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Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "as Low as Practicable" Guides—Fabrication of Light-Water Reactor Fuels Containing Plutonium

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CHEMICAL TECHNOLOGY DIVISION

CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND THE ENVIRONMENTAL
IMPACT OF WASTE EFFLUENTS IN THE NUCLEAR FUEL CYCLE FOR USE IN
ESTABLISHING "AS LOW AS PRACTICABLE" GUIDES — FABRICATION
OF LIGHT-WATER REACTOR FUELS CONTAINING PLUTONIUM

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MAY 1975

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PUBLICATION NOTICE

This engineering survey report was developed for the Nuclear Regulatory Commission (NRC) - Office of Standards Development (formerly the Regulatory Office of the Atomic Energy Commission). It is one of a series of draft reports on segments of the nuclear fuel cycle that were prepared in 1973 and 1974 and were made available to the public in December 1974. These draft reports are subject to revision prior to, and subsequent to, their publication by the NRC in conjunction with draft environmental statements for comment by the public and government agencies.

The reports in this series are:

B. C. Finney, R. E. Blanco, R. C. Dahlman, F. G. Kitts, and J. P. Witherspoon, Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides - Nuclear Fuel Reprocessing, ORNL-TM-4901 (May 1975).

W. H. Pechin, R. E. Blanco, R. C. Dahlman, B. C. Finney, R. B. Lindauer, and J. P. Witherspoon, Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides - Fabrication of Light-Water Reactor Fuel from Enriched Uranium Dioxide, ORNL-TM-4902 (May 1975).

M. B. Sears, R. E. Blanco, R. C. Dahlman, G. S. Hill, A. D. Ryon, and J. P. Witherspoon, Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides - Milling of Uranium Ores, ORNL-TM-4903, Vol. 1 (May 1975).

A. D. Ryon and R. E. Blanco, Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides - Appendix A. Preparation of Cost Estimates for Volume 1, Milling of Uranium Ores, ORNL-TM-4903, Vol. 2 (May 1975).

W. S. Groenier, R. E. Blanco, R. C. Dahlman, B. C. Finney, A. H. Kibbey, and J. P. Witherspoon, Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides - Fabrication of Light-Water Reactor Fuels Containing Plutonium, ORNL-TM-4904 (May 1975).

L. R. McKay (Ed.), A Methodology for Calculating Radiation Doses from Radioactivity Released to the Environment, ORNL-4992 (1975). (This report serves as Appendix B for all of the above reports.)

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CONTENTS

	<u>Page</u>
List of Tables	vii
List of Figures	x
Abstract	xiii
1.0 Summary and Conclusions	1
2.0 Introduction	5
3.0 Objectives and Assumptions	8
3.1 Objectives	8
3.2 Selection of the Model Plant	9
3.3 Management of Radioactive Wastes	11
3.4 Cost Parameters	12
3.5 Equipment Operation	13
3.6 Plant Siting	13
3.7 Radiological Impact	14
3.8 References	14
4.0 Source Term for Radioactive Releases	16
4.1 Origin of the Radioactive Wastes in LWR Mixed-Oxide Fuel Fabrication Plants	16
4.1.1 Oxalate Process for Production of Plutonium Oxide.	17
4.1.2 Fuel Fabrication Process	17
4.1.3 Recycle System	18
4.1.4 Scrap Recovery System	18
4.1.5 Scrubber Systems	19
4.1.6 Miscellaneous Liquid Wastes	19
4.1.7 Miscellaneous Solid Wastes	19
4.1.8 Process Gaseous Effluent	20
4.1.9 Ventilation Gaseous Effluent	21
4.2 Composition and Amount of Radioactive Material Entering Model Plant.	21
4.3 Description of Waste Treatment Methods	24
4.3.1 Gaseous Radwaste Treatment Systems	24
4.3.2 Liquid Radwaste Treatment Systems	32
4.3.3 Solid Radwaste Treatment System	34
4.4 Selection of Case Studies.	34
4.5 Description of Case Studies and Calculation of Source Terms	34
4.5.1 Gaseous and Liquid Radwaste Treatment Cases	35
4.5.2 Calculation of Source Terms	36
4.6 References	37

CONTENTS

	<u>Page</u>
5.0 Nonradioactive Wastes	41
5.1 Nonradioactive Chemical Releases	41
5.2 Recovery and Reuse of Chemicals	41
5.3 Chemical and Sanitary Waste	41
5.4 References	41
6.0 Costs	43
6.1 Capital Costs	43
6.1.1 Direct Costs	44
6.1.2 Indirect Costs	44
6.2 Annual Fixed Charge and Operating Costs	44
6.3 References	45
7.0 Environmental Impact	46
7.1 Meteorology	47
7.2 Population	49
7.3 Radiation Dose from Gaseous Effluents	50
7.3.1 Individual and Population Dose	51
7.3.2 Dose to Organs of Individuals	52
7.4 Radiation Dose from Aquatic Pathways	53
7.5 Total Radiation Dose from All Pathways	54
7.6 Radiation Doses to Organisms Other Than Man	54
7.7 Estimates of Error for Atmospheric Dilution and Population Parameters	54
7.8 Exposures from Long-Lived Actinides Released into the Environment from a Mixed-Oxide Fuel Fabrication Plant	55
7.8.1 Source Term	56
7.8.2 Pathways of Exposure	57
7.8.3 Dose Estimates	59
7.9 References	60
8.0 Correlation of Environmental Impact with Cost of Waste Treatment	63
8.1 Comparison of Gaseous Radwaste Treatment Costs and Radiological Dose	64
8.2 Comparison of Gaseous Radwaste Treatment Costs and Power Costs	67
Tables	68
Figures	101
Appendix A. Preparation of Cost Estimate	121

LIST OF TABLES

		<u>Page</u>
Table 4.1	Material Flow in the Oxalate Process for the Production of Plutonium Oxide	68
Table 4.2	Material Flow in the Scrap Recovery System	69
Table 4.3	Material Flow in the Scrap Recovery System	70
Table 4.4	Liquid Radwaste Generated by the Model Mixed-Oxide Fuel Fabrication Plant Before Effluent Treatment	71
Table 4.5	Characteristics of the Isotopes in the Feed to the Model Mixed-Oxide Fuel Fabrication Plant	72
Table 4.6	Isotopic Concentrations and Relative Inhalation Hazards in the Feed to the Model Mixed-Oxide Fuel Fabrication Plant	73
Table 4.7	Distribution of Alpha and Beta Radioactivity in the 4.2 wt % Plutonium Mixed-Oxide Feed to the Fabrication Plant	74
Table 4.8	Solid Radioactive Wastes	75
Table 4.9	Summary of Variables for Model LWR Mixed-Oxide Fuel Fabrication Plant Gaseous Radwaste Treatment Systems . . .	76
Table 4.10	Source Terms for Model Mixed-Oxide Fuel Fabrication Plant - Calculated Release of Radioactive Material in Gaseous Effluents	77
Table 4.11	Material Flow in the Oxalate Process Liquid Radwaste Treatment System	78
Table 4.12	Material Flow in the Scrap Recovery Liquid Radwaste Treatment System	79
Table 5.1	Water Usage and Overall Liquid Material Balance	80
Table 6.1	Estimated Annual Costs and Contribution to Power Cost for the 300-Metric Ton/yr Model Mixed-Oxide Recycle Fuel Fabrication Plant Gaseous Radwaste Treatment Cases	81
Table 6.2	Installed Equipment Costs for Model Mixed-Oxide Fuel Fabrication Plant	82

LIST OF TABLES

	<u>Page</u>
Table 7.1 Latitude-Longitude Coordinates Used to Derive Data Sets for Population Distribution	83
Table 7.2 Representative Population Distribution at Successive Distances for Midwestern Site	84
Table 7.3 Representative Population Distribution at Successive Distances for Coastal Plain Site	85
Table 7.4 Summary of Annual Doses to Individuals and Population from Gaseous Effluent of a Model Mixed-Oxide Fuel Fabrication Plant on a Coastal and a Midwestern Site . .	86
Table 7.5 Average Annual Doses to the Organs of the Population . .	87
Table 7.6 Contribution of Exposure Modes to Total Body Dose from the Gaseous Effluent of a Model Mixed-Oxide Fuel Fabrication Plant	88
Table 7.7 Cumulative Population and Dose (man-rem) from Gaseous Effluents as a Function of Distance from a Model Mixed-Oxide Fuel Fabrication Plant on a Coastal and a Midwestern Site	89
Table 7.8 Major Radionuclides Contributing to Dose to Individuals from Gaseous Effluents via Terrestrial Pathways at 0.5 Mile from a Model Mixed-Oxide Fuel Fabrication Plant	90
Table 7.9 Percent Contributions of Inhaled and Ingested Radio- nuclides from the Gaseous Effluent of a Model Mixed- Oxide Fuel Fabrication Plant to Individual Organ Doses	90
Table 7.10 Annual Total Body Dose (mrem) from Aquatic Pathways at a Model Mixed-Oxide Fuel Fabrication Plant	91
Table 7.11 Annual Dose to Biota Living in an Estuary Near a Model Mixed-Oxide Fuel Fabrication Plant at a Coastal Site	92
Table 7.12 Annual Dose to Biota Living in a Freshwater River Near a Model Mixed-Oxide Fuel Fabrication Plant at a Midwestern Site	93

LIST OF TABLES

	<u>Page</u>
Table 7.13 Typical Variability of X/Q' Values and Population Data at Midwestern and Coastal Sites	94
Table 7.14 Curies of Actinides Released During Lifetime of the Model Fuel Fabrication Plant	95
Table 7.15 Contribution of Radionuclides and Exposure Modes to the Average Annual Total Body Dose to Individuals from the Time of Cessation of Plant Operation and Until the Ultimate Decay of all Radionuclides	96
Table 7.16 Average Annual Doses to Individuals (Resulting from the Radionuclides Released During the Operation of the Model Fuel Fabrication Plant) from the Time of Cessation of Plant Operation and Until the Ultimate Decay of all Radionuclides	97
Table 7.17 Average Annual Dose to the Population (Resulting from Radionuclides Released from the Model Fuel Fabrication Plant) From the Time of Cessation of Plant Operation and Until the Ultimate Decay of all Radionuclides	98
Table 8.1 Radiation Dose from Gaseous Effluents and Annual Cost of Radwaste Treatment at Model Mixed-Oxide Fuel Fabrication Plant	99
Table 8.2 Incremental Gaseous Radwaste Treatment Cost and Total Body Dose Between Case Studies at Model Mixed-Oxide Fuel Fabrication Plant at Coastal or Midwestern Sites	100

LIST OF FIGURES

	<u>Page</u>
Fig. 4.1 Oxalate Process for Production of Plutonium Oxide (0.042 metric ton Pu/day)	101
Fig. 4.2 Fabrication of Fuel for Plutonium Recycle Reactors (1.0 metric ton U+Pu/day)	102
Fig. 4.3 Recycle System (0.1 metric ton U+Pu/day)	103
Fig. 4.4 Scrap Recovery System (0.02 metric ton U+Pu/day)	104
Fig. 4.5 Plant Ventilation and Off-Gas Systems Before Final Gaseous Radwaste Treatment (Cases 1 and 2)	105
Fig. 4.6 Gaseous Radwaste Treatment System (Case 1)	106
Fig. 4.7 Gaseous Radwaste Treatment System (Case 2)	107
Fig. 4.8 Plant Ventilation, Off-Gas, and Gaseous Radwaste Treatment Systems (Case 3)	108
Fig. 4.9 Oxalate Process Liquid Radwaste Treatment System	109
Fig. 4.10 Scrap Recovery Liquid Radwaste Treatment System	110
Fig. 4.11 Solid Radwaste Treatment System	111
Fig. 4.12 Fuel Fabrication and Radwaste Systems	112
Fig. 4.13 Miscellaneous Liquid Waste Treatment	113
Fig. 5.1 Water Usage and Overall Liquid Flowsheet	114
Fig. 7.1 Pathways for External and Internal Exposure of Man	115
Fig. 7.2 Minimum and Maximum X/Q' for Ground Level Release at Midwestern Site. Average values of X/Q' for 16 sectors fall between these limits at respective distances	116
Fig. 7.3 Minimum and Maximum X/Q' for Ground Level Release at Coastal Plain Site. Average values of X/Q' for 16 sectors fall between these limits at respective distances	117

LIST OF FIGURES

	<u>Page</u>
Fig. 8.1 Annual Cost for Reduction of Maximum Annual Dose from Gaseous Effluents at 0.5-Mile Distance from Model Mixed-Oxide Fuel Fabrication Plant. (Doses are not significantly different for coastal and midwestern locations.)	118
Fig. 8.2 Annual Cost for Reduction of Annual Population Dose out to a Radius of 55 Miles from Gaseous Effluent from Model Mixed-Oxide Fuel Fabrication Plant	119

4

5

6

7

ABSTRACT

A cost-benefit study was made to determine the cost and effectiveness of radioactive waste (radwaste) treatment systems for decreasing the release of radioactive materials from a model light-water plutonium recycle reactor fuel fabrication plant, and to determine the radiological impact (dose commitment) of the released materials on the environment. The study is designed to assist in defining the term "as low as practicable" in relation to limiting the release of radioactive materials from nuclear facilities. The base case model plant is representative of current plant technology and has an annual capacity of 300 metric tons of LWR plutonium recycle fuel. Additional radwaste treatment equipment is added to the base case plants in a series of case studies to decrease the amounts of radioactive materials released and to reduce the radiological dose commitment to the population in the surrounding area. The cost for the added waste treatment operations and the corresponding dose commitment are calculated for each case. In the final analysis, radiological dose is plotted vs the annual cost for treatment of the radwastes. The status of the radwaste treatment methods used in the case studies is discussed. Some of the technology used in the advanced cases is in an early stage of development and is not suitable for immediate use. The methodology used in estimating the costs and the radiological doses, detailed calculations, and tabulations are presented in Appendixes A and B.

CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND THE ENVIRONMENTAL
IMPACT OF WASTE EFFLUENTS IN THE NUCLEAR FUEL CYCLE FOR USE IN
ESTABLISHING "AS LOW AS PRACTICABLE" GUIDES - FABRICATION
OF LIGHT-WATER REACTOR FUELS CONTAINING PLUTONIUM

W. S. Groenier	B. C. Finney
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R. C. Dahlman	J. P. Witherspoon

1.0 SUMMARY AND CONCLUSIONS

A study was made to determine the cost and the effectiveness of radioactive waste (radwaste) treatment systems for decreasing the release of radioactive materials from a model light-water plutonium recycle reactor fuel fabrication plant and to determine the radiological impact (dose commitment) of the released radioactive materials on the environment. The model plant is representative of currently proposed commercial designs of plants that will fabricate uranium and plutonium mixed-oxide pellets which are inserted into fuel rods. The pellets are fabricated from plutonium oxide and natural uranium oxide powders which are received as feed materials. Alternatively, an aqueous plutonium nitrate solution can be received as feed and converted to plutonium oxide powder. The model plant processes 300 metric tons of uranium and plutonium (as metal) per year, i.e., a nominal one ton per day on a 300-day-per-year basis. The radionuclides entering the plant in the plutonium feed are those in existence following an aging time of 24 months after plutonium purification in the fuel reprocessing plant. The uranium radioisotopes are those that are in equilibrium in natural uranium. These radionuclides are considered in the radiological impact studies. The gaseous waste effluents from the plant are treated to remove radioactive materials and noxious chemicals (nitrogen oxides, ammonia), and the gaseous effluents are then released to the environment. The liquid wastes are treated to recover uranium and plutonium values and to recycle nitric acid and water. The treated liquid radwastes are solidified and shipped to licensed commercial burial grounds. No radioactive liquids are released. The model plant is evaluated at two locations, a midwestern site and a southeastern coastal site. Typical meteorological

patterns and population densities for these areas are used for each site.

Three conceptual gaseous radwaste treatment cases and their corresponding flowsheets were prepared for treating the wastes from the model plant. Case 1, the base case, represents the lowest cost and current practice. In each of the succeeding cases, gaseous radwaste treatment equipment is added to accomplish specific objectives. An additional bank of High Efficiency Particulate Air (HEPA) filters is added in Case 2. In Case 3, the treatment systems for the process off-gas, the alpha enclosure ventilation air, and the plant ventilation air are redesigned to feature recycle of 98% of the treated process off-gas and alpha enclosure ventilation air streams and to include the addition of several banks of HEPA filters. All of the equipment is presently available. However, some additional development may be required for the design and operation of air recycle control systems and in the construction and maintenance of sealed filter bank enclosures. The liquid and solid radwaste systems are considered as part of the base plant (Case 1) and are not variables in the study. The case studies and cost estimates for the model plant are based on the design and construction of a new plant. Backfitting of existing plants is not evaluated. The efficiency of a treatment system or plant for retention of radioactive material is expressed as a decontamination factor (DF), i.e., the ratio of the amount of material entering a plant to that released to the environment. The general plans for the studies are summarized in Table 4.9.

The annual amounts of radioactive materials released (the source terms), the capital, annual, and contribution to power costs, and the radiological impact are calculated for each case. The dose commitments for each case were calculated for: (1) the maximum annual individual total body, bone, liver, lung, and kidney doses at 0.5 mile from the plant (factors are provided to project the maximum dose to greater distances); (2) the incremental maximum annual individual dose at 0.5 mile, which represents the difference in dose between a given case and the preceding case; and (3) the annual average population total body dose out to a distance of 55 miles. The costs are estimated as the total required for treatment of

the radwaste effluent in each case. The difference in cost between adjacent cases is the incremental cost. The costs and doses are summarized in Tables 6.1 and 7.4. Additional correlations are presented in Sect. 8.0. The difference in dose commitment at the two sites is the result of differences in meteorology and population distribution at the two sites. Internal exposure to radiation through inhalation and ingestion of radionuclides from gaseous effluents accounts for 99% of the total body dose to individuals and population around the plant. The principal radionuclides contributing to this dose are ^{238}Pu and ^{241}Pu . Estimated maximum total body doses do not exceed 0.01 millirem/yr to individuals living within 0.5 to 1 mile from the base (Case 1) plant at either site. These doses are low as compared with the population dose from background radiation, i.e., 100 to 170 millirem/yr. The maximum dose to individuals is not significantly different at the two sites. However, the population dose is slightly higher at the midwestern site because of the greater population density. Population dose commitments of 0.0082 man-rem for the coastal site and 0.011 man-rem for the midwestern site out to a distance of 55 miles from the plant are also low.

Annual total body doses were estimated for exposure by aquatic pathways, assuming river and estuary contamination by particle fallout from the atmosphere. These doses were much less than those estimated for terrestrial pathways.

The long-term average annual total body dose to individuals living within 50 miles of the model plant (in Case 1) for the period of time after the plant has closed is estimated to be about 2.8×10^{-7} millirem (Sect. 7.8.3). This estimate is based on the assumptions that all of the actinides are deposited within 50 miles of the plant and that none of the actinides are lost by runoff in rainwater, deep penetration into the soil, etc. The estimated average annual dose is based on very conservative assumptions.

The doses in Case 3 are about a factor of 10^7 lower than in Case 1. The largest dose is for bone, followed by liver, kidney, total body and lung doses. The maximum annual individual dose from gaseous effluents at 0.5 mile is compared with the annual gaseous radwaste treatment cost

in Fig. 8.1. For the coastal site, the total body dose decreases from 0.0085 millirem in Case 1 to 8.5×10^{-10} millirem in Case 3 for an additional annual cost of \$463,000. Similarly, the annual average dose to the population at the coastal site decreases from 0.0082 man-rem in Case 1 to 8.2×10^{-10} man-rem in Case 3 for the same additional cost (Fig. 8.2).

The incremental costs and doses between the case studies indicate that the cost-benefit ratio, in terms of dollars per millirem reduction of maximum annual total body dose from gaseous effluents at 0.5 mile, increases from \$21,600,000 for the Case 1 to Case 2 increment, to \$3,310,000,000 for the Case 2 to Case 3 increment. The cost-benefit ratio for the initial Case 1 treatment, i.e., the increment from no final off-gas treatment to Case 1, is \$224 per millirem. Thus, a cost-benefit ratio increase by a factor of 96,000 occurs from Case 1 to Case 2, and by a factor of 150 for Case 2 to Case 3, indicating that Case 1 offers the optimum cost-benefit ratio.

The capital cost of the total plant for the base case (Case 1) is taken as \$40 million. This includes the \$2.7 million cost for the gaseous radwaste treatment system. The total annual cost of the off-gas treatment of \$0.76 million in Case 1 corresponds to a contribution to power cost of 0.00988 mill/kWhr. Capital costs for the gaseous radwaste treatment systems in Cases 2 and 3 range from \$3.35 to \$4.4 million, or up to about 11% of the capital cost of the total base plant. The annual charges associated with the advanced cases of gaseous radwaste treatment range from \$0.94 to \$1.2 million and are equivalent to contribution to power costs of 0.0122 and 0.0159 mill/kWhr, respectively. All of these values are less than about 0.2% of an estimated total power generation cost of 7 to 10 mill/kWhr. Thus, while the absolute dollar costs for advanced gaseous radwaste treatment systems are high, the percentage of the total capital cost and the contribution to total power generation costs are low.

2.0 INTRODUCTION

This study was performed to determine the cost and the effectiveness of radioactive waste (radwaste) treatment systems that are used, or could be used, at plants which fabricate plutonium-bearing fuels for light-water reactors (LWRs) to decrease the amount of radioactive and nonradioactive materials released to the environment. A second objective is to determine the radiological impact (dose commitment) of these releases on the environment. The effectiveness of the alternate radwaste treatment systems under consideration is measured by comparing the quantities of radioactive materials released by the various systems and the relative impact of each release on the environment. The amount of radioactive material released in each case is designated "the source term," since these values are used in evaluating the impact of radioactive releases on the environment. The impact on the environment is assessed and compared with the radwaste treatment costs as the basis for a cost-benefit analysis.

Light-water plutonium recycle reactor fuels are fabricated from plutonium that has been generated at LWR power stations in previous fuel loadings. This plutonium is recovered and separated from the uranium and fission products in spent LWR fuels in a fuel reprocessing plant. The LWR power stations that use recycle plutonium fuels are called light-water plutonium recycle reactors, or mixed-oxide reactors. The term "mixed oxide" is often applied because plutonium recycle reactors contain fuels composed of both plutonium oxide and natural uranium oxide ($\text{PuO}_2\text{-UO}_2$), as well as enriched uranium oxide (UO_2). Conventional LWRs contain only enriched UO_2 . The LWR recycle plutonium fuel contains about 3 wt % fissionable plutonium in place of ^{235}U , the usual fissionable constituent in enriched uranium LWR fuel; the remainder of the fuel is natural uranium. The fuel is fabricated from uranium and plutonium oxide powders which are shipped to the fabrication plant from enriched uranium fuel fabrication plants and fuel reprocessing plants (or plutonium storage facilities), respectively. Alternatively, in plants considered for the near future, aqueous plutonium nitrate solution is shipped from the plutonium storage facility and is converted to plutonium oxide powder in the fabrication

plant. Fuel rods are fabricated from solid pellets formed from the uranium and plutonium oxide powders, and the pellets are inserted into zirconium or stainless steel tubes. The fuel rods are shipped to an enriched uranium fuel fabrication plant, where they are formed into fuel assemblies prior to shipment to nuclear power plants. A fuel assembly for a pressurized water reactor contains only mixed-oxide ($\text{PuO}_2\text{-UO}_2$) fuel rods, whereas a boiling water reactor assembly contains both enriched uranium oxide and mixed-oxide fuel rods. The radioactive materials entering the fuel fabrication plant consist primarily of various isotopes of uranium and plutonium along with americium, which is formed by the radioactive decay of plutonium. Small amounts of other radioactive decay products are also present. A small fraction of the radioactive materials is suspended in the off-gas from process areas as dusts or aerosols. These are formed during the chemical and mechanical fuel fabrication operations. Treatment systems are used to minimize the release of these materials in the gaseous effluent from the plant. Liquid effluent treatment systems are used to recover uranium, plutonium, and nonradioactive materials such as nitric acid or water, and to recycle these materials to the processing operations. No radioactive liquids are released from the plant. Residues from the treatment of liquid radwastes are solidified and shipped offsite for disposal.

A model plant that is typical of current designs for LWR recycle plutonium fuel fabrication plants is used as the base case for this study. The feed materials for the model plant consist of uranium and plutonium oxide powders or, alternatively, in plants considered for the near future, uranium oxide powder and aqueous plutonium nitrate solution. The radiological impact of the plant is considered at two typical sites, i.e., a midwestern and a southeastern coastal plain. Increasingly effective gaseous radwaste treatment systems are added to the "base" plant in case studies, and the annual cost and environmental impact of each case are calculated as the basis for cost and benefit analysis. It was not feasible to include all possible variations of plant types and waste treatment systems. However, sufficient information is provided in the study to estimate costs and impacts for other radwaste treatment systems by

extrapolation from the data provided. The base case study illustrates important features of plants currently being designed. No sizable production operation exists at this time. The advanced cases use advanced design concepts, which include the recycle of treated process off-gases and alpha enclosure ventilation air and the use of additional high-efficiency (HEPA) filter banks. All of the treatment equipment is presently available. However, some additional development may be required for the design and operation of air recycle control systems and in the construction and maintenance of sealed filter bank enclosures.

3.0 OBJECTIVES AND ASSUMPTIONS

3.1 Objectives

The objectives of this study are: (1) to determine the dollar cost to reduce the amount of radioactive and noxious nonradioactive materials released to the environment from that achieved in plants designed to use current treatment systems, to very low levels by means of advanced, complex treatment systems; and (2) to determine the radiologic environmental impact (dose) of the radioactive effluents released from these conceptual installations. The definition of the incremental value of additional radioactive waste treatment equipment in terms of additional effectiveness is an important part of the basic objective and is emphasized in the study. Generally, these values will not change with size of the plant. For example, the amount of waste effluent to be treated generally increases with the plant size and, in turn, larger treatment systems are required. However, the fraction released is essentially the same for large and small systems. Therefore, a larger total amount of radioactive material is released by the larger system when operating on the same type, but larger volume, of radioactive effluent. The calculated total amounts of radioactive materials released are also presented but are of less importance in this study, since these values vary with plant size. Consequently, the incremental and absolute values derived in this study for a single size of conceptual plant may be extrapolated to larger or smaller plants. The volumes of radwastes were selected on the assumption that a careful internal waste management program has been followed.

Estimates are made of the average annual radioactive and nonradioactive releases and the annual cost of waste treatment over the 20-yr operating lifetime of the fabrication plant. In a similar study for nuclear power reactors, emphasis was placed on maintaining continuous operation of the power plant.¹ Consequently, the more complex radwaste treatment systems contained redundant (parallel) treatment units to ensure continued operation should one of the units become inoperable. In the fuel fabrication study, less emphasis is placed on continuous operation, since the plant could temporarily cease operations in the event that a major radwaste treatment

unit failed. Only potential releases from normal operations, including anticipated operational occurrences, have been considered in this study.

3.2 Selection of the Model Plant

The model plant selected for the base case (Case 1) is similar to plants being designed in 1973 and is representative of the plants that will fabricate the major load of fuel throughout the next two decades.²⁻⁵ The plant will process 300 metric tons of heavy metal (U + Pu) per year, i.e., a nominal one-ton-per-day plant operating for 300 days per year. Natural uranium oxide and plutonium oxide powders or plutonium nitrate solutions are received as feed materials at the plant. Depleted uranium could also be used, but this variation is not included in the present study. The natural uranium oxide powder is blended with plutonium oxide powder to form a mixed oxide containing 4 to 5 wt % total plutonium, which is pelletized and loaded into zirconium or stainless steel tubes. Alternatively, plutonium nitrate solutions are converted to plutonium oxide (by the oxalate process) for use as a feed material. In the oxalate process, plutonium oxalate, $\text{Pu}(\text{C}_2\text{O}_4)_2 \cdot 6\text{H}_2\text{O}$, is precipitated from an aqueous plutonium nitrate solution. The plutonium oxalate is subsequently dried and calcined to form plutonium oxide.^{6,7} Present federal regulations permit the shipment of a solution of plutonium nitrate.⁸ However, the availability of plutonium nitrate as a feed material is probably limited to the next few years unless the fuel fabrication facility is located adjacent to a reprocessing plant. A proposed regulation would limit the shipment of plutonium to plutonium oxide.⁹ A long-range view of mixed-oxide fuel fabrication generally considers that only specification-grade UO_2 and PuO_2 powders will make up the feed material such that no further purification is required at the fabrication plant.

The relative quantities of uranium and plutonium in the feed to the fabrication plant are based on calculations of the lifetime average reload fuel requirement for a 1000-MW(e) plutonium recycle reactor of the boiling water type, assuming 12 years of plutonium recycle before plutonium equilibrium is reached. Also assumed is "nominal" self-generation, which is the use of all self-generated plutonium in each cycle plus additional

plutonium to attain a charge that is 15% greater than would be achieved by the reactor at self-generating equilibrium. The overall radionuclide content of the feed is shown in Sect. 4.2.

All processing steps which involve radioactive materials are performed in process vessels, process cells, or alpha enclosures (such as glove boxes). The gaseous effluents or off-gases from the processing steps each receive a separate pretreatment. The treated process gases and alpha enclosure ventilation air are combined with the ventilation air from personnel operating areas for final treatment. Similar treatments are used for the combined, final gaseous effluents regardless of whether plutonium oxide powder or plutonium nitrate solution is received as feed material, since the composition and volume of off-gases are similar in each instance. In the model plant where plutonium nitrate solution is received as feed material, the off-gases from the equipment that is used to process plutonium and uranium solutions receive an extra purification treatment in scrubbers prior to being combined with the other off-gases. Thus, the amount of radioactive materials released from the model plant (source terms) is the same whether the plant processes plutonium oxide powder or converts plutonium nitrate solution to plutonium oxide powder (Sects. 4.1.8, 4.3.1, and 4.5.1). Three types of liquid radwastes are produced, i.e., the oxalate process radwaste, the scrap recovery process radwaste, and the miscellaneous radwaste. Ten percent of the production of the plant, or 30 metric tons per year of U+Pu as clean $\text{UO}_2\text{-PuO}_2$, is processed through the recycle system. This material, which consists of cracked or chipped pellets, powder, etc., does not meet physical specifications. This is a mechanical recycle process, and no liquid radwaste is generated. Two percent of the plant production, or 6 metric tons/yr, is processed through the scrap recovery system.² The scrap consists of incinerator ash, off-specification $\text{UO}_2\text{-PuO}_2$ powder, decontamination solutions, etc. The miscellaneous waste from floor drains, personnel showers, etc., is not normally radioactive but is a potentially radioactive waste. Liquid radwastes from the model plant that are produced when the plant converts the plutonium nitrate solution to plutonium oxide powder are treated in the same manner as those that are produced when the plant processes only oxide

powders. Two of the three liquid radwastes listed above are normally radioactive. These are incorporated into cement after treatment, and the resultant solid is handled as a solid radwaste. No radioactive liquid effluents are released to the environment.

The mixed-oxide fuel fabrication plant produces fuels having slightly different concentrations of plutonium in the $\text{PuO}_2\text{-UO}_2$ pellets. Segregation of materials is accomplished using parallel production lines, each operating at a given time with a single concentration of plutonium. Recycle of reject pellets and similar materials occurs within each production line to maintain the segregation of materials. Mechanical systems for regrinding or oxidation and reduction of reject material are included in the base model plant. The small quantities of radioactive scrap materials that are generated cannot be effectively processed separately in each production line; therefore, a single system is specified. The model plant includes a system for recovering uranium and plutonium from scrap materials. Thus, the model plant illustrates the problems involved in limiting releases of radioactive materials to the environment for a completely self-sufficient plant. Alternatively, a fabrication plant situated adjacent to a reprocessing plant could transfer scrap materials to a joint scrap recovery unit located at the reprocessing plant. In this situation, the problems of shipping plutonium feed and scrap materials are eliminated.

3.3 Management of Radioactive Wastes

Gaseous Effluents. - Gaseous effluents from process vessels and from processing cells or alpha enclosures contain radioactive particles that are produced directly as solids or are formed from aerosols of process solutions that subsequently dry to become solids. On this basis, the source terms are calculated assuming that separation of radionuclides does not occur and the relative proportion of radionuclides in the gaseous effluent is the same as that fed to the plant. Americium-241 is separated from the plutonium by the solvent extraction step in the scrap recovery system. However, only 2% of the plutonium processed by the plant passes through the scrap recovery system and, consequently, the resultant separation of americium and plutonium is assumed to have a negligible effect on the

isotopic ratio of the radionuclides in the off-gases. The gaseous effluent from the plant also includes ventilation air from personnel operating areas. The combined process and ventilation effluent is treated such that increasingly small fractions of the radionuclides are released to the environment in the various case studies. The most complex flowsheet in this study illustrates a very low, but not "zero," release of radionuclides in the gaseous effluents. Treated gases are released through roof vents at a height of approximately 60 ft. However, the gases are assumed to be released at ground level in the meteorological and radiological assessment of the impact of these releases (Sect. 7.0).

Liquid Effluents. - Liquid radwastes from process vessels and miscellaneous liquids from processing cells or alpha enclosures contain dissolved and suspended compounds of uranium and plutonium. Process considerations indicate that the relative proportions of radioactive chemical constituents will be the same in the liquid radwastes as in the solids formed in a given operation. The liquid radwastes are treated to recover valuable constituents, and the residues are converted to solids. No radioactive liquids are released to the environment.

Solid Wastes. - Combustible solid wastes are incinerated, and the incinerator ash is processed by the scrap recovery system. Other solid wastes are segregated according to plutonium content and are then compacted and packaged for disposal, or are incorporated in cement. Filter residues and liquid wastes are incorporated in cement and packaged in steel drums for storage onsite prior to eventual shipment offsite for disposal. The waste materials could also be incorporated in plasticizers or asphalt instead of cement; however, cement is selected to avoid the possibility of combustion in a fire during storage or shipment and to avoid excessive leaching of the plasticizer product should the drum fail and expose the solidified waste to water.^{10,11}

3.4 Cost Parameters

A base case is selected which is similar to plants being designed in 1973. The capital and annual costs are estimated for gaseous radwaste effluent treatment systems which are added to the base case in a series of

case studies. The calculation of the annual costs is a primary objective of this study. They are correlated with the changes in environmental impact for each case study in Sect. 8.0. The estimated costs are based on an amortization period of 15 years, although the operating lifetime of the plant is assumed to be 20 years. The costs are based on a new model plant, and no attempt is made to estimate backfitting costs for present plants. The capital cost of the model plant is set at \$40 million in 1973 as an extrapolation from the estimated cost of a plant currently proposed for construction.² This is not a precise value, since it will vary considerably with the type of facility constructed. This cost is used for a qualitative comparison with the incremental capital costs of radwaste treatment systems in the case studies. The cost estimating procedure is presented in Sect. 6.0.

3.5 Equipment Operation

It is assumed that all radioactive wastes will be treated by the radwaste treatment equipment, i.e., wastes will not bypass treatment systems and be discharged. The equipment is adequately sized to ensure high operating flexibility and efficiency factors. For example, if the liquid radwaste is not purified to the desired degree in a single evaporation, it may be recycled and reevaporated.

3.6 Plant Siting

The model plant is located at each of two sites which have environments characteristic of those surrounding contemporary nuclear fuel reprocessing and fuel fabrication facilities. Site 1 is located in a plain in a rural southeastern coastal area adjacent to a continuously flowing stream that empties into an ocean estuary. Cities with moderate populations are located a short distance from the site. Site 2 is located on a plain in a rural midwestern area adjacent to a continuously flowing stream which empties into a large river. Cities with moderate population and a large city are located within the survey area. Meteorological data for Sites 1 and 2 are derived from first-order weather stations in the coastal southeastern and midwestern areas of the United States. The population

distribution for the sites was determined by averaging the distribution around several nuclear installations in the southeastern and midwestern areas. Site selection is described in detail in Sect. 7.0.

3.7 Radiological Impact

Radiation doses to the population and biota surrounding the model plant are estimated using the procedures that have been standardized for environmental impact statements for light-water-cooled nuclear power stations by the USAEC-Regulatory.¹ Pathways both for external radiation dose from sources outside the body and for internal dose from sources within the body are considered. Immersion in the gaseous effluents as they are diluted and dispersed leads to external exposure; inhalation causes internal exposure. The deposition of radioactive particles on the land surface leads to direct external exposure and to internal exposure by the ingestion of food products through various food chains. Similarly, external exposure results from contact with water containing radionuclides, while internal exposure results from consumption of the water or of marine life harvested from the water. In the cases of this study, no radioactive material is released in liquid effluents. However, the effect of contamination of the natural water by radioactive particle fallout is considered.

The estimated radiation doses to individuals, to the human population, and to the biota are calculated for annular distances out to 55 miles in 22.5° sectors using the site parameters listed in Sect. 3.6. Doses to individuals are calculated for the total body and for individual organs. Population doses (man-rem) are the sum of the total body doses to all individuals in the population considered. Details of dose models, assumptions, and methods are given in Sect. 7.0.

3.8 References

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3. Jersey Nuclear Co., Applicant's Environmental Report - Mixed Oxide Fuel Plant, JN-12 Add. 2, USAEC DOCKET 70-1257 (April 1972).
4. Nuclear Fuel Services, Inc., Environmental Report - Fuels Fabrication Plant, West Valley, NY, USAEC DOCKET 70-1292 (December 1971).
5. J. M. Selby et al., Considerations in the Assessment of the Consequences of Effluents from Mixed-Oxide Fuel Fabrication Plants, BNWL-1697 (June 1973).
6. O. J. Wick (Ed.), Plutonium Handbook - A Guide to the Technology, p. 559, Gordon and Breach, 1967.
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9. Federal Register 38(147), 20482 (Aug. 1, 1973).
10. A. H. Kibbey and H. W. Godbee, A Critical Review of Solid Radioactive Waste Practices at Nuclear Power Plants, ORNL-4924 (March 1974).
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4.0 SOURCE TERM FOR RADIOACTIVE RELEASES

4.1 Origin of the Radioactive Wastes in LWR Mixed-Oxide Fuel Fabrication Plants

The following sections describe the processing steps that produce the radwaste effluents and present the amounts and compositions of these wastes. The treatment of radwaste effluents can be significantly affected by the presence of nonradioactive materials in the effluent stream. Consequently, complete assays of the waste streams are presented.

In the model fuel fabrication plant, natural uranium oxide (UO_2) powder is received from a separate plant. The UO_2 is blended with plutonium oxide (PuO_2) powder as described in Sect. 3.2. Plutonium is shipped to the fuel fabrication plant from a plutonium storage facility or from a fuel reprocessing plant as PuO_2 powder or as a solution of plutonium nitrate.

Powder shipments are received in sealed metal containers. Typically, natural UO_2 powder is shipped in a plastic bag within a sealed metal drum. The PuO_2 powder is contained in a plastic bag within a sealed metal can which has critically (nuclear) safe geometry. The primary containment can is positioned within a second container equipped with a "bird cage" structure to maintain critically (nuclear) safe geometry and can-to-can clearances.¹⁻⁴ Aqueous plutonium nitrate solutions are shipped in plastic bottles, each fitted in a sealed can [of critically (nuclear) safe geometry] which is within a second container provided with a critically safe clearance structure. This mode of shipment provides three layers of containment plus critically safe (nuclear) geometry for both the PuO_2 powder and the plutonium nitrate. The containment is not breached until after the complete assembly has been introduced into the processing cell or alpha enclosure system within the model fabrication plant. All handling and processing occur inside these enclosures. Major zones of the model plant, personnel operating areas, cells, hoods, glove boxes, etc., are isolated from each other by appropriate ventilation system design. Air flow is from non-processing areas to areas having greater potential for contamination. Thus, radioactivity level and process function dictate the ventilation zoning within the plant.

4.1.1 Oxalate Process for Production of Plutonium Oxide

Plutonium oxalate is precipitated in aqueous media from plutonium nitrate feed solution (230 g of Pu per liter, ~ 3.7 M HNO_3) that has been adjusted to plutonium and nitric acid concentrations of 155 g/liter and 6 M, respectively, using an excess of ~ 1 M oxalic acid (Fig. 4.1). The feed solution must contain sufficient nitric acid to make the final slurry acidity 1.5 to 4.5 M in order to ensure the formation of a precipitate which is easily filtered.^{5,6} Hydrogen peroxide is used to maintain the plutonium in the +4 valence state. The plutonium oxalate is recovered in a centrifuge and clarifier, and is subsequently dried at 120°C and calcined at temperatures of 650 to 850°C to form PuO_2 powder. The filtrate liquor contains about 1% of the plutonium that was present in the feed solution. This plutonium is recovered in the oxalate process liquid radwaste treatment system. Off-gases from the dryer and calciner operations are purified in the oxalate process gaseous radwaste scrubber system and in the subsequent plant gaseous radwaste treatment systems. The amounts of material flowing through the process are listed in Table 4.1.

4.1.2 Fuel Fabrication Process

The PuO_2 powder is mechanically blended with UO_2 powder to the required enrichment, and this mixture is milled, agglomerated, and granulated to produce a uniform free-flowing product of 85- to 1400- μm particle size for feed to the pellet press (Fig. 4.2).^{5,7-9} "Green" pellets 40 to 55% of theoretical density are sintered at temperatures of 1500 to 1700°C, wet-"centerless" ground to dimensional tolerances, inspected, washed, dried, outgassed at 600 to 800°C in vacuum, and loaded into stainless steel or zirconium tubes. Small amounts of solid waste from the pellet press and grinder are treated in the scrap recovery system. Pellet wash liquids and fuel rod decontamination liquids are treated in the oxalate or scrap recovery liquid radwaste treatment systems. All process gaseous waste streams flow through the plant gaseous radwaste treatment systems.

4.1.3 Recycle System

The reject UO_2 - PuO_2 pellets that do not meet physical specifications, including cracked and chipped pellets, off-sized pellets, etc., are mechanically processed in the recycle system by regrinding or oxidation and reduction (Fig. 4.3). No liquid or solid radwastes are generated. System off-gases are processed through the plant gaseous radwaste treatment systems. The amount of material flowing through the recycle system is $\sim 10\%$ [0.1 metric ton (U+Pu)/day] of that fed to the plant.

4.1.4 Scrap Recovery System

In the scrap recovery system, materials such as incinerator ashes, alpha-enclosure cleaning liquids and sweepings, sludge from pellet pressing and grinding operations, and off-specification pellets are treated to recover contained uranium and plutonium values (Fig. 4.4) which amount to about 2% [0.02 metric ton (U+Pu)/day] of that fed to the plant. The scrap is leached with nitric acid containing a small amount of hydrofluoric acid to dissolve the heavy metals, and the resulting solution is filtered to remove insoluble impurities. The solution is processed in a solvent extraction system which is designed to achieve a high recovery of uranium and plutonium and a high degree of separation of uranium and plutonium from nonextractable impurities. In this system, the adjusted dissolver solution, 0.6 M in HNO_3 and containing 55 g (U+Pu)/liter, is passed counter-current to a solvent containing 20 vol % n-tributyl phosphate in an aliphatic hydrocarbon diluent using a 2-in.-diam by 20-ft-high pulsed column. The heavy metals are recovered from the solvent by contacting the solvent with ~ 0.02 M HNO_3 in a second solvent extraction contactor. The solvent is then reused.¹⁰ The barren dissolver solution, or raffinate, contains about 0.03% of the uranium and plutonium fed to solvent extraction. This solution is processed in the scrap recovery liquid radwaste treatment system.

The recovered uranium and plutonium solution from the solvent stripping operation is neutralized, and the insoluble ammonium diuranate and plutonium hydroxide are coprecipitated using an aqueous strike solution

containing 1.5 wt % ammonia.¹¹ The solids are collected in a centrifuge and clarifier and dried at a temperature of 180°C. A calciner is used to thermally decompose and reduce the solids at temperatures of 750 to 850°C to form $\text{UO}_2\text{-PuO}_2$ powder. The clarified liquid is processed in the scrap recovery liquid radwaste treatment system. Off-gases are treated in the scrap recovery gaseous radwaste scrubber system and in subsequent plant gaseous radwaste treatment systems. The amounts of material flowing through the scrap recovery system are listed in Tables 4.2 and 4.3.

4.1.5 Scrubber Systems

All chemical process gaseous effluents are passed through spray-type water scrubbers before being released to other gaseous radwaste treatment systems. The liquids from these scrubbers contain traces of uranium and plutonium as well as nonradioactive chemical constituents. They are added to the liquid radwastes from the process generating the particular gaseous effluent. For example, the scrubbing liquids from the off-gas scrubbers in the scrap recovery system are added to the scrap recovery system liquid radwaste stream.

4.1.6 Miscellaneous Liquid Wastes

Miscellaneous liquid wastes are generated from the laundering of clothing, personnel showers, floor drains, laboratory drains, etc. Since all processing operations are carried out within processing cells or alpha enclosures, this liquid waste is normally free of radioactive contamination. The potential for contamination exists, however, and so a miscellaneous liquid waste treatment system exists to monitor and treat this waste. All liquid wastes generated by various sources in the mixed-oxide fuel fabrication plant are listed in Table 4.4.

4.1.7 Miscellaneous Solid Wastes

Miscellaneous solid wastes, including glove-box gloves, cleaning materials, filters, etc., are separated into combustible and noncombustible types. An incinerator is used to reduce combustible wastes to an ash which is processed in the scrap recovery system. Radioactive materials in the

incinerator off-gas are retained by a filter system attached to the incinerator unit that is considered to be part of the base plant. Thus, it is common to all of the case studies. The off-gas from the incinerator system is then combined with other off-gases and passed through the plant gaseous radwaste treatment systems. Noncombustible wastes are mechanically compacted, where feasible, and transferred to the solid radwaste treatment system for packaging.

4.1.8 Process Gaseous Effluent

All processing cells, glove boxes, or other alpha enclosures, and process equipment units are connected with ducting for the collection of gaseous effluents. The combined process gaseous effluent contains small quantities of radioactive and nonradioactive materials, including gases that are produced in the various operations and are not removed by the scrubbers. Aerosols of solutions which dry to particulates represent a complete spectrum of the radioactive and nonradioactive materials in the process liquids. Additional particles are derived from drying and calcining operations, from powder handling procedures in the recycle system and pellet and fuel rod fabrication operations, and from ventilation of alpha enclosures by resuspension of settled particles. This gaseous effluent is combined with the plant ventilation air from personnel areas for treatment in the plant gaseous radwaste treatment system (Fig. 4.5).

Stack sample measurements of entrained radioactivity at enriched uranium fuel fabrication plants have indicated that $\sim 0.001\%$ of the activity fed to the plant is found in the process off-gas after treatment with a scrubber and roughing filter, and that $\sim 0.003\%$ is present in ventilation air from processing areas after roughing filters.¹²⁻¹⁴ Assuming an efficiency of 90% for a scrubber (see Sect. 4.3.1) and assuming no retention by the roughing filters, the amount of activity in the process off-gas and process area ventilation air before treatment is estimated as 0.01% and 0.003% of that fed to the plant, respectively. The source terms in this study of mixed-oxide fuel fabrication are calculated based on the conservative estimate that 0.02% of the radioactive materials entering the plant will be suspended in the off-gas prior to any treatment of the off-gas

(i.e., in the streams leaving the process equipment boxes shown in Fig. 4.5). The alpha-enclosure ventilation air is assumed to contain about 0.004% of the radioactive materials entering the plant before any treatment of the ventilation air occurs (i.e., in streams leaving the alpha-enclosure boxes shown in Fig. 4.5). Using these assumptions, the estimated amount of radioactive material in the gaseous effluent from the plant in Case 1 (the source term, see Sect. 4.5.2) is 89% of the Radiation Concentration Guide* for soluble materials.

4.1.9 Ventilation Gaseous Effluent

The ventilation air in the fabrication plant for personnel areas is normally free of radioactive contamination, since all process operations are carried out within processing cells or alpha enclosures. The potential for contamination exists, however, and consequently the plant ventilation system is designed to provide air flow from areas having a low probability of contamination to those with greater potential for contamination. The ventilation air is combined with the process gaseous effluent, and the combined off-gas is treated in the plant gaseous radwaste treatment systems (Fig. 4.5). Current designs for plutonium fabrication facilities use high ventilation and process air flow rates, such that the total plant gaseous effluent amounts to 350 to 500 scfm per metric ton of annual capacity.^{9,15} Hence, a total flow of ~120,000 scfm is used in the final gaseous radwaste treatment system for the model fuel fabrication plant.

4.2 Composition and Amount of Radioactive Material Entering Model Plant

A list of the radionuclides considered in this study is presented in Table 4.5. The selection of this list is based on the following criteria:

1. The feed to the fabrication plant is based on 9.35 metric tons of natural uranium and 0.41 metric ton of plutonium

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*Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Column I.

for each reference 1000-MW(e) light-water plutonium recycle reactor.¹⁶ These quantities represent average annual reactor reload values over a 30-year lifetime for a blended BWR-type reactor, assuming 12 years of plutonium recycle before equilibrium is attained and also assuming a self-generation level plus 15% for plutonium values. This corresponds to a fuel that is 4.20 wt % plutonium. The reference reactor assumed for the ORIGEN¹⁷ computer code calculations operated with an average burnup of 27,500 MWd/ton, an 80% load factor, and was on a 4-yr refueling cycle.

2. The plutonium feed has aged for 2 yr since purification in a reprocessing plant, during which time ^{241}Am has formed as a decay product of ^{241}Pu . An aging time of 2 yr is a compromise between incurring additional amortization charges for the plutonium, if longer times are used, and allowing adequate time for conversion of plutonium nitrate to plutonium oxide and the transfer of the product to the fuel fabrication facility, if shorter time periods are considered. Other environmental reports and economic surveys also use a 2-yr aging time.^{18,19} Uranium-237 is in secular equilibrium with the portion of ^{241}Pu that undergoes alpha decay (0.0023%) and requires 43.7 days to grow back to 99% of secular equilibrium with ^{241}Pu . A small quantity of ^{237}Np is present as a decay product of both ^{241}Am and ^{237}U , and a small amount of ^{236}U is present as a decay product of ^{240}Pu . The other plutonium isotopes (^{238}Pu , ^{239}Pu , and ^{242}Pu) produce very small amounts of ^{234}U , ^{235}U , and ^{238}U by radioactive decay during the 2-yr aging period.
3. Extremely small amounts of fission products and transplutonium elements follow the plutonium through the reprocessing plant and are associated with the plutonium feed. The amounts present in the plutonium feed to the fabrication plant are based on the calculated average amounts of fission products in the spent reactor fuel that enters the fuel reprocessing

plant after a cooling time of 150 days (calculated using the ORIGEN computer code); decontamination factors (DFs) in the reprocessing plant of 8×10^6 for Ru, ^{95}Zr , and ^{95}Nb , and 10^8 for all other fission products and transplutonium elements;²⁰ and the conservative assumption that the impurities remaining after fuel reprocessing emerge with the plutonium product. Curium-244 was selected as representative of the rare-earth and transplutonium nuclides.

4. The natural uranium feed includes small amounts of ^{230}Th , ^{231}Th , ^{234}Th , ^{231}Pa , and ^{234}Pa , which are radioactive decay products associated with natural uranium. Only ^{231}Th , ^{234}Th , and ^{234}Pa contribute significantly to the radioactivity of the uranium feed. Thorium-231 is in secular equilibrium with ^{235}U and requires 7.1 days to grow back to 99% of secular equilibrium. Thorium-234 and ^{234}Pa are in secular equilibrium with ^{238}U and with each other. Growth times to 99% of secular equilibrium are 160 days for ^{238}U and ^{234}Th , and 7.8 min for ^{234}Th and ^{234}Pa . Since the natural UO_2 has been produced from uranium hexafluoride in the enriched uranium fuel fabrication facility, no radium or other naturally occurring impurities are present.

The feed to the model plant contains the isotopic composition shown in Table 4.6. The plant processes 300 metric tons of heavy metal (U+Pu) per year at the nominal rate of 1 ton/day.

The relative inhalation hazard for each nuclide is estimated by dividing the curies present in 1 ton of feed to the model plant by the Radiation Concentration Guide* for that nuclide in the soluble form. Nuclides whose contribution to the total relative inhalation hazard are $<0.02\%$ are excluded from consideration when calculating source terms (Table 4.6). Radionuclides that are excluded on this basis are examined to ensure that they would not contribute more than 0.02% of the total body dose for individuals in the case studies as the result of bioaccumulation

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*Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Column 1.

in the environment. Table 4.6 lists the radionuclides selected as constituents of the source term, along with their relative masses. Uranium isotopes are also considered in source term calculations although they do not contribute significant amounts of radioactivity. The uranium isotopes are of interest because of the large quantities present in the fuel cycle. The distribution of alpha and beta radioactivity in the feed materials is given in Table 4.7. About 80% of the total alpha activity is contributed by ^{238}Pu and 100% of the total beta activity by ^{241}Pu .

4.3 Description of Waste Treatment Methods

4.3.1 Gaseous Radwaste Treatment Systems

The radioactivity of gaseous effluent streams arises from the entrainment of very small particles of uranium and plutonium compounds and the heavy-metal decay products. These particles are generated by the drying of entrained droplets of process liquids or from the entrainment of fine material in the fabrication operations. In addition, about 0.1% of the fine particles that deposit on the surfaces of alpha enclosures and **processing cells are resuspended in the ventilation air.**⁹ Gaseous radioactive constituents are not present in the uranium and plutonium feed materials, and volatile radioactive materials are not formed in the plant processes. Consequently, the gaseous radwaste treatment systems are designed to retain solid particles — not gaseous radioactive materials. The off-gas from vessels, where chemical processing occurs, is passed through scrubbers to remove nonradioactive soluble chemicals and a fraction (>90%) of the particulate matter. These streams, as well as individual off-gas streams from alpha enclosures and ventilation air from personnel areas, pass through roughing filters and a single stage of high-efficiency particulate air (HEPA) filters (at each location) which are part of the base fabrication plant and are not included in the cost of the waste treatment systems (Fig. 4.5). The combined gaseous effluent from all sources in the base plant then undergoes final treatment in the gaseous radwaste treatment system. Three designs for increasingly efficient treatment systems are described in the case studies in Sect.

4.5.1. The cost for each off-gas treatment system in the three case studies is estimated and is presented in Sect. 6.0. The design of the gaseous treatment systems in the base plant represents contemporary practice for design of fuel fabrication facilities (Sect. 3.2). Normal practice is to use 40% of the incoming air for process purposes and 60% for general plant ventilation. In the model plant, since all processing is performed in alpha enclosures, one-third of the general plant ventilation air entering the plant is assumed to be distributed to alpha enclosures and two-thirds to personnel areas. A schematic diagram showing the gaseous radwaste pretreatment systems and the relative airflow distribution within the plant is given in Fig. 4.5.

Scrubbers. - Wet spray scrubbers are credited with an efficiency of >90% for removal of entrained solids from gaseous effluents.^{21,22} In a scrubber, the gaseous effluent passes countercurrent to a spray of liquid and the entrained particles of solids impinge on and are retained by the liquid droplets. Scrubber units are used on the off-gases from the oxalate process and from the scrap recovery system. The oxalate process scrubber system is also used to treat the off-gas from the oxalate process liquid radwaste treatment system. The off-gases may contain particles of plutonium nitrate, oxalate, oxide, and hydroxide as well as gases and vapors of hydrogen, carbon dioxide, nitrogen oxides, nitric acid, and ammonia. They are scrubbed with water or dilute nitric acid. The scrubber in the scrap recovery system is similar to that in the oxalate process system. Both scrubbers are included in the base plant (Case 1).

The use of more efficient scrubbers, such as venturi scrubbers, was considered in the advanced case studies for treating the total gaseous effluent from the plant. This is a difficult engineering problem because of (1) the large air flow rate, and (2) the small size of the particles that are present. These particles have already passed through the upstream HEPA filters. Mixed-oxide fuel fabrication plants are currently designed to use air flows of 350 to 500 scfm per metric ton of annual capacity, or about five times that used in uranium fuel fabrication plants.^{9,15} Thus, the model 1-metric-ton(U+Pu)-per-day plant has a total gaseous effluent of about 120,000 scfm (once-through). Conventional scrubbers are not

effective in removing submicron-sized particles from air moving at these large rates of flow. Removals are estimated at about 55%.^{21,22} The advanced type venturi scrubber was considered for Case 3, where most of the process air is recycled and the net amount of air to be treated is greatly reduced.

Venturi scrubbers rely upon the shear stresses of the air stream traveling at velocities of 12,000 to 20,000 fpm to break up the water introduced for scrubbing in the nozzle throat. The turbulence that is created disperses the fog of droplets and makes possible the collision of dust and liquid particles. Venturi scrubbers are reported to be 98% effective in the removal of micron-sized, high-density particles but operate with a larger pressure drop (10 to 13 in. H₂O) than is generally available.^{22,23} An added advantage is the altering of the basic characteristics of the gas via pressure surge and humidification. However, the higher initial cost and power requirements of venturi scrubbers in comparison to conventional methods discourage application to large gas streams. In Case 3, 98% of the process gases are recycled. The remaining relatively small stream of ~1,440 scfm could be elevated in pressure to allow the use of a venturi scrubber. This stream, however, will have already passed through multiple stages of HEPA filtration, and a large fraction of the particles will be in the submicron range. Consequently, a 98% efficiency for removal of micron-size particles cannot be used in this application. Since the necessary engineering data are not available for predicting the removal efficiency for submicron particles, the venturi scrubber is not used in this study.

Deep-Bed (Sand) Filters. — Sand filters are constructed of graded layers of aggregate and sand from relatively coarse (2.5 in. x 1.5 in.) to fine particles (#20-#50 mesh). Good resistance to heat, shock, and chemical attack with disadvantages of higher cost, higher pressure drop, and lower aerosol collection efficiency are salient features of sand filters compared with other common types of filters.²⁴ Other disadvantages include the problems involved in (1) testing the efficiency of the filters while they are in use, (2) the recovery of plutonium should any substantial amount enter the sand filter, and (3) the final disposal of a large volume of contaminated sand.

Large fixed-bed sand filters have been used for ~20 years at Hanford without maintenance or replacement; at Savannah River they were in operation for about 13 years before water inleakage forced a shutdown. Collection efficiencies at both installations were >99%. Penetration rate tests have demonstrated that a 30-in.-deep sand bed is roughly equivalent to a single HEPA filter for the particles remaining airborne after two stages of HEPA filtration.²⁵

The installed capital cost of a sand filter for use on a fuel fabrication facility is considered to be excessive. The cost is estimated at about \$2 million for the 1-metric-ton-per-day model plant in Cases 1 and 2 for off-gas flow rates of 120,000 cfm. The cross section of the filter in these cases is ~20,000 ft². The cost decreases to about \$1 million in Case 3, where the off-gas flow rate is ~60,000 cfm. An added advantage of deep-bed sand filters, i.e., the shock (tornado) protection they offer to other filter elements located upstream from the deep-bed filter in regions where meteorological conditions would indicate such protection to be desirable, makes this a technical alternative for such cases. However, the recommended design guidelines do not specify that sand filters be used.²⁶ Consequently, because of the disadvantages listed above and the high installation cost, sand filters are not used in this study.

High-Efficiency Particulate Air (HEPA) Filters. — HEPA filters have been used for many years in the nuclear industry to remove radioactive particles from air streams. A standard HEPA filter has a 2 x 2 ft cross section and a depth of 1 ft for an air capacity of about 1000 cfm.^{25,27} These filters, which are composed of expendable (single use) pleated mats of fiberglass paper, are installed in banks to achieve the required system capacity. They are specified to exhibit a minimum efficiency of 99.97% for 0.3- μ m particles and a maximum resistance (when clean) of 1.0 in. H₂O pressure when operated at rated airflow. Tests of filter efficiency are conducted in special facilities which ensure that no significant leakage occurs around the sides of the filter or through other bypasses. It is necessary to construct an equally tight filter enclosure in a field installation to achieve the rated filtration efficiency. The construction of large, tight filter enclosures is a difficult engineering task. Testing

of the individual filter banks in place in the enclosure, both before and periodically during the service period, by the dioctyl phthalate (DOP) smoke test is required to ensure that no significant leaks are present in either the filter or the enclosure.

Variables that have been considered in HEPA filter performance analyses include the particle size distribution of the various plutonium aerosols encountered. A literature survey by Davis, however, does not indicate a gross variation in the range of reported particle sizes in field operations.²⁸

Several tests have been carried out with plutonium aerosols in small laboratory and large-scale field installations. In a detailed survey Hetland and Russell found large-scale filter systems which produced overall mass removal efficiencies of 10^7 or greater.²⁵ One such system at Rocky Flats showed a removal efficiency of 99.999% across the first two banks of a system of four HEPA filter banks in series, 94% across the third filter bank, and 83% across the fourth filter bank. The low efficiency value for the fourth bank was attributed to probable bypassing of gases and was not considered to be a measure of filter medium performance. This system is about 15 yr old and does not represent the latest design practice for HEPA installations. Ettinger *et al.* have performed laboratory tests using plutonium aerosols in small installations that are tightly sealed and tested periodically for leaks with DOP.^{29,30} They have observed removal efficiencies of at least 99.97% for each of three single filter stages in series. AEC Regulatory Guide 3.12 for the design of plutonium ventilation systems indicates that removal efficiencies of >99.95% should be obtained for a single bank of HEPA filters if the installation containing the filters is constructed according to the recommended guidelines and is tested for leaks after the filters have been installed.²⁶ Consequently, a value of 99.95% has been used in this study to represent the rated efficiency of each HEPA filter.

Several factors must be considered, however, in predicting the overall installed efficiency of multiple filters in series even though each bank is tested separately in place with DOP and shows an efficiency of 99.95 to 99.99%. First, several tests show that the second and third

filters are exposed to much lower concentrations of particles with a size distribution that is strongly biased toward the smaller sizes.²⁹ Secondly, filter efficiencies are sensitive to gas flow rate, and possibly all filters in a bank may not experience the same flow rate. Finally, the concentration of particles is different for each stage of filtration and filter efficiency varies with particle concentration.³¹ For these reasons, Burchsted recommends the assignment of lower overall efficiencies to filter systems that use HEPA filters in series until more experimental information is available from large installations.³¹ Consequently, the overall in-stalled filter system DFs selected for use in this study for HEPA filters in series are based on a lower efficiency than the rated DF values. For each case study, this approach will result in costs and doses that are realistically conservative.

The individual HEPA filters that are located on each alpha enclosure, process equipment unit, and plant area air exhaust are occasionally subjected to severe conditions such as chemical fumes, mechanical shock, or high radioactivity. Roughing filters are placed upstream from each HEPA to remove the larger particulates and to collect the bulk of the uranium and plutonium for recovery. The roughing filters also minimize the blinding of the HEPA filters and assist in protecting them from fumes, shock, and radiation. The difficulty in maintaining rated filter efficiencies under these conditions is well recognized. In addition, these filters are generally not tested periodically in place with DOP and are monitored for efficiency by observing the pressure drop across the filters. Consequently, an efficiency of 95% is assigned to these "low-efficiency" HEPA filters. No credit is taken for the roughing filters. This filter system is considered to be part of the base plant, and the cost for this system is not included in the costs that are estimated for the final gaseous radwaste treatment system for the plant.

The installed efficiencies of the HEPA filters used in this study are summarized as follows:

<u>HEPA Filter System</u>	<u>Percent Removal</u>	<u>DF</u>
Tested Periodically in Place with DOP		
First train of series filters:		
First filter	99.95	2×10^3
Second filter	99.5	2×10^2
Third filter	99	1×10^2
Second train of series filters:		
First filter	99.9	1×10^3
Second filter	99.5	2×10^2
Not Tested Periodically in Place with DOP; Subjected to Shock, Fumes, or Radiation		
Single Filter	95	20

The volume of gaseous radwastes released to the environment, the concentration of radioactive materials in these gases, and the total amount of radioactive materials released can be decreased by purifying (filtering) and recycling for reuse a large fraction of the off-gases from the process and alpha enclosure areas. A small fraction of this purified off-gas is combined with the ventilation air from the personnel operating areas, and the combined off-gases are filtered in the final plant gaseous radwaste treatment system. This design principle is applied in the Case 3 study for the model plant; it is also applied in existing and proposed plutonium fuel fabrication plants.^{9,15,32}

The final gaseous radwaste treatment system for the model plant in Case 1 of this study is fitted with two HEPA filter banks in series and a standby parallel installation (Fig. 4.6). The overall rated efficiency for two HEPA filters in series is equivalent to a DF of 4.0×10^6 . A conservative installed DF of 4.0×10^5 is used for this case. The parallel installation is used to ensure filtration service in the event that one set of filters in series should become inoperable. An additional (third) stage of filtration in series is specified in Case 2, which provides an additional removal of 99% of the particulate materials, for an overall installed DF of 4.0×10^7 for the three banks in series (Fig. 4.7). The rated DF for this case is 8.0×10^9 . In Case 3, a single HEPA installation is specified

(efficiency 99.95%) for recycled process gases and alpha-enclosure ventilation air and two banks of HEPA filters in series for nonrecycled gases (Fig. 4.8). Both the nonrecycled gases and the plant ventilation air pass through a final system containing two HEPA banks in series. Although the final installation represents the fourth and fifth stages of HEPA filtration, the installed efficiencies are assumed to approximate those of a first and second bank. These efficiencies are used because the introduction of plant ventilation air at this point alters the character of entrained solids through variations in humidity and pressure. The overall rated and installed DF values for the final gaseous radwaste treatment system in Case 3 are 8.0×10^{14} and 4.0×10^{12} , respectively. The rated DF of 8.0×10^{14} for the process off-gas (Fig. 4.8) final gaseous treatment system is based on 98% recycle (DF = 50) and four HEPA filters (DF = 2000 each). The installed DF of 4.0×10^{12} for the system is obtained by multiplying the following DFs: 98% recycle (DF = 50), treatment by two HEPA filters (DF = 2000 for first, 200 for second), and a final treatment with two HEPA filters after blending with plant ventilation air (DF = 1000 for first, 200 for second). The overall installed plant DF (or retention factor) of 1.33×10^{18} for Case 3 (Table 4.9) is obtained by multiplying the overall installed DF of 4.0×10^{12} for the gaseous radwaste treatment system by the following DFs when processing plutonium nitrate solution: treatment by the "low-efficiency" HEPA filters on the alpha enclosures and process off-gas (DF = 20) and a suspension factor of 0.004% (DF = 2.5×10^4) for 33% of the suspended material (Sect. 4.1.8), and a suspension factor of 0.02% (DF = 5×10^3) for 67% of the suspended material. A single suspension factor of 0.004% (DF = 2.5×10^4) is used when processing plutonium oxide powder. This latter calculation gives an overall plant DF of 2×10^{18} , but it will be decreased to approximately 1.2×10^{18} because the off-gas from the scrap recovery system will continue to provide a small fraction of the off-gas flow through the process equipment with a suspension factor of 0.02%.

4.3.2 Liquid Radwaste Treatment Systems

The radioactivity of the liquid effluents arises from the contained uranium and plutonium compounds and decay products. An objective of liquid radwaste treatment is to return valuable uranium and plutonium components to the process lines along with a minimum amount of impurities. Small quantities of these components cannot be recovered economically and are incorporated in cement along with liquids which cannot be recycled. The solid radwastes (cemented wastes) are packaged in steel containers and stored onsite prior to shipment offsite for final disposal. No radioactive liquids are released from the model plant to the environment. Miscellaneous liquid wastes are released after they have been filtered to remove solid matter and then sampled and analyzed to ensure that the stream is free of radioactive contamination. If radioactive materials are detected in the miscellaneous liquid waste, i.e., the radioactive level is higher than background, the water is recycled to the plant waste evaporator (Sect. 5.3, Table 5.1, Fig. 4.13, and Fig. 5.1).

Treatment of Oxalate Process Liquid Radwaste. - The liquid radwaste from the oxalate process contains about 1% of the plutonium entering the process (Fig. 4.1) as soluble plutonium nitrate. Small particles of plutonium oxalate that pass through the clarifier are also present. Excess oxalic acid and hydrogen peroxide from the precipitation step and nitric acid are the major constituents of this waste stream. Recovery of the residual plutonium is accomplished by solvent extraction after the solution has been treated to remove excess hydrogen peroxide and oxalic acid and the plutonium and nitric acid concentrations have been adjusted to levels suitable for the solvent extraction step (Fig. 4.9). Potassium permanganate (0.4 M) is used to oxidize and eliminate the hydrogen peroxide and oxalic acid. This step results in the formation of a manganese dioxide precipitate and soluble potassium and manganous nitrate salts. The manganese dioxide precipitate scavenges (occludes) the residual plutonium oxalate particles. These and other solids are collected on a filter, and the solids are incorporated in cement as a solid radwaste material.

The filtrate is acidified to 3 M HNO_3 to prevent the formation of polymeric species of plutonium during evaporation, and then evaporated to

achieve a plutonium concentration of ~ 11 g/liter.¹¹ Much of the nitric acid is recovered by fractionation and recycled. Final adjustment of the solution to ~ 2 g of plutonium per liter in 3 M HNO_3 is made by dilution. The plutonium is extracted from the potassium and manganous nitrate solution using 15 vol % *n*-tributyl phosphate in an aliphatic hydrocarbon diluent at a feed:solvent ratio of 1:2 in a pulsed extraction column.¹⁰ The solvent is stripped with 0.3 M nitric acid containing ~ 0.3 M hydroxylamine in a second contactor using a solvent:strip ratio of 1:6. The product solution is recycled as feed solution to the oxalate process. Barren raffinate from the solvent extraction system is neutralized with lime before being diluted and converted to a solid waste (cement) for disposal.

Plutonium loss to the solvent extraction raffinate after seven stages of extraction is estimated as 0.01% of that in the feed solution, or $9.5 \times 10^{-5}\%$ of the plutonium feed to the oxalate precipitation step (the plant). This amounts to ~ 12 g of plutonium per year.

Treatment of Scrap Recovery Liquid Radwaste. — The liquid radwaste from the scrap recovery system includes: (1) raffinate from the solvent extraction system, and (2) clarified liquid effluent from ammonia precipitation of recovered uranium and plutonium (Fig. 4.4).

Treatment of the second radwaste listed is accomplished by providing additional residence time to obtain more complete recovery of uranium and plutonium (Fig. 4.10). A hold time of 16 to 20 hr results in additional precipitation, coalescence of colloidal particles, and settling of solids. This separates the waste into a solids-rich portion and a relatively clear supernate. The solids-rich portion from the holding-settling operation is treated in a centrifuge, which provides an acceleration of several thousand times that of gravity to remove the bulk of the solids. Continuous rotating-drum (or other type) filters are used to clarify the liquids, which contain small (100 ppm or less) amounts of solids. The combination holding-settling tank and filter-centrifuge system results in the removal of about 83% of the uranium and plutonium from the waste stream.

The final (treated) liquid waste stream is blended with raffinate waste liquids, neutralized with lime, and converted to a solid waste for disposal. Plutonium losses are estimated as 0.0029% of the plutonium feed to the plant, or 0.36 kg/yr.

4.3.3 Solid Radwaste Treatment System

Solid radwastes consisting chiefly of solidified liquid radwastes are generated in the amounts shown in Table 4.8. Solid waste from other sources is sorted according to radioactivity level, compacted where feasible, and packaged for disposal. The solid radwaste is treated according to the flowsheet shown in Fig. 4.11.

4.4 Selection of Case Studies

The case studies are selected so as to obtain improved containment of radioactive materials with increased sophistication of the radwaste treatment systems. The latter systems are limited to currently available treatment techniques and apply to the gaseous radwaste. No radioactive liquids are released. Current designs of mixed-oxide plutonium fuel fabrication plants include the use of multiple banks of HEPA filters for the treatment of gaseous effluents. Similar treatment is used in the Case 1 study. The use of additional treatments and air recycle in the advanced cases represents the application of the limit of currently proven technology. The cases apply to mixed-oxide plutonium fuel fabrication plants which use either plutonium oxide powder or plutonium nitrate solution as a feed material. The cases that are studied, along with the treatment systems and DFs for these systems, are summarized in Table 4.9.

4.5 Description of Case Studies and Calculation of Source Terms

The treatment methods used in the individual case studies are discussed below. The concentrations of radionuclides in the gaseous effluents and the annual amounts of radioactive material discharged (source term) in each case study are presented in Table 4.10. Parameters used in the calculation of source terms are presented in Sect. 4.5.2. Figure 4.12

is a summary flowsheet which shows the material flows between the various sections of the plant and the waste treatment systems.

4.5.1 Gaseous and Liquid Radwaste Treatment Cases

Case 1. — Case 1 is the base case. The liquid radwaste from the plutonium oxalate process is treated according to the flowsheet shown in Fig. 4.9, which describes the recovery of plutonium values by solvent extraction. The material flows for this system are presented in Table 4.11. The liquid radwaste from the scrap recovery system is treated according to the flowsheet shown in Fig. 4.10. Material flows for the scrap recovery liquid radwaste treatment are presented in Table 4.12. The miscellaneous liquid effluents are treated as shown in Fig. 4.13 and subsequently released to the general lagoon. These effluents, which are free of radioactive materials, are the only liquids released other than sanitary and cooling tower blowdown waste waters. (No radioactive liquids are released.)

The gaseous radwaste effluents are treated as shown in Figs. 4.5 and 4.6. This system involves the use of scrubbers, roughing filters, and HEPA filters to decrease the release of radioactive materials. The final treatment consists of passing the effluents through two HEPA filter banks in series. When properly installed and tested, these filter banks provide a solids removal efficiency corresponding to a DF of 4×10^5 or higher, as described in Sect. 4.3.1.

The amount of radioactive material released in the gaseous effluent is estimated to be the same whether the plant receives and processes solid plutonium oxide or liquid plutonium nitrate (Sect. 4.3.1). The off-gases from vessels where chemical processing occurs, i.e., the oxalate process, the oxalate radwaste process, and the scrap recovery process, are subjected to scrubbing which removes the soluble chemical impurities and greater than 90% of the particulate matter. The amount of plutonium that is handled in the scrap recovery system when plutonium nitrate and oxalate solutions are processed is only 10% greater than when dry plutonium oxide is processed as a feed material (Tables 4.2 and 4.3).

Case 2. - Liquid radwastes are treated as in Case 1. The final gaseous radwaste treatment system, shown in Fig. 4.7, consists of three banks of HEPA filters in series (one more than Case 1). The rated solids removal efficiency of three HEPA filters in series corresponds to a DF of 4×10^7 or higher.

Case 3. - The liquid wastes are treated as in Case 1. The gaseous radwaste treatment for Case 3 consists of recycle of 98% of the process off-gases and alpha-enclosure ventilation air through one stage of HEPA filtration. The remaining effluent is treated with two stages of HEPA filtration and is blended with the plant ventilation air. The combined total plant off-gas is then passed through two stages of HEPA filters (Fig. 4.8). It is assumed that all filters are properly installed and designed for in-place testing. Thus, an overall DF of 4×10^{12} or higher applies to this installation.

4.5.2 Calculation of Source Terms

The radionuclide concentrations in the gaseous effluent streams were multiplied by the average specific activity values from Table 4.7 to calculate the source terms. The source terms for individual isotopes were obtained by multiplying the total radionuclide specific activity by the fraction of activity contributed by each given isotope. The source terms for gaseous effluents are listed in Table 4.10.

The design of the model plant is based on contemporary designs for plutonium fuel fabrication plants, and the generation rate for radioactive particulates in processing areas is derived from that observed in enriched uranium fuel fabrication plants as described in Sect. 3.2. The estimated releases of radioactive materials from the model plant can be compared with the federal regulations concerning the release of radioactive materials and with the releases estimated for contemporary plutonium fuel fabrication plants which have been proposed for construction. The calculated concentration of radioactive material in the gaseous effluent at the exit from the stack of the model plant in Case 1 is 89% of the Radiation Concentration Guide* for release of soluble radioactive materials to unrestricted areas.

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*Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Column 1.

This percentage is obtained by calculating the ratio of the concentration of each of the radionuclides in the gaseous effluent to the Radiation Concentration Guide (soluble) for that radionuclide for unrestricted areas and summing the ratios. Unrestricted areas are defined as areas that are beyond the plant exclusion area boundary. Radiation Concentration Guides for release to restricted areas (10 CFR 20, Appendix B, Table I, Column 1) are more than ten times higher than for the unrestricted areas. Also, releases from the model plant stack are diluted by a factor of at least 10^6 before reaching the boundary of the plant at 0.5 mile (Sect. 7.1). Thus, the model plant for Case 1 is well within the federal guidelines listed for release of radioactive materials. The estimated concentrations of alpha and beta radioactive materials in the gaseous effluent from the model plant are 4.3×10^{-14} $\mu\text{Ci/ml}$ and 8.8×10^{-13} $\mu\text{Ci/ml}$, respectively. These values are comparable to the concentrations of 5×10^{-14} $\mu\text{Ci/ml}$ of alpha and 1.2×10^{-12} $\mu\text{Ci/ml}$ of beta emitters estimated to be present in the releases from a proposed plutonium fuel fabrication plant.⁹

4.6 References

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5.0 NONRADIOACTIVE WASTES

5.1 Nonradioactive Chemical Releases

Nonradioactive chemical releases occur only in the gaseous effluents and in the miscellaneous liquid waste, since all liquid radioactive wastes are converted to solids for disposal. The miscellaneous waste stream contains small amounts of biodegradable detergents. Chemical releases through the gaseous effluent systems include small amounts of ammonia and nitrogen oxides which are not economically recoverable. Other off-gas constituents such as small amounts of carbon dioxide and hydrogen are innocuous.

5.2 Recovery and Reuse of Chemicals

The recovery and reuse of nitric acid and water in the model plant are accomplished, wherever practical, to minimize the impact of excessive quantities of these materials on the waste solidification process. This reduces the cost of storage and shipping solid radwastes.

5.3 Chemical and Sanitary Waste

A water usage diagram for the model plant, based on the design of current plants,¹⁻³ is shown in Fig. 5.1. If radioactive materials are detected in the miscellaneous waste, it is recycled to the plant waste evaporator. The cost of this evaporator is included in the base cost of the plant. An evaporator with a capacity of 1 gpm would be sufficient to handle all of the miscellaneous waste (0.6 gpm or 830 gal/day), if necessary. The discharged miscellaneous liquid waste is diluted to ~50 times its volume with sanitary and cooling tower blowdown waste waters in the general lagoon. The total volume of liquid effluent amounts to 32,000 to 35,000 gal/day. A material balance is listed in Table 5.1.

5.4 References

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6.0 COSTS

Costs for the gaseous waste treatment cases for the 300-metric ton/yr model mixed-oxide ($\text{PuO}_2\text{-UO}_2$) recycle fuel fabrication plant are estimated as additions to the base plant. Treatment of the liquid wastes from the oxalate process, scrap recovery, and miscellaneous waste systems is considered as part of the base plant and is not a variable in this study. The capital costs, annual fixed charges, annual operating cost, total annual cost, and contribution to the cost of power for the various cases are summarized in Table 6.1. A list of the installed equipment costs is given in Table 6.2.

Annual fixed charges are estimated at 26% of total capital investment. This is typical of investor-owned fuel reprocessing and waste treatment facilities. The basis for calculation of the fixed charge rate and the operating cost is discussed in detail in Sect. 6.2. An annual operating expense is added to the annual fixed charge on capital to give the total annual cost of a radwaste treatment case. The annual operating and maintenance cost is assumed to be the sum of all or part of the following: (1) 3% of the fixed capital; (2) blower power cost; (3) DOP filter testing cost; and (4) filter replacement cost. The cost of the waste treatment system in each case is also calculated on the basis of its contribution to the cost of electric power in terms of mills/kWhr. This cost is obtained by dividing the total annual cost for waste treatment in each case by the amount of electricity produced from the fuel fabricated in the plant in one year. A fuel fabrication plant with a nominal annual production rate of 300 metric tons of uranium plus plutonium can service a nuclear economy of approximately eleven 1000-MW(e) LWRs (based on a burnup of 33,000 MWd/metric ton, 80% load factor, and 32.5% thermal efficiency). All costs are estimated in terms of early 1973 dollars. No attempt has been made to include the effect of future inflation. The cost estimates are expected to have an accuracy of about $\pm 30\%$.

6.1 Capital Costs

The capital costs of the radwaste treatment cases are the sum of the

direct costs and the indirect costs. The interest during construction and the contingency allowance are included as indirect costs.

6.1.1 Direct Costs

The major equipment components consist of HEPA filters, filter housings, blowers, dampers and drives, and ducts. The size and cost of each component are estimated based on costs experienced at ORNL for similar items (Table 6.2).¹⁻⁴ Building requirements are estimated based on equipment size. The costs of warehouse and other related facilities are not included. The total direct cost for each gaseous radwaste treatment case is the complete installed equipment (material and labor) cost.

6.1.2 Indirect Costs

For the purpose of this study, indirect costs are estimated as follows:

	<u>Percentage of Direct Cost</u>
Engineering and supervision	15
Construction expense and contractor's fee	20
Engineering design (A-E)	15
Contingency	45
Other owner's cost	10
Interest*	<u>35</u>
Total	140

6.2 Annual Fixed Charge and Operating Costs

The annual fixed charge rate on invested capital, as based on an estimating system used by the Fuel Recycle Task Force, amounted to 24%.¹ The basis for this estimate is as follows:

Plant lifetime	15 years
Capital investment in bonds	30%

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*Interest is applied to the cumulative total cost at the rate of 8% per year over a 5-yr cash flow expenditure period.

Capital investment in equity	70%
Interest rate on bonds	5%
Rate of return on equity (after taxes)	16%
Federal income tax rate	50%
State income tax rate	3%
Local property tax rate	3.2%
Annual cost of replacements	0.35%
Annual property insurance rate	0.25%

By present-day standards, the 5% bond interest rate is probably low. Increasing it to 8% would increase the fixed charge rate to about 26%. Consequently, for this study, a fixed charge rate on invested capital of 26% is used. The plant is amortized over a 15-yr period, although the operating lifetime of the plant is 20 years (Sect. 3.1).

The estimated annual operating and maintenance cost, which is based on the conceptual design of each gaseous radwaste treatment case, is 5.1% of the fixed capital cost in Cases 1 and 2 and 4.5% of the capital cost in Case 3. The total annual cost of each radwaste treatment case is the sum of the annual fixed charge and the annual operating cost.

6.3 References

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7.0 ENVIRONMENTAL IMPACT

The radiological impact of the model mixed-oxide fuel fabrication plant is assessed by calculating radiation doses to individuals, populations, and selected biota for each site and radwaste treatment case. Potential pathways for radiation exposure to man from radionuclides originating in a nuclear facility are presented schematically in Fig. 7.1. Those shown in the figure are not exhaustive, but they illustrate the principal pathways of exposure based on experience.

Estimates of the average dose per year of plant operation to both individuals and to the population within 55 miles, which may result from the expected radionuclide discharges during normal operation, are discussed below. Annual radiation dose commitments to individuals (in millirems) and to the population (in man-rems) are estimated from the release of radioactive gaseous effluent from the model plant. Radioactive materials taken into the body by inhalation or ingestion (internal exposure) continuously irradiate the body until removed by processes of metabolism and radioactive decay. A dose calculated for 1 year of radionuclide intake (internal-exposure pathways) is an estimate of the total dose an individual will accrue within his lifetime as a result of that 1 year of exposure (i.e., dose commitment). All of the doses estimated in this report represent dose commitments.

The radiation doses to the total body and internal organs from exposure to penetrating radiation from external sources are nearly the same. However, they may vary considerably for internal exposure from ingested or inhaled materials because some radionuclides concentrate in certain organs of the body. For this reason, estimates of radiation dose to the total body and major organs are considered for all pathways of internal exposure based on parameters applicable to an average adult.

Radiation doses to the internal organs of children in the population vary from those of an average adult because of differences in metabolism, organ size, and diet. Differences between the organ doses of a child and those of an average adult by more than a factor of 3 would be unusual for all pathways of internal exposure except the atmosphere-pasture-cow-milk pathway.

The population dose estimates are the sums of the total body doses to individuals within 55 miles of the plant. Total body doses from gamma exposures approximate those to gonads; therefore, these values were used in the man-rem estimates because gonads have the most restrictive dose limits.^{1,2} Since radiation doses to the total body are relatively independent of age,³ the man-rem estimates are based on total body doses calculated for adults.

7.1 Meteorology

The release of gaseous effluents to the atmosphere is the principal mode of environmental contamination from fuel fabrication facilities. No radioactive liquids are released from the model plant. Atmospheric transport of radioactive materials to the terrestrial environment is calculated according to the Gaussian plume model.⁴ A computer code⁵ has been modified to calculate the approximate annual average concentrations of short- and long-lived nuclides in the atmosphere at various distances from the source. The meteorologic data required for the calculations are joint frequency distributions of velocity and direction summarized by stability class. Meteorologic data from representative midwestern and southeastern coastal regions⁶ are used to calculate average values of X/Q' ($\text{sec} \cdot \text{m}^{-3}$), i.e., factors that are used to calculate the concentration of radioactive material at a reference point per unit of source strength. The X/Q' values are calculated for sectors in the 16 principal compass directions bounded by radial distances of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 10.0, 15.0, 25.0, 35.0, 45.0, and 55.0 miles from the point of release. Although dilution increases with distance from the point of release, X/Q' values decrease. The X/Q' values in this survey are based on a ground level release. Maximum and minimum annual X/Q' values at successive

distances from the release point are given in Figs. 7.2 and 7.3 for the midwestern and southeastern coastal sites, respectively. All values, irrespective of sector or direction, range between the maximum and minimum values shown at a given distance. Magnitudes of X/Q' values are somewhat similar at the two sites, but directions at which maximum or minimum values were attained at each site are different.

For a ground-level release (the condition assumed for this study), the maximum concentration of radioactive substances in air (largest X/Q' , least dilution) occurs at the point of release. For release heights close to ground level, 10 m, for example, the X/Q' values would be slightly less than those given for a ground level release. At 0.5 mile, the X/Q' for a release at a height of 10 m would be smaller by a factor of 0.75 and at 1.0 mile by a factor of 0.95. The ground-level release is the more conservative assumption which leads to a higher estimated dose. The X/Q' values decrease according to a power function of distance from the source (Figs. 7.2 and 7.3). Although a site boundary is not specified for the fuel fabrication facility, X/Q' values at one mile, for example, range from 1.7×10^{-6} to 6.5×10^{-7} $\text{sec} \cdot \text{m}^{-3}$ for the coastal site. X/Q' values for the same distance ranged from 1.7×10^{-6} to 4.6×10^{-7} $\text{sec} \cdot \text{m}^{-3}$ for the midwestern site. The average X/Q' values used in this study at a distance of 0.5 mile from the plant are 5.9×10^{-6} $\text{sec} \cdot \text{m}^{-3}$ at the coastal site and 4.2×10^{-6} $\text{sec} \cdot \text{m}^{-3}$ at the midwestern site. The X/Q' values decrease by approximately two orders of magnitude at a distance of 55 miles from the source. For each sector, radionuclide concentrations in air are used to calculate dose via inhalation and submersion in air. These concentrations in air in various sectors are also used in conjunction with particle deposition velocities to estimate a steady-state radionuclide concentration on the ground for annual exposures.

Accumulation of radioactive materials on the ground surface is represented with an infinite plane source model for external radiation exposure. The ground deposits are assimilated into food which, when ingested, results in an additional dose via the food chain pathway. Radioactive materials from the atmosphere are deposited on the ground surface through mechanisms of dry deposition and washout. Dry deposition,

as used in this analysis, represents an integrated deposition of radioactive materials by processes of gravitational settling, adsorption, particle interception, diffusion, and chemical-electrostatic effects, and is calculated from deposition velocity,⁷ V_g , for a one-year time interval. Deposition velocity values for particles and reactive gases commonly range from 0.1 to 1.0 $\text{cm}\cdot\text{sec}^{-1}$.^{7,8} For micron-sized particles, V_g 's may approach 10 $\text{cm}\cdot\text{sec}^{-1}$. A value of 1.0 $\text{cm}\cdot\text{sec}^{-1}$ is used for calculation of ground concentrations of radioactive particles.

Although many variables influence the washout of radioactivity from the atmosphere,⁹ Cowser et al.⁸ showed that washout would cause only a negligible decrease in annual air concentration based on a washout weight of 0.038 (Oak Ridge, Tennessee) and a washout coefficient of 10^{-1} sec^{-1} . The annual increase in ground concentration from washout would likewise be nominal. Thus, for model mixed-oxide fuel fabrication plants, total transfer of radioactive materials from the atmosphere to the ground surface is included in the dry deposition rate term.

7.2 Population

Population distributions were derived which would be representative of southeastern coastal and midwestern environments. The population distributions are the average of population distributions around two fuel fabrication plants and one reprocessing plant for each area, i.e., the midwestern and southeastern coastal sites. Distributions for sites near St. Louis, Mo., and Wilmington, S. C., were included in the averaging because the meteorologic data used for atmospheric transport of radioactive substances are based on these areas. The Wilmington site also represents the half-annulus distribution which is representative of areas adjacent to the ocean.

Average population distributions are calculated from data sets for areas determined by the latitude-longitude coordinates specified in Table 7.1. Actual population distributions from these locations were summarized from 1970 Census Bureau tape records to obtain representative distributions for midwestern and southeastern coastal regions (Tables

7.2 and 7.3). The computer code, PANS,¹⁰ provides sector summaries for annuli bounded by distances of 0.0, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 10, 15, 25, 35, 45, and 55 miles. The sector summaries correspond to the same sectors in the 16 compass directions for which X/Q' values are calculated. The computer code summaries of population data from census tapes are accurate beyond a five-mile radius. Within five miles, where sectors represent relatively small areas, distributions are somewhat disconnected because census enumeration districts encompass several sectors while the population records are reported in a single sector. Averaging data from three locations smooths the major discontinuities and results in cumulative totals which are somewhat similar to those reported for actual fuel fabrication facilities.^{11,12}

Population distributions for the two sites of the model fuel fabrication facilities have somewhat different characteristics (Tables 7.2 and 7.3). The average density within the 55-mile radial distance was 50 to 60 individuals per square mile for the coastal plain site except for a factor of 5 increase to 289 individuals per square mile, representing a small city, in the 5- to 10-mile annulus. The 9500-square-mile area encircling the coastal site is distinctly rural (58 individuals per square mile) in terms of population density. By comparison, the population density of the midwestern site within the 5-mile radius is nearly twice as great (95 vs 55) as that for the coastal site. Beyond five miles, the density increases to 126 individuals per square mile at 10 miles and to 440 individuals per square mile in the 25- to 50-mile annulus. A large city is included in a portion of the 55-mile area encircling the model fuel fabrication facility. Cumulative population in the midwestern site is approximately six times greater than for the coastal site.

7.3 Radiation Dose from Gaseous Effluents

Concentrations of radionuclides in air and on the soil surface are used to estimate the radiation dose to individuals at various distances and directions from the model plant. The doses resulting from submersion in the gaseous effluent, exposure to contaminated ground surface, and

intake of radionuclides through inhalation and ingestion are calculated with computer codes¹³ which use dosimetric criteria of the International Commission on Radiological Protection and other recognized authorities.

Estimates of intake of radionuclides by man through terrestrial food chains were made with a model and computer code¹⁴ which considers transfers of all radionuclides to man via ingestion of crop plants, beef, and milk. Many basic environmental parameters used in this model are conservative; that is, values are chosen to maximize intake by man. Reducing factors, such as shielding provided by dwellings and time spent away from the "reference" location, are not considered. Moreover, in estimating the dose to individuals via ingestion of plants, meat, and milk, an individual is assumed to obtain all of his food at the reference location specified in the calculation. This event is not impossible, but extremely unlikely. Thus, individual dose estimates calculated by these methods are higher than actually expected. Assumptions, models, and codes used to estimate radiation doses are given in Appendix B (ORNL-4992, see p. iii).

7.3.1 Individual and Population Dose

The maximum annual total body dose and organ doses to individuals from gaseous effluents at 0.5 mile from the model plant are summarized in Table 7.4 for all radwaste treatment cases for the coastal and midwestern sites. The total population dose out to a radius of 55 miles is also presented. The maximum dose to individuals at 1.0 mile is approximately 25% of the dose at 0.5 mile. Estimated maximum total body doses do not exceed 0.01 millirem/year to individuals living within 0.5 to 1 mile from the model plant at either site. Average annual doses to organs of the populations are given in Table 7.5. The relative contributions of exposure modes to total body dose from gaseous effluents are given in Table 7.6. Internal exposure from inhalation and ingestion accounts for 99% of the total body dose.

Maximum total body doses and population doses are similar for the coastal and midwestern sites. Although the population around the midwestern site is over six times greater than that around the coastal site, the dose to this population in man-rem is only 1.3 times greater. This

is because the gaseous effluents are released at building height (assumed to be ground level in this survey) and the radioactive materials tend to be deposited closer to the plants than would be the case with gaseous releases from a tall stack. Also, the average doses at various distances from the plant are smaller for the midwestern plant due to meteorological differences. Average total body doses are 34% and 47% lower than maximum doses for the coastal and midwestern sites, respectively. The cumulative dose to populations as a function of distance from the plant and population distribution is given in Table 7.7 for the base case.

The relative contributions of radionuclides in the gaseous effluent of a mixed-oxide fuel fabrication plant to total body dose are given in Table 7.8. Most of the internal dose (inhalation and ingestion) and dose from contaminated ground is due to the plutonium radionuclides and ^{241}Am . The dose from submersion in air is less than 0.1% of the total dose. Since about 98% of the total body dose is due to inhalation of radioactivity, the plutonium radionuclides, which account for 95% of the dose due to inhalation, are the most important radionuclides in the gaseous effluent of the plant.

7.3.2 Dose to Organs of Individuals

The maximum annual doses to organs of individuals from gaseous effluents at 0.5 mile from a model plant located at each site are given in Table 7.4 for the three radwaste treatment cases. Only organs receiving doses greater than those to the total body are listed. The average doses to organs would be 34% and 47% lower than these maximum values for the coastal and midwestern sites, respectively.

Table 7.9 gives the relative contributions of radionuclides in the gaseous effluent to individual organ doses. Most of the organ doses (over 90%) are due to plutonium radionuclides. The only other important contribution to organ doses is from ^{241}Am .

Radiation doses to organs are largely dependent on the specificity of certain radionuclides for accumulating in certain organs. Therefore, radwaste treatment cases which reduce the presence of a given radionuclide in the environment will reduce the dose to that organ which is

is exposed to the radionuclide via inhalation or ingestion pathways. For the model fuel fabrication plant, radwaste treatment Case 2 is effective in reducing doses to body organs by two orders of magnitude from those for radwaste Case 1.

7.4 Radiation Dose from Aquatic Pathways

The model mixed-oxide fuel fabrication plant has no radioactive liquid effluent. However, to evaluate aquatic pathways leading to a potential radiation dose to man and other biota, it is assumed that radioactive materials from the gaseous effluent would be deposited in an estuary at the coastal site and in a freshwater river at the midwestern site at the same rates and amounts as on a similar area of land.

For the coastal site, it is assumed that an estuary, 1 mile long by 0.5 mile wide by 2 m deep, is located 0.5 mile from the model plant in the direction of the prevailing wind. Gaseous effluents are deposited in this estuary for 1 year. All radionuclides remain in the water with no further dilution due to tidal influences or settling out.

For the midwestern site, it is assumed that a segment of a river, 1 mile long by 0.1 mile wide by 3 m deep, is located 0.5 mile from the model plant in the direction of the prevailing wind. Gaseous effluents are deposited in this river segment for 1 year. All radionuclides remain in the water with no further dilution by volume flow or settling out.

The annual total body doses estimated for exposures by aquatic pathways are given in Table 7.10. These doses are a small fraction of the dose to individuals estimated for terrestrial pathways, being less than 2×10^{-11} millirems. These estimates were made for treatment Case 1 (the base case plant). Eating fish from the estuary or drinking river water results in the largest portion of the total dose from aquatic pathways. For swimming, eating fish, or drinking water, ^{238}Pu , ^{241}Pu , and ^{241}Am contribute most of the radiation dose.

7.5 Total Radiation Dose from All Pathways

The total individual doses from gaseous effluents from the model mixed-oxide fuel fabrication plant obtained through both the terrestrial and the aquatic pathways are several orders of magnitude less than the normal annual background dose of 100 to 170 millirems in the United States.

7.6 Radiation Doses to Organisms Other Than Man

Radiation doses to aquatic plants, invertebrates, fish, and waterfowl are estimated for the coastal estuary and the freshwater river. Bio-accumulation factors for freshwater¹⁵ and saline¹⁶ organisms are used in these calculations. Tables 7.11 and 7.12 give annual doses to organisms living in the estuary and the river, respectively. The concentrations of radionuclides in these two aquatic environments are also given. Doses to organisms in the estuary are about 22% higher than those for the river.

In general, the dose to algae, invertebrates, and fish (saline and freshwater) is due primarily to ^{238}Pu , ^{241}Pu , and ^{241}Am . For waterfowl, 70% of the total dose from saline and freshwater is from ^{241}Am .

7.7 Estimates of Error for Atmospheric Dilution and Population Parameters

Atmospheric concentration of radioactive substances and population distribution are parameters which determine the radiation dose commitment to the human population. These parameters are used with dose conversion factors in the calculation of total body and organ doses for each sector. Variability of X/Q' values among direction sectors at a given distance is less for the coastal area than for the midwestern area (Table 7.13). The standard deviation for X/Q' ranges from 25% to 50% of the mean at both areas, however.

The variation in the cumulative population distribution is characterized by standard deviations which range from 30% to 100% of the mean for coastal and midwestern regions, respectively (Table 7.13). Population distributions for certain annuli, e.g., a 10- to 15-mile increment (Table

7.2), exhibit standard deviations which often exceeded the mean. For certain sectors with relatively sparse population, standard deviations are twice the mean value.

Results of this limited error analysis of X/Q' values and population distribution indicate that variability of these parameters would influence estimates of dose to individuals and population groups by factors of 2 to 4. This is based on the approximate assumption that 95% of the X/Q' values and population distributions would fall within two standard deviations of the mean. Dose to an individual at any distance would vary by as much as a factor of 2 ($CV = 0.5$ for midwestern X/Q'), while dose commitment to the population would vary by as much as a factor of 4 ($CF = 1.0$ for midwestern population). This analysis considers error sources independently; no attempt is made to estimate cumulative or multiplicative sources of error.

7.8 Exposures from Long-Lived Actinides Released into the Environment from a Mixed-Oxide Fuel Fabrication Plant

Potential releases of radionuclides during plant operation and estimations of resulting radiation doses to individuals and populations are discussed in Sections 7.3.1-7.6. In this section, estimates are presented of future potential radiation doses to individuals and populations exposed to the long-lived actinide radionuclides that are deposited on the land surface as a result of plant operation.

These estimates involve many complex considerations. All of the information necessary to make accurate predictions is not available. In the absence of complete information, estimates are made using the best current knowledge. Conservative assumptions are used in areas where deficiencies of knowledge exist. These assumptions make it likely that the estimates of health consequence are well above the probable effects. A more-detailed assessment of the radiation exposure to future generations from transuranic elements has been included in a recent environmental analysis of the LMFBR program.¹⁷

7.8.1 Source Term

The model fuel fabrication plant (Case 1) releases 1.36×10^{-3} Ci of actinides (Pu and Am) per year of operation. During this time, individuals and populations are exposed to a gaseous radioactive cloud from which they receive radiation doses due to immersion in the cloud and inhalation. At the same time, radionuclides deposited on the ground surface from the cloud lead to exposures from contaminated ground and ingestion of contaminated food.

During the lifetime of the plant, radionuclides are deposited and accumulate in the environment around the plant. The radionuclides with long half-lives continue to expose people long after the plant has ceased operation. Table 7.14 lists these radionuclides and the total quantities released from the model fuel reprocessing facility. The longest-lived radionuclides, ^{239}Pu , ^{240}Pu , ^{242}Pu , and ^{241}Am , will remain in the environment for generations.

The distribution of these radionuclides around the plant must be estimated in order to define the radiation dose to the population. For this assessment, it is estimated that essentially all of the actinide elements are deposited in a 50-mile radius of the plant. This follows from consideration of the meteorology at the model plants and from the use of a settling rate for particles of $1 \text{ cm} \cdot \text{sec}^{-1}$ from a source which is released at ground level. The same assumptions are used in estimating the dose to the population from releases from the operating plant. Other estimates of the deposition of these materials indicate that as much as 70% of the materials are deposited within 50 miles, even though the release point is the top of a 100-m-high stack.¹⁸

The average exposure to individuals and populations is estimated using the assumption that the radionuclides deposited during the operational lifetime of the model plant are uniformly distributed in the 50-mile radius area ($2.03 \times 10^{10} \text{ m}^2$). The use of this assumption causes an underestimation of the dose to individuals living near the facility or in areas of the prevailing wind direction and an overestimation of the dose to individuals living in the outer annulus of the 50-mile radius of the plant.

7.8.2 Pathways of Exposure

Resuspended Air Activity. — After airborne particulates are removed from the atmosphere and reach the ground by deposition and washout, they may again enter the atmosphere by resuspension processes. If they do, they may be inhaled. There is presently no general model which may be used to predict the levels of resuspended air activity with due regard to the geometrical configuration of the land surface, the particle characteristics of the deposited radioactivity and the parameters of host soil, the vegetation cover, and the meteorological conditions. These highly variable factors and others related to land use, such as the disturbance of soil surfaces by human activity, must be considered in preparing a precise estimate of resuspended radioactivity.

A resuspension factor can be estimated from measurements made above aged contaminated soil and from consideration of natural tracers such as ^{238}U . Resuspension factors of 10^{-9} and 10^{-10} m^{-1} were obtained from recent measurements of ^{239}Pu made at the Nevada Test Site in an area contaminated 17 years previously. Measurements of ^{239}Pu in the vicinity of the Rocky Flats plant several years after deposition indicated a resuspension factor of 10^{-9} m^{-1} .¹⁷ Discounting airborne material of industrial origin, it appears from the data concerning movement of natural ^{238}U that a realistic estimate of the resuspension of aged radioactive material in surface soil lies between 10^{-8} and 10^{-10} m^{-1} .¹⁷ This is in agreement with the field measurements for ^{239}Pu . An intermediate value of 1×10^{-9} is used in this survey to estimate the amounts of actinides inhaled over a long period of time for the relatively large, well-vegetated regions around a fuel fabrication facility. It is assumed that this value remains constant even though the deposited actinides may not remain on or near the surface of the soil. Actually, a continuation in the reduction of the availability of these materials beyond the current measurement experience of 20 years can be expected. Thus, the use of a constant resuspension factor is a conservative assumption which will maximize the estimated dose. Resuspended radionuclides are also assumed to enter terrestrial food pathways (vegetables, milk, and beef) via redistribution on foliage of crops and pastures. For estimating

intake via inhalation of resuspended actinides, the expression is:

$$\text{Ci intake yr}^{-1} = \text{Ci m}^{-2} \times 10^{-9} \text{ m}^{-1} \times 7200 \text{ m}^3 \text{ inhaled yr}^{-1} .$$

Ingestion. - The actinides that are not inhaled by man remain in the environment for times proportional to their radiological half-lives. During this time they may be ingested by man. Plants may be contaminated by direct deposition of airborne particles onto foliar parts and by root uptake of isotopes leached from or exchanged with particles deposited in soil. Plant uptake studies show that plutonium is strongly excluded from plant uptake and poorly translocated by plant systems. The general findings from greenhouse experiments indicate that the percentage uptake is on the order of 10^{-4} to 10^{-6} of the activity added to the test soil or that concentration factors (ppm dried plant material/ppm dried soil) are about 10^{-3} to 10^{-5} .¹⁷ Lower factors may occur under field conditions. Although various plant and soil types have been tested, the list is not all-inclusive. Two studies have shown greater uptake 2 to 5 years after the initial contamination, which may be due to increased root development and to organic complexation associated with fungi on decayed root material.¹⁷ Longer-term changes in plant uptake are unknown. Several competing processes can influence the changes, including downward movement of activity in soil, which can reduce availability to higher plants, and reactions with soil organic matter and microbial transformations, which may increase availability.

The fraction of actinide elements that enters man during their long existence in the environment will depend on their distribution, their chemical and physical behavior in the environment for thousands of years, and climatological conditions and land use patterns specific to the area. Sufficiently detailed and accurate knowledge regarding the many factors influencing the movement of these elements through the environment over the periods of hundreds to tens of thousands of years during which they may enter man through the ingestion pathway is not available to permit a precise estimate of the dose to man. It is appropriate, therefore, to estimate potential human ingestion using conservative parameters and assumptions. In preparing the estimate for this survey, it is assumed

that plant material accumulates a concentration of actinides equal to 10^{-3} of the concentration in the soil in which the plants grow, that there is no downward movement of the actinides in the soil beyond the root zone (15 cm), and that actinides are not lost by drainage of water. With a soil density of 1.5 g cm^{-3} , the actinides deposited on a square meter are contained in $2.25 \times 10^5 \text{ g}$ of soil. The following expression is used to estimate the intake via ingestion of plants:

$$\text{Ci yr}^{-1} \text{ ingested} = \text{Ci m}^{-2} \div 2.25 \times 10^5 \text{ g soil} \times 10^{-3} \times 91,250 \text{ g plant ingested yr}^{-1} .$$

Additional intake from the ingestion of plants contaminated via resuspended radionuclides was calculated using the TERMOD code referenced in Section 7 and with assumptions given in ORNL-4992 (see p. iii).

Contaminated Ground. - Exposure via contaminated ground is also estimated. It is assumed that there is no loss of deposited actinides except through radioactive decay. Other assumptions are given in ORNL-4992.

7.8.3 Dose Estimates

The radiation dose to an individual residing within the uniformly contaminated area of 7.85×10^3 square miles was estimated for total body and for the organs that are known to accumulate actinides. No additional population assumptions are made, and population doses are expressed as man-rem per million persons.

All radiation doses from ingestion and inhalation are 50-year dose commitments from 1 year of exposure, i.e., the dose an individual will accrue over a 50-year period (essentially a lifetime dose) from 1 year of intake of radionuclides. External doses (exposure to contaminated ground) are annual doses from 1 year of exposure.

It is conservative to call a dose commitment an annual dose in the case of a single year's intake of long-lived radionuclides. However, for assessing a situation where people are continually exposed over long periods of time and radionuclides have reached steady-state conditions

in the environment, dose commitments approximate annual doses.

Individual and Organ Dose. — As a result of the deposition of long-lived radionuclides such as the actinides, persons living within a 50-mile radius of the model fuel fabrication plant will continue to receive some radiation dose above background long after plant operation has been terminated, or actually until the ultimate decay of all the radionuclides. The average annual doses to the individual out to 50 miles for the various radionuclides and exposure modes are shown in Table 7.15. Almost 68% of the total body dose of 2.8×10^{-7} millirem resulted from exposure to contaminated ground. The average annual total body dose due to ^{238}Pu , which accounted for about 64% of the total dose, was 1.8×10^{-7} millirem. These doses are the average doses out to 50 miles, and the dose range, as a function of distance, may be indicated by the fact that during operation the average total body dose to an individual at a distance of 1 mile is about three orders of magnitude higher than the dose to an individual at a 50-mile distance.

The average annual doses to the organs resulting from the various radionuclides and for the major internal pathways are shown in Table 7.16. The bone receives the highest organ dose, which is about 8 times the dose to the kidney and liver and 46 times that to the lungs.

Population Doses. — The average annual dose to the population, given as man-rem per million persons, is shown in Table 7.17. The average annual dose to the population (total body and organs) is again primarily due to ^{238}Pu . The bone receives the highest organ dose.

7.9 References

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8.0 CORRELATION OF ENVIRONMENTAL IMPACT WITH COST OF WASTE TREATMENT

The relationships between the annual costs (Sect. 6.0) of the radwaste treatment systems described in Section 4.5 and the impact of radioactive releases (dose) from these systems as described in Section 7.0 are presented in this section. The accuracy of the cost estimates is about $\pm 30\%$, and the dose commitments represent maximum values. The most advanced treatment system uses conventional technology, but its technical feasibility has not been verified in a plant installation. Similarly, many of the models for the movement and concentration of radionuclides in the environment are receiving additional study to increase their accuracy. In all cases, the various assumptions made in estimating the makeup of the feed to the fabrication plant, selecting treatment efficient ratings for equipment, estimating costs, defining the movement of radionuclides in the environment, and selecting food and liquid consumption patterns were realistically conservative, and this is reflected in the costs and doses.

The annual costs and dose commitments for the base case (Case 1) and succeeding case studies (Cases 2 and 3) at the midwestern and coastal sites are summarized in Table 8.1, Fig. 8.1, and Fig. 8.2. The estimated annual costs required for additional radwaste treatment in each case beyond that required for the previous case, i.e., the added incremental costs, are presented in Table 8.2. The dose commitments from the gaseous effluents are reported on several bases, including (1) the maximum annual individual total body, bone, liver, kidney, and lung doses at 0.5 mile from the plant, which represent the doses from all radioactive materials released from the fabrication plant in each case study; (2) incremental maximum annual individual doses at 0.5 mile, which represent the differences in dose between a given case and the preceding case; and (3) the annual average population total body dose out to a distance of 55 miles. Factors for calculating maximum doses at distances greater than 0.5 mile are given in Section 7.0. Average individual total body doses out to a distance of 55 miles are also listed in Section 7.0. The maximum, rather than the average, individual doses to total body, bone, liver, kidney, lung,

and the average population dose, are used to illustrate the cost-benefit relationships in this section and thus maintain the principle of the selection of maximum effect in this study. Total body dose was selected because of its obvious importance, and bone, liver, kidney and lung doses because the principal radionuclides that contribute to the total body dose also contribute to bone, liver, kidney, and lung doses. Two plutonium isotopes, ^{238}Pu and ^{241}Pu , contribute 81 to 87% of the radiological doses.

Since liquid radwastes are contained and isolated from the environment, the dose calculations are based only upon the radioactive particulates released in the gaseous effluent from the plant. The calculated population doses for the midwestern site are about 30% greater than those for the coastal site because of variations in atmospheric dispersion patterns and population densities. This difference, as applied to the average annual population total body dose, is shown in Fig. 8.2.

The estimated maximum individual annual doses are <1 millirem for bone and <0.01 millirem for total body in Case 1, the case which represents the greatest release of radionuclides. These values are low compared with the natural background radiation dose of 100 to 170 millirem/yr in the United States. The population dose commitments of 0.0082 man-rem for the coastal site and 0.11 man-rem for the midwestern site out to a distance of 55 miles from the plant are also low as compared with the population dose from background radiation. The concentrations of radioactive materials in the gaseous radwaste effluent in Case 1 are well below the guidelines listed in the Code of Federal Regulations (10 CFR 20) and are comparable to those estimated for plutonium fabrication plants which are proposed for construction (Sect. 4.5.2).

8.1 Comparison of Gaseous Radwaste Treatment Costs and Radiological Dose

Individual Total Body Dose. — The maximum annual individual total body dose is derived mostly from ^{238}Pu (57%) and ^{241}Pu (27%). The annual costs of reducing this dose at 0.5 mile are presented in Tables 8.1 and 8.2 and Fig. 8.1. The total body dose is reduced by a factor of 100, i.e., from 8.5×10^{-3} to 8.5×10^{-5} millirem, from Case 1 to Case 2 by

installing an additional bank of HEPA filters at a total annual cost increase of \$182,000. A cost-benefit ratio for this increment is \$21,600,000 per millirem, corresponding to an annual expenditure of ~0.5% of the \$40 million capital cost for the plant. A further reduction in dose by a factor of 10^5 occurs in Case 3, where the limit of available technology is applied. Most of the process gases are recycled in this case, and only a small fraction is released after intensive treatment. This reduction in dose is achieved at an added cost of \$281,000 per year, which corresponds to a cost-benefit ratio of \$3,310,000,000 per millirem. The high cost-benefit ratio results from the small amounts of radioactive materials that are available for removal after the treatments applied in Case 2, rather than from the magnitude of the treatment cost. The incremental expenditure between Case 2 and Case 3 (\$281,000) amounts to about 0.7% of the plant capital cost. The treatment of the gaseous effluents in the basic model plant (Case 1) achieves a dose reduction of 4×10^5 at an annual cost of \$762,000 to provide a cost-benefit ratio of \$224 per millirem. Thus, the lowest cost-benefit ratio is attained in Case 1. The value rises quickly for succeeding case increments owing primarily to the low residual amounts of radioactive materials.

Bone Dose. — The maximum annual individual bone dose is derived mostly from ^{238}Pu (55%) and ^{241}Pu (32%). Annual costs to reduce the bone dose are presented in Tables 8.1 and 8.2 and Fig. 8.1. The initial dose reduction by a factor of 4×10^5 achieved by the final off-gas treatment system in the model plant (Case 1) provides a cost-benefit ratio of \$5.4 per millirem. An additional dose reduction by a factor of 100 in Case 2 is obtained at a cost-benefit ratio of \$525,000 per millirem. Further reductions in bone dose (by a factor of 10^5) in Case 3 are obtained at the very high cost-benefit ratio of \$80,300,000 per millirem. The most efficient system, as measured by the cost-benefit ratio, is the basic model plant (Case 1).

Liver and Kidney Doses. — The maximum annual individual liver and kidney doses are also derived from ^{238}Pu (67% and 53%, respectively) and ^{241}Pu (14% and 28%). Cost-benefit ratios for the model plant

(Case 1) off-gas treatment system are \$47 and \$51 per millirem for liver and kidney doses, respectively. The ratios that represent the effects of equipment additions in Case 2 are \$4,480,000 and \$4,840,000 per millirem. Case 3 values are \$685,000,000 and \$739,000,000 per millirem. Again, the most efficient system is the basic model plant (Case 1).

Lung Dose. — The maximum annual individual lung dose is derived mostly from ^{238}Pu (82%) and to a much lesser degree from ^{240}Pu (9%). The model plant (Case 1) provides an initial reduction in dose of 2×10^5 for a cost-benefit ratio of \$248 per millirem. The Case 2 equipment additions provide a cost-benefit ratio of \$23,900,000 per millirem. The Case 3 cost-benefit ratio is \$3,650,000,000 per millirem. The most efficient system is again the basic model plant (Case 1).

Population Dose. — The annual cost of reducing the average annual population total body dose (man-rem) out to a distance of 55 miles is presented in Table 8.1 and Fig. 8.2. A cost-benefit ratio of \$235 per man-rem results from the factor of 4×10^5 reduction in the initial dose achieved by the model plant (Case 1) final off-gas treatment system at the coastal site. The ratio is \$173 per man-rem at the midwestern site. The population dose values for Case 1 are quite low, i.e., 0.0082 and 0.011 man-rem for the coastal and midwestern sites, respectively. The cost-benefit ratios are much higher in Cases 2 and 3, where additional gaseous radwaste treatment equipment is used to decrease the release of radioactive materials. The population dose is reduced by a factor of 100 in Case 2 at an increased annual cost of \$182,000 (or ~0.5% of the capital investment). This corresponds to cost-benefit ratios of \$2,240,000 and \$1,670,000 per man-rem for the coastal and midwestern sites, respectively. Additional dose reductions from Case 2 values to near "zero" values in Case 3 are estimated at an increased annual expense of \$281,000 (or ~0.7% of the capital investment). Cost-benefit ratios for this increment are \$3,430,000,000 and \$2,550,000,000 per man-rem for the coastal and midwestern sites, respectively.

8.2 Comparison of Gaseous Radwaste Treatment Costs and Power Costs

The capital cost of the total model plant for the base case (Case 1) is \$40 million. The estimated capital cost of the gaseous radwaste treatment system in this plant is \$2.7 million (Table 6.1). The corresponding annual off-gas treatment and contribution to power costs are \$0.76 million and 0.00988 mill/kWhr. Capital costs for gaseous radwaste treatment in advanced cases range from \$3.35 to \$4.4 million, or up to about 11% of the capital cost of the base plant. The annual costs for the advanced cases of gaseous radwaste treatment range from \$0.94 to \$1.2 million and are equivalent to contribution to power costs of 0.0122 and 0.0159 mill/kWhr, respectively. All of these values are less than 0.2% of an estimated total power generation cost of 7 to 10 mill/kWhr. Thus, the cost of gaseous radwaste treatment is a small fraction of total capital and power generation costs.

Table 4.1. Material Flow in the Oxalate Process for the Production of Plutonium Oxide

Stream	Total Volume (gal/day)	Flow Rate (lb/day)								
		$\text{Pu}(\text{NO}_3)_4$	$\text{Pu}(\text{NO}_3)_3$	HNO_3	H_2O	NH_4NO_3	$\text{H}_2\text{C}_2\text{O}_4$	H_2O_2	PuO_2	$\text{Pu}(\text{C}_2\text{O}_4)_2 \cdot 6\text{H}_2\text{O}$
1	48.2	188	-	93.1	302	-	-	-	-	-
2	4.4	-	1.57	1.39	35.4	0.30	-	-	-	-
3	19.4	-	-	133	88.6	-	-	-	-	-
4	133	-	-	-	1040	-	100	-	-	-
5	6.4	-	-	-	26.5	-	-	26.5	-	-
6	217	2.06	-	351	1490	0.32	33.0	28.4	-	206
7	206	1.95	-	334	1420	0.30	31.4	26.9	-	5.18
8	16.5	0.16	-	26.7	113	0.02	2.51	2.16	-	3.88
9	189	1.80	-	307	1300	0.28	28.9	24.8	-	1.29
10	-	-	-	-	-	-	-	-	-	1.08
11	10.8	0.10	-	17.6	74.5	0.02	1.65	1.42	-	202
12	-	-	-	-	-	-	-	-	105	-

Table 4.2. Material Flow in the Scrap Recovery System
(Model plant does not include oxalate process.)

[illegible]

Table 4.4. Liquid Radwaste Generated by the Model Mixed-Oxide
Fuel Fabrication Plant Before Effluent Treatment

Source	Volume (gal/day)	Percent of Total Volume	Concentration (ppm)		Primary Chemical Constituents	
			U	Pu	Type	Concentration (M)
<u>Interim Plant</u>						
Plutonium Oxalate Process	189.3	14	-	886	HNO ₃ H ₂ O ₂ H ₂ C ₂ O ₄ NH ₄ NO ₃	3.08 0.46 0.20 0.002
Scrap Recovery System:						
Raffinate waste	122.9	8.8	12.0	0.5	HNO ₃ HF	0.82 0.03
Clarifier waste	121.4	8.7	268	12.3	NH ₄ NO ₃	0.36
Miscellaneous	828	59	-	-	Detergent	Variable
Gas Scrubbers:						
Oxalate process	94.0	6.7	-	-	HNO ₃	0.82
Scrap recovery system	38.0	2.7	-	-	NH ₄ NO ₃	1.43
<u>Advanced Plant</u>						
Scrap Recovery System:						
Raffinate waste	122.9	13	12.0	0.5	HNO ₃ HF	0.82 0.03
Clarifier waste	121.4	13	268	11.7	NH ₄ NO ₃	0.36
Miscellaneous	675	70	-	-	Detergent	Variable
Gas Scrubber	38.0	4.0	-	-	NH ₄ NO ₃	1.43

Table 4.5. Characteristics of the Isotopes in the Feed
to the Model Mixed-Oxide Fuel Fabrication Plant^a

Nuclide	Half-Life	Type of Decay
Th-231	25.52 hr	β
Th-234	24.10 days	β
Pa-234	1.177 min	β
U-234	2.47×10^5 yr	α
U-235	7.10×10^8 yr	α
U-236	2.42×10^7 yr	α
U-237	6.75 days	β
U-238	4.51×10^9 yr	α
Np-237	2.14×10^6 yr	α
Pu-238	87.4 yr	α
Pu-239	24,390 yr	α
Pu-240	6,600 yr	α
Pu-241	14.3 yr	β
Pu-242	3.87×10^5 yr	α
Am-241	433 yr	α
Cm-244	17.6 yr	α

^aList includes all nuclides considered, based on natural uranium and recycled plutonium isotopic makeup as calculated by computer code ORIGEN.

Table 4.6. Isotopic Concentrations and Relative Inhalation Hazards in the Feed to the Model Mixed-Oxide Fuel Fabrication Plant^a

Nuclide	Abundance (wt %)	Isotopic Mass (kg/yr)	Contribution to Total Relative Inhalation Hazard ^b (%)
Th-231	2.8E-12	8.49E-09	<0.02
Th-234	1.4E-09	4.18E-06	<0.02
Pa-234	4.7E-14	1.42E-10	<0.02
U-234 ^c	7.5E-03	2.25E+01	<0.02
U-235 ^c	6.9E-01	2.07E+03	<0.02
U-236	2.4E-04	7.14E-01	<0.02
U-237	1.6E-08	4.92E-05	<0.02
U-238 ^c	9.5E+01	2.85E+05	<0.02
Np-237	9.2E-05	2.75E-01	<0.02
Pu-238 ^c	1.3E-01	3.83E+02	54.42
Pu-239 ^c	1.9E-00	5.72E+03	3.38
Pu-240 ^c	1.1E-00	3.40E+03	7.40
Pu-241 ^c	5.5E-01	1.65E+03	33.11
Pu-242 ^c	4.2E-01	1.27E+03	0.05
Am-241 ^c	5.5E-02	1.66E+02	1.65
Cm-244	1.8E-07	5.35E-04	<0.02

^aLists includes all nuclides considered.

^bRelative Inhalation Hazard = curies present in 1 metric ton of fuel divided by Radiation Concentration Guide value.

^cNuclides used in calculating source terms.

Table 4.7. Distribution of Alpha and Beta Radioactivity in the
4.2 wt % Plutonium Mixed-Oxide Feed to the Fabrication Plant

Nuclide ^a	Specific Activity of Pure Isotope (Ci/g)	Specific Activity of Each Isotope in 4.2 wt % Fuel (Ci/g fuel)	Percent of Activity Contributed by Each Isotope	Total Activity (Ci/yr)
Pu-238	1.720E+01	2.20E-02	3.66	6.59E+06
Pu-239	6.138E-02	1.17E-03	0.20	3.51E+05
Pu-240	2.259E-01	2.56E-03	0.43	7.68E+05
Pu-241	3.820E-03	1.62E-05	0.0027	4.86E+03
Am-241	3.429E-00	1.90E-03	0.32	5.71E+05
α Totals	-	2.76E-02	4.60	8.28E+06
Pu-241	1.038E+02	5.73E-01	95.40	1.72E+08
β Totals	-	5.73E-01	95.40	1.72E+08
α + β totals	-	6.00E-01	100.00	1.80E+08

^aNuclide list includes only those that contribute >0.02% of the total Relative Inhalation Hazard
(see Table 4.6).

Table 4.8. Solid Radioactive Wastes

Source	Total Volume of Liquid (gal/day)	Chemical Constituents	Total Salt Content	Plutonium (g/day)	Number of Drums of Cement ^a	Activity (Ci/ft ³)
Raffinate from Oxalate Process Liquid Radwaste Treatment System	230	H ₂ O, Ca(NO ₃) ₂ , KNO ₃ , Mn(NO ₃) ₂ , NH ₄ NO ₃	10%	0.040	9	8.6E-03
Clarifier and Raffinate Wastes from Scrap Recovery Liquid Radwaste Treatment System	151.1	H ₂ O, NH ₄ NO ₃ , Ca(NO ₃) ₂ , CaF ₂ , uranium salts	10%	1.15 ^b 1.20 ^c	6	3.7E-01 ^b 3.9E-01 ^c
Solids with Low Activity From Fuel Fabrication	-	Zircaloy, stainless steel	-	Trace	-	-
Filter for Scrap Recovery Dissolver Product	-	MnO ₂	3.8 lb	Trace	-	-
Filter for Miscellaneous Liquid	-	Unknown	-	-	-	-
Miscellaneous Solids	-	Paper, cloth, fiberglass, metals	-	Trace	-	-
Total Average					15 or 110 ft ³ /day	1.4E-01 ^b 1.0E-01 ^c

^a26 gal of liquid assumed to be incorporated into each 55-gal drum of cement.^bWithout oxalate process.^cWith oxalate process.

Table 4.9. Summary of Variables for Model LWR Mixed-Oxide Fuel Fabrication Plant
Gaseous Radwaste Treatment Systems

	Case 1	Case 2	Case 3
Treatment Objective	Base Case	Reduce plutonium release by a factor of at least 100	Clean and recycle most process gaseous radwaste; extensively treat and discharge small fraction of process gaseous radwaste to minimize plutonium release
Plant DF for plutonium and uranium (Ci entering plant/Ci released in gaseous radwaste)	1.33E+11	1.33E+13	1.33E+18
<u>Process Gaseous Radwaste^a</u>			
	Scrubber, roughing filter, HEPA filter; blend with alpha enclosure and plant ventilation air; two HEPA filters in series	Add additional bank of HEPA filters to final filtration in Case 1	Scrubber, roughing filter, HEPA filter; blend with alpha enclosure ventilation air; recycle 98% through HEPA filter; discharge 2% through two HEPA filters in series; blend with plant ventilation air; two HEPA filters in series
Rated DF of Filter Train	8.0E+10	1.6E+14	1.6E+19
Installed DF	8.0E+07	8.0E+09	8.0E+14
<u>Alpha-Enclosure Ventilation Air^b</u>			
	Roughing filter, HEPA filter; blend with process gaseous radwaste and plant ventilation air; two HEPA filters in series	Same as above	Roughing filter, HEPA filter; blend with process gaseous radwaste; recycle 98% through HEPA filter; discharge 2% through two HEPA filters in series; blend with plant ventilation air; two HEPA filters in series
Rated DF of Filter Train	8.0E+09	1.6E+13	1.6E+18
Installed DF	8.0E+06	8.0E+08	8.0E+13
<u>Plant Ventilation Air</u>			
	Roughing filter, HEPA filter; blend with process gaseous radwaste and alpha enclosure ventilation air; two HEPA filters in series	Same as above	Same as Case 1

^aContains 0.02% of the radioactive material entering the plant before treatment.

^bContains 0.004% of the radioactive material entering the plant before treatment.

Table 4.10. Source Terms for Model Mixed-Oxide Fuel Fabrication Plant - Calculated
Release of Radioactive Material in Gaseous Effluents

Nuclide	Case 1		Case 2		Case 3	
	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)
U-234	7.1E-19	1.0E-09	7.1E-21	1.0E-11	1.4E-25	1.0E-16
U-235	2.3E-20	3.3E-11	2.3E-22	3.3E-13	4.5E-27	3.3E-18
U-238	4.9E-19	7.1E-10	4.9E-21	7.1E-12	9.7E-26	7.1E-17
Pu-238	3.4E-14	4.9E-05	3.4E-16	4.9E-07	6.7E-21	4.9E-12
Pu-239	1.8E-15	2.6E-06	1.8E-17	2.6E-08	3.6E-22	2.6E-13
Pu-240	3.9E-15	5.8E-06	3.9E-17	5.8E-08	7.8E-22	5.8E-13
Pu-241	8.8E-13	1.3E-06	8.8E-15	1.3E-05	1.8E-19	1.3E-10
Pu-242	2.5E-17	3.6E-08	2.5E-19	3.6E-10	5.0E-24	3.6E-15
Am-241	2.9E-15	4.3E-06	2.9E-17	4.3E-08	5.8E-22	4.3E-13

Table 4.12. Material Flow in the Scrap Recovery Liquid Radwaste Treatment System

Stream	Total Volume (gal/day)	Flow Rate (lb/day)											
		H ₂ O	NH ₄ NO ₃	(NH ₄) ₂ U ₂ O ₇	Pu(OH) ₃	UO ₂ (NO ₃) ₂	Pu(NO ₃) ₄	HNO ₃	HF	Ca(OH) ₂	Ca(NO ₃) ₂	CaF ₂	U+Pu
1	121	980	29.4	0.35	0.01	-	-	-	-	-	-	-	-
2	38.0	317	36.4	-	-	-	-	-	-	-	-	-	-
3	-	-	-	0.29	0.01	-	-	-	-	-	-	-	-
4	159	1300	65.8	0.06	Trace	-	-	-	-	-	-	-	-
5	123	1000	-	-	-	0.02	Trace	53.3	0.64	-	-	-	-
6	-	-	-	-	-	-	-	-	-	32.5	-	-	-
7	282	2310	65.8	-	-	-	-	-	-	-	69.4	1.25	0.06
8	131	1090	-	-	-	-	-	-	-	-	-	-	-
9	151	1220	65.8	-	-	-	-	-	-	-	69.4	1.25	0.06

Table 5.1. Water Usage and Overall Liquid Material Balance

Stream	Composition	Flow Rate (gal/day)	
		Interim Plant	Advanced Plant
1	H ₂ O	101,500	90,000
2	H ₂ O	82,300	72,100
3	H ₂ O	54,900	48,100
4	H ₂ O	10,900	9,600
5	H ₂ O	16,500	14,400
6	H ₂ O	18,100	17,200
7	H ₂ O	1,070	710
8	H ₂ O	830	670
9	H ₂ O	35,400	32,300
10	H ₂ O	40	40
11	H ₂ O	130	130
12	H ₂ O	110	-
13	H ₂ O	90	-
14	H ₂ O	20	-
15	60% HNO ₃	15	15
16	1.5% NH ₃	116	116
17	Pu(NO ₃) ₄ feed sol.	48	-
18	Pu(NO ₃) ₃ recycle	4	-
19	60% HNO ₃	25	-
20	Liquid radwaste	244	244
21	Liquid radwaste	151	151
22	Liquid radwaste	189	-
23	Liquid radwaste	230	-
24	Liquid radwaste	381	151

Table 6.1. Estimated Annual Costs and Contribution to Power Cost for the 300-Metric Ton/yr Model Mixed-Oxide Recycle Fuel Fabrication Plant Gaseous Radwaste Treatment Cases

Gaseous Radwaste Case	Capital ^a Cost (\$1000)	Annual Fixed Charges (\$1000)	Annual Operating Cost (\$1000)	Total Annual Cost (\$1000)	Contribution to ^b Power Cost (mills/kWhr)
1	2,707	704	58	762	9.88E-03
2	3,353	872	72	944	1.22E-02
3	4,397	1,143	82	1,225	1.59E-02

^aIncludes direct cost (building and installed equipment) and indirect cost. The interest during construction is included as an indirect cost.

^bThe contribution to power cost is calculated on the basis of a 300-metric ton/yr recycle fuel fabrication plant servicing a nuclear economy of eleven 1000-MW(e) light-water reactors (33,000 MWd/metric ton irradiation level, 80% load factor, 32.5% thermal efficiency).

Table 6.2. Installed Equipment Costs for Model Mixed-Oxide Fuel Fabrication Plant

Item	Cost Without Structure (\$1000)	
	Direct ^a	Capital ^b
<u>Case 1</u>		
HEPA Filters		
10 - Modules of 30 filters each, including housing	450	1,080
Blowers		
5 - 40,000 cfm	103	312
Dampers and Drives		
10 - 43-in. diameter	180	432
Duct		
500 ft - 3.6-ft diameter	87	209
<u>Case 2</u>		
HEPA Filters		
5 - Modules of 30 filters each, including housing	225	540
<u>Case 3</u>		
HEPA Filters		
9 - Modules of 42 filters each, including housing	567	1,361
4 - Modules of 2 filters each, including housing	12	29
Blowers		
6 - 40,000 cfm	124	298
2 - 2,000 cfm	5	12
Dampers and Drives		
12 - 51-in. diameter	288	691
2 - 43-in. diameter	36	86
1 - 36-in. diameter	14	34
4 - 12-in. diameter	15	36
Ducts		
150 ft - 5.5-ft diameter	40	96
700 ft - 4.2-ft diameter	141	338
100 ft - 3.6-ft diameter	17	41
100 ft - 3.0-ft diameter	14	34
150 ft - 1.0-ft diameter	7	17

^aCost for 1973. Direct cost includes purchase cost and complete installation cost.

^bCapital costs are calculated by multiplying the direct cost by 2.4. Capital costs include both direct and indirect costs. Interest during construction is included as an indirect cost.

Table 7.1. Latitude-Longitude Coordinates Used to Derive
Data Sets for Population Distribution

Site	Latitude (N)	Longitude (W)
Midwestern	35° 52' 50"	97° 35' 00"
	38° 12' 18"	90° 28' 28"
	41° 22' 43"	88° 16' 36"
Coastal	33° 15' 00"	81° 29' 20"
	33° 53' 13"	80° 55' 58"
	34° 19' 19"	77° 76' 12"

Table 7.2. Representative Population Distribution at Successive Distances for Midwestern Site

Sector	Radial Distance (miles)											
	0-0.5	0.5-1	1-2	2-3	3-4	4-5	5-10	10-15	15-25	25-35	35-45	45-55
N	0	0	0	0	0	252	2007	1037	19193	108738	96229	46889
NNE	0	0	0	0	0	816	847	7688	40643	347330	300030	300804
NE	0	0	0	0	0	709	936	23608	22601	77981	625661	575054
ENE	0	0	0	0	652	1197	1906	1377	8737	85826	192983	110272
E	0	0	0	365	0	452	3506	254	1824	10629	14875	24482
ESE	0	0	0	0	69	2	799	972	3323	4470	8449	4378
SE	0	0	0	13	537	482	1022	696	3241	23827	5080	15453
SSE	0	0	0	0	0	0	1796	706	10056	41868	4461	7339
S	0	0	0	87	0	72	1498	908	30234	100668	10935	17328
SSW	0	0	0	0	0	98	626	586	3588	6416	7425	3933
SW	0	0	146	0	0	0	2233	428	2614	6862	1717	3257
WSW	0	0	0	0	526	0	907	202	1380	8621	2690	4601
W	0	0	0	0	0	0	3128	655	4400	8192	14438	8317
WNW	0	0	0	0	132	77	505	402	1424	6379	4908	3646
NW	0	260	0	0	0	0	346	1083	8288	5991	6200	4146
NNW	0	0	0	0	544	0	579	829	5823	5027	28615	20359
Total (by distance)	0	260 ±449 ^a	146 ±220	465 ±804	2460 ±1453	4157 ±4280	22641 ±8469	40498 ±49447	167369 ±42111	848825 ±378192	1324696 ±1536279	1150618 ±1698458
Cumulative	0	260	406	871	3331	7488	30129	70627	237996	1086821	2411517	3562135
Density (ind./mile ²)	← 95 → 96 ← 126 → ← 440 →											

^aStandard deviation of the mean (total).

Table 7.3. Representative Population Distribution at Successive Distances for Coastal Plain Site

Sector	Radial Distance (miles)											
	0-0.5	0.5-1	1-2	2-3	3-4	4-5	5-10	10-15	15-25	25-35	35-45	45-55
N	0	0	0	151	0	46	10358	7761	3512	4060	4835	9942
NNE	0	0	0	0	0	0	965	1147	1978	3115	5985	17515
NE	0	0	0	0	0	0	438	284	1139	6646	27892	7382
ENE	0	0	0	0	443	0	847	1119	4112	6321	12413	9022
E	0	0	0	0	0	239	2539	801	1553	17556	4215	5544
ESE	0	0	0	0	0	0	1726	420	660	2463	4700	6466
SE	0	0	0	0	246	213	1710	933	1453	3261	2909	4130
SSE	0	0	0	35	282	0	5954	1780	3546	2991	3247	3380
S	0	0	0	0	250	570	12327	1095	2803	9367	2829	2744
SSW	0	0	0	0	0	0	0	318	1518	2978	5556	4590
SW	0	0	0	0	0	0	710	990	1620	3953	4320	4846
WSW	0	1112	0	0	0	0	0	470	732	3309	2833	13724
W	0	0	0	0	0	0	1313	669	1975	5684	7106	10573
WNW	0	0	0	0	0	0	1568	4341	5456	42402	24875	7668
NW	0	0	0	0	0	7	7970	11817	8353	13856	4110	7239
NNW	0	0	0	0	421	310	15334	22775	4024	8447	5564	9189
Total (by distance)	0	1112 ±1926 ^a	0 -	186 ±237	1642 ±927	1385 ±1555	63759 ±54948	56720 ±79376	44434 ±17548	136409 ±93262	123389 ±30247	123954 ±29498
Cumulative	0	1112	1112	1298	2940	4325	68084	12804	169238	305631	42902	552974
Density (ind./mile ²)	<----- 55 ----->						289	<----- 61 ----->		<----- 51 ----->		

^aStandard deviation of the mean (total).

Table 7.4. Summary of Annual Doses to Individuals^a and Population from Gaseous Effluent of a Model Mixed-Oxide Fuel Fabrication Plant on a Coastal and a Midwestern Site

Site	Radwaste Treatment Case	Maximum Annual Individual Dose at 0.5 Mile (mrem)					Average Total Body Dose to Population out to 55 miles (man-rem)
		Total Body	Bone	Kidney	Liver	Lung	
Coastal	1	8.5E-03	3.5E-01	3.8E-02	4.1E-02	7.7E-03	8.2E-03
	2	8.5E-05	3.5E-03	3.8E-04	4.1E-04	7.7E-05	8.2E-05
	3	8.5E-10	3.5E-08	3.8E-09	4.1E-09	7.7E-10	8.2E-10
Midwestern	1	8.6E-03	3.5E-01	3.9E-02	4.1E-02	7.8E-03	1.1E-02
	2	8.6E-05	3.5E-03	3.9E-04	4.1E-04	7.8E-05	1.1E-04
	3	8.6E-10	3.5E-08	3.9E-09	4.1E-09	7.8E-10	1.1E-09

^aDose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Values in this table may be multiplied by 0.244 to give maximum doses at 1 mile.

Table 7.5. Average Annual Doses to the Organs
of the Population

Gaseous Radwaste Case No.	Dose to Organ (man-rem)			
	Bone	Liver	Kidney	Lung
Coastal Site				
1	3.3E-01	3.9E-02	3.7E-02	7.4E-03
2	3.3E-03	3.9E-04	3.7E-04	7.4E-05
3	3.3E-08	3.9E-09	3.7E-09	7.4E-10
Midwestern Site				
1	4.3E-01	5.0E-02	4.8E-02	9.6E-03
2	4.3E-03	5.0E-04	4.8E-04	9.6E-05
3	4.3E-08	5.0E-09	4.8E-09	9.6E-10

Table 7.6. Contribution of Exposure Modes to Total Body Dose
from the Gaseous Effluent of a Model Mixed-Oxide Fuel
Fabrication Plant^a

Exposure Mode	Annual Dose (mrem)	Percent of Total Dose
Submersion in air	1.6E-10	<0.1
Contaminated ground	8.3E-05	0.9
Inhalation	8.4E-03	98.3
Ingestion	5.9E-05	0.7

^aMaximum total body dose at 0.5 mile, coastal site treatment Case 1.

Table 7.7. Cumulative Population and Dose (man-rem) from
Gaseous Effluents as a Function of Distance from a Model
Mixed-Oxide Fuel Fabrication Plant^a on a Coastal
and a Midwestern Site

Distance (miles)	Coastal		Midwestern	
	Population	Dose	Population	Dose
0.5	0	0	0	0
1	1,112	4.1E-03	260	9.1E-04
2	1,112	4.1E-03	406	9.7E-04
3	1,298	4.2E-03	871	1.1E-03
4	2,940	4.4E-03	3,371	1.4E-03
5	4,325	4.5E-03	7,488	1.8E-03
10	68,080	6.7E-03	30,130	2.7E-03
15	124,900	7.3E-03	71,560	3.3E-03
25	169,300	7.5E-03	238,900	4.4E-03
35	305,700	7.9E-03	1,088,000	7.0E-03
45	429,100	8.1E-03	2,412,000	9.3E-03
55	552,974	8.2E-03	3,562,135	1.1E-02

^aTreatment Case 1.

Table 7.8. Major Radionuclides Contributing to Dose to Individuals from Gaseous Effluents via Terrestrial Pathways at 0.5 Mile from a Model Mixed-Oxide Fuel Fabrication Plant^a

Radionuclide	Percent of Total Body Dose			
	Submersion in Air	Contaminated Ground	Inhalation	Ingestion
²³⁸ Pu	<0.1	0.6	56.0	0.4
²³⁹ Pu	<0.1	<0.1	3.3	<0.1
²⁴⁰ Pu	<0.1	<0.1	7.3	<0.1
²⁴¹ Pu	<0.1	<0.1	27.0	0.2
²⁴¹ Am	<0.1	0.3	4.7	0.1
Others	<0.1	<0.1	<0.1	<0.1

^aCoastal site, treatment Case 1.

Table 7.9. Percent Contributions of Inhaled and Ingested Radionuclides from the Gaseous Effluent of a Model Mixed-Oxide Fuel Fabrication Plant^a to Individual Organ Doses

Radionuclide	Bone	Kidney	Lung	Liver
²³⁸ Pu	55.2	53.3	82.3	67.0
²³⁹ Pu	3.3	3.1	4.1	3.9
²⁴⁰ Pu	7.5	7.0	9.1	8.7
²⁴¹ Pu	31.8	28.2	1.9	14.1
²⁴¹ Am	1.7	7.9	2.4	5.2
Others	<0.1	<0.1	<0.1	<0.1

^aCoastal site, treatment Case 1.

Table 7.10. Annual Total Body Dose (mrem) from Aquatic Pathways^a
at a Model Mixed-Oxide Fuel Fabrication Plant

Exposure Pathway	Coastal Estuary	Midwestern River
Submersion in water ^b	2.4E-14	1.9E-14
Eating fish ^c	2.4E-12	1.8E-12
Drinking water ^d	-	1.7E-11
Total	2.4E-12	1.9E-11

^aTreatment Case 1.

^bSwimming for 1% of the year.

^cConsumption of 20 g of fish per day.

^dConsumption of 1.2 liters of water per day.

Table 7.11. Annual Dose to Biota Living in an Estuary^a Near a Model Mixed-Oxide Fuel Fabrication Plant^b at a Coastal Site

Radionuclide	Concentration ($\mu\text{Ci}/\text{ml}$)	Annual Dose (mrad)			
		Algae	Invertebrates	Fish	Waterfowl
²³¹ Th	9.7E-25	9.8E-15	6.6E-15	3.3E-14	1.0E-19
²³⁴ Pa	2.2E-23	1.1E-12	7.5E-13	3.7E-12	3.7E-16
²³⁴ U	3.0E-23	1.8E-12	2.8E-13	2.8E-13	2.8E-15
²³⁵ U	9.9E-25	5.7E-14	8.5E-15	8.5E-13	8.5E-17
²³⁷ U	9.0E-22	5.3E-11	7.9E-12	7.9E-12	7.9E-14
²³⁸ U	2.1E-23	1.1E-12	1.7E-13	1.7E-13	1.7E-15
²³⁸ Pu	1.5E-18	5.5E-07	1.6E-07	5.5E-09	5.2E-08
²³⁹ Pu	7.8E-20	2.7E-08	7.7E-09	2.7E-10	7.5E-09
²⁴⁰ Pu	1.7E-19	6.0E-08	1.7E-08	6.0E-10	1.6E-08
²⁴¹ Pu	3.9E-17	5.9E-07	1.7E-07	5.9E-09	3.6E-10
²⁴² Pu	1.1E-21	3.6E-10	1.0E-10	3.6E-12	1.2E-10
²⁴¹ Am	1.3E-19	6.9E-07	1.4E-07	3.4E-09	1.8E-07
Total dose		1.9E-06	4.9E-07	1.6E-08	2.6E-07

^aEstuary is 1 mile long by 0.5 mile wide and located 0.5 mile from the plant in the direction of the prevailing wind.

^bTreatment Case 1.

Table 7.12. Annual Dose to Biota Living in a Freshwater River^a
Near a Model Mixed-Oxide Fuel Fabrication Plant^b at a
Midwestern Site

Radionuclide	Concentration ($\mu\text{Ci}/\text{ml}$)	Annual Dose (mrad)			
		Algae	Invertebrates	Fish	Waterfowl
²³¹ Th	7.9E-25	4.0E-15	1.3E-15	7.7E-17	4.1E-20
²³⁴ Pa	1.7E-23	4.4E-13	1.5E-13	8.7E-15	1.4E-16
²³⁴ U	2.3E-23	1.1E-14	1.3E-12	2.1E-13	1.5E-17
²³⁵ U	7.7E-25	3.3E-16	4.0E-14	6.6E-15	4.8E-19
²³⁷ U	7.0E-22	3.1E-13	3.7E-11	6.2E-12	4.4E-16
²³⁸ U	1.7E-23	6.6E-15	8.0E-13	1.3E-13	9.6E-18
²³⁸ Pu	1.2E-18	4.3E-07	1.2E-07	4.3E-09	4.1E-08
²³⁹ Pu	6.1E-20	2.1E-08	6.0E-09	2.1E-10	5.8E-09
²⁴⁰ Pu	1.4E-19	4.7E-08	1.3E-08	4.7E-10	1.3E-08
²⁴¹ Pu	3.0E-17	4.6E-07	1.3E-07	4.6E-09	2.1E-09
²⁴² Pu	8.4E-22	2.8E-10	8.0E-11	2.8E-12	9.2E-11
²⁴¹ Am	1.0E-19	5.4E-07	1.1E-07	2.7E-09	1.4E-07
Total dose		1.5E-06	3.8E-07	1.2E-08	2.0E-07

^aRiver segment is 1 mile long by 0.1 mile wide and located 0.5 mile from the plant in the direction of the prevailing wind.

^bTreatment Case 1.

Table 7.13. Typical Variability of X/Q' Values and Population Data
at Midwestern and Coastal Sites

		Midwestern	Coastal
X/Q' ^a	Mean, sec·m ⁻³	2.67E-08	2.93E-08
	Standard deviation, sec·m ⁻³	1.24E-08	0.77E-08
	Coefficient of variation (CV)	0.46	0.26
Population ^b	Mean	3.56E+06	5.53E+05
	Standard deviation	3.34E+06	1.86E+05
	Coefficient of variation (CV)	0.93	0.33

^aBased on maximum X/Q' values at 0.7 mile from point of release. Represents directional variability at a given distance.

^bBased on cumulative population for area with a 55-mile radius.

Table 7.14. Curies of Actinides Released During Lifetime^a
of the Model Fuel Fabrication Plant

Radionuclide	Half-life (yr)	Curies Released ^b
²³⁸ Pu	8.6E+01	9.8E-04
²³⁹ Pu	2.4E+04	5.2E-05
²⁴⁰ Pu	6.6E+03	1.2E-04
²⁴¹ Pu	1.3E+01	2.6E-02
²⁴² Pu	3.9E+05	7.2E-07
²⁴¹ Am	4.6E+02	8.6E-05

^aA 20-year lifetime was assumed for plant operation.

^bTreatment Case 1. These values divided by $2.03 \times 10^{10} \text{ m}^2$ give the deposition assumed for the assessment of radiation doses.

Table 7.15. Contribution of Radionuclides and Exposure Modes to the Average Annual Total Body Dose^a to Individuals from the Time of Cessation of Plant Operation and Until the Ultimate Decay of all Radionuclides

Radionuclide	Exposure Mode			
	Contaminated Ground (mrem)	Inhalation (mrem)	Ingestion (mrem)	Total (mrem)
²³⁸ Pu	1.3E-07	5.1E-08	6.5E-10	1.8E-07
²³⁹ Pu	2.5E-09	3.0E-09	3.8E-11	5.5E-09
²⁴⁰ Pu	1.3E-08	6.6E-09	8.6E-11	1.9E-08
²⁴¹ Pu	0	2.4E-08	3.1E-10	2.4E-08
²⁴² Pu	7.8E-11	3.9E-11	5.1E-13	1.2E-10
²⁴¹ Am	5.1E-08	4.2E-09	1.8E-10	5.5E-08
Total	1.9E-07	8.9E-08	1.3E-09	2.8E-07

^aDose is the average total body dose of the individual out to a distance of 50 miles.

Table 7.16. Average Annual Doses to Individuals^a (Resulting from the Radionuclides Released During the Operation of the Model Fuel Fabrication Plant) from the Time of Cessation of Plant Operation and Until the Ultimate Decay of All Radionuclides

Radionuclide	Total Body Dose (mrem)	Organ Dose (mrem) per Exposure Mode							
		Bone		Kidney		Liver		Lung	
		Inhalation	Ingestion	Inhalation	Ingestion	Inhalation	Ingestion	Inhalation	Ingestion
²³⁸ Pu	1.8E-07	2.0E-06	2.6E-08	2.1E-07	2.8E-09	2.9E-07	3.7E-09	6.3E-08	6.5E-10
²³⁹ Pu	5.5E-09	1. E-07	1.6E-09	1.3E-08	1.6E-10	1.7E-08	2.1E-10	3.3E-09	3.8E-11
²⁴⁰ Pu	1.9E-08	2.7E-07	3.5E-09	2.8E-08	3.6E-10	3.7E-08	4.8E-10	7.4E-09	8.6E-11
²⁴¹ Pu	2.4E-08	1.2E-06	1.5E-08	1.2E-07	1.5E-09	5.9E-08	7.6E-10	1.5E-09	3.1E-10
²⁴² Pu	1.2E-10	1.6E-09	2.0E-11	1.7E-10	2.2E-12	2.2E-10	2.8E-12	4.4E-11	5.1E-13
²⁴¹ Am	5.5E-08	6.4E-08	2.8E-09	3.2E-08	1.4E-09	2.2E-08	9.6E-10	1.9E-09	1.8E-10
Total	2.8E-07	3.6E-06	4.9E-08	4.0E-07	6.2E-09	4.3E-07	6.1E-09	7.7E-08	1.3E-09

^aDose is the average total body and organ dose of the individual out to a distance of 50 miles.

Table 7.17. Average Annual Dose to the Population^a (Resulting from Radionuclides Released from the Model Fuel Fabrication Plant) From the Time of Cessation of Plant Operation and Until the Ultimate Decay of All Radionuclides

Radionuclide	Dose (man-rem/10 ⁶ persons)				
	Total Body	Bone	Kidney	Liver	Lung
Actinides	2.8E-04	3.6E-03	4.1E-04	4.4E-04	7.8E-05

^aDose to the population is average total body dose out to a distance of 50 miles.

Table 8.1. Radiation Dose from Gaseous Effluents and Annual Cost of Radwaste Treatment at Model Mixed-Oxide Fuel Fabrication Plant

Gaseous Radwaste Case	<u>Maximum Annual Individual Dose at 0.5 Mile (mrem)</u>					Annual Average Dose to Population out to 55 Miles (man-rem)	Annual Cost of Gaseous Radwaste Treatment (dollars)
	Total Body	Bone	Liver	Kidney	Lung		
<u>Coastal Site</u>							
1	8.5E-03	3.5E-01	4.1E-02	3.8E-02	7.7E-03	8.2E-03	7.6E+05
2	8.5E-05	3.5E-03	4.1E-04	3.8E-04	7.7E-05	8.2E-05	9.4E+05
3	8.5E-10	3.5E-08	4.1E-09	3.8E-09	7.7E-10	8.2E-10	1.2E+06
<u>Midwestern Site</u>							
1	8.6E-03	3.5E-01	4.1E-02	3.9E-02	7.8E-03	1.1E-02	7.6E+05
2	8.6E-05	3.5E-03	4.1E-04	3.9E-04	7.8E-05	1.1E-04	9.4E+05
3	8.6E-10	3.5E-08	4.1E-09	3.9E-09	7.8E-10	1.1E-09	1.2E+06

Table 8.2. Incremental Gaseous Radwaste Treatment Cost and Total Body Dose
Between Case Studies at Model Mixed-Oxide Fuel Fabrication Plant
at Coastal or Midwestern Sites^a

Case Increment	Decrease in Maximum Annual Individual Total Body Dose at 0.5 Mile (mrem)	Increase in Annual Cost for Treatment of Gaseous Radwaste (dollars)	Cost-Benefit (\$1000/mrem)
1/2	8.41E-03	1.82E+05	2.16E+04
2/3	8.50E-05	2.81E+05	3.31E+06

^aDoses are essentially equal at the two sites.

Fig. 4.1. Oxalate process for production of plutonium oxide (0.042 metric ton Pu/day).

Fig. 4.2. Fabrication of fuel for plutonium recycle reactors (1.0 metric ton U+Pu/day).

Fig. 4.3. Recycle system (0.1 metric ton U+Pu/day).

Fig. 4.4. Scrap recovery system (0.02 metric ton U+Pu/day).

Fig. 4.5. Plant ventilation and off-gas systems before final gaseous radwaste treatment (Cases 1 and 2).

Fig. 4.6. Gaseous radwaste treatment system (Case 1).

Fig. 4.7. Gaseous radwaste treatment system (Case 2).

Fig. 4.8. Plant ventilation, off-gas, and gaseous radwaste treatment systems (Case 3).

Fig. 4.10. Scrap recovery liquid radwaste treatment system.

Fig. 4.11. Solid radwaste treatment system.

Fig. 4.12. Fuel fabrication and radwaste systems.

Fig. 4.13. Miscellaneous liquid waste treatment.

Fig. 5.1. Water usage and overall liquid flowsheet.

Fig. 7.1. Pathways for external and internal exposure of man.

Fig. 7.2. Minimum and maximum X/Q' for ground level release at midwestern site. Average values of X/Q' for 16 sectors fall between these limits at respective distances.

Fig. 7.3. Minimum and maximum X/Q' for ground level release at coastal plain site. Average values of X/Q' for 16 sectors fall between these limits at respective distances.

Fig. 8.1. Annual cost for reduction of maximum annual dose from gaseous effluents at 0.5-mile distance from model mixed-oxide fuel fabrication plant. (Doses are not significantly different for coastal and midwestern locations.)

Fig. 8.2. Annual cost for reduction of annual population dose out to a radius of 55 miles from gaseous effluent from model mixed-oxide fuel fabrication plant.

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APPENDIX A. PREPARATION OF COST ESTIMATE

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1.0 INTRODUCTION

This Appendix presents the details of the methods used to estimate the capital costs and annual costs of the installations required for treating the gaseous radwastes at a model mixed-oxide ($\text{PuO}_2\text{-UO}_2$) recycle fuel fabrication plant. Treatment of the liquid wastes from the oxalate process, scrap recovery, and miscellaneous waste systems is included in the base plant and is not a variable in this study. No liquid wastes are released from the plant. The methods used for estimating the capital costs, annual fixed charges, annual operating and maintenance costs, and total annual costs are presented in Sect. 6.0 of the survey report. In summary, the total annual cost is the sum of the annual fixed charge, annual operating, and maintenance costs.

Annual fixed charges are estimated at 26% of total capital investment. This is typical of investor-owned fuel reprocessing and waste treatment facilities. The basis for calculation of the fixed charge rate is discussed in detail in Sect. 6.2 of the survey report. An annual operating and maintenance cost is added to the annual fixed charge on capital to give the total annual cost of a gaseous radwaste treatment case (Table A-1). The annual operating and maintenance cost is the sum of the following: (1) 3% of the direct cost, (2) blower power cost, (3) DOP filter testing cost, and (4) filter replacement cost. All costs are based on new construction costs where all of the equipment that is listed for each case study is included in an integrated plant. Backfitting costs for existing plants are not considered. All costs are estimated in terms of early 1973 dollars. The effect of future inflation is not included. The cost estimates are expected to have an accuracy of about $\pm 30\%$.

1.1 Capital Cost

The capital costs of the gaseous radwaste treatment cases are the sum of the direct costs and indirect costs. The methods used for estimating the direct and indirect costs are presented in the following sections.

1.1.1 Direct Costs

The major equipment components consist of HEPA filters including housings, blowers, dampers and drives, and ducts. The size and cost of each component are estimated based on cost experience at ORNL and data presented by Guthrie and other literature sources.¹⁻⁶ Building requirements are estimated based on equipment size. The costs of warehouse and related facilities are not included. The total direct cost for each gaseous radwaste treatment case is the sum of the installed equipment (material and labor) cost and the cost of the building space required.

1.1.2 Indirect Costs

Indirect costs are estimated as follows:

	<u>Percentage of Direct Cost</u>
Engineering and supervision	15
Construction expense and contractor's fee	20
Engineering design (A-E)	15
Contingency	45
Other owner's cost	10
Interest	<u>35</u>
	140

The interest during construction and the contingency allowance are included as indirect costs to simplify the calculations. Interest is applied to the cumulative total cost at the rate of 8% per year over a 5-yr cash flow expenditure period.

1.2 Gaseous Radwaste Treatment Case 1

The combined building ventilation and process gaseous flow rate is estimated to be 120,000 cfm. The treatment system consists of parallel HEPA filter modules as shown in Fig. A-1. The filter installation consists of five parallel HEPA filter modules. Each module is rated at 30,000 cfm and consists of two banks of 30 HEPA filters each in series within a housing. Each module is equipped with a 40,000-cfm blower and dampers with drives for isolating a module from the system for filter replacement and/or DOP leak testing. One module can be out of service at any given time and the remaining four modules have sufficient capacity to handle the 120,000-cfm gaseous flow. An isolation valve in the exhaust duct is considered part of the base plant and it is not included in the total equipment cost.

Direct Cost

HEPA Filters. — The total installation cost (labor and materials) for HEPA filter installations is estimated to be \$1500 per 1000-cfm HEPA filter.¹ This figure includes the filter housing and the leak testing, weld inspection, etc., that are required to assure a high-efficiency performance for the total installation.

$$10 \times 30 \times \$1500 = \$450,000 = \text{Total HEPA filter cost}$$

Blowers. — The cost of the five 40,000-cfm blowers² is calculated as follows:

$$5 \times 7 \times 40,000^{0.68} \times 1.06^5 \times 1.03 \times 1.59 = \$103,000$$

Duct. — The equivalent of 500 ft of stainless steel, welded duct is required for the Case 1 gaseous treatment system. Each duct is sized for a volumetric flow of 30,000 cfm at a velocity of 3000 fpm.

$$\text{Duct cross-section area} = 10 \text{ ft}^2$$

$$\text{Duct diameter} = \sqrt{4 \times 10 / 3.14} = 3.6 \text{ ft}$$

The installed cost of the duct (14 gauge stainless steel) is estimated as follows:

$$\frac{3.6 \times 3.14 \times 0.078 \times 500}{12} \times 4.10 \times 1.45 = \$173/\text{linear ft}$$

$$173 \times 500 = \$86,500$$

Dampers and Drives. - The purchase price of dampers and drives as a function of diameter is presented in Fig. A-2.³

Ten 43-in.-diam dampers and drives are required and the cost of installation (labor and materials) is equivalent to 20% of the purchase price.

$$10 \times 15,000 \times 1.2 = \$180,000$$

Structure. - An area 70 ft by 80 ft of a Class I building (\$55/ft²) including services and auxiliaries is required for the Class I gaseous treatment system.⁴

$$70 \times 80 \times 55 = \$308,000$$

Total Direct Cost

HEPA filters	\$ 450,000
Blowers	103,000
Ducts	86,500
Dampers and drives	180,000
Structure	<u>308,000</u>
	\$1,127,500
Use	\$1,128,000

Indirect Cost

$$1.4 \times 1,128,000 = \$1,579,200$$

Capital Cost

$$\text{Direct cost} + \text{indirect cost} = \$2,707,000$$

Annual Fixed Charge

$$0.26 \times 2,707,000 = \$704,000$$

Annual Operating and Maintenance Cost (O&M)

The annual operating and maintenance cost is taken as the sum of the following: (1) 3% of direct cost, (2) blower power cost, (3) DOP leak test cost, and (4) filter replacement cost.

Maintenance Cost

$$0.03 \times 1,038,000^a = \$31,140$$

Blower Power Cost

$$4 \times 80 \times 0.746 \times 8760 \times 1.0 \times 0.0075 = \$15,700$$

DOP Leak Test - The HEPA filters are tested with DOP twice a year and the test of a single bank of filters requires 30 minutes for 2 men at a labor charge of \$15/MH.⁵ Allowing for set-up time, etc., a labor charge of 2 man-hours or \$30/module is used.

$$30 \times 10 \times 2 = \$600$$

Filter Replacement Cost. - The HEPA filters are replaced every two years. The estimated cost (labor + materials) for replacing the filters is based on the following information⁶ and presented in Fig. A-3. To change 1 1000-cfm HEPA requires 2 men 2 hours (4 MH) and to change a bank of 50 HEPAs requires 4 men 8 hours (32 MH). The cost of a single filter is estimated at \$60 and the labor charge at \$15/MH.

$$\frac{2100 \times 10}{2} = \$10,500$$

$$\text{Total Annual O\&M Cost} = \$57,940 \quad \text{Use } \$58,000$$

Total Annual Cost (Case 1)

$$\text{Annual fixed charge} + \text{annual O\&M} = \$762,000$$

---

^aExcluding duct cost, since little O&M is required for ducts.

1.3 Gaseous Radwaste Treatment Case 2

Case 2 consists of adding a third bank of five HEPA modules in series with the two banks of HEPA modules in Case 1. Each module contains 30 1000-cfm filters (Fig. A-4).

Direct Cost (in addition to Case 1)

HEPA Filters. - The costing method is similar to that for Case 1.

$$5 \times 30 \times 1500 = \$225,000$$

Structure. - An additional 800 ft² of floor area of a Class I building (\$55/ft²) is required for the third bank of five HEPA filter modules.

$$800 \times 55 = \$44,000$$

Total Direct Cost

HEPA filters	\$225,000
Structure	44,000
	<u>\$269,000</u>

Indirect Cost

$$1.4 \times 269,000 = \$376,600$$

Capital Cost

$$\text{Direct cost} + \text{indirect cost} = \$645,600$$

Annual Fixed Charge

$$0.26 \times 645,600 = \$167,856 \quad \text{Use } \$168,000$$

Annual Operating and Maintenance Cost (O&M)

The annual operating and maintenance cost is estimated on the same basis as Case 1.

Maintenance Cost

$$0.03 \times 269,000 = \$8070$$

DOP Leak Testing Cost

$$30 \times 2 \times 5 = \$300$$

Filter Replacement Cost

$$\frac{2100 \times 5}{2} = \$5250$$

$$\underline{\text{Total Annual O\&M Cost}} = \$13,620 \quad \text{Use } \$13,600$$

Total Annual Cost (Case 2)

$$\text{Fixed charge} + \text{O\&M} = \$181,600 \quad \text{Use } \$182,000$$

The annual cost of \$182,000 for Case 2 is the incremental increase in annual cost over that for Case 1. The total cost for Case 2 is the sum of the Case 1 costs and the incremental increase for Case 2 resulting in total costs as follows: Capital cost - \$3,353,000; Annual Fixed Charge - \$872,000; Annual Operating Cost - \$72,000; and Total Annual Cost - \$944,000.

1.4 Gaseous Radwaste Treatment Case 3

The gaseous radwaste treatment for Case 3 consists of recycle of 98% of the process off-gases and alpha enclosure ventilation air through one stage of HEPA filtration. The remaining effluent (2% of air flow) is treated with two stages of HEPA filtration and is blended with the fume hood and plant ventilation air. The combined total plant off-gas is then passed through two stages of HEPA filters (Fig. A-5). The method used for costing the equipment and structure is similar to that for Case 1.

Direct CostsHEPA Filters

9 - 6 x 7 modules

$$9 \times 42 \times 1500 = \$567,000$$

4 - 1 x 2 modules

$$4 \times 2 \times 1500 = \$12,000$$

$$\text{Total} = \$579,000$$

Blowers

6 - 40,000 cfm

$$6 \times 7 \times 40,000^{0.68} \times 1.06^5 \times 1.03 \times 1.59 = \$124,000$$

2 - 2000 cfm

$$2 \times 7 \times 2000^{0.68} \times 1.06^5 \times 1.03 \times 1.59 = \$5,400$$

Total = \$129,400

Dampers and Drives

12 - 51-in. diameter

$$12 \times 20,000 \times 1.20 = \$288,000$$

2 - 43-in. diameter

$$2 \times 15,000 \times 1.20 = \$36,000$$

1 - 36-in. diameter

$$1 \times 12,000 \times 1.2 = \$14,400$$

4 - 12-in. diameter

$$4 \times 3200 \times 1.2 = \$15,360$$

Total = \$354,000

Ducts. - The specifications for the various ducts are listed in the order of length, volumetric flow rate, gas velocity, and duct diameter.

150 ft - 70,000 cfm - 3000 fpm - 5.5 ft diameter - 14 gage

$$\frac{5.5 \times 3.14 \times 0.078 \times 1 \times 500}{12} \times 4.10 \times 1.15 = \$265/\text{ft}$$

$$265 \times 150 = \$39,750$$

700 ft - 40,000 cfm - 3000 fpm - 4.2 ft diameter - 14 gage

$$\frac{4.2 \times 3.14 \times 0.078 \times 1 \times 500}{12} \times 4.10 \times 1.15 = \$202/\text{ft}$$

$$202 \times 700 = \$141,400$$

100 ft - 30,000 cfm - 3000 fpm - 3.6 ft diameter - 14 gage

$$\frac{3.6 \times 3.14 \times 0.078 \times 1 \times 500}{12} \times 4.10 \times 1.15 = \$173/\text{ft}$$

$$173 \times 100 = \$17,300$$

100 ft - 20,000 cfm - 3000 fpm - 3.0 ft diameter - 14 gage

$$\frac{3.0 \times 3.14 \times 0.078 \times 1 \times 500}{12} \times 4.10 \times 1.15 = \$144/\text{ft}$$

$$144 \times 100 = \$14,400$$

150 ft - 2000 cfm - 3000 fpm - 1.0 ft diameter - 14 gage

$$\frac{1.0 \times 3.14 \times 0.078 \times 1.0 \times 500}{12} \times 4.10 \times 1.15 = \$48/\text{ft}$$

$$48 \times 150 = \$7200$$

$$\text{Total} = \$220,000$$

Structure. - An area of 10,000 ft² of a Class I building (\$55/ft²) is required to house the filters, blowers, dampers and drives, and ducts.

$$10,000 \times 55 = \$550,000$$

Total Direct Cost

Filters	\$ 579,000
Blowers	129,400
Dampers and drives	354,000
Ducts	220,000
Structure	<u>550,000</u>
Total	\$1,832,400

Indirect Cost

$$1.4 \times 1,832,400 = \$2,565,000$$

Capital Cost

$$\text{Direct cost} + \text{indirect cost} = \$4,397,000$$

Annual Fixed Charge

$$0.26 \times 4,397,000 = \$1,143,000$$

Annual Operating and Maintenance Cost (O&M)

The annual operating and maintenance cost is estimated to be the sum of the following: (1) 3% of direct cost, (2) blower power cost, (3) DOP leak test cost, and (4) filter replacement cost.

Maintenance Cost

$$0.03 \times 1,832,400 = \$54,972^a$$

---

^aIncluding duct cost, since the complicated ducting system may require significant O&M.

Blower Power Cost

$$4 \times 80 \times 0.746 \times 8760 \times 1.0 \times 0.0075 = \$15,700$$

$$1 \times 4 \times 0.746 \times 8760 \times 1.0 \times 0.0075 = \$785$$

$$\text{Total} = \$16,485$$

DOP Leak Testing Cost

$$30 \times 13 \times 2 = \$780$$

Filter Replacement Cost

$$\frac{200 \times 4}{2} = \$400$$

$$\frac{2100 \times 9}{2} = \$9450$$

$$\text{Total} = \$9850$$

$$\text{Total Annual O\&M Cost} = \$82,087 \quad \text{Use } \$82,000$$

Total Annual Cost (Case 3)

$$\text{Fixed charge} + \text{O\&M} = \$1,225,000$$

1.5 References

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4. V. O. Haynes and M. L. Myers, Cost Estimates for Radwaste Systems for Two-Reactor PWR and BWR Plants, ORNL-CF-72-6-9.
5. J. J. Smith, Inspection Engineering, ORNL, unpublished data.
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Table A-1. Summary of Capital and Annual Costs for Model Mixed-Oxide ($\text{PuO}_2\text{-UO}_2$) Fuel Fabrication
Plant - Gaseous Radwaste Treatment Cases 1-3

	Case 1	Case 2	Case 3
Direct Cost ^a			
HEPA Filters	\$ 450,000	\$ 675,000	\$ 579,000
Blowers	103,000	103,000	129,400
Ducts	86,500	86,500	354,000
Dampers and Drives	180,000	180,000	220,000
Structure	<u>308,000</u>	<u>352,000</u>	<u>550,000</u>
Total	\$1,127,500	\$1,396,500	\$1,832,400
Indirect Cost, 140%	\$1,579,200	\$1,995,100	\$2,565,400
Capital Cost ^b	\$2,707,000	\$3,352,000	\$4,397,800
Annual Fixed Charge ^c	\$ 704,000	\$ 872,000	\$1,143,000
Annual Operating (O&M) Cost	\$ 48,000	\$ 72,000	\$ 82,000
Total Annual Cost	\$ 762,000	\$ 944,000	\$1,225,000

^aDirect cost is complete equipment installation and structure cost (material and labor).

^bCapital cost is the sum of the direct cost and indirect cost.

^cAnnual fixed charge is estimated at 26% of capital cost.

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Fig. A-1. Gaseous radwaste treatment system (Case 1).

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Fig. A-2. Purchase price of dampers and drives as a function of damper diameter.

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Fig. A-3. Complete cost (labor and materials) for replacing HEPA filters as a function of volumetric gaseous flow rate.

Fig. A-4. Gaseous radwaste treatment system (Case 2).

Fig. A-5. Gaseous radwaste treatment system (Case 3).

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