity			
Table No.	5.6-1				5.6-3		5.6-2				
Section No.	5.6.1				5.6.3		5.6.2				
Specific endpoint	Cancer fatalities during plant lifetime	Cancer fatalities during 1st hundred yrs after shutdown (a)	Genetic defects during plant lifetime	Genetic defects during 1st hundred yrs after shutdown (a)	Cancer fatalities	Genetic defects	Fatalities	NFDL accidents	NDL accidents	Illnesses	Lost work days (LWD)
Yr of first exposure to risk	1	40	1	40	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	1	40	1	40	40	40	40	40	40	40
Latency period (yrs)	20	20	#N/A	#N/A	20	#N/A	0	0	0	0	0
Expected cases resulting from each annual exposure	0.0605	0.039045	0.0535	0.039045	0.048	0.023	0.02007515	2.9812131	1.798175	0.12034	80.687
Damage per case valued at time of exposure (1989$)	$1,319,113	$1,319,113	#N/A	#N/A	$1,319,113	#N/A	$3,500,000	$21,000	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (1989$ / yr) (e)	$79,806	$426	#N/A	#N/A	$63,317	#N/A	$70,263	$62,605	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.00977357	5.22152E-05	#N/A	#N/A	0.00775424	#N/A	0.00860483	0.007667	#N/A	#N/A	#N/A

Table A-2. Damage estimates with 5% discount, Southeast site, mid estimate (continued)

Annual damages from tl

Cycle step	Electricity generation-normal operations				
Substep	General operation				
Startpoint	Airborne radon emissions	Waterborne radon emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6.7-6			?	
Section No.	6.7.3		6.7.2	?	
Specific endpoint	Latent cancer fatalities	Latent cancer fatalities	Latent cancer fatalities	Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	5.00E-05	1.00E-04	0.12	0.08	7.7
Damage per case valued at time of exposure (1989$)	$1,319,113	$1,319,113	$1,319,113	$3,500,000	$10,300
Damage levelized over plant lifetime (1989$ / yr) (e)	$66	$132	$158,294	$280,000	$79,310
Damage levelized over plant lifetime (mills/kWh)	8.0773E-06	1.6155E-05	0.01938559	0.03429049	0.009713

Table A-2. Damage estimates with 5% discount, Southeast site, mid estimate (continued)

Annual damages from t

Cycle step	Decommissioning											
Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
General endpoint	Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality	
Table No.	6.5-2											
Section No.	6.6.2											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
Damage per case valued at time of exposure (1989$)	$3,500,000	$127,000 (b)	$1,319,113	$1,319,113	$3,500,000	$127,000 (b)	$1,319,113	$1,319,113	$3,500,000	$127,000 (b)	$1,319,113	$1,319,113
Damage levelized over plant lifetime (1989$ / yr) (e)	$728	$3,641	$4,539	$0	$1,706	$1,001	$378	$83	$0	$0	$0	$0
Damage levelized over plant lifetime (mills/kWh)	8.9101E-05	0.000445942	0.00055583	5.7898E-11	0.00020893	0.000122634	4.6319E-05	1.019E-05	0	0	0	0

Table A-2. Damage estimates with 5% discount, Southeast site, mid estimate (continued)

Annual damages from tl

Cycle step	**Transportation shipments during plant lifetime**						**Severe reactor accidents**		
Substep									
Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill		Severe reactor accident risk		
Exposure	Public	Worker	Public	Worker	Public		Public		
General endpoint	Mortality				Mortality		Morbidity	Mortality	
Table No.	8.5.1-1	8.5.2-1	8.5.1-1	#N/A	8.5.1-4		7.6.2-1		
Section No.	8.5.1	8.5.2	8.5.1	#N/A	8.5.1		7.6.1		
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury	Nonfatal cancer cases	Early fatalities	Cancer fatalities
Yr of first exposure to risk	1	1	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0	(c)	0	(c)
Expected cases resulting from each annual exposure	0.00333899	0.00029405	0.02409442	#N/A	0.00796457	29.62963	0.161739 (e)	5.1E-08 (e)	0.087 (e)
Damage per case valued at time of exposure (1989$)	$1,319,113	$1,319,113	$1,319,113	$1,319,113	$3,500,000	$9,359	(c)		(c)
Damage levelized over plant lifetime (1989$ / yr) (e)	$4,405	$388	$31,783	#N/A	$27,876	$277,304	$28,340	$0.18	$174,709
Damage levelized over plant lifetime (mills/kWh)	0.0005394	4.7503E-05	0.00389237	#N/A	0.00341386	0.0339603	0.003470748	2.19E-08	0.021396

Table A-2. Damage estimates with 5% discount, Southeast site, mid estimate (continued)

Annual damages from tl

Cycle step	
Substep	
Startpoint	
Exposure	
General endpoint	
Table No.	
Section No.	
Specific endpoint	
Yr of first exposure to risk	
Total consecutive yrs of exposure to risk	
Latency period (yrs)	
Expected cases resulting from each annual exposure	

Annual damages from the nuclear fuel cycle (1989$), Southeast site: mid estimates, 5% discount rate

Damage per case valued at time of exposure (1989$)	All	Public	Occupational	Mining and milling	Electricity generation-normal operations	Transportation shipments during plant lifetime	Severe reactor accidents
Damage levelized over plant lifetime (1989$ / yr) (e)	$1,351,101	$624,931	$726,170	$276,419	$529,878	$341,755	$203,049
Damage levelized over plant lifetime (mills/kWh)	0.165464013	0.076533	0.088931224	0.033851896	0.06489203	0.041853426	0.024866661

Table A-2. Damage estimates with 5% discount, Southeast site, mid estimate (continued)

(a) Assumes all the exposure occurs in the first yr after shutdown
(b) Value taken from Martinello and Meng, 1992, for major injuries
(c) Varied with cancer type. For more detail, see Section 7.6.2
(d) Based on annual probabilities of three possible outcomes:

P(massive containment failure)= 0.000046
P(limited containment failure)= 0.000016
P(no failure)= 1 - 0.000046 - 0.000016 = 0.999938

(e) Example calculation:

Occupational latent cancer fatalities from radiation exposure during decommissioning operations at site

1) Find Damage per case valued at time of exposure
= Present value(Damage per case valued at time of ocurrence= $3,500,000, discount rate = 5%,
number of yrs in the future = latency period=20)
= $1,319,113
2) Calculate Damages resulting from each annual exposure
= Damage per case valued at time of exposure* Expected number of cases resulting from each annual exposure
= $1,319,113 * 0.0960 = $126,635
3) Calculate Total damages from all years of exposure valued at start of exposure
=Present value(stream of damages resulting from each annual exposure = $126,635,
number of years =Total consecutive yrs of exposure to risk = 5, discount rate = 5%)
= $575,676
4) Calculate Present value of total damages resulting from all years of exposure to risk
= Present value(Total damages from all years of exposure valued at start of exposure= $575,676,
number of yrs in the future = First year of exposure to risk = 41, discount rate = 5%)
= $77,878
5) Calculate Damage levelized over plant lifetime (1989$ / yr)
=Annuity(Present value of total damages resulting from all yrs of exposure to risk= $77,878,
number of yrs in the future = plant lifetime = 40, discount rate = 5%)
= $4,539
6) Calculate Damage levelized over plant lifetime in mills/kWh
= Damage levelized over plant lifetime (1989$ / yr) / kWh per yr *(1000 mills/ $)
= 0.00056 mills / kWh

Table A-3. Damage estimates with 5% discount, Southeast site, high estimate

Annual damages from the nuclear fuel cycle (1989$), Southeast site: high estimates, 5% discount rate

Cycle step	Uranium mining and milling										
Substep											
Startpoint	Radon emissions						Nonradiological occupational risk				
Exposure	Public				Miners		Miners and Millers				
General endpoint	Mortality		Morbidity		Mortality	Morbidity	Mortality	Morbidity			
Table No.	5.6-1				5.6-3		5.6-2				
Section No.	5.6.1				5.6.3		5.6.2				
Specific endpoint	Cancer fatalities during plant lifetime	Cancer fatalities during 1st hundred yrs after shutdown (a)	Genetic defects during plant lifetime	Genetic defects during 1st hundred yrs after shutdown (a)	Cancer fatalities	Genetic defects	Fatalities	NFDL accidents	NDL accidents	Illnesses	Lost work days (LWD)
Yr of first exposure to risk	1	40	1	40	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	1	40	1	40	40	40	40	40	40	40
Latency period (yrs)	20	20	#N/A	#N/A	20	#N/A	0	0	0	0	0
Expected cases resulting from each annual exposure	0.0605	0.039045	0.0535	0.039045	0.048	0.023	0.02007515	2.9812131	1.798175	0.12034	80.687
Damage per case valued at time of exposure (1989$)	$3,241,250	$3,241,250	#N/A	#N/A	$3,241,250	#N/A	$8,600,000	$34,000	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (1989$ / yr) (e)	$196,096	$1,048	#N/A	#N/A	$155,580	#N/A	$172,646	$101,361	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.02401505	0.0001283	#N/A	#N/A	0.01905326	#N/A	0.0211433	0.0124133	#N/A	#N/A	#N/A

Table A-3. Damage estimates with 5% discount, Southeast site, high estimate (continued)

Annual damages from tl

Cycle step	Electricity generation-normal operations				
Substep	General operation				
Startpoint	Airborne radon emissions	Waterborne radon emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6.7-6			?	
Section No.	6.7.3		6.7.2	?	
Specific endpoint	Latent cancer fatalities	Latent cancer fatalities	Latent cancer fatalities	Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	5.00E-05	1.00E-04	0.12	0.08	7.7
Damage per case valued at time of exposure (1989$)	$3,241,250	$3,241,250	$3,241,250	$8,600,000	$34,000
Damage levelized over plant lifetime (1989$ / yr) (e)	$162	$324	$388,950	$688,000	$261,800
Damage levelized over plant lifetime (mills/kWh)	1.9847E-05	3.9694E-05	0.04763316	0.08425664	0.032062

Table A-3. Damage estimates with 5% discount, Southeast site, high estimate (continued)

Annual damages from tl

Cycle step	Decommissioning											
Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
General endpoint	Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality	
Table No.	6.5-2											
Section No.	6.6.2											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
Damage per case valued at time of exposure (1989$)	$8,600,000	$127,000 (b)	$3,241,250	$3,241,250	$8,600,000	$127,000 (b)	$3,241,250	$3,241,250	$8,600,000	$127,000 (b)	$3,241,250	$3,241,250
Damage levelized over plant lifetime (1989$/yr) (e)	$1,788	$3,641	$11,152	$0	$4,192	$1,001	$929	$204	$0	$0	$0	$0
Damage levelized over plant lifetime (mills/kWh)	0.00021893	0.000445942	0.00136574	1.4226E-10	0.00051336	0.000122634	0.00011381	2.5039E-05	0	0	0	0

Table A-3. Damage estimates with 5% discount, Southeast site, high estimate (continued)

Annual damages from tl

Cycle step	**Transportation shipments during plant lifetime**						**Severe reactor accidents**		
Substep									
Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill		Severe reactor accident risk		
Exposure	Public	Worker	Public	Worker	Public		Public		
General endpoint	Mortality				Mortality		Morbidity	Mortality	
Table No.	8.5.1-1	8.5.2-1	8.5.1-1	#N/A	8.5.1-4		7.6.2-1		
Section No.	8.5.1	8.5.2	8.5.1	#N/A	8.5.1		7.6.1		
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury	Nonfatal cancer cases	Early fatalities	Cancer fatalities
Yr of first exposure to risk	1	1	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0	(c)	0	(c)
Expected cases resulting from each annual exposure	0.00333899	0.00029405	0.02409442	#N/A	0.00796457	29.62963	0.161739 (e)	5.1E-08 (e)	0.087 (e)
Damage per case valued at time of exposure (1989$)	$3,241,250	$3,241,250	$3,241,250	$3,241,250	$8,600,000	$9,359	(c)		(c)
Damage levelized over plant lifetime (1989$ / yr) (e)	$10,822	$953	$78,096	#N/A	$68,495	$277,304	$28,340	$0.18	$174,709
Damage levelized over plant lifetime (mills/kWh)	0.00132539	0.00011672	0.00956411	#N/A	0.00838835	0.0339603	0.003470748	2.19E-08	0.021396

Table A-3. Damage estimates with 5% discount, Southeast site, high estimate (continued)

Annual damages from tl

Cycle step	
Substep	
Startpoint	
Exposure	
General endpoint	
Table No.	
Section No.	
Specific endpoint	
Yr of first exposure to risk	
Total consecutive yrs of exposure to risk	
Latency period (yrs)	
Expected cases resulting from each annual exposure	

Damage per case valued at time of exposure (1989$)	All	Public	Occupational	Mining and milling	Electricity generation-normal operations	Transportation shipments during plant lifetime	Severe reactor accidents
	Annual damages from the nuclear fuel cycle (1989$), Southeast site: high estimates, 5% discount rate						
Damage levelized over plant lifetime (1989$ / yr) (e)	$2,627,595	$835,601	$1,791,994	$626,731	$1,362,144	$435,671	$203,049
Damage levelized over plant lifetime (mills/kWh)	0.321791158	0.102333	0.219458429	0.076753231	0.166816408	0.053354858	0.024866661

Table A-3. Damage estimates with 5% discount, Southeast site, high estimate (continued)

(a) Assumes all the exposure occurs in the first yr after shutdown
(b) Value taken from Martinello and Meng, 1992, for major injuries
(c) Varied with cancer type. For more detail, see Section 7.6.2
(d) Based on annual probabilities of three possible outcomes:
P(massive containment failure)= 0.000046
P(limited containment failure)= 0.000016
P(no failure)= 1 - 0.000046 - 0.000016 = 0.999938
(e) Example calculation:
Occupational latent cancer fatalities from radiation exposure during decommissioning operations at site
1) Find Damage per case valued at time of exposure
= Present value(Damage per case valued at time of ocurrence= $8,600,000, discount rate = 5%,
number of yrs in the future = latency period=20)
= $3,241,250
2) Calculate Damages resulting from each annual exposure
= Damage per case valued at time of exposure* Expected number of cases resulting from each annual exposure
= $3,241,250 * 0.0960 = $311,160
3) Calculate Total damages from all years of exposure valued at start of exposure
=Present value(stream of damages resulting from each annual exposure = $311,160,
number of years =Total consecutive yrs of exposure to risk = 5, discount rate = 5%)
= $1,414,518
4) Calculate Present value of total damages resulting from all years of exposure to risk
= Present value(Total damages from all years of exposure valued at start of exposure= $1,414,518,
number of yrs in the future = First year of exposure to risk = 41, discount rate = 5%)
= $191,358
5) Calculate Damage levelized over plant lifetime (1989$ / yr)
=Annuity(Present value of total damages resulting from all yrs of exposure to risk= $191,358,
number of yrs in the future = plant lifetime = 40, discount rate = 5%)
= $11,152
6) Calculate Damage levelized over plant lifetime in mills/kWh
= Damage levelized over plant lifetime (1989$ / yr) / kWh per yr *(1000 mills/ $)
= 0.00137 mills / kWh

Table A-4. Damage estimates with 5% discount, Southwest site, low estimate

Damages from the nuclear fuel cycle (1989$), Southwest site: low estimates, 5% discount rate

Cycle step	Uranium mining and milling										
Substep											
Startpoint	Radon emissions						Nonradiological occupational risk				
Exposure	Public				Miners		Miners and Millers				
General endpoint	Mortality		Morbidity		Mortality	Morbidity	Mortality	Morbidity			
Table No.	5.6-1				5.6-3		5.6-2				
Section No.	5.6.1				5.6.3		5.6.2				
Specific endpoint	Cancer fatalities during plant lifetime	Cancer fatalities during 1st hundred yrs after shutdown (a)	Genetic defects during plant lifetime	Genetic defects during 1st hundred yrs after shutdown (a)	Cancer fatalities	Genetic defects	Fatalities	NFDL accidents	NDL accidents	Illnesses	Lost work days (LWD)
Yr of first exposure to risk	1	40	1	40	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	1	40	1	40	40	40	40	40	40	40
Latency period (yrs)	20	20	#N/A	#N/A	20	#N/A	0	0	0	0	0
Expected cases resulting from each annual exposure	0.0605	0.039045	0.0535	0.039045	0.048	0.023	0.02007515	2.9812131	1.798175	0.12034	80.687
Damage per case valued at time of exposure (1989$)	$603,023	$603,023	#N/A	#N/A	$603,023	#N/A	$1,600,000	$8,000	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (1989$ / yr) (e)	$36,483	$195	#N/A	#N/A	$28,945	#N/A	$32,120	$23,850	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.00446792	2.38698E-05	#N/A	#N/A	0.00354479	#N/A	0.00393364	0.0029208	#N/A	#N/A	#N/A

Table A-4. Damage estimates with 5% discount, Southwest site, low estimate (continued)

Damages from the nucle

Cycle step	Electricity generation-normal operations				
Substep	General operation				
Startpoint	Airborne radon emissions	Waterborne radon emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6.7-6			?	
Section No.	6.7.3		6.7.2	?	
Specific endpoint	Latent cancer fatalities	Latent cancer fatalities	Latent cancer fatalities	Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	3.00E-06	3.50E-06	0.12	0.08	7.7
Damage per case valued at time of exposure (1989$)	$603,023	$603,023	$603,023	$1,600,000	$8,000
Damage levelized over plant lifetime (1989$ / yr) (e)	$2	$2	$72,363	$128,000	$61,600
Damage levelized over plant lifetime (mills/kWh)	2.2155E-07	2.5847E-07	0.00886198	0.01567565	0.007544

Table A-4. Damage estimates with 5% discount, Southwest site, low estimate (continued)

Damages from the nucle

Cycle step	Decommissioning											
Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
General endpoint	Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality	
Table No.	6.5-2											
Section No.	6.6.2											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
Damage per case valued at time of exposure (1989$)	$1,600,000	$127,000 (b)	$603,023	$603,023	$1,600,000	$127,000 (b)	$603,023	$603,023	$1,600,000	$127,000 (b)	$603,023	$603,023
Damage levelized over plant lifetime (1989$ / yr) (e)	$333	$3,641	$2,075	$0	$780	$1,001	$173	$38	$0	$0	$0	$0
Damage levelized over plant lifetime (mills/kWh)	4.0732E-05	0.000445942	0.00025409	2.6468E-11	9.5509E-05	0.000122634	2.1174E-05	4.6583E-06	0	0	0	0

Table A-4. Damage estimates with 5% discount, Southwest site, low estimate (continued)

Damages from the nucle

Cycle step	**Transportation shipments during plant lifetime**						**Severe reactor accidents**		
Substep									
Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill		Severe reactor accident risk		
Exposure	Public	Worker	Public	Worker	Public		Public		
General endpoint	Mortality				Mortality		Morbidity	Mortality	
Table No.	8.5.1-1	8.5.2-1	8.5.1-1	#N/A	8.5.1-4		7.6.2-1		
Section No.	8.5.1	8.5.2	8.5.1	#N/A	8.5.1		7.6.1		
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury	Nonfatal cancer cases	Early fatalities	Cancer fatalities
Yr of first exposure to risk	1	1	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0	(c)	0	(c)
Expected cases resulting from each annual exposure	0.00333899	0.00012873	0.00396559	#N/A	0.00796457	29.62963	0.016924 (e)	1.6E-10 (e)	0.009 (e)
Damage per case valued at time of exposure (1989$)	$603,023	$603,023	$603,023	$603,023	$1,600,000	$9,359	(c)		(c)
Damage levelized over plant lifetime (1989$ / yr) (e)	$2,013	$78	$2,391	#N/A	$12,743	$277,304	$2,917	$0.00	$17,853
Damage levelized over plant lifetime (mills/kWh)	0.00024658	9.5065E-06	0.00029286	#N/A	0.00156062	0.0339603	0.000357231	7.048E-11	0.002186

Table A-4. Damage estimates with 5% discount, Southwest site, low estimate (continued)

Damages from the nucle

Cycle step
Substep
Startpoint
Exposure
General endpoint
Table No.
Section No.
Specific endpoint
Yr of first exposure to risk
Total consecutive yrs of exposure to risk
Latency period (yrs)
Expected cases resulting from each annual exposure

Damages from the nuclear fuel cycle (1989$), Southwest site: low estimates, 5% discount rate

Damage per case valued at time of exposure (1989$)	All	Public	Occupational	Mining and milling	Electricity generation-normal operations	Transportation shipments during plant lifetime	Severe reactor accidents
Damage levelized over plant lifetime (1989$ / yr) (e)	$706,900	$351,941	$354,958	$121,593	$270,008	$294,529	$20,770
Damage levelized over plant lifetime (mills/kWh)	0.086571217	0.043101	0.043470344	0.014890997	0.033066766	0.036069859	0.002543596

Table A-4. Damage estimates with 5% discount, Southwest site, low estimate (continued)

(a) Assumes all the exposure occurs in the first yr after shutdown
(b) Value taken from Martinello and Meng, 1992, for major injuries
(c) Varied with cancer type. For more detail, see Section 7.6.2
(d) Based on annual probabilities of three possible outcomes:

P(massive containment failure)= 0.000046
P(limited containment failure)= 0.000016
P(no failure)= 1 - 0.000046 - 0.000016 = 0.999938

(e) Example calculation:

Occupational latent cancer fatalities from radiation exposure during decommissioning operations at site

1) Find Damage per case valued at time of exposure
= Present value(Damage per case valued at time of ocurrence= $1,600,000, discount rate = 5%,
number of yrs in the future = latency period=20)
= $603,023

2) Calculate Damages resulting from each annual exposure
= Damage per case valued at time of exposure* Expected number of cases resulting from each annual exposure
= $603,023 * 0.0960 = $57,890

3) Calculate Total damages from all years of exposure valued at start of exposure
=Present value(stream of damages resulting from each annual exposure = $57,890,
number of years =Total consecutive yrs of exposure to risk = 5, discount rate = 5%)
= $263,166

4) Calculate Present value of total damages resulting from all years of exposure to risk
= Present value(Total damages from all years of exposure valued at start of exposure= $263,166,
number of yrs in the future = First year of exposure to risk = 41, discount rate = 5%)
= $35,602

5) Calculate Damage levelized over plant lifetime (1989$ / yr)
=Annuity(Present value of total damages resulting from all yrs of exposure to risk= $35,602,
number of yrs in the future = plant lifetime = 40, discount rate = 5%)
= $2,075

6) Calculate Damage levelized over plant lifetime in mills/kWh
= Damage levelized over plant lifetime (1989$ / yr) / kWh per yr *(1000 mills/ $)
= 0.00025 mills / kWh

Table A-5. Damage estimates with 5% discount, Southwest site, mid estimate

Damages from the nuclear fuel cycle (1989$), Southwest site: mid estimates, 5% discount rate

Cycle step	Uranium mining and milling										
Substep											
Startpoint	Radon emissions						Nonradiological occupational risk				
Exposure	Public				Miners		Miners and Millers				
General endpoint	Mortality		Morbidity		Mortality	Morbidity	Mortality	Morbidity			
Table No.	5.6-1				5.6-3		5.6-2				
Section No.	5.6.1				5.6.3		5.6.2				
Specific endpoint	Cancer fatalities during plant lifetime	Cancer fatalities during 1st hundred yrs after shutdown (a)	Genetic defects during plant lifetime	Genetic defects during 1st hundred yrs after shutdown (a)	Cancer fatalities	Genetic defects	Fatalities	NFDL accidents	NDL accidents	Illnesses	Lost work days (LWD)
Yr of first exposure to risk	1	40	1	40	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	1	40	1	40	40	40	40	40	40	40
Latency period (yrs)	20	20	#N/A	#N/A	20	#N/A	0	0	0	0	0
Expected cases resulting from each annual exposure	0.0605	0.039045	0.0535	0.039045	0.048	0.023	0.02007515	2.9812131	1.798175	0.12034	80.687
Damage per case valued at time of exposure (1989$)	$1,319,113	$1,319,113	#N/A	#N/A	$1,319,113	#N/A	$3,500,000	$21,000	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (1989$ / yr) (e)	$79,806	$426	#N/A	#N/A	$63,317	#N/A	$70,263	$62,605	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.00977357	5.22152E-05	#N/A	#N/A	0.00775424	#N/A	0.00860483	0.007667	#N/A	#N/A	#N/A

Table A-5. Damage estimates with 5% discount, Southwest site, mid estimate (continued)

Damages from the nucle

Cycle step	Electricity generation-normal operations				
Substep	General operation				
Startpoint	Airborne radon emissions	Waterborne radon emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6.7-6			?	
Section No.	6.7.3		6.7.2	?	
Specific endpoint	Latent cancer fatalities	Latent cancer fatalities	Latent cancer fatalities	Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	3.00E-06	3.50E-06	0.12	0.08	7.7
Damage per case valued at time of exposure (1989$)	$1,319,113	$1,319,113	$1,319,113	$3,500,000	$10,300
Damage levelized over plant lifetime (1989$ / yr) (e)	$4	$5	$158,294	$280,000	$79,310
Damage levelized over plant lifetime (mills/kWh)	4.8464E-07	5.6541E-07	0.01938559	0.03429049	0.009713

Table A-5. Damage estimates with 5% discount, Southwest site, mid estimate (continued)

Damages from the nucle

Cycle step	Decommissioning											
Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
General endpoint	Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality	
Table No.	6.5-2											
Section No.	6.6.2											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
Damage per case valued at time of exposure (1989$)	$3,500,000	$127,000 (b)	$1,319,113	$1,319,113	$3,500,000	$127,000 (b)	$1,319,113	$1,319,113	$3,500,000	$127,000 (b)	$1,319,113	$1,319,113
Damage levelized over plant lifetime (1989$ / yr) (e)	$728	$3,641	$4,539	$0	$1,706	$1,001	$378	$83	$0	$0	$0	$0
Damage levelized over plant lifetime (mills/kWh)	8.9101E-05	0.000445942	0.00055583	5.7898E-11	0.00020893	0.000122634	4.6319E-05	1.019E-05	0	0	0	0

Table A-5. Damage estimates with 5% discount, Southwest site, mid estimate (continued)

Damages from the nucle

Cycle step	Transportation shipments during plant lifetime						Severe reactor accidents		
Substep									
Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill		Severe reactor accident risk		
Exposure	Public	Worker	Public	Worker	Public		Public		
General endpoint	Mortality				Mortality		Morbidity	Mortality	
Table No.	8.5.1-1	8.5.2-1	8.5.1-1	#N/A	8.5.1-4		7.6.2-1		
Section No.	8.5.1	8.5.2	8.5.1	#N/A	8.5.1		7.6.1		
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury	Nonfatal cancer cases	Early fatalities	Cancer fatalities
Yr of first exposure to risk	1	1	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0	(c)	0	(c)
Expected cases resulting from each annual exposure	0.00333899	0.00012873	0.00396559	#N/A	0.00796457	29.62963	0.016924 (e)	1.6E-10 (e)	0.009 (e)
Damage per case valued at time of exposure (1989$)	$1,319,113	$1,319,113	$1,319,113	$1,319,113	$3,500,000	$9,359	(c)		(c)
Damage levelized over plant lifetime (1989$ / yr) (e)	$4,405	$170	$5,231	#N/A	$27,876	$277,304	$2,917	$0.00	$17,853
Damage levelized over plant lifetime (mills/kWh)	0.0005394	2.0796E-05	0.00064063	#N/A	0.00341386	0.0339603	0.000357231	7.048E-11	0.002186

Table A-5. Damage estimates with 5% discount, Southwest site, mid estimate (continued)

Damages from the nucle

Cycle step	
Substep	
Startpoint	
Exposure	
General endpoint	
Table No.	
Section No.	
Specific endpoint	
Yr of first exposure to risk	
Total consecutive yrs of exposure to risk	
Latency period (yrs)	
Expected cases resulting from each annual exposure	

Damages from the nuclear fuel cycle (1989$), Southwest site: mid estimates, 5% discount rate

Damage per case valued at time of exposure (1989$)	All	Public	Occupational	Mining and milling	Electricity generation-normal operations	Transportation shipments during plant lifetime	Severe reactor accidents
Damage levelized over plant lifetime (1989$ / yr) (e)	$1,141,862	$415,910	$725,952	$276,419	$529,688	$314,985	$20,770
Damage levelized over plant lifetime (mills/kWh)	0.139839316	0.050935	0.088904517	0.033851896	0.064868848	0.038574976	0.002543596

Table A-5. Damage estimates with 5% discount, Southwest site, mid estimate (continued)

(a) Assumes all the exposure occurs in the first yr after shutdown
(b) Value taken from Martinello and Meng, 1992, for major injuries
(c) Varied with cancer type. For more detail, see Section 7.6.2
(d) Based on annual probabilities of three possible outcomes:

P(massive containment failure)= 0.000046
P(limited containment failure)= 0.000016
P(no failure)= 1 - 0.000046 - 0.000016 = 0.999938

(e) Example calculation:

Occupational latent cancer fatalities from radiation exposure during decommissioning operations at site

1) Find Damage per case valued at time of exposure
= Present value(Damage per case valued at time of ocurrence= $3,500,000, discount rate = 5%,
number of yrs in the future = latency period=20)
= $1,319,113
2) Calculate Damages resulting from each annual exposure
= Damage per case valued at time of exposure* Expected number of cases resulting from each annual exposure
= $1,319,113 * 0.0960 = $126,635
3) Calculate Total damages from all years of exposure valued at start of exposure
=Present value(stream of damages resulting from each annual exposure = $126,635,
number of years =Total consecutive yrs of exposure to risk = 5, discount rate = 5%)
= $575,676
4) Calculate Present value of total damages resulting from all years of exposure to risk
= Present value(Total damages from all years of exposure valued at start of exposure= $575,676,
number of yrs in the future = First year of exposure to risk = 41, discount rate = 5%)
= $77,878
5) Calculate Damage levelized over plant lifetime (1989$ / yr)
=Annuity(Present value of total damages resulting from all yrs of exposure to risk= $77,878,
number of yrs in the future = plant lifetime = 40, discount rate = 5%)
= $4,539
6) Calculate Damage levelized over plant lifetime in mills/kWh
= Damage levelized over plant lifetime (1989$ / yr) / kWh per yr *(1000 mills/ $)
= 0.00056 mills / kWh

Table A-6. Damage estimates with 5% discount, Southwest site, high estimate

Damages from the nuclear fuel cycle (1989$), Southwest site: high estimates, 5% discount rate

Cycle step	Uranium mining and milling										
Substep											
Startpoint	Radon emissions						Nonradiological occupational risk				
Exposure	Public				Miners		Miners and Millers				
General endpoint	Mortality		Morbidity		Mortality	Morbidity	Mortality	Morbidity			
Table No.	5.6-1				5.6-3		5.6-2				
Section No.	5.6.1				5.6.3		5.6.2				
Specific endpoint	Cancer fatalities during plant lifetime	Cancer fatalities during 1st hundred yrs after shutdown (a)	Genetic defects during plant lifetime	Genetic defects during 1st hundred yrs after shutdown (a)	Cancer fatalities	Genetic defects	Fatalities	NFDL accidents	NDL accidents	Illnesses	Lost work days (LWD)
Yr of first exposure to risk	1	40	1	40	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	1	40	1	40	40	40	40	40	40	40
Latency period (yrs)	20	20	#N/A	#N/A	20	#N/A	0	0	0	0	0
Expected cases resulting from each annual exposure	0.0605	0.039045	0.0535	0.039045	0.048	0.023	0.02007515	2.9812131	1.798175	0.12034	80.687
Damage per case valued at time of exposure (1989$)	$3,241,250	$3,241,250	#N/A	#N/A	$3,241,250	#N/A	$8,600,000	$34,000	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (1989$ / yr) (e)	$196,096	$1,048	#N/A	#N/A	$155,580	#N/A	$172,646	$101,361	#N/A	#N/A	#N/A
Damage levelized over plant lifetime (mills/kWh)	0.02401505	0.0001283	#N/A	#N/A	0.01905326	#N/A	0.0211433	0.0124133	#N/A	#N/A	#N/A

Table A-6. Damage estimates with 5% discount, Southwest site, high estimate (continued)

Damages from the nucle

Cycle step	Electricity generation-normal operations				
Substep	General operation				
Startpoint	Airborne radon emissions	Waterborne radon emissions	Occupational radiation exposure	Nonradiological occupational risk	
Exposure	Public		Workers		
General endpoint	Mortality		Mortality		Morbidity
Table No.	6.7-6			?	
Section No.	6.7.3		6.7.2	?	
Specific endpoint	Latent cancer fatalities	Latent cancer fatalities	Latent cancer fatalities	Fatalities	Injuries
Yr of first exposure to risk	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40
Latency period (yrs)	20	20	20	0	0
Expected cases resulting from each annual exposure	3.00E-06	3.50E-06	0.12	0.08	7.7
Damage per case valued at time of exposure (1989$)	$3,241,250	$3,241,250	$3,241,250	$8,600,000	$34,000
Damage levelized over plant lifetime (1989$ / yr) (e)	$10	$11	$388,950	$688,000	$261,800
Damage levelized over plant lifetime (mills/kWh)	1.1908E-06	1.3893E-06	0.04763316	0.08425664	0.032062

Table A-6. Damage estimates with 5% discount, Southwest site, high estimate (continued)

Damages from the nucle

Cycle step	Decommissioning											
Substep	Decommissioning operations				Decommissioning waste transportation				Safe storage			
Startpoint	Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure		Nonradiological occupational risk		Radiation exposure	
Exposure	Workers			Public	Workers			Public	Workers			Public
General endpoint	Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality		Mortality	Morbidity	Mortality	
Table No.	6.5-2											
Section No.	6.6.2											
Specific endpoint	Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities		Fatalities	Serious lost-time injuries	Latent cancer fatalities	
Yr of first exposure to risk	41	41	41	41	41	41	41	41	41	41	41	41
Total consecutive yrs of exposure to risk	5	5	5	5	5	5	5	5	5	5	5	5
Latency period (yrs)	0	0	20	20	0	0	20	20	0	0	20	20
Expected cases resulting from each annual exposure	0.0058	0.8	0.096	0.00000001	0.0136	0.22	0.008	0.00176	0	0	0	0
Damage per case valued at time of exposure (1989$)	$8,600,000	$127,000 (b)	$3,241,250	$3,241,250	$8,600,000	$127,000 (b)	$3,241,250	$3,241,250	$8,600,000	$127,000 (b)	$3,241,250	$3,241,250
Damage levelized over plant lifetime (1989$ / yr) (e)	$1,788	$3,641	$11,152	$0	$4,192	$1,001	$929	$204	$0	$0	$0	$0
Damage levelized over plant lifetime (mills/kWh)	0.00021893	0.000445942	0.00136574	1.4226E-10	0.00051336	0.000122634	0.00011381	2.5039E-05	0	0	0	0

Table A-6. Damage estimates with 5% discount, Southwest site, high estimate (continued)

Damages from the nucle

Cycle step	Transportation shipments during plant lifetime						Severe reactor accidents		
Substep									
Startpoint	Incident-free radiation exposure		Radiation exposure from accident		Toxic chemical spill		Severe reactor accident risk		
Exposure	Public	Worker	Public	Worker	Public		Public		
General endpoint	Mortality				Mortality		Morbidity	Mortality	
Table No.	8.5.1-1	8.5.2-1	8.5.1-1	#N/A	8.5.1-4		7.6.2-1		
Section No.	8.5.1	8.5.2	8.5.1	#N/A	8.5.1		7.6.1		
Specific endpoint	Latent cancer fatalities				Fast fatalities	Permanent renal injury	Nonfatal cancer cases	Early fatalities	Cancer fatalities
Yr of first exposure to risk	1	1	1	1	1	1	1	1	1
Total consecutive yrs of exposure to risk	40	40	40	40	40	40	40	40	40
Latency period (yrs)	20	20	20	20	0	0	(c)	0	(c)
Expected cases resulting from each annual exposure	0.00333899	0.00012873	0.00396559	#N/A	0.00796457	29.62963	0.016924 (e)	1.6E-10 (e)	0.009 (e)
Damage per case valued at time of exposure (1989$)	$3,241,250	$3,241,250	$3,241,250	$3,241,250	$8,600,000	$9,359	(c)		(c)
Damage levelized over plant lifetime (1989$ / yr) (e)	$10,822	$417	$12,853	#N/A	$68,495	$277,304	$2,917	$0.00	$17,853
Damage levelized over plant lifetime (mills/kWh)	0.00132539	5.1098E-05	0.00157411	#N/A	0.00838835	0.0339603	0.000357231	7.048E-11	0.002186

Table A-6. Damage estimates with 5% discount, Southwest site, high estimate (continued)

Damages from the nucle	
Cycle step	
Substep	
Startpoint	
Exposure	
General endpoint	
Table No.	
Section No.	
Specific endpoint	
Yr of first exposure to risk	
Total consecutive yrs of exposure to risk	
Latency period (yrs)	
Expected cases resulting from each annual exposure	

	Damages from the nuclear fuel cycle (1989$), Southwest site: high estimates, 5% discount rate						
Damage per case valued at time of exposure (1989$)	All	Public	Occupational	Mining and milling	Electricity generation-normal operations	Transportation shipments during plant lifetime	Severe reactor accidents
Damage levelized over plant lifetime (1989$ / yr) (e)	$2,379,072	$587,614	$1,791,458	$626,731	$1,361,679	$369,892	$20,770
Damage levelized over plant lifetime (mills/kWh)	0.291355512	0.071963	0.219392805	0.076753231	0.166759447	0.045299238	0.002543596

Table A-6. Damage estimates with 5% discount, Southwest site, high estimate (continued)

(a) Assumes all the exposure occurs in the first yr after shutdown
(b) Value taken from Martinello and Meng, 1992, for major injuries
(c) Varied with cancer type. For more detail, see Section 7.6.2
(d) Based on annual probabilities of three possible outcomes:
P(massive containment failure)= 0.000046
P(limited containment failure)= 0.000016
P(no failure)= 1 - 0.000046 - 0.000016 = 0.999938
(e) Example calculation:
Occupational latent cancer fatalities from radiation exposure during decommissioning operations at site
1) Find Damage per case valued at time of exposure
= Present value(Damage per case valued at time of ocurrence= $8,600,000, discount rate = 5%,
number of yrs in the future = latency period=20)
= $3,241,250
2) Calculate Damages resulting from each annual exposure
= Damage per case valued at time of exposure* Expected number of cases resulting from each annual exposure
= $3,241,250 * 0.0960 = $311,160
3) Calculate Total damages from all years of exposure valued at start of exposure
=Present value(stream of damages resulting from each annual exposure = $311,160,
number of years =Total consecutive yrs of exposure to risk = 5, discount rate = 5%)
= $1,414,518
4) Calculate Present value of total damages resulting from all years of exposure to risk
= Present value(Total damages from all years of exposure valued at start of exposure= $1,414,518,
number of yrs in the future = First year of exposure to risk = 41, discount rate = 5%)
= $191,358
5) Calculate Damage levelized over plant lifetime (1989$ / yr)
=Annuity(Present value of total damages resulting from all yrs of exposure to risk= $191,358,
number of yrs in the future = plant lifetime = 40, discount rate = 5%)
= $11,152
6) Calculate Damage levelized over plant lifetime in mills/kWh
= Damage levelized over plant lifetime (1989$ / yr) / kWh per yr *(1000 mills/ $)
= 0.00137 mills / kWh

RADIONUCLIDE INVENTORY METHODOLOGY: ORIGEN2

In the United States (U.S.), Oak Ridge Isotope GENeration (ORIGEN) (Bell 1973) and, more recently, ORIGEN2 (Croff 1980a; Croff 1980b) are the most widely used computer codes for calculating the buildup and decay of nuclides in nuclear materials. In this report, the ORIGEN2 computer code has been used to model the reference nuclear power plant, as well as to calculate the characteristics of the spent fuel (SF) discharged from this reference reactor. The following paragraphs describe the ORIGEN2 computer code, followed by some background information about the development of ORIGEN2, and, finally, some details about how ORIGEN2 has been used to provide source term information needed in the preparation of this report.

B.1 ORIGEN2 DESCRIPTION

ORIGEN2 (Croff 1980a; Croff 1980b) is a versatile point-depletion and radioactive-decay computer code for use in simulating nuclear fuel cycles and calculating the nuclide compositions and characteristics of materials in nuclear reactors. ORIGEN2 represents a revision and update of the original ORIGEN computer code. Included in ORIGEN2 are provisions for incorporating data generated by more sophisticated reactor physics codes, a free-format input, and a highly flexible and controllable output. With these features, ORIGEN2 has the capability for simulating a wide variety of fuel cycle flow sheets.

In addition to revisions to the ORIGEN2 computer code, an extensive effort was undertaken at ORNL beginning in the late 1970s to provide ORIGEN2 with revised data bases of decay, cross-section, fission product yield, and photon emission have been included to allow ORIGEN2 to simulate fuel cycles in many different types of nuclear reactors, including pressurized-water reactors (PWRs) and boiling-water reactors (BWRs), liquid-metal fast breeder reactors (LMFBRs), and Canadian deuterium uranium reactors (CANDUs).

ORIGEN2 is distributed to users worldwide, either by Oak Ridge National Laboratory (ORNL), through the U.S. Department of Energy's software center, or in cooperation with the International Atomic Energy Agency's NEA data bank in Paris, France. Approximately 1000 scientists and engineers have acquired either ORIGEN or ORIGEN2 directly from ORNL, and many more have probably acquired the code from other sources or have used the code within their respective

organizations. The latest version of the code, called ORIGEN 2.1 [Radiation Shielding Information Center (RSIC) 1991], was last updated in December 1991. This version is capable of operation on all 80386- and 80486-class IBM-compatible personal computers. The following paragraphs describe the background and features of the ORIGEN2 computer code.

B.2 BACKGROUND

The ORIGEN computer code (Bell 1973) was written by ORNL in the late 1960s and early 1970s as a versatile tool for calculating the buildup and decay of nuclides in nuclear materials. ORIGEN was principally intended for use in generating SF and radioactive waste characteristics (composition, thermal power, etc.) that would form the basis for the study and design of fuel reprocessing plants, SF shipping casks, waste treatment and disposal facilities, and waste shipping packages. Since fuel cycle operations were being examined generically, and were expected to accommodate a wide range of fuel characteristics, it was only necessary that the ORIGEN results be representative of this range.

Soon after the ORIGEN computer code was documented, it was made available to users outside ORNL through the RSIC at ORNL. The relative simplicity of ORIGEN, coupled with its convenient and detailed output, resulted in its being acquired by many organizations, both in the U.S. and throughout the world. Some of these organizations began using ORIGEN for applications that required greater precision in the calculated results than those for which it had originally been intended. These applications were generally much more specific than those early ORNL generic fuel cycle studies, such as environmental impact studies that required relatively precise calculations of minor isotopes such as ^{3}H, ^{14}C, ^{232}U, and $^{242,244}Cm$. The initial responses to these requirements were attempts to update specific aspects of ORIGEN and its data bases. However, inconsistencies and a large number of different data bases soon resulted.

In an effort to remedy the problem, ORNL initiated, in 1975, a program to update the ORIGEN computer code and its associated data bases and reactor models. More specifically, five aspects of ORIGEN were examined and updated:

(1) The computer code itself,

(2) cross sections and fission product yields,

(3) decay and photon data,

(4) reactor models, and

(5) miscellaneous input information.

Development of ORIGEN2 resulted in expanding the input, output, and control aspects of ORIGEN without changing the numerical solutions of nuclide generation and depletion. These changes provided substantial improvement in the flexibility and capability of the code. While these changes were fairly significant, more important to the ORIGEN2 project were the development of cross section and fission product yield libraries representing the major light-water reactor and fast-breeder reactor fuel cycle. Whereas the ORIGEN code required the user to be fairly knowledgeable about reactor physics computations to achieve reasonable results, ORIGEN2 data bases provided cross section data libraries developed from sophisticated reactor physics calculations. These data libraries included reactor/fuel cycle models for PWRs and BWRs (Croff 1978; Croff 1980c; Ludwig 1989), CANDUs (Croff 1980d) and fact breeders (Croff 1982; Croff 1983).

Also important to the ORIGEN2 development was the updating of the decay and photon data (Croff 1979). These libraries include data needed to calculate the buildup and decay of the nearly 1300 nuclides handled by ORIGEN2. Information includes half life, branching rations, decay heat, number and energy of photons per decay.

In addition to the data bases developed for ORIGEN2, a significant amount of miscellaneous data was collected, evaluated, and incorporated in ORIGEN2. These data include: (a) neutrons from spontaneous fission, neutron-induced fission, and per (alpha,n) reaction; (b) chemical toxicities of the elements; (c) recoverable energy per fission; and (d) elemental analysis of materials used in the manufacture of reactor components.

B.3 ORIGEN2 APPLICATIONS

ORIGEN2 was used to provide many of the source term data needed in the preparation of this report.

The reference reactor is a 3411 MWth, 1150 MWe PWR, utilizing 4.7 wt% enriched fuel to achieve an extended burnup of 51,700 MWd/MT in three 18-month cycles, while operating at an 81% capacity factor. ORIGEN2 was used to simulate this reactor cycle. For the severe reactor accident, it was assumed that one third of the reactor core (roughly 29 metric tons of fuel) had achieved the full, 3-cycle, design burnup, while the other two thirds of the core had reached the end of the first and second cycles at the time the accident occurs. The source term data needed for analysis of severe reactor accidents include the fairly short-lived nuclides (primarily fission products) that may be released during a severe reactor accident.

For transportation analyses, ORIGEN2 provides the source term for the SF (at 51,700 MWd/MT burnup) as well as the radionuclide content of natural and enriched UF_6 shipments and fresh reactor fuel. UF_6 and fresh fuel only contain minor levels of radioactivity, resulting from the presence of very long-lived isotopes of uranium. SF, on the other hand, is extremely radioactive, and must be shielded in massive shipping containers, called casks. SF, in this report, is assumed to have been cooled for 10 years before shipment.

ORIGEN2 is also used to calculate the composition of the SF to be emplaced in the repository. In this case, while the enrichment and burnup may be the same as the severe reactor case, the characteristics must be calculated at hundred or thousands of years in the future, rather than minutes and hours.

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APPENDIX C:

RADIONUCLIDE TRANSPORT METHODOLOGY

C.1 ATMOSPHERIC TRANSPORT

Radiation doses to the public due to normal-operation releases of radionuclides to the atmosphere were estimated using the CAP-88 package of computer codes (Beres 1990). This package considers exposures to emitted radionuclides via inhalation of and immersion in contaminated air; ingestion of meat, milk, and vegetables; and direct exposure to contaminated land surfaces. Radiation dose equivalents are calculated to a selected individual (a hypothetical person assumed to reside at the location at which the maximum radiation dose could occur), to individuals residing at specified locations (including the location of a residence at which a real person could receive the maximum individual dose), and to regional populations, usually within 80 km of the emission source.

Atmospheric transport of radionuclides is modeled using a slightly revised version of the AIRDOS-EPA computer code (Moore et al. 1979). This code uses a modified Gaussian plume equation to calculate radionuclide-specific, annual-average, ground-level air concentrations at selected locations. These concentrations are used to estimate deposition of the radionuclides on the ground and, using the terrestrial food chain models and parameter values given in United States Nuclear Regulatory Commission (USNRC) Regulatory Guide 1.109 (NRC 1977), to estimate nuclide concentrations in produce, leafy vegetables, milk, and meat and to estimate subsequent intakes of the radionuclides by man.

Emission sources may be modeled as elevated or ground-level point or area sources. Effective release heights are calculated by summing the physical release height and the calculated height increment due to either buoyant (heat-induced) or momentum (mechanically-induced) plume rise. For normal-operation releases from the reactor, the annual airborne radionuclide amounts for 36 pressurized-water reactor (PWR) plants are given in Table C.1-1 and the average of these is given in Table 6.4-1.

Meteorological data used by AIRDOS-EPA must be in the format of a STAR data file, which contains the joint frequencies of wind speed class, stability class, and wind direction. The basic data may be collected on-site (preferred alternative) or may be obtained from a nearby, representative airport. Airport data

Table C.1-1. Annual airborne radionuclide releases for 36 W-PWRs (1988 data)

AIRBORNES: #	FACILITY	NAMEPL'T CAPACITY (MWE)	1988 MW-HR THERMAL GEN (MW-HR TH)	T-3 (12.3 y)	Ar-41 (1.8 h)	Cr-51 (27.7 d)	Mn-54 (312 d)	Co-57 (272 d)	Co-58 (71 d)	Co-60 (5.2 y)	Kr-85 (10.7 y)	Kr-85M (4.48 h)	Kr-87 (1.27 h)
1	BEAVER VALLEY 1	923	1.64E+07	2.16E+01	1.51E-01		7.30E-08		6.30E-06	6.25E-05	2.36E-01	1.22E-06	
2	BEAVER VALLEY 2	923	2.13E+07	2.16E+01	1.51E-01		7.30E-08		6.30E-06	6.25E-05	2.36E-01	1.22E-06	
3	BRAIDWOOD 1	1175	1.04E+07	2.73E+00	3.31E-01				1.20E-07	1.90E-07	1.78E-01	1.87E-02	6.38E-04
4	BRAIDWOOD 2	1175	4.08E+06	2.66E+00	7.84E-01						1.45E-02	1.19E-02	9.60E-05
5	BYRON 1	1175	1.99E+07	8.10E-01	3.29E-01						5.30E+00	1.99E-01	2.79E-03
6	BYRON 2	1175	2.04E+07	8.10E-01	3.29E-01						5.30E+00	1.99E-01	2.79E-03
7	CALLAWAY 1	1236	2.76E+07	1.53E+01	6.10E-01						8.20E+01	2.50E+00	
8	CATAWBA 1	1305	2.29E+07	3.03E+01	5.99E+00	6.34E-07	2.85E-06		1.52E-05	6.81E-06	2.08E+00	9.23E-01	1.31E-01
9	CATAWBA 2	1305	1.88E+07	3.03E+01	5.99E+00	6.34E-07	2.85E-06		1.52E-05	6.81E-06	2.08E+00	9.23E-01	1.31E-01
10	COOK 1	1152	2.42E+07	3.02E+00	1.95E-01		1.70E-06		3.42E-05	1.71E-07	7.60E-01	7.25E-02	6.35E-02
11	COOK 2	1133	7.41E+06	3.02E+00	1.95E-01		1.70E-06		3.42E-05	1.71E-07	7.60E-01	7.25E-02	6.35E-02
12	DIABLO CANYON 1	1137	1.66E+07	3.26E+01	1.03E+00	2.38E-06	1.17E-04		1.14E-04	1.59E-05	4.50E+00	5.15E-02	7.90E-04
13	DIABLO CANYON 2	1164	1.98E+07	3.26E+01	1.03E+00	2.38E-06	1.17E-04		1.14E-04	1.59E-05	4.50E+00	5.15E-02	7.90E-04
14	FARLEY 1	860	1.92E+07	1.16E+02	2.63E+01	2.40E-04	2.85E-05		7.47E-05	4.06E-05	6.86E+02	6.11E-01	6.27E-02
15	FARLEY 2	860	2.29E+07	5.96E+01	3.56E+01						4.58E+02		
16	HARRIS 1	951	1.71E+07		3.55E-01	6.04E-06			3.45E-05	3.96E-06		4.86E+01	1.62E+01
17	INDIAN POINT 2	1310	1.95E+07	1.69E+00	7.40E-01	1.56E-02			1.52E-04	5.65E-03		2.16E-01	4.57E-02
18	INDIAN POINT 3	1013	2.14E+07	4.56E+00	3.58E-01				8.96E-06		3.26E+00	1.46E-01	5.92E-02
19	MC GUIRE 1	1305	2.26E+07	2.40E+01	8.77E+00	1.88E-06	8.25E-07		6.48E-05	7.28E-05	3.69E+01	4.92E+00	7.05E-01
20	MC GUIRE 2	1305	2.41E+07	2.40E+01	8.77E+00	1.88E-06	8.25E-07		6.48E-05	7.28E-05	3.69E+01	4.92E+00	7.05E-01
21	MILLSTONE 3	1253	2.33E+07	7.16E+01			5.27E-07		3.11E-04	1.56E-05		2.14E-03	
22	NORTH ANNA 1	947	2.20E+07	4.72E+01	4.28E-04		1.04E-06		3.80E-06	3.52E-05	1.82E+00	1.48E-02	1.86E-04
23	NORTH ANNA 2	947	2.50E+07	4.72E+01	4.28E-04		1.04E-06		3.80E-06	3.52E-05	1.82E+00	1.48E-02	1.86E-04
24	SALEM 1	1170	2.32E+07	4.00E+02	7.51E-03				3.66E-05	1.42E-03	1.10E+00	3.58E-01	
25	SALEM 2	1170	1.90E+07	3.70E+02	1.55E-02				7.05E-05	1.42E-03	1.82E+00	3.08E+00	5.66E-01
26	SEQUOYAH 1	1221	5.16E+05	6.85E+00	1.24E-01					7.35E-05	1.00E+00	8.75E-02	
27	SEQUOYAH 2	1221	1.26E+07	6.85E+00	1.24E-01					7.35E-05	1.00E+00	8.75E-02	
28	SOUTH TEXAS 1	1311	8.81E+06	1.72E+01	7.59E+02							1.71E-01	2.20E-01
29	SUMMER 1	900	1.61E+07	1.50E+00	3.73E-01				1.10E-05		4.09E+00	2.03E+00	5.25E-03
30	SURRY 1	848	8.45E+06	1.39E+01	6.10E-01	1.45E-04	5.50E-05	4.30E-06	5.22E-05	9.50E-04	2.06E+00	9.40E-02	4.66E-03
31	SURRY 2	848	1.16E+07	1.39E+01	6.10E-01		5.50E-05	4.30E-06		9.50E-04	2.06E+00	9.40E-02	4.66E-03
32	TROJAN	1216	1.98E+07	6.44E+01	8.46E-01				1.85E-04	4.27E-06	2.73E+00	3.55E-01	9.72E-02
33	VOGTLE 1	1215	2.18E+07	8.33E+01	3.16E+01				1.49E-06		6.37E-05	1.13E-04	
34	WOLF CREEK 1	1236	2.01E+07	1.46E+02	9.72E-01				1.09E-05	1.61E-05	1.17E+00	7.66E-01	2.82E-04
35	ZION 1	1085	1.97E+07	1.85E+02	5.20E-02		1.90E-08		2.88E-05	7.55E-05	1.70E+00	5.70E-03	
36	ZION 2	1085	2.08E+07	1.85E+02	5.20E-02				2.88E-05	7.55E-05	1.70E+00	5.70E-03	
	MEAN	1116	1.80E+07	5.96E+01	2.55E+01	1.60E-03	2.27E-05	4.30E-06	5.49E-05	4.13E-04	4.23E+01	2.05E+00	7.83E-01
	SUM			2.09E+03	8.92E+02	1.60E-02	3.86E-04	8.60E-06	1.48E-03	1.12E-02	1.35E+03	7.16E+01	1.91E+01

Table C.1-1. Annual airborne radionuclide releases for 36 W-PWRs (1988 data) (continued)

#	FACILITY	NAMEPL'T CAPACITY (MWE)	1988 MW-HR THERMAL GEN (MW-HR TH)	Rb-88 (17.7 m)	Kr-88 (2.84 h)	Sr-89 (50.6 d)	Sr-90 (29.1 y)	Nb-95 (35 d)	Zr-95 (64 d)	Tc-99M (6.01 h)	Ag 110M (250 d)	I-131 (8 d)	Xe-131M (11.9 d)
	BEAVER VALLEY 1	923	1.64E+07				4.85E-09					7.80E-05	8.95E-02
	BEAVER VALLEY 2	923	2.13E+07				4.85E-09					7.80E-05	8.95E-02
	BRAIDWOOD 1	1175	1.04E+07		1.63E-02							3.22E-04	5.33E-01
	BRAIDWOOD 2	1175	4.08E+06		5.66E-04							7.61E-05	8.85E-01
	BYRON 1	1175	1.99E+07		1.26E-02							6.40E-03	3.36E+00
	BYRON 2	1175	2.04E+07		1.26E-02							6.40E-03	3.36E+00
	CALLAWAY 1	1236	2.76E+07	8.30E-02	7.28E-01							1.87E-05	2.40E+00
	CATAWBA 1	1305	2.29E+07	7.96E-05	1.03E+00		3.26E-07	7.70E-08	4.15E-10	3.79E-09	2.38E-09	7.62E-04	1.22E+01
	CATAWBA 2	1305	1.88E+07	7.96E-05	1.03E+00		3.26E-07	7.70E-08	4.15E-10	3.79E-09	2.38E-09	7.62E-04	1.22E+01
	COOK 1	1152	2.42E+07		3.52E-01			1.34E-07	3.30E-06			3.40E-03	4.04E-01
	COOK 2	1133	7.41E+06		3.52E-01			1.34E-07	3.30E-06			3.40E-03	4.04E-01
	DIABLO CANYON 1	1137	1.66E+07		5.80E-02				6.00E-06			3.49E-04	7.80E+00
	DIABLO CANYON 2	1164	1.98E+07		5.80E-02				6.00E-06			3.49E-04	7.80E+00
	FARLEY 1	860	1.92E+07		2.02E-01							1.18E-03	1.15E+00
	FARLEY 2	860	2.29E+07									2.36E-06	
	HARRIS 1	951	1.71E+07		8.10E+01			1.48E-06					
	INDIAN POINT 2	1310	1.95E+07		2.85E-01		1.09E-08					4.02E-05	
	INDIAN POINT 3	1013	2.14E+07		2.08E-01							3.41E-03	8.32E+00
	MC GUIRE 1	1305	2.26E+07	1.70E-04	4.64E+00	1.03E-06		5.58E-10		2.31E-08		5.58E-03	1.07E+01
	MC GUIRE 2	1305	2.41E+07	1.70E-04	4.64E+00	1.03E-06		5.58E-10		2.31E-08		5.58E-03	1.07E+01
	MILLSTONE 3	1253	2.33E+07			6.96E-06	4.31E-06					9.45E-03	2.03E-01
	NORTH ANNA 1	947	2.20E+07	2.03E-06				2.87E-10			7.20E-11	7.80E-04	9.75E-01
	NORTH ANNA 2	947	2.50E+07	2.03E-06				2.87E-10			7.20E-11	7.80E-04	9.75E-01
	SALEM 1	1170	2.32E+07									6.70E-04	7.85E+00
	SALEM 2	1170	1.90E+07		4.15E+00							8.80E-04	2.65E+00
	SEQUOYAH 1	1221	5.16E+05		7.40E-03	5.15E-07	3.32E-07			4.10E-07		1.82E-05	5.45E-01
	SEQUOYAH 2	1221	1.26E+07		7.40E-03	5.15E-07	3.32E-07			4.10E-07		1.82E-05	5.45E-01
	SOUTH TEXAS 1	1311	8.81E+06		3.22E-01							8.18E-04	
	SUMMER 1	900	1.61E+07	8.44E-03	2.91E+00							2.28E-03	1.52E+00
	SURRY 1	848	8.45E+06	1.08E-03	7.50E-03	8.40E-07	1.29E-07	3.78E-06			1.32E-10	4.79E-03	9.85E-01
	SURRY 2	848	1.16E+07	1.08E-03	7.50E-03	8.40E-07	1.29E-07	3.78E-06			1.32E-10	4.79E-03	9.85E-01
	TROJAN	1216	1.98E+07		1.17E-01	1.74E-05	7.29E-06	3.15E-06				2.88E-03	2.51E+00
	VOGTLE 1	1215	2.18E+07		3.79E-04							9.45E-06	
	WOLF CREEK 1	1236	2.01E+07		1.10E+00							5.66E-05	4.09E+00
	ZION 1	1085	1.97E+07	3.21E-03	6.55E-03	1.60E-07		4.10E-09	1.25E-09	4.65E-08	1.05E-07	5.75E-04	3.22E-01
	ZION 2	1085	2.08E+07	3.21E-03	6.55E-03	1.60E-07		4.10E-09	1.25E-09	4.65E-08	1.05E-07	5.75E-04	3.22E-01
	MEAN	1118	1.80E+07	8.38E-03	2.56E+00	2.95E-06	1.20E-06	9.02E-07	2.33E-06	1.21E-07	2.69E-08	1.93E-03	3.46E+00
	SUM			1.01E-01	1.03E+02	2.95E-05	1.32E-05	1.26E-05	1.86E-05	9.67E-07	2.15E-07	6.76E-02	1.07E+02

Table C.1-1. Annual airborne radionuclide releases for 36 W-PWRs (1988 data) (continued)

#	FACILITY	NAMEPL'T CAPACITY (MWE)	1988 MW-HR THERMAL GEN (MW-HR TH)	I-132 (2.3 h)	Xe-133 (5.24 d)	I-133 (20.8 h)	Xe-133M (2.19 d)	Cs-134 (2 y)	I-134 (53 m)	Xe-135 (9.1 h)	I-135 (6.6 h)	Xe-135M (15.3 m)	Cs-137 (30 y)	Xe-138 (14 m)
1	BEAVER VALLEY 1	923	1.64E+07		1.16E+00	7.95E-05				2.22E-01	1.06E-05	1.18E-02	6.85E-07	
2	BEAVER VALLEY 2	923	2.13E+07		1.16E+00	7.95E-05				2.22E-01	1.06E-05	1.18E-02	6.85E-07	
3	BRAIDWOOD 1	1175	1.04E+07		4.02E+01	1.27E-04	2.70E-01		2.40E-02	3.81E-01				
4	BRAIDWOOD 2	1175	4.08E+06		3.65E+01	1.38E-05	1.09E-01			3.73E-02	3.26E-06			
5	BYRON 1	1175	1.99E+07	2.47E-04	8.65E+02	1.86E-03	6.25E+00		1.26E-05		5.60E-04		1.16E-05	
6	BYRON 2	1175	2.04E+07	2.47E-04	8.65E+02	1.86E-03	6.25E+00		1.26E-05		5.60E-04		1.16E-05	
7	CALLAWAY 1	1236	2.76E+07		5.60E+02		2.56E+00			3.73E+01				
8	CATAWBA 1	1305	2.29E+07	2.30E-06	1.51E+03	4.50E-06	1.55E+01	3.41E-08	1.44E-06	1.80E+01	1.88E-06	5.68E-03	5.68E-03	3.60E-03
9	CATAWBA 2	1305	1.88E+07	2.30E-06	1.51E+03	4.50E-06	1.55E+01	3.41E-08	1.44E-06	1.80E+01	1.88E-06	5.68E-03	5.68E-03	3.60E-03
10	COOK 1	1152	2.42E+07		1.23E+02	4.07E-04	6.25E-01	1.70E-04		4.06E+00	3.32E-05	6.25E-02	4.02E-04	5.20E-02
11	COOK 2	1133	7.41E+06		1.23E+02	4.07E-04	6.25E-01	1.70E-04		4.06E+00	3.32E-05	6.25E-02	4.02E-04	5.20E-02
12	DIABLO CANYON 1	1137	1.66E+07		1.44E+02	1.80E-04	4.58E-01	2.36E-05		5.85E+00		2.22E-03	1.49E-05	4.88E-04
13	DIABLO CANYON 2	1164	1.98E+07		1.44E+02	1.80E-04	4.58E-01	2.36E-05		5.85E+00		2.22E-03	1.49E-05	4.88E-04
14	FARLEY 1	860	1.92E+07		1.83E+02	1.30E-06	2.18E+00	1.48E-08		6.03E+01		2.58E-07	1.28E-06	8.20E-02
15	FARLEY 2	860	2.29E+07		7.41E+01	5.00E-09	1.90E-01	9.36E-09		2.38E+01			1.46E-07	5.32E-02
16	HARRIS 1	951	1.71E+07	3.40E-06	1.94E+03		3.24E+01			1.13E+02				1.62E+01
17	INDIAN POINT 2	1310	1.95E+07		2.05E+02	2.97E-03	4.34E-01			1.13E+01		4.99E-01	1.77E-03	3.52E-03
18	INDIAN POINT 3	1013	2.14E+07		2.87E+02	5.47E-04	2.02E+00	1.49E-06		8.24E+00		1.32E-02	2.40E-06	3.30E-03
19	MC GUIRE 1	1305	2.26E+07	1.20E-03	1.79E+03	1.83E-03	2.44E+01	4.73E-05	1.12E-07	7.09E+01	6.91E-07	1.39E-02	1.11E-04	1.08E-03
20	MC GUIRE 2	1305	2.41E+07	1.20E-03	1.79E+03	1.83E-03	2.44E+01	4.73E-05	1.12E-07	7.09E+01	6.91E-07	1.39E-02	1.11E-04	1.08E-03
21	MILLSTONE 3	1253	2.33E+07		7.77E+01	4.45E-03	5.02E-01			5.96E+00			1.63E-05	
22	NORTH ANNA 1	947	2.20E+07	3.28E-06	2.37E+02	2.50E+01	2.91E-01	7.70E-05		1.30E+00	6.25E-06		2.47E-04	
23	NORTH ANNA 2	947	2.50E+07	3.28E-06	2.37E+02	2.50E+01	2.91E-01	7.70E-05		1.30E+00	6.25E-06		2.47E-04	
24	SALEM 1	1170	2.32E+07		5.00E+02		9.90E-01			1.90E+01		2.37E-04	5.69E-06	
25	SALEM 2	1170	1.90E+07		1.12E+03		6.08E+00			3.43E+01		4.99E+00	6.66E-06	
26	SEQUOYAH 1	1221	5.16E+05		1.08E+02		1.07E+02			1.83E+00			1.90E-06	
27	SEQUOYAH 2	1221	1.26E+07		1.08E+02		1.07E+02			1.83E+00			1.90E-06	
28	SOUTH TEXAS 1	1311	8.81E+06		9.56E+01		5.90E-02			1.28E+00		4.67E-02		
29	SUMMER 1	900	1.61E+07	2.30E-04	2.97E+02	1.13E-03	1.06E+00	3.46E-06	2.10E-06	2.27E+01	1.05E-04		2.25E-05	
30	SURRY 1	848	8.45E+06	5.45E-04	1.77E+02	2.35E-03	3.01E-01	4.40E-04	4.60E-06	2.28E+00	2.06E-04	6.41E-03	1.17E-03	
31	SURRY 2	848	1.16E+07	5.45E-04	1.77E+02	2.35E-03	3.01E-01	4.40E-04	4.60E-06	2.28E+00	2.06E-04		1.17E-03	
32	TROJAN	1216	1.98E+07	2.25E-07	3.84E+02	1.02E-03	1.36E+00	2.18E-08		6.45E+00	7.01E-06	7.13E-01	5.48E-08	2.54E-01
33	VOGTLE 1	1215	2.18E+07		7.75E+01	4.84E-05	5.44E-02			6.28E+00				
34	WOLF CREEK 1	1236	2.01E+07		7.57E+02		7.66E+02			1.88E+01			2.26E-05	
35	ZION 1	1085	1.97E+07	8.25E-04	6.95E+02	2.05E-04	1.78E-01	9.70E-06	1.31E-04	2.76E+01	9.10E-05			
36	ZION 2	1085	2.08E+07	8.25E-04	6.95E+02	2.05E-04	1.78E-01	9.70E-06	1.31E-04	2.76E+01	9.10E-05			
	MEAN	1118	1.80E+07	3.92E-04	4.68E+02	1.79E+00	3.31E+01	6.10E-05	2.03E-03	1.86E+01	1.02E-04	3.59E-01	6.11E-04	1.19E+00
	SUM			5.88E-03	1.79E+04	5.00E+01	1.13E+03	1.54E-03	2.43E-02	6.33E+02	1.94E-03	6.46E+00	1.71E-02	1.67E+01

SUM(ALL AIRBORNES) 2.44E+04

are available from the National Weather Service. Climatological data requirements include the annual rainfall, average temperature, and average mixing layer height. The climatological parameters may be evaluated using data for the year of interest or multi-year averaged site-specific or regional data.

Ground-surface and soil concentrations are calculated for dry deposition (using dry deposition factors, V_d) and precipitation scavenging. Deposition is assumed to occur for a long period (50 years in this study). This is equivalent to assuming an equilibrium release situation and corresponds to establishing a 50-year cutoff for the time following a release when any significant intake or external exposure associated with deposition might take place. Only particulates and reactive gases are assumed to deposit on ground surfaces.

Special consideration is given to tritium, carbon-14, and radon-222. The specific activity of tritium in air is calculated for an absolute humidity of 8 mg/m^3. The specific activity of carbon-14 is calculated for a carbon dioxide concentration of 330 ppm by volume. Concentrations of these radionuclides in vegetation are calculated on the assumption that the water and carbon content of the vegetation is in equilibrium with their concentrations in air (e.g., the specific activities of these nuclides in vegetation are the same in vegetation and air). In the case of radon-222, its daughter radionuclides are of interest. Radon daughter concentrations, expressed in units of working level, are estimated by varying their degree of equilibrium as a function of downwind distance (actually as the product of time since release and the average wind speed over that time). The maximum equilibrium fraction is limited to a value of 0.7.

Agricultural data consist of the numbers of beef and milk cattle and the fraction of land used for crop (produce and leafy vegetables) production. The FOODJOB utility program is available for use with CAP-88. This program uses state-average agricultural data to estimate cattle and food production in each segment of the area surrounding the source. The user may supply a site-specific distribution.

The distribution of people around the source can be obtained using a utility computer code called SECPOP. This code uses 1980 census data to estimate the number of persons residing in each segment of the circular grid drawn about the source. The user may supply site-specific population data, if it is available. This feature is useful for estimating collective exposures near the source, where the gross distribution pattern from the Census data is most inaccurate. For calculating maximum individual doses, the user should input the actual location of the individual or the locations of several such individuals, if the location of the maximum is uncertain.

The program RADRISK (Beres 1990; Dunning et al. 1980) is used to calculate effective dose equivalent conversion factors. The dose equivalent factors are calculated using the organ weighting factors given in ICRP Publication Nos. 26 and 30 (ICRP 1977; ICRP 1978). These factors are stored in the ALLRAD88 radionuclide data file. Factors are provided for the pathways of ingestion and inhalation intake, ground-level air immersion, and ground surface irradiation. The factors are further broken down by particle size, clearance class, and gut-to-blood transfer factors. These factors are generated once and stored for future use in a database.

Estimation of radiation doses is made using the DARTAB computer code (Beres 1990; Begovich et al. 1981). Radiation doses via ingestion and inhalation are obtained by multiplying the quantities of radionuclides ingested and inhaled by man and the corresponding dose factors from the ALLRAD88 data base. Radiation doses via external exposures to airborne and ground-deposited radionuclides are obtained by multiplying the air and ground concentrations calculated by AIRDOS-EPA, the durations of exposure to these concentrations (one year for immersion in air and 50 years for ground-surface exposure), and the immersion and surface dose factors from the ALLRAD88 data base. DARTAB lists the dose to the "selected" individual, to the average individual, and to the entire population within the specified study area. Doses also are tabulated as a function of radionuclide, pathway, location, and organ.

The EPA feels that the CAP-88 suite of computer codes represents the best available verified codes for the purpose of making comprehensive dose and risk assessments. The Gaussian plume model, used in CAP-88 to estimate the dispersion of radionuclides in air, is one of the most commonly used models in government guide books. It produces results that agree with experimental data as well as any model, is fairly easy to work with, and is consistent with the random nature of atmospheric turbulence.

The EPA's Office of Radiation Programs has made comparisons between the predictions of annual-average ground-level concentration to actual environmental measurements, and found very good agreement. Based on a comparison of AIRDOS-EPA-predicted ground-level airborne radionuclide concentrations and measured values from environmental monitoring stations at five DOE sites, the EPA concluded that as often as not, AIRDOS-EPA predictions are within a factor of 2 of actual concentrations (Jack Faucett Associates and SC&A Inc. 1985).

Limitations inherent in the CAP-88 system include the requirement that all sources (up to 6) must be collocated, all sources must have the same plume rise mechanism (momentum or buoyant), no correction can be made for the effects of building wakes or stack tip down wash, an area source must emit radionuclides

uniformly over its entire area, and the assessment area is treated as a flat plain (terrain effects cannot be modeled. Errors arising from these limitations will be negligible for assessments where the distance to exposed individuals is large compared to the stack height, the source area, or the facility size.

C.2 AQUATIC TRANSPORT

Radiation doses to the public due to releases of radionuclides to surface water were estimated using a modified version of LADTAP XL (Hamby 1991), which is a spreadsheet adaptation of the LADTAP II computer code (RSIC 1980). This software package is intended for use in estimating radiation doses to man from routine releases of nuclear reactor liquid effluents. This code considers exposures to waterborne radionuclides via drinking water, eating fish, swimming, boating, and shoreline activities.

The transport model estimates annual-average concentrations of radionuclides in river segments by dividing total quantities of radionuclides discharged to the river by the appropriate river-segment volume. The only depletion mechanism considered is radioactive decay. Credit is not taken for sedimentation, but a simple shoreline concentration model is used to conservatively predict shoreline concentrations of radionuclides. This model simply assumes a constant radionuclide deposition rate (100 times the water concentration) that is adjusted for radioactive decay over a period of 50 years.

Exposure pathways considered include ingestion of untreated water and fish from the river, swimming and boating in the river, and use of the shoreline. This code performs these calculations using the models and parameter values recommended on Regulatory Guide 1.109 (NRC 1977). Dose conversion factors used to convert quantities ingested to effective dose equivalents were obtained from Federal Guidance Report No. 11 (EPA 1988); factors used to convert exposures to contaminated shoreline and from swimming were obtained from DOE/EH-0071 (DOE 1988).

Annual normal-operation emissions of liquid radionuclides from reactors are given in Table C.2-1 for 36 PWR plants, and the average of these is given in Table 6.4-3.

Table C.2-1. Annual liquid radionuclide releases for 36 W-PWRs (1988 data)

LIQUID EFFLUENTS: IN CURIES >>>		NAMEPL'T CAPACITY (MWE)	1988 MW-HR THERMAL GEN (MW-HR TH)	VOL LIQ REL PRI. TO DIL (LITERS)	VOL OF DILUTION WATER (LITERS)	T-3 (12.3 y)	Na-24 (15 h)	Cr-51 (27.7 d)	Mn-54 (312 d)	Fe-55 (2.73 y)	Co-57 (272 d)	Co-58 (71 d)	Fe-59 (44.5 d)	Co-60 (5.27 y)	Zn-65 (244 d)
V	FACILITY V														
1	BEAVER VALLEY 1	923	1.64E+07	4.50E+06	3.55E+09	2.05E+02	7.10E-06	1.38E-05	2.91E-04	3.04E-03	1.04E-04	2.23E-02		1.06E-02	1.16E-05
2	BEAVER VALLEY 2	923	2.13E+07	4.50E+06	3.55E+09	2.05E+02	7.10E-06	1.38E-05	2.91E-04	3.04E-03	1.04E-04	2.23E-02		1.06E-02	1.16E-05
3	BRAIDWOOD 1	1175	1.04E+07	4.63E+07	1.81E+10	2.74E+02	2.77E-03	5.56E-03	2.14E-01		6.75E-03	8.03E+00	5.75E-13	1.40E-01	
4	BRAIDWOOD 2	1175	4.08E+06	3.41E+07	1.39E+10	2.44E+02	2.55E-03	5.56E-03	1.52E-01		3.52E-03	2.62E+00	2.57E-03	8.71E-02	
5	BYRON 1	1175	1.99E+07	1.85E+07	1.50E+10	5.05E+02	6.50E-06	9.45E-02	1.46E-02		5.20E-04	2.98E-01	1.38E-02	4.01E-01	4.07E-04
6	BYRON 2	1175	2.04E+07	1.85E+07	1.50E+10	5.05E+02	6.50E-06	9.45E-02	1.46E-02		5.20E-04	2.98E-01	1.38E-02	4.01E-01	4.07E-04
7	CALLAWAY 1	1236	2.76E+07	9.77E+07	2.69E+09	8.93E+02			1.88E-03	1.50E-02	4.11E-05	3.75E-03	1.43E-05	1.05E-02	
8	CATAWBA 1	1305	2.29E+07	2.46E+08	1.15E+11	3.53E+02	3.34E-04	5.25E-02	2.14E-02	1.82E-01	4.75E-04	1.17E-01	1.02E-02	5.41E-02	4.02E-04
9	CATAWBA 2	1305	1.88E+07	2.46E+08	1.15E+11	3.53E+02	1.38E-06	6.34E-07	2.85E-06			1.52E-05		6.81E-06	
10	COOK 1	1152	2.42E+07	1.39E+08	1.14E+12	5.50E+02	2.03E-04	3.56E-03	1.20E-02	1.85E-02		3.65E-02		3.36E-02	8.90E-04
11	COOK 2	1133	7.41E+06	1.39E+08	1.14E+12	5.50E+02	2.03E-04	3.56E-03	1.20E-02	1.85E-02	2.47E-04	3.65E-02		3.36E-02	8.90E-04
12	DIABLO CANYON 1	1137	1.66E+07	1.84E+08	3.20E+11	2.15E+02	3.75E-06	9.35E-03	1.80E-02	1.75E-01	1.46E-03	4.26E-01	2.84E-03	1.00E-01	4.52E-05
13	DIABLO CANYON 2	1164	1.98E+07	1.84E+08	3.20E+11	2.15E+02	3.75E-06	9.35E-03	1.80E-02	1.75E-01	1.46E-03	4.26E-01	2.84E-03	1.00E-01	4.52E-05
14	FARLEY 1	860	1.92E+07	3.99E+08	5.99E+10	5.16E+02	1.00E-05	7.14E-03	5.04E-04	9.48E-03	1.91E-05	7.14E-03	1.49E-04	1.38E-02	6.86E-06
15	FARLEY 2	860	2.29E+07	4.04E+08	5.91E+10	7.53E+02	7.74E-05	5.37E-03	6.85E-04	2.04E-02	6.45E-06	6.48E-03	2.71E-04	1.41E-02	1.04E-05
16	HARRIS 1	951	1.71E+07	7.31E+07	6.40E+09	4.01E+02		4.36E-02	5.02E-03	2.11E-03	7.78E-05	6.14E-02	7.46E-04	6.50E-03	
17	INDIAN POINT 2	1310	1.95E+07	1.89E+08	1.17E+12	4.39E+02		2.11E-01	9.53E-03	6.71E-01	3.70E-04	4.85E-01	6.95E-03	4.56E-01	6.46E-05
18	INDIAN POINT 3	1013	2.14E+07	8.84E+06	1.14E+12	5.73E+02	7.25E-05	1.79E-02	1.53E-03	1.17E-01	1.21E-05	3.96E-02	4.52E-03	1.52E-02	
19	MC GUIRE 1	1305	2.26E+07	1.95E+07	3.30E+12	5.29E+02	2.00E-03	3.01E-01	8.24E-02	4.17E-01	3.66E-03	1.03E+00	1.79E-02	3.69E-01	2.96E-03
20	MC GUIRE 2	1305	2.41E+07	1.95E+07	3.30E+12	5.29E+02	2.00E-03	3.01E-01	8.24E-02	4.17E-01	3.66E-03	1.03E+00	1.79E-02	3.69E-01	2.96E-03
21	MILLSTONE 3	1253	2.33E+07	2.03E+07	1.63E+12	5.47E+02	1.86E-02	3.57E-02	3.91E-01	2.42E-01	5.97E-03	8.01E-01	2.09E-02	6.17E-01	2.02E-03
22	NORTH ANNA 1	947	2.20E+07	1.69E+08	1.55E+12	9.70E+02	3.31E-03		1.12E-03			8.35E-03		6.70E-02	
23	NORTH ANNA 2	947	2.50E+07	1.69E+08	1.55E+12	9.70E+02	3.31E-03		1.12E-03			8.35E-03		6.70E-02	
24	SALEM 1	1170	2.32E+07	3.23E+07	1.56E+11	6.35E+02	1.38E-02	2.38E-02	1.01E-01	2.98E-01	4.00E-03	1.27E+00	2.66E-04	2.77E-01	5.49E-04
25	SALEM 2	1170	1.90E+07	1.27E+08	6.51E+11	3.68E+02	1.04E-02	3.17E-03	1.74E-01	3.81E-01	4.55E-03	1.32E+00	2.93E-05	2.97E-01	
26	SEQUOYAH 1	1221	5.16E+05	8.30E+08	2.28E+09	1.01E+02		1.43E-05	8.20E-04	3.86E-02	2.98E-05	4.00E-05		1.22E-01	
27	SEQUOYAH 2	1221	1.26E+07	8.30E+08	2.28E+09	1.01E+02		1.43E-05	8.20E-04	3.86E-02	2.98E-05	4.00E-05		1.22E-01	
28	SOUTH TEXAS 1	1311	8.81E+06	1.07E+07	4.20E+11	1.99E+02	4.23E-05	1.94E-02	3.29E-03			1.45E-01	1.12E-03	3.33E-03	
29	SUMMER 1	900	1.61E+07	1.98E+08	1.73E+12	7.55E+02	2.66E-04	2.76E-02	1.72E-02	6.12E-02	6.98E-04	2.34E-01	1.83E-03	7.16E-02	6.49E-04
30	SURRY 1	848	8.45E+06	1.29E+08	7.65E+11	2.47E+02	3.33E-04	8.05E-02	5.55E-03	1.41E-01	3.49E-04	1.69E-01	3.31E-03	2.21E-01	4.44E-05
31	SURRY 2	848	1.16E+07	1.29E+08	7.65E+11	2.47E+02	3.33E-04	8.05E-02	5.55E-03	1.41E-01	3.49E-04	1.69E-01	3.31E-03	2.21E-01	4.44E-05
32	TROJAN	1216	1.98E+07	4.46E+07	6.39E+10	3.75E+02		2.04E-02	1.27E-03	7.50E-02	5.03E-05	2.53E-02	6.76E-04	3.51E-02	
33	VOGTLE 1	1215	2.18E+07	8.50E+06	3.11E+09	3.90E+02	3.90E-03	2.62E-01	4.72E-02	1.97E-01	2.26E-03	9.48E-01	3.20E-02	5.19E-02	1.41E-03
34	WOLF CREEK 1	1236	2.01E+07	8.41E+06	2.65E+10	4.06E+02	4.19E-06	1.97E-02	1.21E-02	7.66E-02	7.04E-04	1.47E-01	8.69E-03	6.32E-02	3.47E-04
35	ZION 1	1085	1.97E+07	1.31E+08	1.19E+12	4.11E+02	4.74E-04	4.27E-02	9.75E-03	7.20E-02	1.12E-03	6.61E-01	6.24E-03	2.85E-01	
36	ZION 2	1085	2.08E+07	9.75E+07	1.20E+12	5.58E+02	2.14E-03	2.22E-01	8.07E-03	1.45E-03	6.61E-04	6.12E-01	2.52E-02	5.19E-01	
	MEAN	1118	1.80E+07	1.50E+08	8.65E+11	4.47E+02	2.24E-03	6.07E-02	4.00E-02	1.43E-01	1.47E-03	5.98E-01	7.34E-03	1.57E-01	6.75E-04
	SUM					1.61E+04	6.72E-02	2.00E+00	1.44E+00	4.01E+00	4.40E-02	2.15E+01	1.98E-01	5.67E+00	1.42E-02

Table C.2-1. Annual liquid radionuclide releases for 36 W-PWRs (1988 data) (continued)

#	FACILITY	NAMEPL'T CAPACITY (MWE)	1988 MW-HR THERMAL GEN (MW-HR TH)	Kr-85M (4.48 h)	Sr-89 (50.5 d)	Sr-90 (29.1 y)	Nb-95 (35 d)	Zr-95 (64 d)	Mo-99 (2.75 d)	Tc-99M (6.01 h)	Ru-103 (39.3 d)	Ag-110M (250 d)	Sn-113 (115 d)	Sb-124 (60.2 d)	Sb-125 (2.76 y)
1	BEAVER VALLEY 1	923	1.64E+07				5.30E-06		9.75E-06	9.55E-06	2.75E-06	8.95E-04		9.90E-04	1.26E-02
2	BEAVER VALLEY 2	923	2.13E+07				5.30E-06		9.75E-06	9.55E-06	2.75E-06	8.95E-04		9.90E-04	1.26E-02
3	BRAIDWOOD 1	1175	1.04E+07		6.68E-04		1.75E-03	9.58E-04	1.02E-04			4.49E-05	2.58E-05	4.51E-02	1.23E-03
4	BRAIDWOOD 2	1175	4.08E+06				1.70E-03	9.13E-04	1.02E-04				2.58E-05	5.65E-03	1.23E-03
5	BYRON 1	1175	1.99E+07	1.90E-04			1.95E-02	1.21E-02	1.01E-04	1.15E-05	4.18E-04	1.90E-05	2.68E-04	4.81E-04	7.15E-03
6	BYRON 2	1175	2.04E+07	1.90E-04			1.95E-02	1.21E-02	1.01E-04	1.15E-05	4.18E-04	1.90E-05	2.68E-04	4.81E-04	7.15E-03
7	CALLAWAY 1	1236	2.76E+07	3.33E-06	4.69E-03	1.96E-03	5.71E-04	1.71E-04				4.07E-06	7.47E-06	1.41E-05	
8	CATAWBA 1	1305	2.29E+07	1.32E-05	6.09E-05	1.34E-05	6.51E-03	4.12E-03	5.35E-05	3.37E-04	3.08E-04	3.15E-04	9.75E-04	7.32E-03	2.29E-02
9	CATAWBA 2	1305	1.88E+07	9.33E-01		3.26E-07	7.70E-08	4.15E-10		3.79E-09		2.38E-09			
10	COOK 1	1152	2.42E+07		1.83E-04	8.20E-05	1.45E-03	1.45E-03		4.42E-05		1.35E-02	1.34E-04	9.90E-04	2.33E-02
11	COOK 2	1133	7.41E+06		1.83E-04	8.20E-05	1.45E-03	1.45E-03		4.42E-05		1.35E-02	1.34E-04	9.90E-04	2.33E-02
12	DIABLO CANYON 1	1137	1.66E+07	3.34E-06	9.60E-04	6.95E-05		4.86E-03	7.95E-04		6.60E-05	1.55E-04	1.62E-04	3.16E-03	3.81E-02
13	DIABLO CANYON 2	1184	1.96E+07	3.34E-06	9.60E-04	6.95E-05		4.86E-03	7.95E-04		6.60E-05	1.55E-04	1.62E-04	3.16E-03	3.81E-02
14	FARLEY 1	860	1.92E+07			1.74E-05	2.89E-03	7.78E-04	8.59E-06	4.11E-05	9.22E-04	4.78E-03		5.56E-04	2.21E-02
15	FARLEY 2	860	2.29E+07				2.82E-03	5.77E-04		2.23E-05	7.21E-04	5.66E-03		7.52E-04	2.31E-02
16	HARRIS 1	951	1.71E+07	1.79E-04		2.52E-06	3.83E-04	3.83E-04		1.60E-05	5.77E-06		8.80E-05	2.95E-04	6.59E-04
17	INDIAN POINT 2	1310	1.95E+07		1.93E-04	2.25E-05	1.60E-02	2.53E-03			1.87E-04	6.57E-03		4.47E-02	2.94E-01
18	INDIAN POINT 3	1013	2.14E+07	7.51E-06	4.90E-06		9.33E-04	2.15E-04		1.55E-04		1.38E-02	9.50E-05	3.74E-03	3.30E-02
19	MC GUIRE 1	1305	2.26E+07	1.26E-03	7.76E-05	9.44E-06	6.05E-02	3.66E-02	8.15E-04	3.23E-03	3.31E-03	1.38E-02	7.22E-03	7.48E-03	6.71E-02
20	MC GUIRE 2	1305	2.41E+07	1.26E-03	7.76E-05	9.44E-06	6.05E-02	3.66E-02	8.15E-04	3.23E-03	3.31E-03	1.38E-02	7.22E-03	7.48E-03	6.71E-02
21	MILLSTONE 3	1253	2.33E+07	3.39E-03	6.18E-04	1.26E-04	5.71E-02	2.12E-02	8.85E-03	5.14E-03		3.33E-02		3.95E-03	2.01E-02
22	NORTH ANNA 1	947	2.20E+07	5.40E-05			1.74E-03	2.14E-04		9.90E-04		5.55E-02		1.54E-04	3.12E-02
23	NORTH ANNA 2	947	2.50E+07	5.40E-05			1.74E-03	2.14E-04		9.90E-04		5.55E-02		1.54E-04	3.12E-02
24	SALEM 1	1170	2.32E+07	6.01E-04	1.25E-02	2.36E-03	1.53E-02	1.23E-02	1.57E-03	4.75E-03	1.61E-03	4.96E-03	4.41E-05	6.31E-02	9.34E-02
25	SALEM 2	1170	1.90E+07	1.08E-03	1.69E-02	4.10E-03	6.55E-03	3.15E-03	1.19E-04	3.28E-03	1.37E-03	1.04E-02	1.03E-04	5.44E-02	9.26E-02
26	SEQUOYAH 1	1221	5.16E+05	1.33E-06	2.29E-04	1.65E-04	1.80E-06	3.42E-05		5.35E-05		9.40E-05			1.09E-02
27	SEQUOYAH 2	1221	1.26E+07	1.33E-06	2.29E-04	1.65E-04	1.80E-06	3.42E-05		5.35E-05		9.40E-05			1.09E-02
28	SOUTH TEXAS 1	1311	8.81E+06				3.62E-03	3.69E-03	7.99E-05	9.93E-05					
29	SUMMER 1	900	1.81E+07	4.17E-03			8.60E-03	8.60E-03	4.90E-04	1.10E-03	1.16E-03	1.76E-04	3.66E-04	5.69E-03	1.79E-02
30	SURRY 1	848	8.45E+06	4.38E-05			6.05E-03	3.09E-03	7.40E-05	9.55E-05	3.71E-03	3.65E-03		2.00E-02	1.83E-01
31	SURRY 2	848	1.16E+07	4.38E-05			6.05E-03	3.09E-03	7.40E-05	9.55E-05	3.71E-03	3.65E-03		2.00E-02	1.83E-01
32	TROJAN	1216	1.98E+07		2.20E-03	3.79E-04	6.02E-03	3.28E-03	1.46E-05	1.54E-05	2.63E-03	1.91E-03	3.06E-04		3.22E-03
33	VOGTLE 1	1215	2.18E+07	1.31E-05			3.10E-02	1.99E-03	1.03E-03	1.24E-03	3.34E-05			2.28E-02	1.60E-02
34	WOLF CREEK 1	1236	2.01E+07	6.08E-04	2.79E-03	3.19E-05	5.30E-03	1.84E-03	2.01E-03	3.62E-05		3.47E-03	1.84E-03	2.04E-03	1.79E-02
35	ZION 1	1085	1.97E+07	2.00E-05			1.15E-02	6.88E-03	2.60E-05		3.30E-05	8.30E-02	7.20E-04	2.86E-02	1.29E-01
36	ZION 2	1085	2.08E+07	4.90E-05			3.54E-02	2.27E-02	8.30E-05	2.90E-04	3.68E-03	1.26E-01	9.17E-03	3.67E-02	1.70E-01
	MEAN	1118	1.80E+07	3.78E-02	2.42E-03	5.99E-04	1.03E-02	6.27E-03	7.55E-04	8.76E-04	1.26E-03	1.47E-02	1.39E-03	1.26E-02	5.02E-02
	SUM			9.46E-01	4.36E-02	9.66E-03	3.92E-01	2.13E-01	1.81E-02	2.54E-02	2.77E-02	4.72E-01	2.91E-02	3.92E-01	1.71E+00

Table C.2-1. Annual liquid radionuclide releases for 36 W-PWRs (1988 data) (continued)

#	FACILITY	NAMEPL'T CAPACITY (MWE)	1988 MW-HR THERMAL GEN (MW-HR TH)	I-131 (8.04 d)	Xe-131M (11.9 d)	I-132 (2.3 h)	Xe-133 (5.24 d)	I-133 (20.8 h)	Xe-133M (2.19 d)	Cs-134 (2.07 y)	I-135 (6.6 h)	Xe-135 (9.1 h)	Cs-136 (13.2 d)	Cs-137 (30 y)	Ba-140 (12.75 d)	La-140 (1.68 d)
1	BEAVER VALLEY 1	923	1.64E+07	1.81E-04			7.85E-03	4.47E-05	6.00E-05	5.50E-04		1.14E-04		1.21E-03	3.60E-06	1.80E-06
2	BEAVER VALLEY 2	923	2.13E+07	1.81E-04			7.85E-03	4.47E-05	6.00E-05	5.50E-04		1.14E-04		1.21E-03	3.60E-06	1.80E-06
3	BRAIDWOOD 1	1175	1.04E+07	1.87E-02		6.56E-02	1.26E-02	1.29E-03		1.92E-03	3.28E-05	1.09E-04	1.28E-04	8.82E-03	9.45E-04	9.45E-04
4	BRAIDWOOD 2	1175	4.08E+06	1.74E-02		6.55E-02	1.21E-02	1.28E-03		1.92E-03	1.37E-05	1.09E-04	1.28E-04	8.82E-03	9.45E-04	6.80E-04
5	BYRON 1	1175	1.99E+07	1.35E-02	3.16E-02	5.05E-04	2.54E+00	4.83E-04	4.18E-02	2.22E-02	1.81E-04	6.70E-03	4.07E-04	2.72E-02	2.18E-03	2.18E-05
6	BYRON 2	1175	2.04E+07	1.35E-02	3.16E-02	5.05E-04	2.54E+00	4.83E-04	4.18E-02	2.22E-02	1.81E-04	6.70E-03	4.07E-04	2.72E-02	2.18E-03	2.18E-05
7	CALLAWAY 1	1236	2.76E+07	3.29E-04	4.53E-03		7.04E-01	3.35E-06	5.86E-03	1.29E-02		5.47E-03		2.02E-02	1.46E-05	
8	CATAWBA 1	1305	2.29E+07	9.78E-03	1.63E-04	1.54E-04	7.12E-02	2.19E-03	1.61E-03	5.92E-03	9.37E-05	7.86E-02	4.28E-05	9.24E-03	6.29E-05	1.44E-03
9	CATAWBA 2	1305	1.88E+07	7.62E-04	1.22E+01	2.30E-06	1.51E+03	4.50E-04	1.55E+01	3.41E-08	1.88E-06	1.80E+01		5.74E-08	8.32E-10	
10	COOK 1	1152	2.42E+07	1.97E-02	3.68E-03		2.85E-01	5.70E-04	2.67E-03	1.46E-02		7.40E-04	1.65E-03	1.89E-02	1.41E-04	1.41E-04
11	COOK 2	1133	7.41E+06	1.97E-02	3.68E-03		2.85E-01	5.70E-04	2.67E-03	1.46E-02		7.40E-04	1.65E-03	1.89E-02	1.41E-04	1.41E-04
12	DIABLO CANYON 1	1137	1.66E+07	3.18E-02	1.45E-05	1.11E-05	4.44E-02	8.50E-03	1.60E-04	8.15E-02	5.60E-04	1.12E-03	9.70E-04	9.50E-02		1.03E-03
13	DIABLO CANYON 2	1164	1.98E+07	3.18E-02	1.45E-05	1.11E-05	4.44E-02	8.50E-03	1.60E-04	8.15E-02	5.60E-04	1.12E-03	9.70E-04	9.50E-02		1.03E-03
14	FARLEY 1	860	1.92E+07	2.89E-04		2.15E-03	1.40E-01	4.31E-06		8.90E-04	1.87E-06	2.45E-04	5.70E-05	3.28E-03		2.19E-04
15	FARLEY 2	860	2.29E+07	6.10E-05		6.24E-04	2.23E-01	2.02E-05		9.98E-05	2.08E-06	2.97E-04	8.53E-05	9.96E-04	1.45E-05	1.43E-04
16	HARRIS 1	951	1.71E+07	2.94E-04	1.80E-04	8.74E-03	4.25E-01	2.63E-05				3.89E-03		2.08E-04	2.32E-05	2.32E-05
17	INDIAN POINT 2	1310	1.95E+07	3.07E-02		2.75E-02	1.43E-02	1.56E-01		1.22E-02	9.70E-02	3.23E-03		5.31E-02	1.43E-03	6.26E-03
18	INDIAN POINT 3	1013	2.14E+07	2.96E-02	4.66E-02	1.24E-05	2.17E+00	4.05E-04	1.97E-02	1.95E-02		1.85E-02	1.44E-04	1.87E-02		5.32E-04
19	MC GUIRE 1	1305	2.26E+07	6.86E-02	1.97E-02	3.97E-04	6.99E+00	7.66E-03	1.15E-01	7.01E-03	2.02E-02	1.98E-01	1.77E-04	1.24E-02	3.11E-04	2.94E-03
20	MC GUIRE 2	1305	2.41E+07	6.86E-02	1.97E-02	3.97E-04	6.99E+00	7.66E-03	1.15E-01	7.01E-03	2.02E-02	1.98E-01	1.77E-04	1.24E-02	3.11E-04	2.94E-03
21	MILLSTONE 3	1253	2.33E+07	2.66E-01	2.67E-03	1.35E-02	1.15E-01	4.93E-02		1.58E-01	1.07E-03	4.74E-02	7.99E-03	2.29E-01		
22	NORTH ANNA 1	947	2.20E+07	6.05E-03	4.73E-02	9.15E-05	4.87E+02	1.17E-02	3.81E-02	4.05E-03	6.25E-03	1.92E-02		9.65E-03		
23	NORTH ANNA 2	947	2.50E+07	6.05E-03	4.73E-02	9.15E-05	4.87E+02	1.17E-02	3.81E-02	4.05E-03	6.25E-03	1.92E-02		9.65E-03		
24	SALEM 1	1170	2.32E+07	5.53E-02	5.05E-02	9.72E-03	8.77E+00	2.80E-02	9.46E-02	1.31E-01	1.68E-02	9.13E-02	9.31E-05	1.34E-01	2.80E-04	3.89E-04
25	SALEM 2	1170	1.90E+07	1.35E-01	2.43E-02	4.68E-02	5.80E+00	8.80E-02	5.19E-02	9.53E-02	1.90E-02	9.41E-02	2.20E-03	1.08E-01	1.57E-03	1.03E-03
26	SEQUOYAH 1	1221	5.16E+05	8.10E-04	4.90E-04		1.68E-01	3.08E-05	4.80E-04	1.37E-02		2.91E-04		3.75E-02		
27	SEQUOYAH 2	1221	1.26E+07	8.10E-04	4.90E-04		1.68E-01	3.08E-05	4.80E-04	1.37E-02		2.91E-04		3.75E-02		
28	SOUTH TEXAS 1	1311	8.81E+06	5.03E-03			2.50E+00	7.82E-05				2.97E-03				
29	SUMMER 1	900	1.61E+07	4.66E-02	4.16E-02	1.18E-02	3.70E+00	2.47E-02	4.57E-02	1.01E-01	1.64E-02	7.13E-02	3.21E-03	7.18E-02	1.12E-03	1.12E-03
30	SURRY 1	848	8.45E+06	4.18E-02	4.08E-02	3.87E-04	2.39E+00	7.85E-04	9.90E-03	6.80E-02	2.91E-05	2.11E-02	2.71E-04	2.48E-01	4.43E-03	1.55E-03
31	SURRY 2	848	1.16E+07	4.18E-02	4.08E-02	3.87E-04	2.39E+00	7.85E-04	9.90E-03	6.80E-02	2.91E-05	2.11E-02	2.71E-04	2.48E-01	4.43E-03	1.55E-03
32	TROJAN	1216	1.98E+07	2.64E-04	1.64E-03		3.70E-02		1.56E-05	3.12E-04		1.41E-04		7.92E-04		2.38E-04
33	VOGTLE 1	1215	2.18E+07	2.75E-03	8.63E-03	1.89E-04	8.56E-01	4.75E-03	6.11E-03		1.39E-03	1.66E-02		1.55E-04		5.87E-04
34	WOLF CREEK 1	1236	2.01E+07	1.41E-03	1.72E-01		8.05E+00	4.43E-06	4.08E-02	1.19E-03		1.27E-02		1.96E-03		6.76E-05
35	ZION 1	1085	1.97E+07	2.91E-03	1.89E-02	8.90E-03	2.33E+00	2.80E-04	1.76E-02	9.89E-02	5.80E-05	1.32E-02	5.20E-03	1.26E-01		1.24E-03
36	ZION 2	1085	2.08E+07	1.94E-02	1.05E-02	1.08E-02	2.78E+00	4.54E-03	1.71E-02	4.72E-02	2.40E-04	1.18E-02	3.53E-03	7.68E-02	1.20E-05	1.72E-03
	MEAN	1118	1.80E+07	2.80E-02	4.60E-01	1.06E-02	7.07E+01	1.20E-02	5.79E-01	3.37E-02	5.61E-03	6.27E-01	1.36E-03	5.06E-02	9.34E-04	1.00E+03
	SUM			1.01E+00	1.29E+01	2.76E-01	2.55E+03	4.21E-01	1.62E+01	1.11E+00	2.07E-01	1.90E+01	2.98E-02	1.77E+00	2.05E-02	2.80E-02

SUM(ALL LIQUIDS) 1.87E+04 NON-T3 LIQUIDS 2.82E+03 TRITIUM 1.61E+04

Table C.2-1. Annual liquid radionuclide releases for 36 W-PWRs (1988 data) (continued)

#	FACILITY	NAMEPLATE CAPACITY (MWE)	TOTAL NON-TRITIUM ISOT IN LIQ (Ci)	TOTAL NON-T, NON-NOBLE GAS IN LIQ (Ci)	DISSOLVED NOBLE GASES
1	BEAVER VALLEY 1	923	6.09E-02	5.29E-02	8.02E-03
2	BEAVER VALLEY 2	923	6.09E-02	5.29E-02	8.02E-03
3	BRAIDWOOD 1	1175	8.56E+00	8.55E+00	1.27E-02
4	BRAIDWOOD 2	1175	2.99E+00	2.98E+00	1.22E-02
5	BYRON 1	1175	3.55E+00	9.29E-01	2.62E+00
6	BYRON 2	1175	3.55E+00	9.29E-01	2.62E+00
7	CALLAWAY 1	1236	7.92E-01	7.20E-02	7.20E-01
8	CATAWBA 1	1305	6.62E-01	5.10E-01	1.52E-01
9	CATAWBA 2	1305	1.56E+03	1.24E-03	1.56E+03
10	COOK 1	1152	4.94E-01	2.02E-01	2.92E-01
11	COOK 2	1133	4.94E-01	2.02E-01	2.92E-01
12	DIABLO CANYON 1	1137	1.05E+00	1.00E+00	4.56E-02
13	DIABLO CANYON 2	1164	1.05E+00	1.00E+00	4.56E-02
14	FARLEY 1	860	2.17E-01	7.72E-02	1.40E-01
15	FARLEY 2	860	3.06E-01	8.31E-02	2.23E-01
16	HARRIS 1	951	5.60E-01	1.31E-01	4.29E-01
17	INDIAN POINT 2	1310	2.61E+00	2.59E+00	1.75E-02
18	INDIAN POINT 3	1013	2.57E+00	3.17E-01	2.25E+00
19	MC GUIRE 1	1305	9.87E+00	2.55E+00	7.32E+00
20	MC GUIRE 2	1305	9.87E+00	2.55E+00	7.32E+00
21	MILLSTONE 3	1253	3.18E+00	3.01E+00	1.68E-01
22	NORTH ANNA 1	947	4.87E+02	2.07E-01	4.87E+02
23	NORTH ANNA 2	947	4.87E+02	2.07E-01	4.87E+02
24	SALEM 1	1170	1.16E+01	2.58E+00	9.01E+00
25	SALEM 2	1170	8.85E+00	2.88E+00	5.97E+00
26	SEQUOYAH 1	1221	3.95E-01	2.26E-01	1.69E-01
27	SEQUOYAH 2	1221	3.95E-01	2.26E-01	1.69E-01
28	SOUTH TEXAS 1	1311	2.69E+00	1.85E-01	2.50E+00
29	SUMMER 1	900	4.60E+00	7.37E-01	3.86E+00
30	SURRY 1	848	3.67E+00	1.21E+00	2.46E+00
31	SURRY 2	848	3.67E+00	1.21E+00	2.46E+00
32	TROJAN	1216	2.18E-01	1.79E-01	3.88E-02
33	VOGTLE 1	1215	2.52E+00	1.63E+00	8.87E-01
34	WOLF CREEK 1	1236	8.65E+00	3.70E-01	8.28E+00
35	ZION 1	1085	3.96E+00	1.58E+00	2.38E+00
36	ZION 2	1085	4.78E+00	1.96E+00	2.82E+00
		AVE >>>	8.60E+01	1.38E+00	8.48E+01
		SUMS >>>>	2.64E+03	4.32E+01	2.60E+03

APPENDIX D
REACTOR ACCIDENT ANALYSIS: MACCS

The following pages provide a complete listing of the calculated health impacts for the Southeastern site, Oak Ridge Reservation, and the Southwestern site. Please note that the phrase "source term 1 of 2" refers to the MCF case and that "source term 2 of 2 refers to the LCF case.

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
				Quantities		
ERL FAT/TOTAL	0-16.1 KM	.0689	3.17E-03	0.00E+00	0.00E+00	5.89E-04
ERL INJ/PRODROMAL VOMIT	0-16.1 KM	.4997	5.52E-02	0.00E+00	9.31E-02	1.90E-01
ERL INJ/DIARRHEA	0-16.1 KM	.2056	1.38E-02	0.00E+00	1.56E-02	3.85E-02
ERL INJ/PNEUMONITIS	0-16.1 KM	.0230	6.24E-04	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-16.1 KM	.6869	5.12E-01	3.20E-02	1.38E+00	2.37E+00
ERL INJ/SKIN ERYTHEMA	0-16.1 KM	.9047	3.33E+01	3.82E+00	9.43E+01	1.48E+02
ERL INJ/TRANSEPIDERMAL	0-16.1 KM	.6849	4.20E+00	1.60E-01	9.67E+00	2.02E+01
CAN FAT/TOTAL	0-16.1 KM	1.0000	2.02E+01	1.71E+01	3.35E+01	4.03E+01
CAN FAT/LUNG	0-16.1 KM	1.0000	4.21E+00	3.46E+00	7.40E+00	9.05E+00
CAN FAT/THYROID	0-16.1 KM	1.0000	1.37E+00	5.19E-01	3.81E+00	6.26E+00
CAN FAT/BREAST	0-16.1 KM	1.0000	1.64E+00	1.33E+00	3.01E+00	3.39E+00
CAN FAT/GI	0-16.1 KM	1.0000	6.31E+00	5.69E+00	1.01E+01	1.13E+01
CAN FAT/LEUKEMIA	0-16.1 KM	1.0000	2.35E+00	2.13E+00	3.44E+00	3.92E+00
CAN FAT/BONE	0-16.1 KM	1.0000	6.06E-01	5.24E-01	9.63E-01	1.07E+00
CAN FAT/OTHER	0-16.1 KM	1.0000	3.72E+00	3.22E+00	6.66E+00	7.67E+00
CAN INJ/TOTAL	0-16.1 KM	1.0000	4.44E+01	3.50E+01	8.02E+01	1.08E+02
CAN INJ/LUNG	0-16.1 KM	1.0000	4.70E+00	3.84E+00	8.01E+00	1.00E+01
CAN INJ/THYROID	0-16.1 KM	1.0000	1.37E+01	5.19E+00	3.81E+01	6.26E+01
CAN INJ/BREAST	0-16.1 KM	1.0000	4.83E+00	4.18E+00	8.69E+00	1.02E+01
CAN INJ/GI	0-16.1 KM	1.0000	1.08E+01	9.77E+00	1.66E+01	2.04E+01
CAN INJ/LEUKEMIA	0-16.1 KM	1.0000	2.35E+00	2.13E+00	3.44E+00	3.92E+00
CAN INJ/BONE	0-16.1 KM	1.0000	6.06E-01	5.24E-01	9.63E-01	1.07E+00
CAN INJ/OTHER	0-16.1 KM	1.0000	7.44E+00	6.73E+00	1.23E+01	1.43E+01

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	16.1-80.5 KM	.0565	4.28E+00	0.00E+00	0.00E+00	9.04E+00
ERL INJ/TRANSEPIDERMAL	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	16.1-80.5 KM	1.0000	2.93E+02	2.11E+02	6.06E+02	7.20E+02
CAN FAT/LUNG	16.1-80.5 KM	1.0000	6.75E+01	4.21E+01	1.37E+02	1.79E+02
CAN FAT/THYROID	16.1-80.5 KM	1.0000	9.36E+00	5.94E+00	2.17E+01	2.65E+01
CAN FAT/BREAST	16.1-80.5 KM	1.0000	2.84E+01	1.97E+01	6.29E+01	7.57E+01
CAN FAT/GI	16.1-80.5 KM	1.0000	8.20E+01	6.08E+01	1.53E+02	2.01E+02
CAN FAT/LEUKEMIA	16.1-80.5 KM	1.0000	3.57E+01	2.81E+01	6.77E+01	7.73E+01
CAN FAT/BONE	16.1-80.5 KM	1.0000	9.61E+00	6.30E+00	2.01E+01	2.49E+01
CAN FAT/OTHER	16.1-80.5 KM	1.0000	6.09E+01	4.26E+01	1.16E+02	1.36E+02
CAN INJ/TOTAL	16.1-80.5 KM	1.0000	5.60E+02	4.08E+02	1.07E+03	1.18E+03
CAN INJ/LUNG	16.1-80.5 KM	1.0000	7.53E+01	4.76E+01	1.61E+02	2.14E+02
CAN INJ/THYROID	16.1-80.5 KM	1.0000	9.36E+01	5.94E+01	2.17E+02	2.65E+02
CAN INJ/BREAST	16.1-80.5 KM	1.0000	8.37E+01	5.76E+01	1.81E+02	2.19E+02
CAN INJ/GI	16.1-80.5 KM	1.0000	1.40E+02	1.06E+02	2.82E+02	3.21E+02
CAN INJ/LEUKEMIA	16.1-80.5 KM	1.0000	3.57E+01	2.81E+01	6.77E+01	7.73E+01
CAN INJ/BONE	16.1-80.5 KM	1.0000	9.61E+00	6.30E+00	2.01E+01	2.49E+01
CAN INJ/OTHER	16.1-80.5 KM	1.0000	1.22E+02	8.62E+01	2.54E+02	3.10E+02

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	80.5-1609 KM	1.0000	5.02E+03	3.20E+03	1.13E+04	1.39E+04
CAN FAT/LUNG	80.5-1609 KM	1.0000	7.07E+02	4.82E+02	1.54E+03	2.07E+03
CAN FAT/THYROID	80.5-1609 KM	1.0000	1.02E+02	5.69E+01	2.55E+02	3.20E+02
CAN FAT/BREAST	80.5-1609 KM	1.0000	4.55E+02	2.93E+02	1.03E+03	1.25E+03
CAN FAT/GI	80.5-1609 KM	1.0000	1.66E+03	9.95E+02	4.05E+03	5.33E+03
CAN FAT/LEUKEMIA	80.5-1609 KM	1.0000	7.68E+02	5.84E+02	1.59E+03	2.08E+03
CAN FAT/BONE	80.5-1609 KM	1.0000	1.25E+02	1.04E+02	2.54E+02	3.14E+02
CAN FAT/OTHER	80.5-1609 KM	1.0000	1.20E+03	6.84E+02	2.89E+03	3.65E+03
CAN INJ/TOTAL	80.5-1609 KM	1.0000	9.29E+03	5.69E+03	2.23E+04	2.97E+04
CAN INJ/LUNG	80.5-1609 KM	1.0000	7.89E+02	5.44E+02	1.77E+03	2.22E+03
CAN INJ/THYROID	80.5-1609 KM	1.0000	1.02E+03	5.69E+02	2.55E+03	3.20E+03
CAN INJ/BREAST	80.5-1609 KM	1.0000	1.34E+03	8.62E+02	3.05E+03	3.79E+03
CAN INJ/GI	80.5-1609 KM	1.0000	2.84E+03	1.62E+03	6.81E+03	9.15E+03
CAN INJ/LEUKEMIA	80.5-1609 KM	1.0000	7.68E+02	5.84E+02	1.59E+03	2.08E+03
CAN INJ/BONE	80.5-1609 KM	1.0000	1.25E+02	1.04E+02	2.54E+02	3.14E+02
CAN INJ/OTHER	80.5-1609 KM	1.0000	2.40E+03	1.34E+03	5.94E+03	7.62E+03

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	Quantities 50th	90th	95th
ERL FAT/TOTAL	0-1609 KM	.0689	3.17E-03	0.00E+00	0.00E+00	5.89E-04
ERL INJ/PRODROMAL VOMIT	0-1609 KM	.4997	5.52E-02	0.00E+00	9.31E-02	1.90E-01
ERL INJ/DIARRHEA	0-1609 KM	.2056	1.38E-02	0.00E+00	1.56E+00	3.85E-02
ERL INJ/PNEUMONITIS	0-1609 KM	.0230	6.24E-04	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-1609 KM	.6869	5.12E-01	5.12E-01	1.38E+00	2.37E+00
ERL INJ/SKIN ERYTHEMA	0-1609 KM	.9047	3.76E+01	3.83E+00	1.05E+02	1.66E+02
ERL INJ/TRANSEPIDERMAL	0-1609 KM	.6849	4.20E+00	1.60E-01	9.67E+00	2.02E+01
CAN FAT/TOTAL	0-1609 KM	1.0000	5.33E+03	3.45E+03	1.16E+04	1.46E+04
CAN FAT/LUNG	0-1609 KM	1.0000	7.79E+02	5.68E+02	1.62E+03	2.10E+03
CAN FAT/THYROID	0-1609 KM	1.0000	1.13E+02	6.90E+01	2.62E+02	3.25E+02
CAN FAT/BREAST	0-1609 KM	1.0000	4.85E+02	3.24E+02	1.07E+03	1.29E+03
CAN FAT/GI	0-1609 KM	1.0000	1.75E+03	1.08E+03	4.14E+03	5.41E+03
CAN FAT/LEUKEMIA	0-1609 KM	1.0000	8.06E+02	6.13E+02	1.64E+03	2.11E+03
CAN FAT/BONE	0-1609 KM	1.0000	1.35E+02	1.12E+02	2.62E+02	3.15E+02
CAN FAT/OTHER	0-1609 KM	1.0000	1.26E+03	7.50E+02	2.95E+03	3.69E+03
CAN INJ/TOTAL	0-1609 KM	1.0000	9.89E+03	6.48E+03	2.30E+04	3.01E+04
CAN INJ/LUNG	0-1609 KM	1.0000	8.69E+02	6.26E+02	1.84E+03	2.26E+03
CAN INJ/THYROID	0-1609 KM	1.0000	1.13E+03	6.90E+02	2.62E+03	3.25E+03
CAN INJ/BREAST	0-1609 KM	1.0000	1.43E+03	9.63E+02	3.16E+03	3.87E+03
CAN INJ/GI	0-1609 KM	1.0000	3.00E+03	1.83E+03	7.01E+03	9.22E+03
CAN INJ/LEUKEMIA	0-1609 KM	1.0000	8.06E+02	6.13E+02	1.64E+03	2.11E+03
CAN INJ/BONE	0-1609 KM	1.0000	1.35E+02	1.12E+02	2.62E+02	3.15E+02
CAN INJ/OTHER	0-1609 KM	1.0000	2.53E+03	1.44E+03	5.99E+03	7.66E+03

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
				Quantities		
ERL FAT/TOTAL	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	0-16.1 KM	1.0000	2.77E+00	2.06E+00	5.88E+00	7.78E+00
CAN FAT/LUNG	0-16.1 KM	1.0000	3.99E-01	3.00E-01	8.47E-01	1.07E+00
CAN FAT/THYROID	0-16.1 KM	1.0000	5.66E-02	4.59E-02	1.08E-01	1.37E-01
CAN FAT/BREAST	0-16.1 KM	1.0000	2.70E-01	2.02E-01	5.69E-01	7.33E-01
CAN FAT/GI	0-16.1 KM	1.0000	9.04E-01	6.58E-01	1.94E+00	2.53E+00
CAN FAT/LEUKEMIA	0-16.1 KM	1.0000	4.04E-01	3.02E-01	7.70E-01	9.95E-01
CAN FAT/BONE	0-16.1 KM	1.0000	6.38E-02	4.81E-02	1.13E-01	1.31E-01
CAN FAT/OTHER	0-16.1 KM	1.0000	6.77E-01	4.99E-01	1.45E+00	2.06E+00
CAN INJ/TOTAL	0-16.1 KM	1.0000	5.17E+00	3.73E+00	1.03E+01	1.25E+01
CAN INJ/LUNG	0-16.1 KM	1.0000	4.45E-01	3.32E-01	9.47E-01	1.13E+00
CAN INJ/THYROID	0-16.1 KM	1.0000	5.66E-01	4.59E-01	1.08E+00	1.37E+00
CAN INJ/BREAST	0-16.1 KM	1.0000	7.94E-01	5.78E-01	1.65E+00	2.14E+00
CAN INJ/GI	0-16.1 KM	1.0000	1.09E+00	1.09E+00	3.09E+00	4.28E+00
CAN INJ/LEUKEMIA	0-16.1 KM	1.0000	3.02E-01	3.02E-01	7.70E-01	9.95E-01
CAN INJ/BONE	0-16.1 KM	1.0000	4.81E-02	4.81E-02	1.13E-01	1.31E-01
CAN INJ/OTHER	0-16.1 KM	1.0000	1.35E+00	9.98E-01	2.91E+00	3.71E+00

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	16.1-80.5 KM	1.0000	5.82E+00	3.96E+00	1.22E+01	1.69E+01
CAN FAT/LUNG	16.1-80.5 KM	1.0000	8.95E-01	6.10E-01	2.01E+00	2.56E+00
CAN FAT/THYROID	16.1-80.5 KM	1.0000	1.38E-01	1.06E-01	2.90E-01	4.08E-01
CAN FAT/BREAST	16.1-80.5 KM	1.0000	5.78E-01	3.83E-01	1.23E+00	1.66E+00
CAN FAT/GI	16.1-80.5 KM	1.0000	1.89E+00	1.24E+00	4.09E+00	5.90E+00
CAN FAT/LEUKEMIA	16.1-80.5 KM	1.0000	7.53E-01	5.56E-01	1.44E+00	2.03E+00
CAN FAT/BONE	16.1-80.5 KM	1.0000	1.19E-01	8.83E-02	2.37E-01	3.05E-01
CAN FAT/OTHER	16.1-80.5 KM	1.0000	1.44E+00	1.01E+00	3.15E+00	4.44E+00
CAN INJ/TOTAL	16.1-80.5 KM	1.0000	1.11E+01	7.82E+00	2.34E+01	3.25E+01
CAN INJ/LUNG	16.1-80.5 KM	1.0000	9.99E-01	6.85E-01	2.20E+00	2.84E+00
CAN INJ/THYROID	16.1-80.5 KM	1.0000	1.38E+00	1.06E+00	2.90E+00	4.08E+00
CAN INJ/BREAST	16.1-80.5 KM	1.0000	1.70E+00	1.15E+00	3.62E+00	4.85E+00
CAN INJ/GI	16.1-80.5 KM	1.0000	3.24E+00	2.18E+00	7.00E+00	1.00E+01
CAN INJ/LEUKEMIA	16.1-80.5 KM	1.0000	7.53E-01	5.56E-01	1.44E+00	2.03E+00
CAN INJ/BONE	16.1-80.5 KM	1.0000	1.19E-01	8.83E-02	2.37E-01	3.05E-01
CAN INJ/OTHER	16.1-80.5 KM	1.0000	2.89E+00	2.01E+00	6.48E+00	9.01E+00

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
				Quantities		
ERL FAT/TOTAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	80.5-1609 KM	1.0000	1.78E+01	1.02E+01	3.96E+01	5.02E+01
CAN FAT/LUNG	80.5-1609 KM	1.0000	2.43E+00	1.67E+00	5.41E+00	6.60E+00
CAN FAT/THYROID	80.5-1609 KM	1.0000	4.49E-01	2.19E-01	1.02E+00	1.11E+00
CAN FAT/BREAST	80.5-1609 KM	1.0000	1.61E+00	1.00E+00	3.57E+00	4.43E+00
CAN FAT/GI	80.5-1609 KM	1.0000	6.08E+00	3.18E+00	1.36E+01	1.71E+01
CAN FAT/LEUKEMIA	80.5-1609 KM	1.0000	2.42E+00	1.87E+00	5.02E+00	6.11E+00
CAN FAT/BONE	80.5-1609 KM	1.0000	3.55E-01	3.12E-01	6.47E-01	7.82E-01
CAN FAT/OTHER	80.5-1609 KM	1.0000	4.51E+00	2.40E+00	1.04E+01	1.18E+01
CAN INJ/TOTAL	80.5-1609 KM	1.0000	3.41E+01	1.96E+01	7.74E+01	9.51E+01
CAN INJ/LUNG	80.5-1609 KM	1.0000	2.71E+00	1.89E+00	6.00E+00	7.22E+00
CAN INJ/THYROID	80.5-1609 KM	1.0000	4.49E+00	2.19E+00	1.02E+01	1.11E+01
CAN INJ/BREAST	80.5-1609 KM	1.0000	4.74E+00	2.99E+00	1.04E+01	1.16E+01
CAN INJ/GI	80.5-1609 KM	1.0000	1.04E+01	5.59E+00	2.39E+01	3.01E+01
CAN INJ/LEUKEMIA	80.5-1609 KM	1.0000	2.42E+00	1.87E+00	5.02E+00	6.11E+00
CAN INJ/BONE	80.5-1609 KM	1.0000	3.55E-01	3.12E-01	6.47E-01	7.82E-01
CAN INJ/OTHER	80.5-1609 KM	1.0000	9.01E+00	4.84E+00	2.13E+01	2.63E+01

Southeastern Site
(Permanent Population)

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
				Quantities		
ERL FAT/TOTAL	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	0-1609 KM	1.0000	2.64E+01	2.07E+01	5.23E+01	5.83E+01
CAN FAT/LUNG	0-1609 KM	1.0000	3.72E+00	3.06E+00	7.09E+00	7.62E+00
CAN FAT/THYROID	0-1609 KM	1.0000	6.43E-01	6.45E-01	1.15E+00	1.26E+00
CAN FAT/BREAST	0-1609 KM	1.0000	2.46E+00	2.01E+00	4.79E+00	5.28E+00
CAN FAT/GI	0-1609 KM	1.0000	8.87E+00	6.64E+00	1.78E+01	2.10E+01
CAN FAT/LEUKEMIA	0-1609 KM	1.0000	3.58E+00	2.96E+00	6.31E+00	7.22E+00
CAN FAT/BONE	0-1609 KM	1.0000	5.37E-01	4.68E-01	8.31E-01	9.66E-01
CAN FAT/OTHER	0-1609 KM	1.0000	6.63E+00	5.04E+00	1.18E+01	1.32E+01
CAN INJ/TOTAL	0-1609 KM	1.0000	5.04E+01	3.85E+01	1.01E+02	1.08E+02
CAN INJ/LUNG	0-1609 KM	1.0000	4.16E+00	3.35E+00	7.77E+00	8.72E+00
CAN INJ/THYROID	0-1609 KM	1.0000	6.43E+00	6.45E+00	1.15E+01	1.26E+01
CAN INJ/BREAST	0-1609 KM	1.0000	7.23E+00	5.90E+00	1.18E+01	1.32E+01
CAN INJ/GI	0-1609 KM	1.0000	1.52E+01	1.06E+01	3.12E+01	3.42E+01
CAN INJ/LEUKEMIA	0-1609 KM	1.0000	3.58E+00	2.96E+00	6.31E+00	7.22E+00
CAN INJ/BONE	0-1609 KM	1.0000	5.37E-01	4.68E-01	8.31E-01	9.66E-01
CAN INJ/OTHER	0-1609 KM	1.0000	1.33E+01	1.00E+01	2.72E+01	3.10E+01

Oak Ridge Reservation Workers
(MCF Case Only)

Health Effects Cases		Prob Non-zero	Mean	Quantities 50th	90th	95th
ERL FAT/TOTAL	0-16.1 KM	.0002	8.96E-05	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	0-16.1 KM	.0152	3.37E-03	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	0-16.1 KM	.0020	5.21E-04	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	0-16.1 KM	.0000	3.00E-07	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-16.1 KM	.0501	1.65E-01	0.00E+00	0.00E+00	1.08E-02
ERL INJ/SKIN ERYTHEMA	0-16.1 KM	.1015	1.47E+01	0.00E+00	8.61E-02	2.41E+01
ERL INJ/TRANSEPIDERMAL	0-16.1 KM	.0321	4.66E-01	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	0-16.1 KM	.4756	1.88E+00	0.00E+00	5.33E+00	7.51E+00
CAN FAT/LUNG	0-16.1 KM	.4756	5.21E-01	0.00E+00	1.35E+00	2.39E+00
CAN FAT/THYROID	0-16.1 KM	.4756	2.43E-01	0.00E+00	5.40E-01	1.70E+00
CAN FAT/BREAST	0-16.1 KM	.4756	1.51E-01	0.00E+00	4.76E-01	6.46E-01
CAN FAT/GI	0-16.1 KM	.4756	4.33E-01	0.00E+00	1.20E+00	1.73E+00
CAN FAT/LEUKEMIA	0-16.1 KM	.4756	1.53E-01	0.00E+00	4.58E-01	6.32E-01
CAN FAT/BONE	0-16.1 KM	.4756	5.23E-02	0.00E+00	1.46E-01	2.61E-01
CAN FAT/OTHER	0-16.1 KM	.4756	3.30E-01	0.00E+00	1.02E+00	1.45E+00
CAN INJ/TOTAL	0-16.1 KM	.4756	5.06E+00	0.00E+00	1.18E+01	2.50E+01
CAN INJ/LUNG	0-16.1 KM	.4756	5.82E-01	0.00E+00	1.50E+00	2.62E+00
CAN INJ/THYROID	0-16.1 KM	.4756	2.43E+00	0.00E+00	5.40E+00	1.70E+01
CAN INJ/BREAST	0-16.1 KM	.4756	4.45E-01	0.00E+00	1.33E+00	1.95E+00
CAN INJ/GI	0-16.1 KM	.4756	7.41E-01	0.00E+00	2.19E+00	3.08E+00
CAN INJ/LEUKEMIA	0-16.1 KM	.4756	1.53E-01	0.00E+00	4.58E-01	6.32E-01
CAN INJ/BONE	0-16.1 KM	.4756	5.23E-02	0.00E+00	1.46E-01	2.61E-01
CAN INJ/OTHER	0-16.1 KM	.4756	6.59E-01	0.00E+00	2.03E+00	2.68E+00

Southwestern Site

Health Effects Cases		Prob Non-zero	Mean	Quantities 50th	90th	95th
ERL FAT/TOTAL	0-16.1 KM	.0013	1.02E-05	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	0-16.1 KM	.1110	1.23E-03	0.00E+00	1.25E-04	1.70E-03
ERL INJ/DIARRHEA	0-16.1 KM	.0223	1.61E-04	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-16.1 KM	.2056	1.57E-02	0.00E+00	3.47E-03	3.51E-02
ERL INJ/SKIN ERYTHEMA	0-16.1 KM	.6150	9.89E-01	2.43E-03	9.86E-01	3.49E+00
ERL INJ/TRANSEPIDERMAL	0-16.1 KM	.1681	1.32E-01	0.00E+00	2.02E-02	1.48E-01
CAN FAT/TOTAL	0-16.1 KM	1.0000	2.01E+00	2.04E+00	3.29E+00	3.69E+00
CAN FAT/LUNG	0-16.1 KM	1.0000	1.21E-01	8.59E-02	2.08E-01	2.67E-01
CAN FAT/THYROID	0-16.1 KM	1.0000	1.87E-02	8.91E-03	2.74E-02	5.07E-02
CAN FAT/BREAST	0-16.1 KM	1.0000	5.94E-02	5.52E-02	1.00E-01	1.14E-01
CAN FAT/GI	0-16.1 KM	1.0000	7.27E-01	7.41E-01	1.10E+00	1.17E+00
CAN FAT/LEUKEMIA	0-16.1 KM	1.0000	7.56E-01	8.12E-01	1.11E+00	1.16E+00
CAN FAT/BONE	0-16.1 KM	1.0000	1.52E-01	1.44E-01	2.35E-01	2.53E-01
CAN FAT/OTHER	0-16.1 KM	1.0000	1.73E-01	1.31E-01	2.73E-01	3.40E-01
CAN INJ/TOTAL	0-16.1 KM	1.0000	3.00E+00	3.04E+00	4.61E+00	5.49E+00
CAN INJ/LUNG	0-16.1 KM	1.0000	1.35E-01	9.86E-02	2.31E-01	3.31E-01
CAN INJ/THYROID	0-16.1 KM	1.0000	1.87E-01	8.91E-02	2.74E-01	5.07E-01
CAN INJ/BREAST	0-16.1 KM	1.0000	1.75E-01	1.31E-01	2.88E-01	3.42E-01
CAN INJ/GI	0-16.1 KM	1.0000	1.24E+00	1.07E+00	2.01E+00	2.21E+00
CAN INJ/LEUKEMIA	0-16.1 KM	1.0000	7.56E-01	8.12E-01	1.11E+00	1.16E+00
CAN INJ/BONE	0-16.1 KM	1.0000	1.52E-01	1.44E-01	2.35E-01	2.53E-01
CAN INJ/OTHER	0-16.1 KM	1.0000	3.46E-01	3.33E-01	5.46E-01	6.52E-01

Southwestern Site

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	16.1-80.5 KM	.0015	1.15E-04	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	16.1-80.5 KM	.2776	2.13E-01	0.00E+00	7.07E-01	9.70E-01
ERL INJ/TRANSEPIDERMAL	16.1-80.5 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	16.1-80.5 KM	1.0000	4.64E+01	1.74E+01	1.04E+02	1.11E+02
CAN FAT/LUNG	16.1-80.5 KM	1.0000	9.95E+00	3.25E+00	2.55E+01	3.24E+01
CAN FAT/THYROID	16.1-80.5 KM	1.0000	2.11E+00	5.30E-01	5.47E+00	6.20E+00
CAN FAT/BREAST	16.1-80.5 KM	1.0000	5.02E+00	1.70E+00	1.09E+01	1.17E+01
CAN FAT/GI	16.1-80.5 KM	1.0000	1.30E+01	5.09E+00	3.06E+01	3.24E+01
CAN FAT/LEUKEMIA	16.1-80.5 KM	1.0000	4.98E+00	2.34E+00	1.06E+01	1.14E+01
CAN FAT/BONE	16.1-80.5 KM	1.0000	1.08E+00	4.96E-01	2.66E+00	3.61E+00
CAN FAT/OTHER	16.1-80.5 KM	1.0000	1.02E+01	3.70E+00	2.72E+01	3.07E+01
CAN INJ/TOTAL	16.1-80.5 KM	1.0000	9.58E+01	3.31E+01	2.23E+02	2.68E+02
CAN INJ/LUNG	16.1-80.5 KM	1.0000	1.11E+01	3.76E+00	2.75E+01	3.57E+01
CAN INJ/THYROID	16.1-80.5 KM	1.0000	2.11E+01	5.30E+00	5.47E+01	6.20E+01
CAN INJ/BREAST	16.1-80.5 KM	1.0000	1.48E+01	4.61E+00	3.68E+01	4.36E+01
CAN INJ/GI	16.1-80.5 KM	1.0000	2.23E+01	8.58E+00	5.44E+01	7.00E+01
CAN INJ/LEUKEMIA	16.1-80.5 KM	1.0000	4.98E+00	2.34E+00	1.06E+01	1.14E+01
CAN INJ/BONE	16.1-80.5 KM	1.0000	1.08E+00	4.96E-01	2.66E+00	3.61E+00
CAN INJ/OTHER	16.1-80.5 KM	1.0000	2.04E+01	7.31E+00	5.12E+01	5.66E+01

Southwestern Site

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	80.5-1609 KM	1.0000	5.03E+02	3.70E+02	1.04E+03	1.19E+03
CAN FAT/LUNG	80.5-1609 KM	1.0000	8.10E+01	5.69E+01	1.92E+02	2.29E+02
CAN FAT/THYROID	80.5-1609 KM	1.0000	8.70E+00	6.43E+00	1.97E+01	2.37E+01
CAN FAT/BREAST	80.5-1609 KM	1.0000	5.35E+01	3.80E+01	1.10E+02	1.33E+02
CAN FAT/GI	80.5-1609 KM	1.0000	1.65E+02	1.22E+02	3.72E+02	4.61E+02
CAN FAT/LEUKEMIA	80.5-1609 KM	1.0000	5.55E+01	4.00E+01	1.20E+02	1.45E+02
CAN FAT/BONE	80.5-1609 KM	1.0000	7.92E+00	5.22E+00	1.96E+01	2.26E+01
CAN FAT/OTHER	80.5-1609 KM	1.0000	1.32E+02	9.85E+01	2.98E+02	3.33E+02
CAN INJ/TOTAL	80.5-1609 KM	1.0000	9.44E+02	6.88E+02	2.07E+03	2.55E+03
CAN INJ/LUNG	80.5-1609 KM	1.0000	9.04E+01	6.47E+01	2.09E+02	2.58E+02
CAN INJ/THYROID	80.5-1609 KM	1.0000	8.70E+01	6.43E+01	1.97E+02	2.37E+02
CAN INJ/BREAST	80.5-1609 KM	1.0000	1.58E+02	1.11E+02	3.36E+02	4.27E+02
CAN INJ/GI	80.5-1609 KM	1.0000	2.83E+02	2.08E+02	6.54E+02	7.77E+02
CAN INJ/LEUKEMIA	80.5-1609 KM	1.0000	5.55E+01	4.00E+01	1.20E+02	1.45E+02
CAN INJ/BONE	80.5-1609 KM	1.0000	7.92E+00	5.22E+00	1.96E+01	2.26E+01
CAN INJ/OTHER	80.5-1609 KM	1.0000	2.63E+02	1.96E+02	5.85E+02	7.28E+02

Southwestern Site

Health Effects Cases		Prob Non-zero	Mean	Quantities 50th	90th	95th
ERL FAT/TOTAL	0-1609 KM	.0013	1.02E-05	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	0-1609 KM	.1122	1.35E-03	0.00E+00	1.35E-04	1.80E-03
ERL INJ/DIARRHEA	0-1609 KM	.0223	1.61E-04	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-1609 KM	.2056	1.57E-02	0.00E+00	3.47E-03	3.51E-02
ERL INJ/SKIN ERYTHEMA	0-1609 KM	.6283	1.20E+00	1.17E-02	1.70E+00	4.33E+00
ERL INJ/TRANSEPIDERMAL	0-1609 KM	.1681	1.32E-01	0.00E+00	2.02E-02	1.48E-01
CAN FAT/TOTAL	0-1609 KM	1.0000	5.52E+02	4.14E+02	1.07E+03	1.21E+03
CAN FAT/LUNG	0-1609 KM	1.0000	9.11E+01	7.02E+01	1.98E+02	2.32E+02
CAN FAT/THYROID	0-1609 KM	1.0000	1.08E+01	9.72E+00	2.01E+01	2.41E+01
CAN FAT/BREAST	0-1609 KM	1.0000	5.86E+01	4.68E+01	1.12E+02	1.34E+02
CAN FAT/GI	0-1609 KM	1.0000	1.79E+02	1.33E+02	3.83E+02	4.72E+02
CAN FAT/LEUKEMIA	0-1609 KM	1.0000	6.12E+01	4.70E+01	1.23E+02	1.48E+02
CAN FAT/BONE	0-1609 KM	1.0000	9.15E+00	7.28E+00	1.99E+01	2.28E+01
CAN FAT/OTHER	0-1609 KM	1.0000	1.42E+02	1.10E+02	2.99E+02	3.34E+02
CAN INJ/TOTAL	0-1609 KM	1.0000	1.04E+03	8.15E+02	2.08E+03	2.56E+03
CAN INJ/LUNG	0-1609 KM	1.0000	1.02E+02	7.98E+01	2.11E+02	2.62E+02
CAN INJ/THYROID	0-1609 KM	1.0000	1.08E+02	9.72E+01	2.01E+02	2.41E+02
CAN INJ/BREAST	0-1609 KM	1.0000	1.73E+02	1.31E+02	3.38E+02	4.27E+02
CAN INJ/GI	0-1609 KM	1.0000	3.06E+02	2.38E+02	6.59E+02	7.78E+02
CAN INJ/LEUKEMIA	0-1609 KM	1.0000	6.12E+01	4.70E+01	1.23E+02	1.48E+02
CAN INJ/BONE	0-1609 KM	1.0000	9.15E+00	7.28E+00	1.99E+01	2.28E+01
CAN INJ/OTHER	0-1609 KM	1.0000	2.84E+02	2.22E+02	6.25E+02	7.29E+02

Southwestern Site

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	0-16.1 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	0-16.1 KM	1.0000	1.26E-01	1.05E-01	2.56E-01	3.11E-01
CAN FAT/LUNG	0-16.1 KM	1.0000	1.61E-02	1.23E-02	3.33E-02	3.99E-02
CAN FAT/THYROID	0-16.1 KM	1.0000	1.71E-03	1.41E-03	3.52E-03	4.27E-03
CAN FAT/BREAST	0-16.1 KM	1.0000	1.10E-02	1.01E-02	2.41E-02	3.08E-02
CAN FAT/GI	0-16.1 KM	1.0000	4.46E-02	3.48E-02	8.89E-02	1.06E-01
CAN FAT/LEUKEMIA	0-16.1 KM	1.0000	1.75E-02	1.27E-02	3.72E-02	3.96E-02
CAN FAT/BONE	0-16.1 KM	1.0000	2.42E-03	2.10E-03	4.19E-03	5.30E-03
CAN FAT/OTHER	0-16.1 KM	1.0000	3.26E-02	3.02E-02	7.46E-02	8.64E-02
CAN INJ/TOTAL	0-16.1 KM	1.0000	2.29E-01	2.02E-01	4.43E-01	5.53E-01
CAN INJ/LUNG	0-16.1 KM	1.0000	1.80E-02	1.38E-02	4.01E-02	5.09E-02
CAN INJ/THYROID	0-16.1 KM	1.0000	1.71E-02	1.41E-02	3.52E-02	4.27E-02
CAN INJ/BREAST	0-16.1 KM	1.0000	3.24E-02	3.02E-02	6.56E-02	7.93E-02
CAN INJ/GI	0-16.1 KM	1.0000	7.63E-02	7.04E-02	1.64E-01	2.08E-01
CAN INJ/LEUKEMIA	0-16.1 KM	1.0000	1.75E-02	1.27E-02	3.27E-02	3.96E-02
CAN INJ/BONE	0-16.1 KM	1.0000	2.42E-03	2.10E-03	4.19E-03	5.30E-03
CAN INJ/OTHER	0-16.1 KM	1.0000	6.53E-02	5.72E+02	1.31E-01	1.62E-01

Southwestern Site

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	80.5-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	80.5-1609 KM	1.0000	9.76E-01	8.18E-01	2.02E+00	2.42E+00
CAN FAT/LUNG	80.5-1609 KM	1.0000	1.53E-01	1.17E-01	3.11E-01	3.54E-01
CAN FAT/THYROID	80.5-1609 KM	1.0000	1.60E-02	1.18E-02	3.23E-02	3.74E-02
CAN FAT/BREAST	80.5-1609 KM	1.0000	9.88E-02	8.28E-02	2.01E-01	2.49E-01
CAN FAT/GI	80.5-1609 KM	1.0000	3.26E-01	2.70E-01	6.94E-01	8.27E-01
CAN FAT/LEUKEMIA	80.5-1609 KM	1.0000	1.11E-01	9.40E-02	2.31E-01	2.80E-01
CAN FAT/BONE	80.5-1609 KM	1.0000	1.61E-02	1.25E-02	3.26E-02	3.93E-02
CAN FAT/OTHER	80.5-1609 KM	1.0000	2.55E-01	2.04E-01	5.50E-01	6.68E-01
CAN INJ/TOTAL	80.5-1609 KM	1.0000	1.82E+00	1.41E+00	3.83E+00	4.72E+00
CAN INJ/LUNG	80.5-1609 KM	1.0000	1.71E-01	1.34E-01	3.54E-01	4.38E-01
CAN INJ/THYROID	80.5-1609 KM	1.0000	1.60E-01	1.18E-01	3.23E-01	3.74E-01
CAN INJ/BREAST	80.5-1609 KM	1.0000	2.92E-01	2.41E-01	6.06E-01	7.27E-01
CAN INJ/GI	80.5-1609 KM	1.0000	5.58E-01	4.55E-01	1.11E+00	1.27E+00
CAN INJ/LEUKEMIA	80.5-1609 KM	1.0000	1.11E-01	9.40E-02	2.31E-01	2.80E-01
CAN INJ/BONE	80.5-1609 KM	1.0000	1.61E-02	1.25E-02	3.26E-02	3.93E-02
CAN INJ/OTHER	80.5-1609 KM	1.0000	5.09E-01	4.26E-01	1.05E+00	1.16E+00

Southwestern Site

Health Effects Cases		Prob Non-zero	Mean	50th	90th	95th
					Quantities	
ERL FAT/TOTAL	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PRODROMAL VOMIT	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/DIARRHEA	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/PNEUMONITIS	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/THYROIDITIS	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/HYPOTHYROIDISM	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/SKIN ERYTHEMA	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ERL INJ/TRANSEPIDERMAL	0-1609 KM	.0000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CAN FAT/TOTAL	0-1609 KM	1.0000	1.86E+00	1.59E+00	3.49E+00	4.00E+00
CAN FAT/LUNG	0-1609 KM	1.0000	2.92E-01	2.71E-01	5.28E-01	5.96E-01
CAN FAT/THYROID	0-1609 KM	1.0000	3.06E-02	2.81E-02	5.54E-02	6.37E-02
CAN FAT/BREAST	0-1609 KM	1.0000	1.88E-01	1.67E-01	3.48E-01	3.99E-01
CAN FAT/GI	0-1609 KM	1.0000	6.21E-01	5.54E-01	1.13E+00	1.26E+00
CAN FAT/LEUKEMIA	0-1609 KM	1.0000	2.15E-01	1.90E-01	3.95E-01	4.75E-01
CAN FAT/BONE	0-1609 KM	1.0000	3.15E-02	2.96E-02	5.61E-02	6.63E-02
CAN FAT/OTHER	0-1609 KM	1.0000	4.83E-01	4.42E-01	9.18E-01	1.04E+00
CAN INJ/TOTAL	0-1609 KM	1.0000	3.46E+00	3.18E+00	6.55E+00	7.34E+00
CAN INJ/LUNG	0-1609 KM	1.0000	3.26E-01	3.05E-01	5.92E-01	6.88E-01
CAN INJ/THYROID	0-1609 KM	1.0000	3.06E-01	2.81E-01	5.54E-01	6.37E-01
CAN INJ/BREAST	0-1609 KM	1.0000	5.53E-01	5.13E-01	1.03E+00	1.14E+00
CAN INJ/GI	0-1609 KM	1.0000	1.06E+00	9.58E-01	2.01E+00	2.37E+00
CAN INJ/LEUKEMIA	0-1609 KM	1.0000	2.15E-01	1.90E-01	3.95E-01	4.75E-01
CAN INJ/BONE	0-1609 KM	1.0000	3.15E-02	2.96E-02	5.61E-02	6.63E-02
CAN INJ/OTHER	0-1609 KM	1.0000	9.66E-01	8.93E-01	1.76E+00	2.08E+00

APPENDIX E
TRANSPORTATION RISK ANALYSIS: RADTRAN 4

Table E-1. Isotopes used to model spent nuclear fuel

Isotope	Ci/shipment	Physical group	Dispersibility category
H-3 GAS	2.89E+02	GAS	10
FE-55	5.19E+02	SOLID	3
CO-60	5.52E+03	HIGH	7
SB-125	3.25E+03	SOLID	3
TE-125M	7.93E+02	SOLID	3
PU-238	1.25E+04	SOLID	3
PU-239	7.95E+02	SOLID	3
PU-240	1.37E+03	SOLID	3
PU-241	1.80E+05	SOLID	3
AM-241	4.02E+03	SOLID	3
CM-244	8.87E+03	SOLID	3
KR-85	1.36E+04	GAS	10
SR-90	1.64E+05	SOLID	3
RU-106	1.27E+03	VOLATILE	7
CS-134	2.05E+04	VOLATILE	7
CS-137	2.33E+05	VOLATILE	7
CE-144	3.17E+02	SOLID	3
PM-147	1.78E+04	SOLID	3
SM-151	9.69E+02	SOLID	3
EU-154	1.49E+04	SOLID	3
EU-155	5.51E+03	SOLID	3

ECOLOGICAL EFFECTS OF THE NUCLEAR FUEL CYCLE

F.1 INTRODUCTION

The purpose of this appendix is to summarize the approach used to characterize the ecological effects of the nuclear 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 impacts on resource categories, and each impact to an external cost or benefit. This appendix defines the resource categories, summarizes the impacts for all phases of the nuclear fuel cycle, and identifies which of those are considered key impacts.

F.2 DEFINITIONS OF RESOURCE CATEGORIES

This section defines the categories to be used in the accounting framework (i.e., the column headings in the matrices that map emissions and impacts). The categories are determined by resources or conditions valued by society, rather than by the medium or path. A particular resource, such as fisheries, can be affected by multiple emissions and by multiple environmental pathways (e.g., both through direct effects of mortality by turbines and by indirect effects of degraded water quality). Resource categories affected by the procurement, processing, transport, and use of fuels for electric power generation can be characterized according to whether they relate to (1) natural biological systems, (2) man-made systems, or (3) nonbiological environmental conditions. The nuclear fuel cycle is not considered to have any impacts on man-made systems such as crops of livestock. Depending on the preexisting conditions and the fuel cycle and energy technology utilized, the impacts discussed under each category (Table F-1) may be adverse or beneficial.

F.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 F-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 destruction or disturbance; physical destruction	Impacts on plants and animals; changes in species composition and community structure
Commercial fishing	Changes in water quality; habitat loss; physical destruction	Diminished production; contamination above regulatory standards and changes in quality
Recreational fishing	Changes in water quality; flow reduction; habitat loss; physical destruction	Diminished opportunity due to reduced production or contamination; increased opportunity due to improved access
Hunting	Habitat/landscape destruction or disturbance; physical destruction	Diminished opportunities to hunt; increased opportunity due to improved access
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 destruction or disturbance; changes in air/water quality; reduced visibility	Changes in opportunities for touring, hiking, swimming, etc.
Nonbiological environmental conditions:		
Land	Altered land use; disturbance; impoundment; contamination	Changes in land values and aesthetics; loss of archeological and historic sites; increased access
Water	Runoff; spills; atmospheric deposition	Changes in availability, clarity, taste, potability and aesthetics
Air	Dust or haze; odors; noise	Changes in visibility and aesthetics

[a]For impacts specific to the nuclear fuel cycle, see Sections 5.7, 6.7, and 7.6.

F.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 pesticide-resistant species), or by the intentional or inadvertent introduction of new gene pools (i.e., hybrid plants or introduced species of animals). Changes in species diversity can result from habitat alterations, extinction of native species, or the introduction of non-native species. Habitat diversity is largely affected by altered land use/land cover patterns. Habitat diversity is especially important for species of animals that require different types of habitats for different life stages or activities (i.e., feeding, shelter, nesting) and for plants that may be dependent on insect pollinators that rely on other habitats (Ranney et al. 1991). Habitat patch size and spatial location is also important, not only in determining animal population size and reproductive success, but also in defining microhabitats, as is the case for animal species which survive only in the interior of large forests.

In general, the greater the biodiversity of desired species, the greater the ecological richness and stability of an area. However, changes in biodiversity at a local level are not necessarily followed by identical changes at the regional or global level. Extinction of native species of plants and animals and their replacement by a greater number of non-native species might be viewed as a local increase in biodiversity; but on a regional or global scale this would represent a decline in biodiversity (Ranney et al. 1991). Threats to biodiversity were recently discussed in the proceedings of the National Forum on Biodiversity (Wilson 1988).

In the context of this report, ecological impacts of fuel technologies on habitats, species, and/or populations, which are not directly related to commercial exploitation or recreational use of natural resources, are considered impacts on biodiversity. Habitat alterations often cause the greatest impacts on biodiversity because numerous species can be affected. In addition, small unique habitats, which may be of limited scenic or recreational value, but which may be considered valuable for commercial development, may contain rare or endangered species of small population size and limited geographic distribution. Specific impacts which are of concern include those on threatened or endangered species, legally protected areas (e.g., Wild and Scenic Rivers), and other ecologically valued natural systems (e.g., wetlands, pine barrens, riparian areas, bogs). These impacts may come about as a result of (1) altered land use, (2) local or regional changes in environmental parameters, or (3) the introduction of toxic substances which may adversely affect the growth or survival of populations.

Although heavily modified by man's activities, the southeastern United States supports a number of endangered and threatened species, as well as relict examples of a number of previously common ecosystem types. Potential hydropower development sites in the Northwestern part of the country are often in remote areas and likely to have valued ecosystems such as old-growth forest or habitat for endangered and threatened species.

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 Fig F-1(a) and F-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 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 damages [Fig. F-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

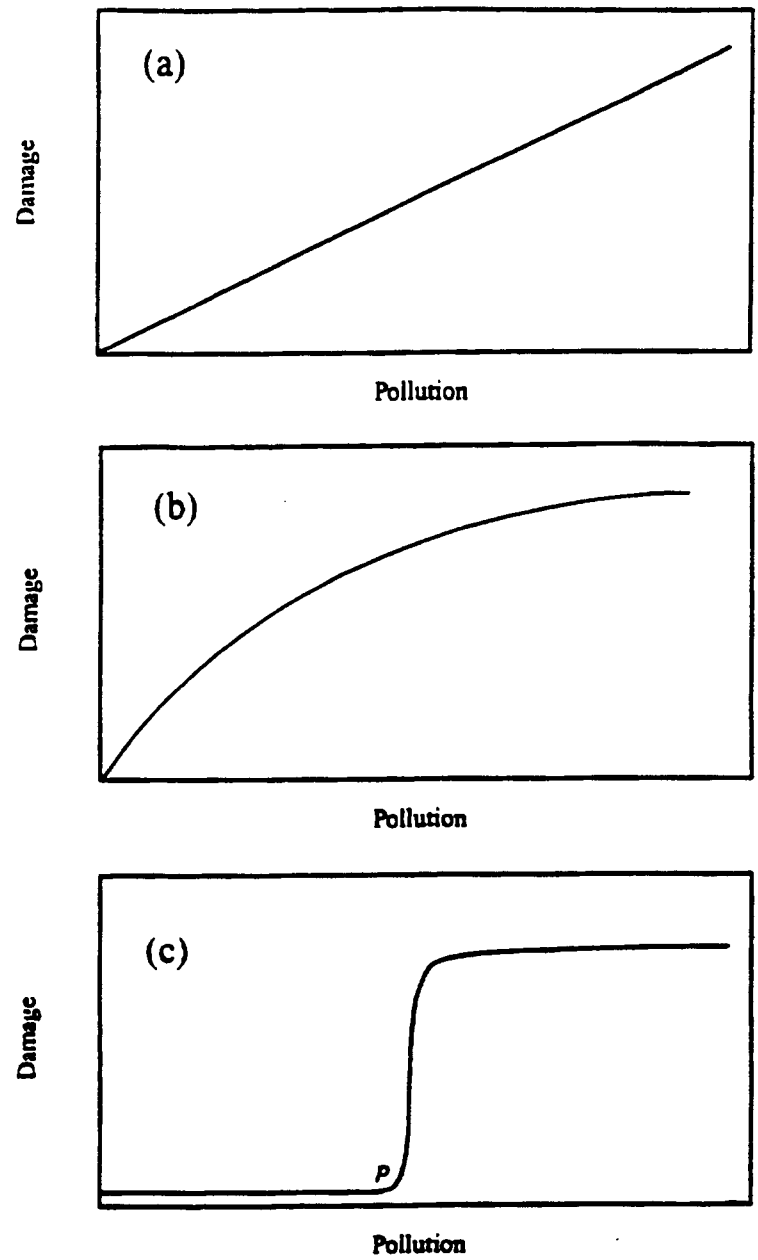

Figure F-1. Relationship between damage and pollution. Marginal assessment of cases (a) and (b) is reasonably straightforward. However, the discontinuity in case (c) complicates analysis. A large increase in damage is associated with the small increment in pollution at point P that raises deposition above a critical load. Note that these figures have been idealized for illustrative purposes.

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 F-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 degradation 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 industrialized 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 (Fig. F-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.

F.2.1.2 Commercially Valuable Natural Resources

Commercially valuable natural resources, such as fisheries and timber, can be affected at various stages of a fuel cycle. Fisheries resources can be affected by physical habitat destruction or alteration (e.g., dewatering of streams) or changes in water quality which can result in the loss of commercially valuable fish such as salmon populations due to direct kills, reductions in productivity (growth, population size or reproductive success), or by the accumulation of contaminants at levels above regulatory standards. Water quality parameters of importance to fisheries are temperature, pH, dissolved oxygen, suspended sediments, plant

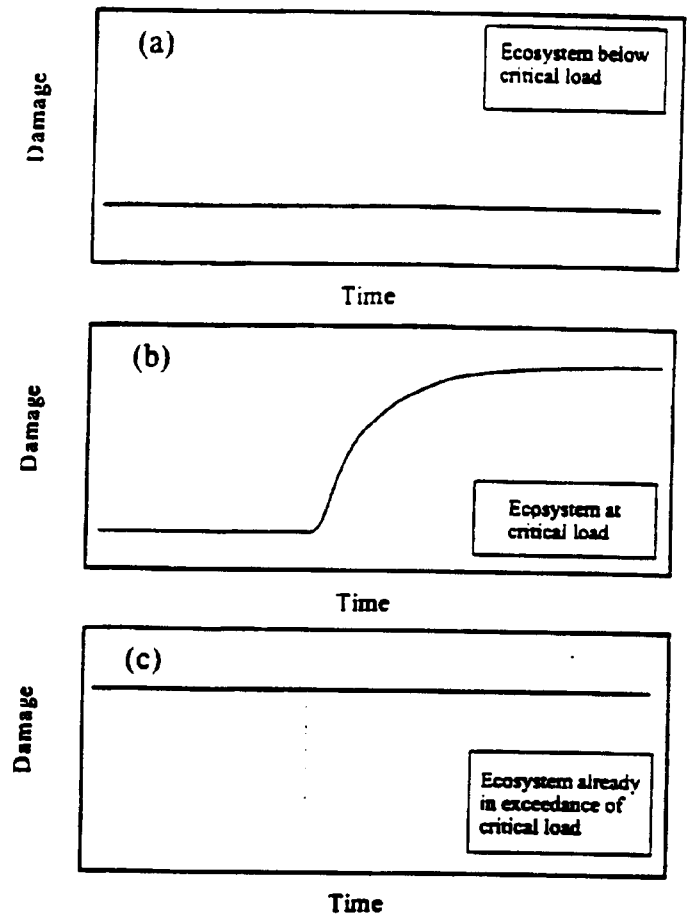

Figure F-2. Theoretical effect of the introduction of an incremental power plant (show by the vertical line) on ecosystems which differ in existing deposition relative to their critical load. This example is based on a scenario under which future emissions do not otherwise change. The ecosystem represented 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 simplified for illustrative purposes.

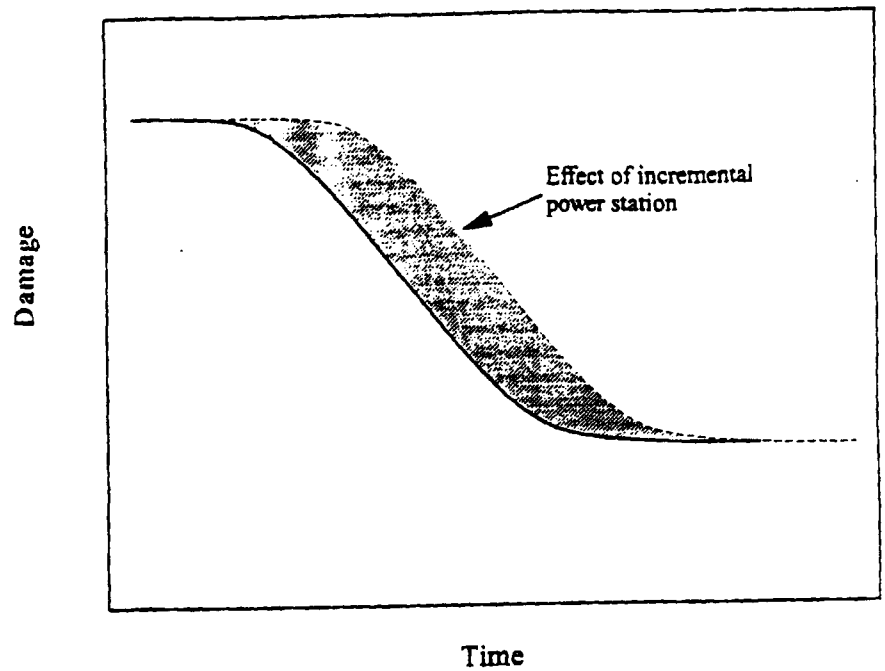

Figure F-3. Recovery of ecosystems following reduction of pollutant deposition to below critical loads/levels. Recovery is shown both with (solid line) and without (dashed line) the incremental power station. The marginal damage is that associated with the delay in recovery, shown by the shaded area 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 foreseeable future.

nitrates), and toxic substances. Water quality can be affected by spills, surface runoff, and atmospheric deposition. The latter pathway has recently been identified as the principal source of PCBs, dioxin, and heavy metals in many water bodies; however, no quantitative estimates of biological impacts from this source are available at this time.

Commercial fishing is not an important industry near either the Southeastern reference site or the Southwestern site.

The timber industry may be affected by the development of a specific energy technology as a result of the elimination of land for forest use, or the deposition of air contaminants on foliage causing direct phytotoxicity or reduced growth, or by soil contamination leading to leaching of soil nutrients. Extensive stands of pines are grown in the Southeast for pulp production, and national forests in the area are utilized for hardwood production. In the Northwest, logging practices in forested areas are more likely to have impacts on ecological resources than is small-scale development.

F.2.1.3 Recreationally Valuable Natural Resources

Forests, parks, streams, lakes, rivers, 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 warm-water 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 and striped bass). Cold-water streams in the southern Appalachians and on the Cumberland Plateau support fisheries for rainbow, brown, and brook trout. Reduced populations and habitat are significant issues with regard to sustainable fish populations.

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.

National forests and the Great Smokey 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).

F.2.2 MAN-MADE SYSTEMS

F.2.2.1 Agricultural, Silvicultural, and Horticultural Industries

Fuel cycles and energy technologies may affect the agricultural, silvicultural, and horticultural industries by reducing the amount of land available for such use, or by reducing crop yields as a result of direct deposition of phytotoxic air contaminants or soil contamination following deposition or irrigation with contaminated water. Small-scale hydroelectric development would not significantly affect man-made systems.

F.2.3 NONBIOLOGICAL ENVIRONMENTAL CONDITIONS

Included in this category are general aesthetic considerations such as physical alterations to the landscape and natural bodies of water; changes in visibility due to increases in moisture content, hydrocarbons, or particulate concentrations in the air; the release of noxious odors from stacks or motor vehicles; changes in water clarity, taste, and potability due to surface runoff or the addition of process or waste water effluents; and increases in noise due to machinery and vehicles. Water availability can also be affected by power generating facilities, and can be a major issue in areas where water resources are limited.